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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

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on

Handling Qualities Criteria

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ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Conference Proceedings No. 106

HANDLING QUALITIES CRITERIA

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Papers and discussion from the AGARD Flight Mechanics Panel Specialists Meeting held at Ottawa, Canada on 28 September – 1 October 1971.

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PREFACE

This Flight Mechanics Panel Specialists Meeting on Handling Qualities Criteria was held to discuss the current status, problems, activities and issues involved in the development and application of handling qualities criteria within the NATO countries. It was structured with six sessions and twenty-one technical papers, with each paper followed by a lead discussor paper and then general floor discussion in order to highlight differences in viewpoint in regard to the major topics. A round-table discussion by Flight Mechanics Panel members provided an overall summary and projection of "Where do we go from here?"

Attendance was limited to assure a small enough group to foster lively discussions. It was carefully planned, however, to include a wide cross section of designers, developers, acceptance and certification authorities, and test pilots, as well as the technical experts and researchers in the various specialties, who were fully conversant in one or more aspects of the subject. As hoped, the assembly of this inter-disciplinary group, concerned with the research, development, specification, application and validation of handling qualities, provided an excellent forum for the sharing of new results and very active discussions. These highlighted problems and identified areas in which future work is required. A tour of the National Research Establishment facilities was included in the three and one-half days of the meeting.

The first two sessions were devoted to the status of flying qualities requirements and criteria, one session for conventional aircraft and one for V/STOL. A review of the most recent U. S. and French flying qualities requirements and the philosophy of the French E.S.A.U., which greatly influenced the specifications, plus papers on commercial flying quality standards, AGARD 408A and flight test validation efforts provided a continuous catalyst for discussion throughout the meeting. The third session reviewed the establishment of flying qualities by use of such techniques as analysis of current aircraft, simulation and analysis, and pilot opinion ratings. The fourth session covered special problems and interfaces, such as stall, post-stall gyrations, turbulence, ride control with flexible airframes and influence of modern flight control systems. The fifth session provided a forum for discussions of man-machine relationships and glimpses of research underway in this important area. The subjective nature of pilot opinion ratings and the role of the pilot as the ultimate judge of the adequacy of flying qualities was a source of considerable discussion. The sixth session provided insight into the more general flying qualities research underway within NASA and the U. S. Navy.

Very active discussions throughout the meeting brought out many facets of each issue and often had to be concluded because of time limitations, despite the desire of many participants to contribute to the discussions. Over one hundred twenty comments were recorded during the meeting and are testimony to the very active discussions that took place. The need for clarification of such basic terms as criteria and specification and the application of handling qualities requirements signaled the importance of improving communications and exchanging research and development information in this area. It was evident that the meeting made an excellent contribution in this direction.

While coverage of the subject was as complete as practical within the time available, the meeting's scope did not permit covering a number of areas of importance. The affect of flying qualities on accomplishment of military functions such as weapon delivery, fighter combat, and air-to-air refueling and impact of the technical development of new flight control systems and pilot displays had to be reserved for a future discussion.

The round-table discussion at the end of the meeting summarized key issues brought out in the meeting and highlighted the useful role that AGARD can play in standardizing many of the important models used in the analysis and simulation of handling qualities, sharing results of mutual interest, identifying important issues, and validating criteria by means of flight tests.

I would like to thank all of those that have contributed to the success of the meeting:

- The National Aeronautical Establishment for its fine hospitality
- Mr. Wasicko for his help in assuring the arrangements
- The Panel Members who assisted in arranging speakers from the participating countries
- Messrs. Westbrook and Carlson of the USAF, who assisted me in the preparation of the program.

WILLIAM E. LAMAR
Member,
Flight Mechanics Panel

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COMPARISON OF FRENCH AND UNITED STATES FLYING QUALITIES REQUIREMENTS

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SUMMARY

This comparison of flying qualities requirements shows that the two sets of criteria are basically the same in intent and goals. Requirements for new aircraft must be more sophisticated because the aircraft are more complex. Requirements have been added to account for equipment failures, the way the aircraft are to be used, where they are to be used, and how well they must fly. All of these items are included in the two specifications, E.S.A.U. and Mil-F-8785B. The use of probability is a significant change from previous criteria, and it is used with equipment failures in both specifications.

The technical requirements that a new airplane must meet are more and more difficult to apply to modern airplanes for the following reasons:

- The classic technical requirements, generally based on established experience, make a priori assumptions on the configuration, the technology, and the use of the airplane or on the reliability of its systems. Consequently, the cases assumed to be critical for which the requirements must be applied are not always the really critical ones experienced in operational use.

- The requirements are often rules of thumb. In other words, they are only methods to insure the safety in particular cases, but the involved elementary objectives of safety are not mentioned. To prescribe a rule of thumb, even if it is well justified by the established experience, may be dangerous for two reasons. It risks stopping the evolution of the technique and does not insure the safety in every case (for instance, a change of configuration or technology may make a rule of thumb useless or even dangerous).

The simple handling qualities requirements become more and more null and void due to the complexity of modern aircraft with their flight envelopes in altitude and speed and with the increasing importance of the capability to take-off and land with bad visibility.

This situation appeared critical on the European side when we had to specify the handling qualities and performance standards for Concorde. The general purpose of requirements is not exactly the same for civil and military airplanes, but the problem of elaboration of requirements is equivalent. After hard, long, slow work and the publication of a great number of working papers, preliminary drafts, drafts, approved text, and revised text, a handling qualities specification, approved by the manufacturers and the Franco British airworthiness authorities, was published in July 69 and called TSS-5, Issue 2. The requirements are based on new principles which were elaborated at this occasion. These principles, known for a moment as "Philosophy of TSS-5", are very general and applicable to every type of piloted airplane; the TSS Standard 5 is only an application of this philosophy to supersonic transports. These principles have been given in their generality in a paper called E.S.A.U. which means "Etude de la Sécurité des Aéronefs en Utilisation"; in other words, Investigation for Safety of Aircraft in Service, and which may be translated by I.S.A.A.C.S. for "Investigation for Safety of Aircraft and Crews in Service".

In this title, the words "in Service" are very important. They mean that it is fundamental to consider the way of use, in other words, the mission of the aircraft. It is evident that the requirements for take-off must not be identical for a supersonic heavy bomber and for a VTOL fighter. This is also true, but not so evident, for a supersonic bomber and a supersonic transport. Indeed, the objective of the requirements shall be the same, i.e., "to assure that no limitations on flight safety will result from deficiencies in flying qualities during take-off"; but since the missions are different, the requirements may be different.

E.S.A.U. put this idea into evidence to show that differences between transport airplanes were not only a question of weight and number of engines but also to show the need to adapt the requirements to the specific mission of supersonic transport. In the new military specification of the US Air Force which was written for every type of aircraft, it was also necessary to use this basic idea.

The objectives of the French and US specifications are similar, but there is a significant difference. It has been stated previously that the French objective is to assure that there will be no limitations on flight safety due to deficiencies in flying qualities. The US objective is to assure that there will be no limitations on flight safety or mission effectiveness due to deficiencies in flying qualities. The addition of the words "mission effectiveness" is the major difference between the two specifications and the requirements in them. There is a need to specify, in as many cases as possible, what is meant by mission effectiveness. The numerical values placed on the flying qualities parameters are done to assure a mission effective airplane.

Specifications are also intended to be used before the airplane is delivered for flight testing. The specification should be used for design requirements and as criteria during the stability and control development which includes analytical work, wind tunnel results, and simulations. The US specification was prepared to be adaptable to this multiple use idea. All the requirements were to

be able to be demonstrated by flight test methods. They were also to be capable of being used during the various phases of development mentioned above. These thoughts were constantly kept in mind during the preparation of the specification which went through the same cycle as the French specification, that is, many drafts and revisions before it was issued in August 1969, just a month later than the French specification. Mil-F-8785B has now been in use for two years and has already undergone one revision. Mil-F-8785B is entirely a military specification and is not used by the civil authorities in the US.

Now to return to the thought of safety and mission effectiveness.

For nearly all commercial airplanes, the mission is the same whether it is to carry a man and his wife on a sightseeing trip around Ottawa on a pleasant afternoon, taking off and landing at the same airport, or flying a rock group from a TV appearance in Paris one day to a TV appearance in New York the next. The mission is the same - take people from take-off to landing safely. In this case, safety and mission success are the same thing. If the passengers arrive safely at their destination, the mission is a success. Perhaps there should be something mentioned about on-time arrival being related to mission success, but that will not be discussed here. Generally, this type of flying involves small excursions of load factor near the load factor of one.

The military situation is different. There is a definite difference between mission success and safety. There are military missions that are the same as the mission of the commercial airplane and involve moving people from one place to another where safety and mission effectiveness are the same. Most military missions are different. For combat aircraft, such as fighters and bombers, mission effectiveness and safety are not the same. The airplane may have returned to its base with complete safety; but if it did not hit the target or did not destroy the enemy aircraft or cause it to turn back, the mission effectiveness was zero. Similarly, if the airplane destroyed the target or the enemy aircraft, it had a very high mission effectiveness even if it did not return from the mission and did not satisfy the desire for safety. The goal is to be successful for both safety and effectiveness. Even the military airplane mentioned previously which carried people may have a mission which must consider this difference. This same airplane may be required to make an aerial delivery of cargo, be used as a gunship, or modified for some other combat mission.

Because of the necessity to consider mission success, it was necessary to prepare requirements that included all the various missions. The task was too complex to have a different requirement for each and every mission. It was possible to group several basic missions together in order to have a classification of aircraft of related or sufficiently similar missions that requirements could be applied to this class. For Mil-F-8785B, four different classifications or groups were made and designated as Classes I, II, III, and IV. The classes are based not only on the intended use of the aircraft, but on size, weight, and maneuverability as well. Weight and maneuverability are used to define the four classes. Class I airplanes are small and light, generally 12,000 pounds or less. Class II airplanes are medium weight with low to medium maneuverability. Class III likewise are low to medium maneuverability but are heavy. Class IV aircraft are the high maneuverability airplanes. If the classification had been done by weight alone, then low, medium, and high maneuverability airplanes would have the same requirements and since their missions are usually quite different, the classes/groups would not make much sense. In such a case, both a fighter and a short range cargo plane would have to meet the same requirements.

Even when the general purpose or class of the airplane has been established, it is necessary to look at the mission and its parts. The type of aircraft gives only a general idea of its use. But it is evident that it is necessary to look at the mission with many more details to specify the requirements.

We divide the flight into a certain number of parts we call Phases.

- A Phase has a general purpose. For instance, the Phase "climb" has the following purpose. From the height of fifty feet after take-off, fly the aircraft until reaching the altitude of cruise, following a given ground pattern. Generally a Phase is still too complex and may include too many different maneuvers. So it is necessary to divide each Phase into a certain number of elementary parts called Sub-Phases. A Sub-Phase has one elementary purpose. For instance, during the Phase "ILS approach", we can look at the Sub-Phase "final descent", the elementary purpose of this Sub-Phase being:

- Using ILS, fly the airplane in descent, until reaching three hundred feet in a good position to make a visual landing. We have to notice that the objective of each Sub-Phase is given with tolerances taking into account the possibility of performing the next Sub-Phase. For instance, we may divide the ILS approach phase in four Sub-Phases which are:

  Sub-Phase 1. Search of the localizer.
  The purpose of this Sub-Phase is to reach the vertical plane of the localizer at the height of one thousand and five hundred feet with good heading. It is evident that there are tolerances in position, altitude, and heading.

  Sub-Phase 2. Waiting the glide.
  The purpose of this Sub-Phase is to reach the glide plane at the height of one thousand and five hundred feet with the good heading.

  Sub-Phase 3. Push over.
  The purpose of this Sub-Phase is to place the airplane in good position and attitude to begin the descent.

  And last, Sub-Phase 4. Final descent.
  We have already seen the purpose of this Sub-Phase. Place the aircraft in good position at three hundred feet to make a visual landing.

The handling qualities required in order to perform each Phase and Sub-Phase are not exactly the same. For instance, high stability is more favorable for the approach phase than for the transonic acceleration phase.

This division into Flight Phases is necessary when building new requirements to be sure not to forget some important criteria to be checked in order to assure that the airplane is able to perform the total flight.

In Mil-F-8785B, there is also the need to look at the mission in its component parts. This mission itself is much too large to have a given set of stability or maneuverability requirements apply at all times with any validity. For this reason, the mission has been broken down into components which are called Flight Phases. As with the French requirements, each Flight Phase has a general purpose. The purpose is usually obvious from the name of the Flight Phase. For example, take-off, climb, air-to-air combat, descent, land, etc. The name of the Flight Phase is descriptive enough without requiring further definition.

Because of the need to consider mission success and to have criteria that will tell the designer what flying qualities must be provided, most of the requirements in Mil-F-8785B are quantitative. The task of providing quantitative requirements for each different Flight Phase was very difficult. To further separate the Flight Phase into more precise Sub-Phases, each with its set of quantitative requirements, would make the job of writing and keeping a listing of all requirements terribly difficult and would result in an intricate and unwieldy set of criteria. In addition, there were not enough data to allow the preparation of such a set of requirements with any feeling that it could be justified. It was even necessary to take the complete list of Flight Phases and combine them into a more usable arrangement.

The various Flight Phases can be grouped according to the type of task that must be accomplished. It was found that in piloting evaluations in flight and in simulators, pilots can rate a mission segment similar to the Flight Phase. The rating assigned will be based on the ability and need to perform certain tasks of varying precision. It was also found that there was a similarity of tasks in many Flight Phases so that the Phases could be grouped. At first, all Phases were separated into a terminal operation group and a non-terminal operation group. Then the non-terminal group was divided into two groups based on the maneuverability or precision required. This resulted in three Categories of Flight Phases, A, B, and C. Category A Phases require high precision or rapid maneuverability or both. Category B Phases require gradual maneuvers and not much precision while Category C Phases are in the vicinity of the airport or base. These Category C maneuvers may have to be very precise but are usually of small amplitude and are classified as gradual.

All the Flight Phases of an aircraft are listed and placed in the proper category. It is not necessary for an airplane to have a Flight Phase in both Category A and B, but C is certainly always required. Every portion of the mission must be included in a Flight Phase so that there are no gaps between Phases.

It is now necessary to describe how well the airplane must fly in the Categories and Flight Phases.

Having given these first definitions taking into account the use of the aircraft, we can ask for the level of handling qualities we require.

It is evident for purely mathematical reasons that we cannot require a level of handling qualities so high that the accident becomes strictly impossible and that we are sure to perform every mission. We ought to accept a not zero probability of accident or of failure of the mission.

The selection of an acceptable value poses more than many philosophical and practical questions. Let us bear in mind that any discussion of this matter must be relegated to the realm of theory, at least for the next decade, since it is not possible to determine the absolute value of the probability P of an accident.

On the point of view of civil transportation, the average passenger is directly concerned about the probability of accident. He would like it to be as small as possible. He may even wish it were absolutely zero! From a scientific point of view, we know that such a condition is unattainable; but we must acknowledge that, for psychological reasons, it is extremely difficult for an individual to admit this. This attitude is one of the stumbling blocks which must be overcome if probability methods of certification are to be pursued. To appreciate the importance of this, we need only imagine the success of an airline company which based its advertisements on the slogan "We have ten times fewer accidents than any other means of transportation" or "You have less chance of perishing over the Atlantic on our airplanes than while crossing the Place de la Concorde, Picadilly Circus, Times Square, or Wellington Street on foot". A company cannot officially admit to the public that a certain accident rate is inevitable, and, what is even more serious, that this accident rate is predictable.

Thus in the silence of the office (where everyone believes that the probability of perishing within the next hour is zero!), we are led to ponder the reasons which prompt an average passenger to unconsciously accept a certain probability of risk. In general, once the necessity of traveling has been established, the selection of a means of transportation is made by weighing the comfort against the risk associated with each available mode. By comfort, we mean a very general term in which the length of the trip is a factor. An increase in comfort can make an increase in risk acceptable.

A rule can be tentatively accepted in order to guide the certification authorities in the definition of a maximum acceptable value.

The probability of accident for a given aircraft should be the same order of magnitude as it is for its competitors. It can be slightly greater if it is acknowledged that an aircraft provides greater comfort by virtue of its speed. In any case, a maximum value which may never be exceeded is derived

from the accident probability of aircraft belonging to the preceding generation.

We have been viewing the situation from the point of view of the average passenger who is only concerned about the probability that he will perish during the flight. If he is to die, he does not care whether he does so in the company of 50 or 500 people. In other words, he does not take the size of the aircraft into consideration. On the other hand, for the airline company, an accident probability per flight represents a certain financial loss which increases with the size of aircraft and the frequency of flights.

The government views the situation in almost the same manner, since the loss of human potential per year for a given value of the probability of accident is proportional to the number of transported passengers.

And last, the selection of the acceptable probability of failure of the mission is governed by similar reasons. It is a question of efficiency of the system taking into account the available numbers of aircraft and pilots, the scheduled number of missions, the scheduled duration of the war, and so on. A cost effectiveness study can theoretically provide the answer. For civil transportation, the only rule we will use is the following.

The accident probability of an aircraft should always be less than that of the aircraft of the preceding generation. An increase in comfort brought about by the introduction of a new generation cannot, in any case, serve as a justification for lowering safety standards.

So to assure that the probability of accident or that the probability of failure of the mission is reasonably low, we ought to require a high level of handling qualities for the flight cases highly probable; but we may accept a lower level of handling qualities for unusual flight cases.

First, look at the concept of Level of handling qualities.

A Level is a relative value or amount of goodness of a stability and control or flying qualities parameter. It is used to relate flying qualities to mission effectiveness and safety. Three Levels of flying qualities have been used in the requirements of 8785B, and they can be directly compared to pilot ratings that have been obtained in flying qualities experiments. The three Levels have been defined in association with the ability to complete the missions for which the airplane was designed. The Levels and the pilot ratings which go with them are:

Level 1 - Flying qualities clearly adequate for the mission Flight Phase. Pilot ratings 1 - 3.5.

Level 2 - Flying qualities adequate to do the mission Flight Phase, but with some increase in pilot workload or loss of mission effectiveness, or both. Pilot rating 3.5 - 6.5.

Level 3 - Flying qualities such that the airplane can be controlled safely, but pilot workload is excessive or mission effectiveness is inadequate, or both. Pilot rating 6.5 - 9+.

The pilot rating scale used here is the Cooper-Harper scale.

It is desired that Level 1 flying qualities be provided to the pilot as often as possible, but it is realized that failures will occur and that a reduced Level will be experienced. When the reduced Levels occur, they must be safe and will probably have some impact on the mission. For Level 2, it is intended that the mission continue with a reduced chance of complete success and with the pilot working harder to achieve the success. For Level 3, it is expected that there will be little chance of success, that the mission will be aborted, and that the pilot workload will be high. If the airplane is performing Category A Flight Phases, they shall be safely terminated, and the Category B and C Phases shall be completed.

In as many places as possible, the requirements have been presented with three values or Levels. In some cases, the data are not available to allow three Levels.

It is intended that Level 3 represent an airplane that is a minimum safe values airplane. This is not always true if only one parameter is considered at a time. Level 3 values, in some cases, were increased over the barely safe value to allow for the degradation of several parameters at once. This has been done with some hesitation because not enough is known about flying with several parameters at the Level 3 value.

If the characteristics fall below the minimums for Level 3, a flight safely problem exists and the return of the aircraft cannot be assured.

With this philosophy and organization of the requirements, it is now necessary to present some definitions. Before considering the probability of a flight case, it is necessary to give some definitions concerning the airplane itself.

The controls may be divided into two types:

- controls we call selectors which are the controls maintained in fixed position during the Sub-Phase,

- and main controls which are the controls used in the pilot loop during the Sub-Phase.

We have to notice that according to their use during the Sub-Phase, controls may be alternately selectors and main controls; for instance, the pitch trim and the throttle are selectors during take-off and main controls during approach.

A Selected Configuration is defined by the position of the different selectors. For each Sub-Phase,

there is one Selected Configuration or a change of Selected Configuration given in the flight manual.

Parallel to the Selected Configuration, we define the True Configuration which is the result of a failure situation on a Selected Configuration. We have to note that for each Sub-Phase, there is only one Selected Configuration but a set of possible True Configurations.

The State of the Airplane during a Sub-Phase is then given by:

- a True Configuration,
- a mass of the airplane,
- and a given distribution of mass. Generally this mass distribution is given by the longitudinal position of the center of gravity.

In the Mil Spec 8785, we find similar definitions:

8785B also uses Configuration and State of the Airplane. The Selected Configuration is defined by the positions and adjustments of the selectors and controls which do not change during the Flight Phase. The other controls that do change, such as elevator, aileron, etc., are not included in the Selected Configuration. The State of the Airplane is the Selected Configuration and the functional status of the equipment - the same as the French True Configuration. In addition, weight and center of gravity envelopes for each Flight Phase must be provided as well as the moment of inertia variations. The requirements apply to all the conditions included in these envelopes. Hence we now have a situation identical to the French State of the Airplane.

We now arrive at a point where the two requirements are different. We shall note here a small difference between the Mil Spec and E.S.A.U. In order to define the Probability of a State, E.S.A.U. takes into account not only the probability of occurrence of the failure of the different systems but also the probability to fly with the mass and the position of center of gravity given in the definition of the state. It is only a theoretical subtlety which does not change anything in practice.

We shall see now a more important difference between E.S.A.U. and the Mil Spec.

In 8785B, the required level of handling qualities is connected with the probability of the State of the Aircraft. Indeed, it would be better to connect it with not only the state of the airplane but also with the State of the Atmosphere.

In E.S.A.U., the State of the Atmosphere is defined by the set of all the characteristic parameters which can modify the behaviour of the airplane and the behaviour of the crew, for instance, wind, temperature, gusts, clouds, rain, hail, birds, and so on. The investigations made on the subject have shown that after having classified some factors like birds and hail among the origins of different failures and consequently through their effect among the different failure states, we can reduce the set of factors to only seven which are:

- Pressure - Temperature and humidity which act mainly on performance.
- Intensity of turbulence which can be measured by the root mean square of the vertical and horizontal components of gust.
- Temperature gradient.
- Visibility.

And last, for the take-off and landing phases, the laws of variation of wind, force, and direction versus altitude.

In a similar way, the State of the Runway is defined by

- its length and width,
- its mean slope,
- its profile, in other words, the undulations, and
- its coefficient of friction.

It is evident that these factors have an influence on the handling qualities, and that it is necessary, for instance, to look at the behaviour of the airplane in rough air or on icy runways.

But we have to confess that for the moment, this point of view is purely theoretical, and that, in the state of our knowledge, it is not easy to build and mainly to check these types of new requirements.

Nevertheless, everybody is working now on the problem of gust measurements, turbulence statistics, gust alleviation devices, friction coefficient measurements, take-off and landing distance predictions on wet and icy runways, and so on. All these investigations still belong to the realm of research but will provide, in the next few years, the necessary basis for modern requirements.

The military specification does not try to assess a probability of a certain mass, distribution of the mass, or the center of gravity. When the extremes of these parameters are defined by the envelopes, a probability of one is assumed for every point enclosed by the envelope. The requirements apply equally

to all these points.

The State of the Atmosphere is also accounted for in a somewhat different manner than by E.S.A.U. The level of turbulence in terms of vertical and horizontal gusts for which the requirements apply is defined in the specification. The particular requirements which must be checked against turbulence have this notation in the individual requirement paragraphs. Also requirements for crosswinds, icy runways, and other special situations are noted in the individual requirements rather than being applied everywhere. In other words, 8785B treats the same problems as E.S.A.U., but one at a time, requirement by requirement, rather than all at once. The problems of the State of the Runway, which are a part of E.S.A.U., are not a part of 8785B. For our use in the United States, these are performance parameters and are specified in performance documents.

An important divergence between E.S.A.U. and Mil Spec is the concept of flight envelope.

In E.S.A.U., a task is defined by:

a Sub-Phase, given by its elementary objective with tolerances, the State of the Airplane, the State of the Atmosphere (and the State of the Runway, if necessary), the chosen Flight Technique and the Secondary Work. By Secondary Work we mean, for instance, radio traffic, navigation, reading checklist, and so on.

The Flight Technique is a guide to help the pilot to observe the limitations during the Sub-Phase, for instance, maximum angle of attack, and to observe the elementary objective of the Sub-Phase within the tolerances. The Flight Technique is generally given in the flight manual by relationships between the different flight parameters used by the pilot (speed, altitude, attitude angles, angle of attack, and so on, if provided on the instrument panel).

Then we define two types of flight envelopes.

- First, the Authorized Flight Envelope, which, chosen by the contractor for each set of State of the Airplane, State of the Atmosphere, is the envelope where the flight, temporarily or permanently out of the ground effect, is authorized. This envelope includes in the plane, altitude-speed, every airpath followed on performing the different tasks in relation to the set State of the Airplane and State of the Atmosphere. The set of tasks in relation with a given set State of the Airplane, State of the Atmosphere is formed, on one hand by the tasks of the same Sub-Phase which differ by the Flight Technique and on the other hand by the tasks belonging to other Sub-Phases, but in relation with the same set of states.

In service, the crew is authorized to fly the airplane for a given set State of the Airplane - State of the Atmosphere, only in the Authorized Flight Envelope related to this set.

- Secondly, the Circumscribing Flight Envelope into which the aircraft may fly. The excursions into this envelope can be due to pilot errors, failure, turbulence, maneuvers, and so on. When the pilot notices that he is flying in this envelope, his first job is to come back to the Authorized Flight Envelope. The Circumscribing Flight Envelope provides a margin between normal flight conditions and dangerous flight conditions, like stall, compressibility buffet, flutter, structural limits, and so on. The procuring activity shall define the width of the Circumscribing Envelope and shall check that no dangerous phenomena occur inside this envelope.

The following remarks can be made about these definitions:

- Flight crews are authorized to fly an aircraft within the Authorized Envelopes; however, this does not mean that they can perform any maneuvers they wish. They must follow only the paths described by the selected Flight Technique.

- Each Authorized Envelope is defined for a Selected Configuration, a failure situation, a mass, a CG location, and a State of the Atmosphere. Each time a change is made in one of these parameters, it is accompanied by a modification of the Authorized Envelope. To simplify matters, the designer will, when possible, define one Authorized Envelope for several States of the Aircraft and of the Atmosphere. For example, for the Selected "Cruise" Configuration, the same Authorized Envelope could be assigned to all States of the Aircraft corresponding to a certain range of masses and CG locations, as well as a certain number of failure situations. On the other hand, in the case of States of the Atmosphere corresponding to appreciable turbulence and in the case of certain failures, different Authorized Flight Envelopes may be defined (e.g., reduction of the maximum authorized speed under turbulent conditions, in case of malfunction in the hydraulic circuit or failed damper).

- If the boundary of the Authorized Envelope is likely to be crossed frequently enough to compromise the safety (this could be due to the lack of a physical boundary or to frequent flights along the boundary), and if the definition of this boundary is very complex, the crew will be alerted by a warning system.

On the other hand, measures must be taken to prevent the crew from flying the aircraft outside the new Authorized Envelope as a result of some modification in the Selected Configuration. In most cases, it is so easy to follow the instructions of the flight manual (e.g., reading the checklist) that the probability of error remains at an acceptably low value. For example, it would not occur to any pilot to accidentally lower the landing gear above the maximum authorized speed. Nevertheless, the certain special cases, it may be necessary to prevent error by the use of an interdiction system which bars variations in configuration outside of the Authorized Envelope.

And last, when the Authorized Flight Envelope corresponding to a given failure state is narrower than the Authorized Flight Envelope corresponding to the normal State of the Aircraft, the new Circumscribing Envelope must be larger than the normal flight envelope. As a matter of fact, in case of

sudden failure during a flight at the boundary of the normal Authorized Envelope, the aircraft is then, nevertheless, in a new Circumscribing Flight Envelope, in other words, far enough from dangerous conditions.

These definitions of flight envelopes are quite different from the old ones. In the previous definitions, the Authorized Flight Envelope was defined by a given margin between the boundary of the envelope and the dangerous phenomenon. For instance, the minimum approach speed was 1.3 times the stall speed. Now the manufacturer defines the minimum approach speed V_{app}, the procuring activity defines the margin of thirty percent and checks only that there is no dangerous phenomenon like stall between V_{app} and $V_{app.1.3}$.

This new approach to the problem had two reasons:

- If the manufacturer has no operational reason to use the aircraft as near as possible to the dangerous phenomenon, there is no need to increase the flight envelope to include unused conditions.

- It is more and more difficult to give a precise definition of a limit speed corresponding to a given dangerous phenomenon. Everybody knows, for instance, that there is not a precise stalling speed for a delta wing.

Let us look now at the definitions of the flight envelopes of the Mil Spec.

It is necessary for 8785B to define in some manner the limits of speed, altitude, and load factor in which the airplane is to perform and in which specific flying qualities are required. It did not make sense to prepare precise requirements and have them apply at all speeds or all altitudes. The precise requirements should only apply at those conditions where they are needed and other values should be required at other conditions. This is done with the view of avoiding overdesign and reducing costs and complexities that occur from overdesign. In 8785B, the method has been to use flight envelopes. The boundaries of the envelopes are not to be determined by flying qualities limitations but on how the airplane is required to be used.

Three different flight envelopes are required for each Flight Phase to be used by the airplane. The envelopes are Operational, Service, and Permissible. The envelopes are three dimensional using speed, altitude, and load factor. Usually they are shown as two dimensional envelopes of speed-altitude and speed-load factor.

The boundaries of the Operational Flight Envelopes enclose the regions where it is necessary for the airplane to operate to perform its design mission, and therefore, regions where it is necessary for the airplane to have good flying qualities. Some of the boundaries can only be determined during detailed design and should be arrived at by discussions between the contractor and the government. The design conditions which describe the operational missions should be inside this envelope. The Operational Flight Envelope should be as large as possible to permit freedom of use but not so large as to result in significant penalties in cost and complexity. Another advantage of using the Operational Envelope is that it shows the user that if the missions are changed after the airplane is designed and flight is now planned outside the original Operational Flight Envelope, it must not be assumed that good flying qualities will be assured.

The next larger envelope is the Service Flight Envelope, and it must always be at least as large as the Operational Flight Envelope. The Service Flight Envelope is prepared considering that there will be occasions when it is necessary to have flight outside the operational Flight Envelope either inadvertently or by some changes in mission requirements. When this happens, there must be some reduced level of mission effectiveness which is sufficient to allow the pilot to accomplish the Flight Phase. The requirements for the Service Envelope are less severe than for the Operational Envelope. The change or deterioration of flying qualities is to be gradual as the airplane leaves the Operational Envelope.

The outermost or largest envelope is the Permissible Flight Envelope, and it bounds all the regions where flight is possible and permissible. This envelope establishes the limits of flight which should not be exceeded. In some cases, the limits cannot be exceeded, for example, thrust or drag or control power limits prevent the airplane from passing outside the boundaries. In other cases, the boundary is a number which the airplane is physically capable of exceeding but must not to avoid structural damage or loss of control, for example, stall angle of attack or limit load factor.

The Operational Flight Envelope boundaries cannot be defined or prescribed by the flying qualities specification since they are determined, for each Flight Phase, by the requirements and needs of the missions. Service and Permissible Flight Envelope boundaries are functions of airplane capabilities rather than mission requirements and have been defined. These boundaries are based on maximum speeds, stall speeds, structural limit load factors, buffet speeds or load factors, and temperature of engine limit speeds.

Something must be said about the number of envelopes that are prepared to satisfy the requirement of 8785B. With three speed-altitude and three speed-load factor envelopes to be prepared for each Flight Phase and other envelopes to account for each possible loading of external stores plus envelopes for different wing sweep position, moments of inertia, center of gravity, etc., it was calculated that for one airplane there could be 367,427 envelopes. In practice, it has been possible to reduce this number to somewhere between 20 and 40 envelopes.

When the envelopes have once been prepared, they provide very valuable information. They define where the airplane will be used. They show where the flying qualities will be best and where they can be reduced because of lower frequency of operation. Airframe and equipment designers can concentrate their efforts on the more important areas and can perform trade-off studies to get the proper balance between aerodynamic and augmented flying qualities.

The envelopes do not change due to failures. It is intended that the envelope describe where the

airplane must perform its functions and even following failure, the same task may have to be done. Therefore, the size of the envelope is the same after failures occur.

The differences in concept and application of the use of envelopes between the two specifications are primarily due to the safety versus mission success philosophy. The Circumscribing Envelope of E.S.A.U. is the same as the Permissible Envelope of 8785B. The Authorized Envelope has the same use as the Service Envelope of 8785B. The Operational Envelope of 8785B is not used in E.S.A.U., and this should be expected since the requirements of E.S.A.U. are for safety. Mil-F-8585B looks for mission success as well as safety and is a specification used by the customer with the mission to perform. Therefore, an Operational Flight Envelope is necessary to define areas of flight where the mission is intended to be flown. E.S.A.U. is a specification for airworthiness standards and an Operational Envelope is not needed. The customers, the airlines, should request their own Operational Envelopes to be used with the Authorized and Circumscribing Envelopes of E.S.A.U.

It is now necessary to bring all these definitions and considerations together and apply them in the form of requirements considering the level of flying qualities.

The general purpose of every requirement is to improve the safety of flight for civil aircraft or to increase the probability of fulfilling the mission for military aircraft.

The study of incidents which may increase the probability of accident or of failure of the mission shows that they can be classed into two categories, the incidents which could have been avoided by a modification of the configuration of the aircraft, of its technology and of its way of use, and on the other hand, the incidents which come from the failure of people or material involved in guidance and in traffic control.

We only have to deal with incidents of the first type which occur when a factor which characterizes the behavior of the airplane or of a part of the airplane crosses over a critical value. The origin of these critical values may be aerodynamic (for instance, maximum value of the angle of attack), structural (for instance, maximum load factor, maximum rpm of the engines), thermodynamic (maximum fuel flow of reheat), and so on. It is easy to see that a limit may be crossed over after a set of events which can be classified into three categories.

First type of event. The pilot has at his disposal all the controls necessary to maintain every factor between limits, but the task is too difficult to fulfill for a human operator, because, for instance, the frequency of data necessary to control the airplane is too high because the pilot does not know the relative values of the critical parameter and its limit. Consequently, the pilot lets the parameter cross over the limit. This type of incident is called a pilotability incident.

It was necessary to create a new word in French and in English, because there is no known word for that type of incident.

For the second and the third types of events, the pilot is not involved. Let us look now at the second type. An external perturbation, a gust, for instance, or an internal one, like a failure, either modifies the value of a critical parameter or modifies the value of the limit itself. For instance, a gust increases the angle of attack, an engine failure increases the side slip angle, a failure in the flowing flap system reduces the limit of angle of attack. This type of event is called incident due to sensitivity to perturbations.

And last, the third type of event. To follow the airpath prescribed by the air traffic control to avoid an obstacle or to meet again the desired airpath after a divergence due to events of the two previous types, the pilot has to make a manœuver which modifies the values of the different factors. For instance, a pitch-up maneuver increases the angle of attack and brings it nearer to the limit. This last type of incident is called maneuverability incident. An example will show more clearly how an accident can occur as a result of a set of events of the three types.

During an ILS approach without visibility, the stability augmentor systems and the autothrottle having failed, the pilot lets the speed and the altitude decrease and loses fifteen knots and fifty feet. This is a pilotability event due to a lack of stability; the safety margin for angle of attack has already been reduced by the loss of speed. Noticing the error in altitude, the pilot begins a pitch-up maneuver; this maneuverability event again increases the angle of attack. And last, a strong gust adds its effect to the two previous increments of angle of attack. The angle of attack reaches the limit which involves a stall.

So a set of events of the three types can bring a parameter beyond the limit.

Consequently, the objective of each requirement of handling qualities is to reduce the probability of occurrence of an event of one of the three types.

As we have already seen, to assure a reasonable level of probability of accident, we must require a high level of handling qualities for the flight cases we meet daily, in other words, for the normal flight cases. But it is possible to reduce the required level for low probability cases; as a matter of fact, the probability to have an accident in a given flight case is the product of the probability to be in this condition by the conditional probability to trespass a limit from this condition. So for a given level of safety, this is to say for a given total probability, the acceptable conditional probability may increase when the probability of the flight case decreases. In other words, the level of handling qualities which is directly related to the conditional probability of trespassing a limit can be degraded for low probability cases.

We have spoken about probability of flight case; let us look quickly at its definition. As we saw above, even if the crew attempts to follow the Flight Technique selected at the beginning of each Sub-Phase for a given State of the Aircraft and the Atmosphere, the Flight Conditions will not correspond

exactly to the path prescribed by the Flight Technique with respect to altitude and speed. Deviation from the ideal path may be due to piloting inaccuracies, instrument error, or gusts (remember that in a turbulence of given intensity, gust of all levels may be encountered). These altitudes and speed deviations from the ideal path corresponding to a given Flight Technique are called Excursions.

Practically, Speed Excursions are the most important, especially in low speed Sub-Phases. Since they are more dependent on variations in flight qualities than are altitude excursions.

A Flight Case is defined by a Task and an Excursion made during this Task. We shall note that we have to relate the requirements to the Flight Cases and that we are theoretically able now to compute the probability of a Flight Case since a Flight Case is defined by a Task (Sub-Phase, State of the Aircraft, State of the Atmosphere, Flight Technique, Secondary Work) and an Excursion since it is always theoretically possible to estimate the probability of each component. A good idea of the probability of excursion may be obtained by flight and simulator tests. We know well enough the atmosphere. Remember that it is not necessary to know the probability cases because we have only to deal with the total probabilities higher than 10^{-9} and that this total probability is the product of the probabilities of the different components of the flight cases. So we have only to deal with probabilities of excursion or probabilities of atmosphere of the order of magnitude of 10^{-3}. The main problem is the estimation of the probability of the State of the Aircraft and more precisely of the probability of the failure situation. It is nearly impossible to show by direct experiments that the probability of a failure state is less than 10^{-4} per flight. This demonstration should need about $2.3\ 10^{4}$ hours of test without encountering the failure (for a confidence level of ninety percent).

In order to show that the loss of an important function has a low probability, we have to compute this probability starting from the probabilities of failure of the different components. This approach has two important consequences.

- We cannot accept that a loss of a function, which may have hazardous consequences for the flight, should be the result of a unique failure. As a matter of fact, we cannot show directly that the probability of this failure is reasonably low. So we have to require to at least double the system, the failure of which may have hazardous consequences. These are the same considerations which have led to the philosophy of fail-safe.

- On computing the probability of loss of a function, we have to be very careful on assuming the independence of the different systems. Even if the systems are physically independent, in other words, if there is no common part (and particularly, it is very difficult to have truly different sources of energy), the occurrences of the failures are not strictly independent because the origins of the failures are not strictly random. The origin of the failure may be vibration, temperature, humidity, moisture, pressure, and so on; and if the independent systems are physically identical, the same causes having the same effects, the conditional probability of failure of a second system after the failure of the first one is not at all equal to zero.

So the reliability analysis of all the systems is, in our opinion, the most important and certainly the most difficult problem we have to solve to build right requirements.

Let us look now at how the Mil Spec deals with this problem.

The two sets of requirements agree on the important point that a high level of flying qualities must be provided for the flight cases that occur frequently.

In the discussion of 8785B, the State of the Airplane has been defined, i.e., the Selected Configuration and the status of the equipment. The Selected Configuration can be listed for each Flight Phase to show the position of the landing gear, wing sweep, augmentation on or off, etc. These have been called Airplane Normal States and represent the conditions of the airplane in an unfailed, or normal status.

The situation after failure has occurred is an Airplane Failure State. All possible failures and combinations of failures are defined and listed so the beginning Normal State may be modified by a large number of possible Failure States. In many cases, these failures can be expected to cause a degradation in flying qualities. The amount of degradation must be determined. It is important to know where in the envelope the failure occurred for the change in flying qualities may be either critical or unaffected by the particular flight condition. We have not been able to specify a probability of being in a particular area of the envelope, so we have said that all points have a probability of one. Therefore, it is necessary to determine the effect of the failure at the most critical condition within the envelope for each Failure State.

It is important to know how often each Failure State occurs. The contractor shall determine the probability of occurrence per flight of each Airplane Failure State.

When the effect of each failure has been determined, then the level (1, 2, 3) of flying qualities for each Failure State is known. With the probability of occurrence of each Failure State per flight then the overall, or cumulative, probability per flight of degradation of flying qualities to Levels 2 and 3 can be made.

Requirements based on levels of flying qualities are used in 8785B. For airplane Normal States, Level 1 flying qualities are required within the Operational Flight Envelope and Level 2 within the Service Flight Envelope. This shows that very good flying qualities are wanted most of the time in order to assure mission success. Acceptable flying qualities are wanted in reasonably likely, yet infrequently expected conditions. Some changes are expected due to failures, but if the probability is high, then there must not be any degradation because the situation occurs too frequently. Within the Operational Flight Envelope, the flying qualities may degrade to Level 2 no more often than once per 100 flights and to Level 3 no more often than once per 10,000 flights. Within the Service Flight Envelope, Level 3 shall not occur more often than once per 100 flights. There are no specific

quantitative requirements for flight outside the Service Flight Envelope (in the Permissible Envelope) because this area is felt to be a transient condition, and it is only necessary that the airplane be capable of quickly returning.

Level 3 is the minimum level of flying qualities to assure that a flyable airplane exists no matter what failures occur. No Failure State (with an exception) shall degrade any flying quality beyond Level 3. The exception is the Special Failure State. Some failures may have such extremely remote probabilities of occurrence that they are difficult to predict. When this occurs, and if the contractor can justify his position, a Special Failure State is approved and such a failure can result in flying qualities outside the Level 3 limit. Typical of failures that would qualify for a Special Failure State are structural failures which would certainly affect flying qualities but are extremely remote. The Special Failure State is not to be used for those readily predictable cases that are worse than Level 3 or those cases where a failure is difficult to correct, and it is easier to ask for a Special Failure State.

This method of specifying flying qualities is directly related to the French idea of pilotability. The use of three different levels is a way of expressing pilotability for they are concerned with how hard the pilot must work to do the mission. Failures can change the amount of work that must be done, and it is only on rare occasions that we allow the pilot to be highly loaded with work because the possibility of an incident increases as the workload increases.

In conclusion, we believe that this comparison of the flying qualities specifications of France and the United States has shown that they are basically the same in intent and goals. Requirements for new aircraft must be more sophisticated than previous criteria because the aircraft themselves are more complex and are capable of doing more things. Many additional considerations must be added to account for equipment failures, the way the airplane is to be used, and how well it must fly in all portions of its flight envelope. All of these items are included in both of the specifications, E.S.A.U. and 8785B, and they have been used in nearly the same way, although there certainly are some differences.

The paper has noted that the two specifications differ in their basic objective: safety for E.S.A.U. and mission success and safety for 8785B. The same methods are used in each specification once these objectives have been defined.

We believe that E.S.A.U. presents the more inclusive and theoretical approach to account for all the possibilities that may arise. The military specification, from the beginning, has made certain simplifying assumptions to permit the practical application of the requirements. It has been necessary to use many simplifying assumptions when applying E.S.A.U. to specific aircraft.

The final results of the work that was conducted in the two countries during the same time period are flying qualities specifications that are extremely similar in the requirements that have been considered, and the way these factors have been applied.

LEAD DISCUSSION

by
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First of all, let me congratulate M. Wanner and Mr. Carlson on the skilful way they have led us through the maze of this complex subject. At first sight, they might appear to have set themselves an impossible task - to give an homogeneous presentation of two sets of flying qualities requirements having unrelated backgrounds, and different intentions. However, on closer examination, the tasks of writing requirements to ensure service acceptance on the one hand, or civil certification on the other hand, are not dissimilar in principle.

In both cases, the task is one of considerable magnitude. To achieve generality, a large range of possibilities must be considered. Modern airframe and engine technology can produce aircraft able to perform over a wide range of speeds and heights, and unique flying qualities problems are likely to occur at different points in the flight envelope. Finally, the subjective nature of good flying qualities makes quantification difficult - a situation which does not arise in other engineering applications.

All Flying Qualities Specifications must have certain common features. First, there must be a classification of the types of aircraft to which the specification applies. Second, there must be a classification of the flight condition/task to which a particular requirement applies, and third, there must be a classification of the configuration/status of the aircraft. The third classification then allows the introduction of the concept of probability of occurrence - a concept which is common to both TSS-5 and MIL 8785B. Simply stated, it says that the more likely a set of circumstances will occur, the better the flying qualities shall be in these circumstances. By incorporating this principle, TSS-5 and MIL 8785B represent a big advance over the older civil and military requirements.

The paper by Wanner and Carlson reveals how two independent Certification Authorities have managed to incorporate the above features into a working document. In addition, it highlights the differences between the two Specifications which inevitably occur in some areas. Such a comparison is invaluable, since it indicates where improvements to either Specification might be possible.

Considering first the problem of aircraft classification, as Mr. Carlson points out, aircraft size or aircraft weight are not by themselves good parameters. It is better to use a classification which incorporates the mission of the aircraft. Applying this principle, MIL 8785B has four aircraft classifications I, II, III, and IV. M. Wanner indicates that ESAU is fundamentally different to MIL 8785B in this respect, because "safety and mission success are the same thing for civil aircraft". It is debateable whether such a clear distinction can be made. The delivery of passengers to a nominated destination is a mission, and can be modified for a variety of reasons without prejudice to safety. Different types of mission, in terms of distance, duration, speed, height and prevailing conditions can be postulated, and surely establish a need for a classification corresponding to that of MIL 8785B.

Considering now the need to classify the flight condition/task, we see that ESAU (and TSS 5) uses the concept of Flight Phases and Sub-Phases. Precise definition of these terms is made. A study of TSS 5 then shows that the specific requirements for handling qualities (in terms of stability or manoeuvreability) are rarely related to either a Phase or a Sub-Phase. In fact one chapter contains handling qualities requirements for up and away flight, and a separate chapter relates solely to low speed, low altitude flight. A further indication of the difficulty of using the Sub-Phase concept is given when TSS 5 states that the Applicant will define the Sub-Phases.

The difficulty arises because of the impossibly large number of cases to consider, if a large set of sub-phases are permutated with various aircraft states, for a multitude of flying quality requirements. As Carlson points out, MIL 8785B gets out of the dilemma by using only three Categories, A, B and C, to group the various phases of flight, and by indicating separately which phases fall into each Category. On the whole, we have found this arrangement satisfactory. Perhaps the only difficulty is to decide where Category A finishes, and Category B starts. For example, in the case of a Class IV aircraft design, a strict interpretation of the Operational Flight Envelope (Table 1) in MIL 8785B leads to the conclusion that Category A covers all conditions other than Category C.

It is in the third classification, that of aircraft configuration/status, that the probability concept may be conveniently introduced. Current aircraft designs can absorb several sub-system failures without disastrous results, and we can even estimate the probability of occurrence of such failures. The new Specifications admit this situation and allow degradation of flying qualities subsequent to failure. There is a correspondence between the concept of Levels in MIL 8785B, and True Configuration of ESAU. Mr. Carlson goes a step further, and he bravely associates with Levels 1, 2 and 3 appropriate values of pilot ratings in the Cooper/Harper scale. Perhaps the development of this scale has made its use in a Specification possible. I wonder if M. Wanner might recommend a more cautious approach, since he has often preached the danger of using pilot rating scales for Acceptance purposes.

In our experience, the concept of Levels 1, 2 and 3 in MIL 8785B can be conveniently applied in the design stage. In the case of a Class IV aircraft with a multiplex CSAS, level 2 becomes superfluous, and no doubt Level 3 becomes superfluous with a simplex CSAS. We have found, however, that Level 3 is unduly severe in some areas (for example minimum stick force per g and minimum roll rate). The effect is to force the designer to an aerodynamic configuration or control layout which is undesireable in other respects (performance or complexity). Mr. Carlson appreciates the problem, and admits that "the Level 3 values in some cases were increased over the barely safe values, to allow the degradation of several parameters at once". We believe that the cumulative effects of degraded handling in all axis is a complex situation, and should be tackled separately - perhaps at this stage by a generalised observation in the Specification. To illustrate this point, a designer so minded could produce an aircraft meeting Level 1 requirements, but which the pilot would find unacceptable, by diabolical choice of permitted stick forces, frequency, damping, friction, and so on. Obviously it is not in the designers interests to

do this: nor is it in his interests to exploit low Level 3 requirements too vigorously. The combined effects of requirements in an area which needs more study. Even if such effects were known, they may be too complex to apply conveniently into a Specification.

Further difficulties arise when the Certification Authority wishes to cover the influence of atmospheric conditions. In the first place, some of the handling qualities criteria on which the requirements are based have been derived in calm air. More work is needed to determine how these criteria change with level of turbulence. Secondly, a convenient means must be found to accommodate any new criteria which appear. In theory, the ESAU method, which combines the state of the aircraft with the state of the atmosphere looks attractive. In practice it may be unworkable, because of the large number of cases which must then be considered. If so, then the MIL 8785B approach, which deals with atmospheric effects on an individual basis, is to be preferred. We can only hope that the research effort referred to by M. Wanner will be fruitful, and that the results can be easily incorporated.

Paradoxically, the strength of the new French and American Specifications - the association of flying qualities requirements with probability of occurrence - is also their weakness. M. Wanner highlights this weakness when he points out that (a) it is virtually impossible to demonstrate that remote failure targets are in fact met, and (b) the assumption that a second failure is independent of a first failure is usually false. The consequence for civil aircraft is that it becomes extremely difficult to introduce a radically new system such as fly-by-wire, or CCV. The Certification Authority can reasonably argue that a new system must be shown to be satisfactory before Acceptance; equally well the manufacturer can claim that the assurance needed will only come from normal operation in service.

A different type of problem will apply to Military Aircraft. Within the Operational Envelope, the Requirements say that Level 3 shall not occur more often than once per 10,000 flights. In other words, it will be a circumstance which is unexpected by, and unfamiliar to the pilot. Inevitably, Air Staffs will insist that regular training for these remote failures is carried out, and so Level 3 conditions will be flown far more frequently than assumed in the Requirements. One might then question the validity of permitting a degradation of handling qualities on the basis of rare occurrence.

One general comment must be made, although it is not directed particularly at either the U.S. or French Requirements. It is a truism to say that to be useful a Set of Requirements must be used. They are addressed primarily to the airframe manufacturer, and their value is diminished if they are structurally complex, difficult to understand, or difficult to apply. Generality may be the initial goal, but when applied to a particular project, detail changes to the Requirements will be necessary. The mechanism to introduce such changes must exist.

Finally, I am not sure that I can accept the title of this joint paper, as describing a Comparison on French and United States Flying Qualities Requirements. To do so ignores the contribution of the British Air Registration Board to the formulation of TSS 5 - a contribution I am sure that M. Wanner will be the first to acknowledge.

References: 1. "Military Specification, Flying Qualities of Piloted Airplanes"
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2. "Supersonic Transport Aircraft Flying Qualities"
TTS Standard No. 5 Issue 2 22nd March, 1968

OPEN DISCUSSION

W.T. Kehrer, Boeing, USA

Is it the intent of the military specification 8785B that the airplane be safe to land under the degraded systems conditions resulting in what is described as Level 3 handling qualities - Pilot rating range 6 1/2 to 9 1/2?

J.W. Carlson, ASD, Dayton, Ohio

Yes, certainly it's the idea that the airplane can safely be returned and landed. Also, it is intended the airplane shall be, under Level 3 conditions, capable of extricating itself from some very difficult maneuver that it might be experiencing at the time of failure under a Level 1 flight condition. It can be safely returned to a controllable situation from that failure and then turn around, come back and make the landing.

W.T. Kehrer, Boeing, USA

Boeing does not agree that the Level 3 can be considered as safe to land, as applied to commercial transport design. The most degraded qualities that Boeing would ever accept in an aircraft design for commercial operation is by pilot rating scale 6 1/2.

Robert J. Woodcock, AF Flight Dynamics Lab, Dayton, Ohio, USA

We have had some problems in getting people to do the kind of probability analysis we had envisioned for showing compliance with MIL-F-8785B. What has been the Anglo-French experience in applying their similar requirements?

J-C. Wanner, Service Technique Aeronautique, Paris, France

I think it would be better to ask the contractors to give you an answer on that point, Mr. Deque for instance. But, I entirely agree with you that it is very difficult to do this type of work about probability. But I think it's better to speak about probability even if it's not the exact probability, known only with an important error, than to assume that these probabilities are zero or one.

Mr. Deque, Aerospatiale, France

We have probably the same difficulty that you have evaluating probabilities. But as Mr. Wanner said, we can at least classify the class of probability even if we cannot obtain the exact number. Also, we have to be very careful when evaluating probabilities to take into account the possibilities of multiple failures. With this approach we have some assurance that we have the correct class of probability.

R.S. Sliff, FAA, USA

I thought it might be appropriate to give some of my views as we've seen these, because we have been very active in working both with MIL specifications and in the comparison and application of the Anglo-French standards. We are in the process, right at the present time, of conducting a very concentrated evaluation of the U.S. tentative standards for the supersonic transport with the Anglo-French, both the constructors and the Air Worthiness authorities. What I wanted to say here, basically, from our viewpoint, on these, most of the things have already been said relative to the difficulties that you foresee in being able to come up with the requirement, per se, rather than the definition of what has to be evaluated. You see, you have to boil it down in the end to what do you test, what is the requirement. This has been one of the things that, I think, is taking the most time and is yet unresolved, when it comes to the U.S. requirement to be applied to, for example, the Concorde. I want to express one thought here, as I see it, sitting and listening to the papers given as one paper by two individuals that have the same objectives, but I do not believe that the requirements as they have been presented are truly the same. For example, as I see the Anglo-French requirements of TSS-5, they are based upon an authority applying a requirement to an aircraft. The Mil spec is a design specification for the purchase of an aircraft. Which, in itself, has a little different attitude towards it and has different deviations that are permitted, in accepting it. It is the basis of how you apply these two as I would see them. So, all I wanted to express here is the difficulty as we see it, from the FAA since, in applying these philosophies (1) we don't want to design airplanes, (2) we have to evaluate again these probabilities with our experts to assure that we are truly looking at what might occur in service of the aircraft, is safe.

R.P. Harper, Cornell Aero Lab, USA

I have three comments. The first one I would like to say that the agreement demonstrated here and much of the philosophy in the results between the two papers that were jointly presented, didn't just happen. I would certainly acknowledge that, thanks to the efforts of the Air Force and Mr. Jack Carlson, that Mr. Wanner had several opportunities to impact the work which Cornell Lab did on the 8785 spec. His contributions were very important, particularly, I think, the philosophical aspects of his contributions in forcing us to face up to the total philosophy of the spec. He made at least two visits to Cornell and we had very important and very helpful discussions. So I would like to acknowledge this personal contribution. The next comment was towards Arthur Barnes. Art said something that surprised me - that the airplane designer could take 8785B and making a Level 3 airplane by choosing a limit of the Level 1 requirement. I don't have any data that says that this isn't possible, but I am interested if you do have any such data, because this is what we at Cornell call a "combination of bads". We are very much interested in what happens when you combine limits of a number of the requirements and produce an airplane whose characteristics are right on the limits of a number of individual requirements. I don't think any substantial amount of research has been done on this, but if anyone in the audience knows of any results or if Arthur himself does, I would surely like to hear about them. One comment

along this line, is that the reference was made that there was a correlation between pilot rating and the Levels in the 8785B. There is a correlation, I think it is the underlying schemes of the Level is the rating but where you draw the particular limit, they don't have to be drawn at the pilot rating boundaries of 3 1/2 and 6 1/2. One final question fo· Mr. Wanner. What about the French military airplanes? Your discussion compared the specifications :·r handling qualities for really commercial transport procurement or operation. With the military specification for U.S. military airplanes, what do you require for the Mirage airplanes, etc. Could you comment on this, please? Wanner - For the military purpose, we intend to apply the philosophy of 8785B but I think now it is not necessary because you have made the job easy. So I think that our military specification shall be the translation of 8785B.

A.G. Barnes, BAC, UK

I think that you're on a good bet if you are trying to produce intentionally bad characteristics in an aircraft. It is more difficult to design good characteristics into an aircraft. On the other hand, there seems to be a law of nature which says that things never go too wrong; for example, if we reduce the short period frequency of the aircraft, the short period damping increases. And the designer would have to do something diabolical. We can be very confident that if he did this diabolical thing, then we would get an airplane which is unacceptable. I think that this is one area in which a lot of work is needed. Not only from the purely academic point of view, just to have a comprehensive set of flying qualities, but also to provide a specification which allows for the interaction of one parameter with another. The example that comes to mind of how to meet the Mil. Spec. with a bad airplane is to provide unharmonized controls - for example light forces and small deflections in roll, and heavy forces and large deflections in pitch. Careful use of the allowable breakout force, friction, hysteresis, and so on will add to the pilot's difficulties.

Two further examples of "combination of bads", applied to the pitch control are:

Case 1: Landing approach, 120 knots, s.p. frequency 3.0 rad/sec, relative damping ratio 0.35, $n_{z/\alpha}$=2.7, stick force/g = 3.0 lbs., stick force per inch = 30 lbs./in/, 3 lbs. breakout force.

Case 2: Ground attack, 350 knots, s.p. frequency 2.4 rad/sec relative damping ratio = 1.30, $n_{z/\alpha}$=20, stick force/g = 12 lbs., stick force per inch = 5 lbs./in., 3 lbs. breakout force.

Case 1 meets the Category C, level 1 requirements, and Case 2 meets the Category A, level 1 requirements, but I think that both cases would be unacceptable, if not dangerous.

Pierre Lecomte, Aerospatiale, France

Mr. Wanner referred to the fact that low probability situations may be associated with low handling qualities level on the grounds of the risks involved. This statement is not so obvious as it looks. It is true only if the assessment of the handling quality level fully considers the knowledge and training of such situations the crews will have in service.

In his comments, Mr. Barnes referred to the use of pilot rating. Unhappily, in our state of ignorance, all handling qualities requirements or critique rest upon pilot assessments of, either directly of the aircraft considered, or indirectly of other aircraft of previous generations or of a simulator.

In the first case, the situation is wide open, and difficult in many respects.

In the second case, the question of the relevance of previous data is also very difficult.

A.G. Barnes, BAC, UK

I think that one purpose of the flying qualities requirements is to try to quantify these elusive factors we call handling qualities. By doing research, we are able without any prejudice to relate what the pilot thinks of one aspect of an aircraft with a measurable parameter such as frequency, damping, or stick force. It seems to me that this should be done in the quiet atmosphere of research and not in the hurly burly of acceptance of either military or commercial aircraft, which has overt ones of cost, delivery, time scale and so on. If you leave the final acceptance simply to a pilot rating then you are losing out in two ways: (1) you aren't taking advantage of all of the background experience relating pilot opinion with measurable parameters and (2) you are also limiting the pilot's ability to express himself. If you say, we will focus the acceptance into one of ten numbers of letters, the pilot is then committed to summarize his opinion and experience with the aircraft into one statement - and this to me is the biggest difficulty, using the pilot rating scale for certification. The second difficulty, which Mr. Wanner pointed out in 1966, is the problem of getting an absolute level from which to measure the pilot rating. Most pilot ratings are made with respect to a certain situation. In the case of certification, it is no longer a relative assessment; it becomes an absolute assessment.

I.L. Ashkenas, Systems Technology, Inc., USA

The initial portion of the paper referred that mission requirements and aircraft type were a strong influence on handling criteria; but later, more emphasis was placed on workload and associated pilot rating. Since the pilot is central, why shouldn't we expect that, for safety at least, flying qualities requirements should be quite universal; i.e., pilot- and task-centered and not airplane type of mission-dependent? As a matter of fact some of our success at consolidating requirements for a variety of aircraft types (e.g., CTOL, VSTOL, helicopters) indicate that basic requirements, expressed in piloting terms, are much the same for all.

Maurice D. White, NASA Ames, USA

Bob Harper requested reference to any work that had been done that showed differences in pilot rating for combined axes in comparison with those for individual axis. Such data are contained in NASA TN D-1888, I believe, of which I was lead author. This describes a simulator study of SST handling qualities in cruise, in which, first the values of the static stability andthe damping derivatives were varied individually and progressively, in each case with the remaining derivatives at their optimum level. Following this an evaluation was conducted in which all the derivatives at the 3 1/2 level were applied in combination. As we might have anticipated the resultant airplane was rated worse than 3 1/2, in fact, 6 1/2!!

THE NATURE AND USE OF THE RULES FOR JUDGING THE ACCEPTABILITY OF THE FLYING QUALITIES OF FIXED WING AIRCRAFT

by

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SUMMARY

In the United Kingdom the flying qualities requirements are laid down in an Aviation Publication (Design Requirements for Service aircraft). The equivalent document in America is a Military Specification (Flying qualities of piloted aeroplanes). The paper considers the general content of these documents in relation to the requirements of the flight tester in assessing the acceptability of fighter aircraft, strike aircraft and trainer aircraft with which the author has been associated. In the same context comment is made upon the flying qualities requirements for V/STOL aircraft.

It is suggested that the requirements documents are of limited use to the flight tester because almost inevitably they are out of date, they are very likely to be inapplicable to new aircraft with special role demands or novel design features and in addition the tester knows that the rigid application of the handling qualities criteria will not necessarily produce an aircraft satisfactory for the user.

It is recommended that, in addition to updating existing requirements, more attention should be given to the direct and immediate application of data derived from known and tried service aircraft.

The views expressed in this Memorandum are those of the author, they do not necessarily represent the official opinion of A&AEE.

1. INTRODUCTION

The definition of rules for the flying qualities of fixed wing aircraft should fulfil at least two particular functions. Firstly they should provide the designer with much of the necessary background information on which to base the required control characteristics of his proposed aircraft. Secondly, the requirements should at least provide the aircraft testing authority with a statement on control characteristics which have been found acceptable in the past, the thus provide a starting point for assessing the capability of the aircraft to meet the users requirement, both in letter and in spirit.

The documents in which these rules are written down in the United Kingdom and in America are, respectively, Aviation Publication (Av.P.) (Design Requirements for Service Aircraft), and Military Specification (Mil. Spec.) (Flying Qualities of Piloted Aeroplanes). Many of the paragraphs of the Av.P. were written a long time ago and are therefore based on relatively old experience, the 1950's era. On the other hand the Mil. Spec. was drafted over the period 1966-1969 and is therefore reasonably well up to date. Some comments will be made in the text of the paper on the relevance of this difference between the two documents.

Because this paper represents the views of the author, and not necessarily those of A&AEE Boscombe Down, it would be appropriate to mention briefly the extent of the author's experience in flight testing. This extends over the past 10 years and has been concerned mainly with trainer and fighter aircraft including the Gnat trainer, various marks of Lightning, the Harrier V/STOL aircraft and its predecessors, and the Anglo-French Jaguar.

Looking back over those 10 years it is surprising how little reference to the specific requirements of the Av.P. has been necessary during assessment flying. Those rules which have been used are a combination of the Av.P. requirements and past experience and it was found that those of real significance which have been used with reasonable frequency could be written down on one side of a sheet of paper, these "rules" are illustrated in Figure 1. In addition to these rules we have used our common sense about features such as trim changes, control harmonization, behaviour at or near the stall and pilot workload to achieve the manoeuvres and tasks implied by the users specification. Our other preoccupation has been with investigation of problem areas and we have found that in these cases the requirements documents are of limited use in giving guidance on acceptability.

Summarising the introduction therefore we can say that as testers we have written guidance on the general design requirements and over the past ten years this has been of limited use, because of the subjective nature of acceptance testing. In the real cases many of our acceptance standards are based on previous experience and common sense. The remainder of the paper will be devoted to the examination of the present requirements, and proposals are put forward for making these requirements more useful to the flight testing authorities.

2. HANDLING QUALITIES CRITERIA IN THE UNITED KINGDOM

2.1 THE PRESENT STATE OF THE UNITED KINGDOM REQUIREMENTS

In the United Kingdom it is acknowledged that the Aviation Publication (Design Requirements for Service Aircraft) is seriously out of date and without going into the reasons why it has fallen into this state it is sufficient to say that consideration is at present being given to the up-dating of the handling qualities requirements. One course which the United Kingdom could take would be to adopt the

Military Specification for the handling section of the Av.P.. The Mil. Spec. is an admirable document in many ways and clearly a great deal of thought and effort has gone into the drafting of the text. For instance requirements are classified according to the aircraft role (Class), the job being done (Flight Phase), and how well the job must be done (Level of Control). Since there are four classes, three flight phases and three levels of control, 36 different values could be specified for a given flying qualities parameter. This sort of breakdown is not in character with the Av.P. as at present produced. It is likely that we should not require so much detailed specification because we believe that over-specification leads to trouble. Readers will undoubtedly know of many cases where the general flying qualities requirements are not met but the handling characteristics are nevertheless accepted into Service without a great deal of trouble.

In spite of the above comments it is very likely that if the Av.P. is updated the experience value contained within the Mil. Spec. will be of tremendous help.

2.2 THE RATE OF OBSOLESCENCE OF FLYING QUALITIES REQUIREMENTS

At the time of writing the average of the dates of the elements which go to make up the Chapter on Flying Qualities in the Av.P. is 1960. The equivalent date for the Mil. Spec. is 1969 and that issue updated the 1968 and 1954 issues. In America therefore it must be assumed that between 1954 and 1968 the requirements remained the same and since many excellent aircraft were produced between 1954 and 1968 the "out-of-dateness" of the requirements was of no great embarrassment.

This is not too surprising in the context of fixed wing aircraft with control columns, rudder pedals, throttles and human pilots.

In the paragraphs which follow the author will try to show that although there is a need for up-dating general flying qualities requirements, there is also an urgent need to accumulate data on specialised role requirements and requirements associated with novel design features. The means of achieving this aim will be suggested.

3. THE NEEDS OF FLIGHT TEST ESTABLISHMENTS IN TERMS OF ACCEPTABILITY CRITERIA

3.1 MEETING THE LETTER AND SPIRIT OF THE SPECIFICATION

As suggested in the introduction acceptability criteria for flying qualities are of use to the designer in deciding the characteristics of his proposed aircraft and are of use to the tester in assessing the capability of the aircraft/pilot combination in the context of the Service specification. In the ideal circumstances of a wellwritten Specification which defines the job or jobs which the aircraft has to do, the testers function is simply to ensure that the "average Service pilot" can use the aircraft to do the task effectively and reliably. As a rule cost effectiveness is a consequence once the effectiveness of the weapon system and its reliability has been proved. In addition simplicity and reliability tend to go together and it is these qualities which are assessed at the test establishment. Figure 2 illustrates the breakdown of aircraft characteristics under the general headings of effectiveness and reliability. If the specifications for flying qualities have any purpose for the flight tester they are there to ensure a sound basis for assessing the effectiveness and reliability of the weapons system in the broadest sense of the words.

3.2 THE RELATIONSHIP BETWEEN HANDLING QUALITIES SPECIFICATION AND THE FLIGHT TESTING TASK

It is proposed under this heading to show that the words written in the handling qualities specification and the major tasks of acceptance flight testing are not very closely related. From the authors point of view one of the best ways of doing this is to list in chronological order those items of flight testing which have taken up the major part of his 10 years flight test experience. The following items are outstanding in the memory because they involved relatively long periods of flight testing, much discussion between pilots and technical staff and close and frequent liaison with the manufacturer on unsatisfactory features of the aircraft, which had to be corrected before entry into Service. Concentrating only on the most outstanding items the list is as follows:

a. Control of a trainer aircraft in circumstances of failure of one of its control systems.

b. Assessment of the spinning characteristics of a trainer on which there was an unusually wide variation of behaviour in the spin under nominally identical conditions.

c. Acceptability of an auto-pilot designed to operate over such a wide range of height and mach number that optimisation and satisfactory operation under all conditions proved to be very difficult to attain.

d. Determination and proving of the worst cases for inertia coupling for a family of aircraft in which small changes of configuration produced unduly large changes in behaviour.

e. Assessing the acceptability of the low speed handling qualities of a neutrally stable or unstable system (V/STOL).

f. Techniques to achieve accuracy of touchdown of a V/STOL aircraft.

g. Manoeuvre boundary behaviour characteristics with a wide range of external stores and marked changes in behaviour with Mach number.

h. Techniques to achieve optimum performance of a STOL aircraft.

i. Statistical study of the effect of handling on the take-off capability particularly in relation to free take-off from aircraft carriers.

j. Peculariities of an unusual control system with cross coupling between control inputs and motions about the 3 aircraft axes.

k. Operations off various types of unprepared surfaces where definition of the surface and effect upon handling were not amenable to systematic and economic testing.

It is these sorts of aircraft handling characteristics which have demanded the greatest attention over the past 10 years. Other items which figure large in the handling qualities specifications such as static stability, stick force per g, short period oscillations, trim changes, maximum and minimum speeds have demanded very little attention because for the most part the pilot has been quickly satisfied with the behaviour and if we had then referred to the handling qualities requirements we should have found that the quantities fell within the acceptability boundaries.

This may be just another way of saying that our designers are so good that they can reproduce the more straightforward control and stability parameters in their new aircraft without great difficulty. To a large extent this is true because knowing human pilot capability and using their past experience and common sense most designers can produce the more conventional control characteristics to the complete satisfaction of the pilot and the achievement of the task. It is in the fringe areas of operation where the trouble is usually found and it is in just these areas where the flying qualities specifications are least helpful.

4. HANDLING QUALITIES CRITERIA FOR FUTURE AIRCRAFT

4.1 DATA DERIVED FROM FULL SCALE SERVICE OR DEVELOPMENT AIRCRAFT

If data is to be made available for use in assessing future aircraft then clearly something must be done fairly quickly and the data must not be contentious and the subject of endless argument. Whereas general requirements do tend to be contentious, the statement of facts derived from existing full scale aircraft tends to be rather less so. It is recommended therefore that we should not take agglomerated experience from many sources and try to crystalize it down into a common set of rules, but rather, take specific experience from the past and present and express it in a form which will be of greatest help to the designer and the testing authority.

Considering for instance, the very wide range of V/STOL aircraft types, Figure 3, it is unthinkable that particular criteria derived from each of these types can form a satisfactory general requirement. On the other hand, data derived from one of those types, for example facts plus pilot ratings, could be of enormous value to the testing authority who were concerned with a similar type or the next logical development step.

To quote an example AGARD Paper No. 408 Ref 1 (2nd Draft Revision of Handling Qualities Criteria for V/STOL aircraft) paper already contains far too many contentious requirements and it is probable that the authors realise its shortcomings because they do quote actual data from a number of differing STOL aircraft.

We in the United Kingdom have used specific data from full scale in assessing aircraft both from our own experience and more importantly the experience of our Research Establishments at RAE Bedford and RAE Farnborough. We have found that data provided by these establishments has been essential in setting acceptability levels for the rather more unusual handling characteristics. We find at these establishments, the individuals who know the subject, the reports that they write giving assimilated data on handling qualities, and we find also the technical capacity to advise on the more immediate problems which demand individual study. This work is within the terms of reference of the research establishments but on occasions we know that it has been an embarrassment to them to devote so much time for the support of the test establishment at the expense of their more forward looking research projects.

4.2 HANDLING QUALITY DATA DERIVED FROM SIMULATORS AND MATHEMATICAL MODELS

It would be wrong not to consider the function of simulators and mathematical models in the establishing of the means for obtaining satisfactory handling qualities at full scale. In the author's opinion, however, these methods are no substitute for the full scale data and are far more useful in problem solving during later stages of development or in very basic investigations in the early stages of design proposals. It is realised that these are rather sweeping statements which can be contradicted in particular cases but it would be inappropriate to enter into a long discourse on the subject of simulators in the context of this paper.

5. CONCLUSIONS AND RECOMMENDATIONS

In view of the above the author would like to recommend that some of the present trends in drafting handling qualities requirements should be changed and the following specific proposals are made.

a. The more general handling qualities criteria should be preserved and updated provided that the updating can be done without protracted argument between the manufacturers and the procuring agency.

b. The tendency to elaborate these documents to cover all cases must be avoided because the subject matter then becomes contenious and it takes far too long to incorporate the proposed amendments in the document and the applicability becomes increasingly doubtful.

c. The form of the present draft documents for V/STOL aircraft is inappropriate because of the wide variation of aircraft configurations and the techniques involved in operating them.

d. In cases where generalisation is difficult and contentious, specific data on named aircraft projects should be made available in a suitably assimilated form so that they are useful both to the designer and the flight tester of aircraft of a similar configuration or operational role.

e. The tendency to write handling qualities criteria into the Specification of the aircraft must be resisted and more attention must be paid to specifying the operational role or roles.

f. Within the research establishments provision must be made for a capacity to collate factual data on handling qualities and pilot ratings, for immediate use by the flight test establishments and designers. The aim should be to present factual evidence on those features which contribute to, or detract from, the operational effectiveness and reliability of an aircraft.

g. The information so collated should form the complementary documents to the general handling qualities requirements which can only be of limited application.

List of References

Ref No.	Title etc
1	Handling Qualities Criteria for V/STOL Aircraft - 2nd Draft Revision, AGARD Publication T.R. 408, dated 1967.

FIGURE 1

ACCEPTABILITY RULES IN COMMON USE

(FIGHTER AND TRAINER AIRCRAFT)

RELEASE TO SERVICE SPEED, MACH NUMBER AND G	- 0.9 OF TEST LIMITS OR NATURAL LIMIT
STATIC STABILITY	- POSITIVE OR NEUTRAL
MANOEUVRE STABILITY	- MIN, APPROX 2 LB/G (1 daN/G) - MAX, APPROX 10 LB/G (5 daN/G)
ROLL RATE (COMBAT SPEED)	- 15°/SEC APPROX
MAX FIN/TAILPLANE LOAD DURING FULL AILERON ROLL	- 70% OF DESIGN VALUE
MAX SINGLE HAND PULL	- APPROX 50 LB (22 daN)
MAX FOOT FORCE	- 100 LB SUSTAINED (50 daN) - 200 LB TRANSIENT (100 daN)
DAMPING, ALL AXES	- APPROX 1 CYCLE TO ½ AMPLITUDE
RATIO OF STALL WARNING TO STALL SPEED	- 1.1

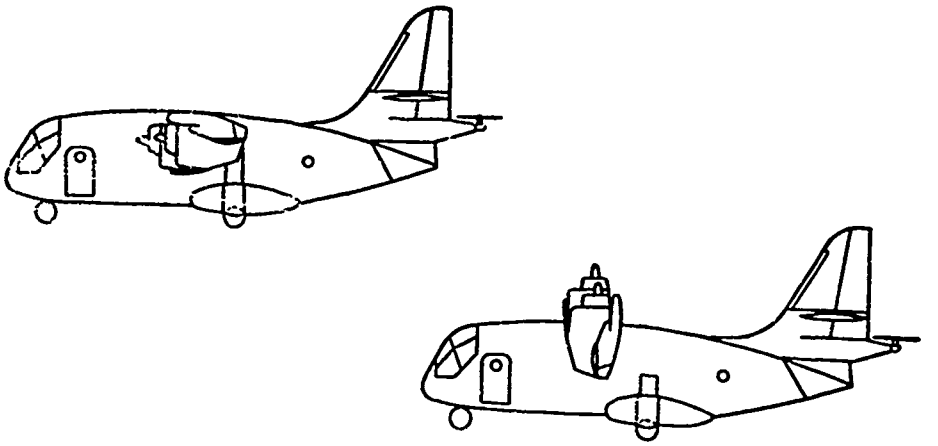
FIGURE 2

Effectiveness	Operational Reliability
1. Controllability as a weapons platform.	1. 3. and 4. under Effectiveness heading.
2. Manoeuvrability in combat, attack or aerobatics.	2. Ruggedness.
3. Insensitivity of control standard to flight environment, (eg turbulence).	3. Simplicity.
4. Insensitivity of behaviour to likely misuse of controls and single failures.	4. Insensitivity to functional or operational environment (eg ease of maintenance of control standard).
5. Cost effectiveness (cost of achieving 1. to 4.).	5. Insensitivity of control to wear and mechanical degradation.
	6. Cost effectiveness (proportion of aborted missions).

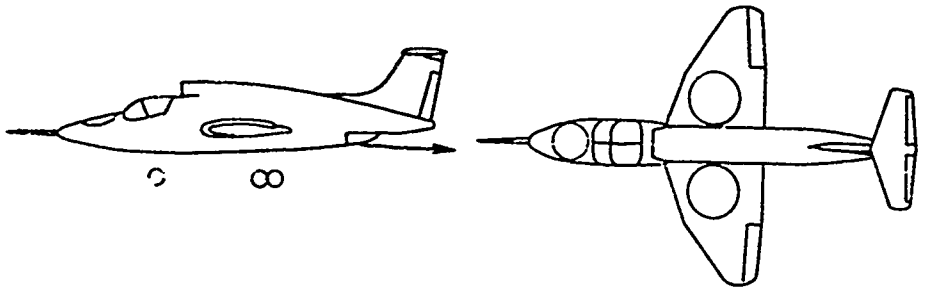
FIG. 3 (a)



TILT NACELLE (U.K)



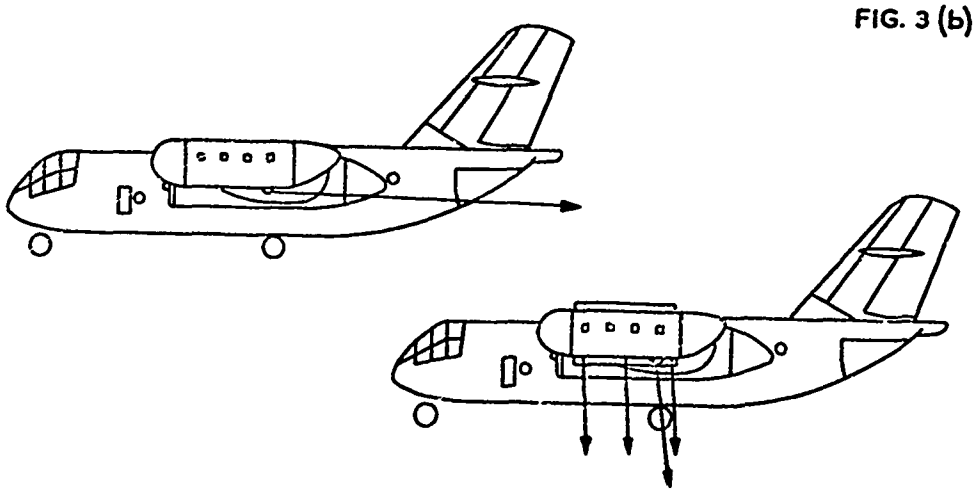
TILT WING (U.S.A.)



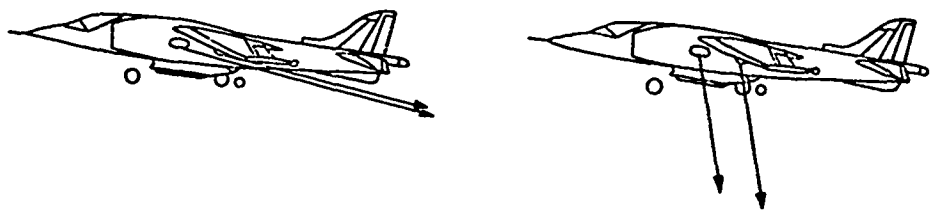
FAN IN WING (U.S.A.)

V/STOL AIRCRAFT

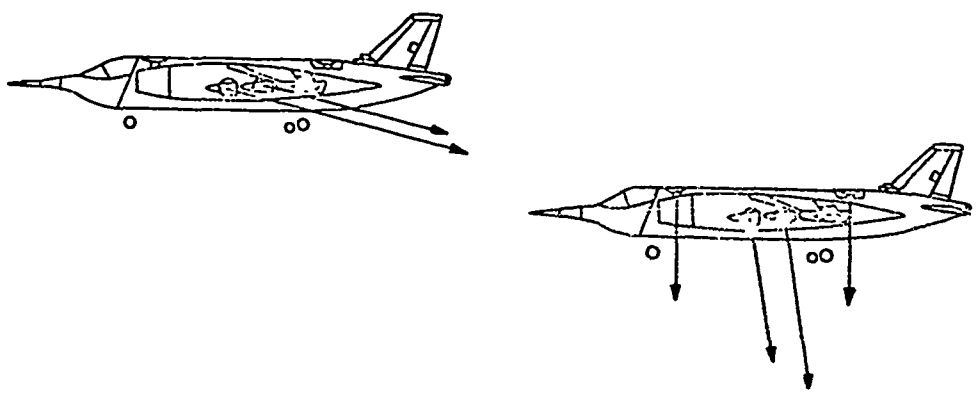
FIG. 3 (b)



LIFT & VECTOR (GER. F.R.)



VECTOR (U.K.)



VECTOR & LIFT (GER. F.R.)

V/STOL AIRCRAFT

LEAD DISCUSSION

by
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To begin with, I would like to express my appreciation to Mr. Andrews for his very interesting paper on flight test aspects of flying qualities requirements. The author has pointed out in a rather dramatic way what can remain of requirements and criteria once the aircraft has reached the flight test phase.

May I try to highlight some of the points made and perhaps add one or two others.

Handling Qualities Criteria in the U.K.

The author has mentioned that the handling qualities chapters of AvP 970 are being updated. Notwithstanding this fact and without trying to extrapolate into the future I want to very briefly try to outline some principles apparent in the present requirements.

Similar to MIL-F-8785, AvP 970 uses four classes of aircraft, and further distinguishes between a defined primary operational envelope and the remaining part of the flight envelope. The backbone of the handling or flying qualities part of AvP 970 is a set of basic requirements - e.g., static stability, attenuation ratios for longitudinal motions, and somewhat broader requirements for the lateral directional modes. These are amplified by a large number of recommendations to the designer, to guide him on the acceptability of his product, to point out difficulties he might encounter or even to indicate means to avoid them. Furthermore, reference is made to a large number of technical reports giving the official research establishments' views on the subject. In the introduction to a leaflet on general flying qualities we find the following sentence:

> "The designer is responsible for the complete operational weapon and must therefore ensure that the stability characteristics of the aeroplane match the equipment and armament carried."

Two points seem to be remarkable in this statement:

- the emphasis on design responsibility of the aircraft manufacturer, and
- the stability characteristics are seen strictly in the context of tasks to be performed.

Many recommendations of AvP 970 are operational in nature and rather qualitative than quantitative, making it often difficult to draw direct comparisons with other requirements such as those in MIL-F-8785. But despite the relatively high average age of these recommendations, this nature has helped to preserve some of them surprisingly long. On the other hand, it may also have contributed to the fact that not many of them survived to the flight test stages.

Handling Qualities Criteria for Future Aircraft

The usefulness of past experience for new projects is self evident, be it in the form of a collection of data on handling qualities parameters and pilot ratings or in the data-reduced form of criteria, backed up by or originating from theoretical analyses and simulator work. Both are needed to gain a better understanding of the mechanisms involved, which will then enable us to improve the written requirements. One of the difficulties which makes this area contentious on occasions may originate from the fact that experience is subjective per se, sometimes difficult to reproduce and not always freely exchangeable. The author's suggestion to create more capabilities to collate factual data on handling qualities must therefore be welcomed.

International programmes force the participating Nations to reconsider their requirements in the light of experiences gained elsewhere and to jointly agree on a common set of standards, at least for one project. This is by no means a simple exercise, but an impact of differing National requirements and principles will then be likely, and this is one more area where such joint programmes have a truly integrating character.

I would like to add two observations to those in the paper. Mr. Andrews points out that existing specifications should be augmented and backed up by data on "effectiveness" and "operational reliability". From the headings listed under these titles in Figure 2 it seems that subjects like "controllability as a weapons platform", "insensitivity to turbulence" and "manoeuvrability in combat, attack or aerobatics" are accessible to at least empirical treatment and have been approached in such a manner in the past, although of course for manoeuvrability in combat there are inputs not under the control of the handling qualities engineer, like SEP and buffet boundaries, which are of paramount importance.

On the other hand, to my knowledge no criteria or data are readily available on "operational reliability", which must be regarded as belonging to handling qualities in rather a wider sense. Most aircraft or subsystem specifications quote values for reliability, failure rates, defect rates, etc., to be calculated using some schematic set of component values, like the RRE data. Apparently these cannot give a true and complete picture of the aircraft system's operating qualities. But terms like "ruggedness" or "simplicity" are difficult to grasp and extensive service experience certainly is required to assess such qualities. It would be interesting to hear what data is available and whether some sort of systematic approach is thought to be possible to the complex of "operational reliability".

Secondly, in his conclusions Mr. Andrews recommends that more attention should be paid to specifying the operational roles of an aircraft. This in principle is desirable because an aircraft is part of a system designed for a given task. However, sets of operational requirements, often involving different types of

equipment or weapons, are sometimes difficult to express in engineering terms because there are more variables, or only partially known factors in this triangle consisting of the pilot, airframe and operational equipment, than can be coped with to give a unique or workable answer.

At the other extreme, overspecification, that is trying to design the aircraft by specifications, is firstly difficult to achieve and secondly has adverse effects on the contractor. For instance, Mr. Barnes might be tempted to undertake something "diabolical". The only way to make specifications work will be by close contact between the manufacturer and the procuring agency, and MIL-F-8785 provides a good basis for this.

OPEN DISCUSSION

A.D. Wood, NRC/NAE, Canada

It may be helpful to recall the distinction sometimes made between "criteria" on the one hand and "requirements" and "specifications" on the other.

If this distinction is made "criteria" may be regarded as providing the best available guidance to designers on how to ensure good handling qualities. The criteria may be elaborate or otherwise and probably change with time, but have no contractual connotations.

"Requirements" and "specifications" entail demonstrations of compliance. If these are extremely detailed, then Andrews' concern may be justified. Possibly, they would be better either reduced to a minimum of essentials or alternatively graded, with contentious items subject to liberal interpretation during demonstration.

S.J. Andrews, A&AFE, UK

We, in the testing field, would certainly welcome the criteria, because it does enable us to assess the nature of the task that we have to deal with and also helps to anticipate where we have to put our greatest effort. What is needed in our business is to know the origin of the points of acceptability so that we are not operating from clouds of these points but from something which can tell us how our new case differs from the old one.

Prof. X. Hafer, Tech. Univ. Darmstadt, Germany

The acceptability rules in common use you give in Figure 1 are valid for airplanes with all augmentation systems on. Besides this, the designer needs data of criteria for operations with systems failures.

J. Scott-Wilson, Hawker Siddeley, UK

There is a critical interface between handling and performance. It is the performance issues that are usually the critical commercial ones. Therefore the related handling requirements want to be as specific as possible - quantified requirements not criteria dependent solely on pilot opinion. As an example, minimum control speed following engine failure for a twin engined aircraft is defined in British Civil Airworthiness Requirements in terms of change of heading, vertical bank and pedal force. These can be measured and are independent of pilot opinion. If V_{mCA} depended on pilot rating assessment only, there would be a totally unsatisfactory position. In rewriting AvP 970 may we keep requirements for performance related handling like this?

J.T. Gallagher, Northrop Corp, USA

Both Northrop and McDonnel-Douglas are in the process of checking aircraft against the intent of 8785B. Northrop is investigating F-5 and McDonnell is investigating the F-4 series. In both cases, the aircraft's shortcomings are covered by 8785 and in general 8785 is a good design guide for fighter aircraft. In summary, conclusion (d) in Mr. Andrew's paper is being taken care of.

FAA Flying Qualities Requirements

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SUMMARY

The need for flexibility and change of Federal Aviation Regulations to accommodate new designs and innovations to flying vehicles is an ever-increasing and complex situation. The current philosophies and projected difficult areas associated with airplane handling qualities are discussed in this paper. The subject is not intended to be covered as to the specific conditions or types of airplanes but, rather, to cover the qualitative evaluation needs for determining compliance with the existing airworthiness rules. Recognizing that aircraft development and capability is an ever-improving science, the relationship of Federal rulemaking procedures to the application of judgment in the requirements to produce timely and adequate determinations of compliance is discussed with consideration of complex control systems and rapidly-expanding flight envelopes.

Airplane flying qualities written requirements are, by necessity, behind the advancement of modern designs, require constant revision and, usually, are developed from actual exposure in flight testing and research projects. Perhaps a brief review of our rulemaking process is in order to establish the time scale for revisions and amendments. First, a need for a change must be apparent. This usually results from design review of a new vehicle, qualitative assessment of the test article, or a similar design, and experience gained from service difficulties, military operation of new designs and research programs. Once a test is developed and commented upon internally by the FAA, it is submitted as a notice of proposed rule making by the FAA to the public for comment. Upon completion of this phase, careful evaluation is given to these comments and suitable revisions made to the content and ultimately an amended or new rule is published.

Obviously, with these procedures for rulemaking, time is consumed beyond the needs of an active certification project. With each new and modern design, the flying qualities requirements become more complex because of complication of control systems, stability augmentation devices and substantial increases in operational envelopes of weight, speed, and altitude. Fortunately, to the present time, many anticipated and predicted problem areas have been found to be minimal or nonexistent in actual flight testing. Examples of these areas are high-inertia effects upon response characteristics in very large transports and operation "behind" the drag curve during approach with aircraft incorporating high-lift devices or being of low aspect ratio.

In view of these comments, the certification of modern transports in the flying qualities area have presented some administrative problems involving timely updatings of Federal Aviation Regulations (FAR) which have been handled, usually on an equivalency basis or special conditions for certification. Satisfactory level of safety findings are provided in this manner. These actions, where appropriate, are used for proposed amendments to the airworthiness rules. Equivalent safety findings are authorized under the provisions of FAR 21, Certification Procedures for Products and Parts. Special condition procedures are contained in paragraph 21.16 of the same Federal Aviation Regulation Part.

Some current and anticipated flying qualities problems in civil airplanes are essentially centered around specific areas and are as follows:

1. Minimum speed or maximum angle of attack characteristics of airplanes which do not possess a classic stall or break in the lift curve.

2. Required damping levels for dynamic stability considering departures from known designs, large moments of inertia, relatively long natural short-period frequencies and aeroelastic flexibility of slender fuselages.

3. Complex, irreversible control systems with the incorporation of stability augmentation with significant authority and their failure effects.

4. Variable center of gravity (in-flight) by means of fuel transfer and the related flight characteristics for supersonic transports.

5. Stability requirements for airplanes which possess "attitude stability" rather than classic static longitudinal stability.

6. Low-speed steep gradient approach characteristics of STOL airplanes.

7. Maneuvering requirements throughout the operational envelope for initial climb, subsonic and transonic cruise, supersonic operation, recovery from departures from desired flight paths due to outside influences and during the approach phases of flight.

8. Flight characteristic minimums for general (light) category airplanes as related to average pilot proficiency.

9. Required level of flight characteristics which may be modified by means of improved flight path guidance systems.

These topics will be discussed individually with, where feasible, our proposed methods of treating them.

Minimum Speed or Maximum Angle of Attack Characteristics

New designs, including slender delta planforms, extremely large and heavy aircraft and those incorporating high-lift devices or, in some cases, direct lift control, reasonably, may require new concepts and evaluations to be substituted for the characteristics normally associated with classic stalls. High thrust to weight ratios combined with high-pitch attitudes such as some SST designs introduce a new variable of substantial contribution in lift from the resultant vector of thrust. If the point of minimum speed is not recognizable by downward pitching or other acceptable inherent aircraft characteristic, the point must be clearly and easily identified by the pilot following suitable warning of the approach to this in-flight limit. Control systems, primarily in pitch, must also have the capability to permit the pilot without using exceptional skill, to discontinue the approach to handle the airplane at and recover from the minimum flight speed condition into normal flight. Problems present themselves in these investigations in the level of thrust to be used and the reasonable limit in nose high-pitch attitude for high thrust to weight (T/W) ratios and the allowable sink rates for very low T/W. We are of the opinion that the present required thrust levels for characteristics investigations of aircraft without classic stall, to be of sufficient range to include with a margin, those expected in operation. However, it seems unreasonable to investigate, for a performance baseline, idle thrust at maximum takeoff weight for a slender delta, for instance, or maximum takeoff thrust at minimum weight for high T/W aircraft. In other words, regulations must recognize advancements in airplane designs which raise performance levels, increase airplane weights to the possible million-pound levels, or become classically unstallable because of lift curve characteristics hich are unique to previous civil aircraft. Modifications to the Federal Aviation Airworthiness Regulations are required. Proposals for these changes are contained in the United States Tentative Airworthiness Standards for supersonic transports.

Dynamic Stability Characteristics

Many research programs, including in-flight and ground-based simulators, analysis of experimental aircraft testing, and analytical mathematic studies have been devoted to the complex area of dynamic stability. Essentially and specifically, the Federal Aviation Regulations (FAR) simply state: "FAR 25.181, Dynamic Longitudinal, Directional, and Lateral Stability. Any short period oscillation occurring between stalling speed and maximum allowable speed appropriate to the configuration of the airplane, (for example, V_{FE}, V_{LE}, or V_{FC}/M_{FC}) must be heavily damped with the primary controls (1) free and (2) in a fixed position." FAR 23.181 of the same title for small aircraft essentially reads the same. Judgment and equivalent safety findings become imperative when applying this rule to all categories of airplanes. For an example, very large and high-inertia airplanes with relatively long natural short-period frequencies, if "heavily" damped, may become unflyable, or nearly so, especially in the approach phase of flight. If damping is high in these cases, the pilot finds great difficulty in correcting the flight path or maneuvering. Research studies show a pilot acceptance and desire for very low damping in these cases, especially in longitudinal axis; otherwise, over control with checking is required to satisfactorily achieve the desired flight path. Likewise, in the lateral directional short period, oscillations commonly known as "Dutch roll," are the roll to yaw ratio, coupling effects with the spiral mode, the particular roll time constant, and the natural undamped frequency of the oscillation are of significant importance. High roll to yaw ratio affects adversely the pilot capability to properly control the airplane. The other effects, such as coupling, are complex and must be considered. It is obvious that if the natural frequency falls into the pilot-induced oscillation (PIO) area, any undamped or weakly-damped oscillation will become unacceptable and, conversely, if the frequency is of suitably long period, the pilot can easily cope with it. When stability augmentation is installed, as in most modern swept-wing or delta airplanes, new and different problems arise. Without proper gain tailoring, washout time periods, or improper authorities, these artificial dampers interfere with turn coordination and, in the case of pitch or roll dampers, they react in a manner such that the pilot must overcome their operation during normal maneuvering. The message in these comments is that the terms of the regulatory language "heavily damped" are satisfactory for a Federal law, but far too simple for application to these complex airplane motions.

Powered and Irreversible Control Systems

In times past, many unsatisfactory, as well as desirable flying qualities, could be directly attributed to direct linked controls to the pilot, flying tab operated surfaces, manual trim systems, and the lack of stabilizing surfaces of enough area to provide needed stability. The deficiencies are well known of these systems, i.e., increased pilot effort required as aircraft become larger and faster, ineffective control due to flow separation on tabs at high Mach numbers, stabilizer trim authority versus elevator power, control surface floating with airplane motion, and performance and resulting economic penalties from the wetted drag area of large stabilization surfaces. New aircraft and, certainly, future airplanes possess powered control systems with which new and unique handling qualities problems appear. Civil regulations must be upgraded to cater to these problem areas. Paramount consideration involves reliability and failure effects. This regulatory area must express a need for thorough evaluation to assure a level of safety required for commercial air transportation. To the FAA compliance test pilot, these new control systems, in relation to handling qualities, manifest themselves into tailored control feel, artificial control centering, possible changes in lag or hysteresis, proportional friction, unusual rates of surface movement, control surface activities from augmentation systems which are not apparent in cockpit control movement, increased control power, and the magnitude of changes in flying characteristics following

failures. In most cases, the use of powered controls, though required to provide sufficient "muscle" to properly control the airplane, increase the designer's capability to tailor the total system to pilot desires in forces, rates and harmony. With probable failures, however, the airplane usually will exhibit greater departures from the normal flying characteristics unless, of course, redundancy provides fail operational conditions.

In-flight Variation of Center of Gravity

With the advent of the supersonic transport, another new approach to efficiency and controllability has been taken. Fuel transfer center of gravity (cg) control has been an accepted practice with military supersonic aircraft for some time, but it is new in the civil airworthiness field. The purpose of such systems is to provide less trim drag at supersonic speeds where the center of pressure moves aft. Without establishment of a supersonic cg, substantial trim is required in the airplane nose-up direction which not only produces a high-drag condition (reduced range), but also reduces the longitudinal control available for maneuvering. The optimum cg for supersonic cruise is usually near or aft of the static and maneuvering neutral point for subsonic flight. These conditions bring on new handling quality considerations. Either reliability of high integrity is necessary, or failure effects testing for stability and control are in order.

Static Longitudinal Stability Requirements

Present airworthiness rules (FAR 25) for stability are simple in nature and, in a strict compliance sense, may be highly undesirable for future aircraft such as supersonic transports and questionable as to need for present day aircraft. Discussions have taken place referring to terms such as "attitude stability" as a substitute for conventional static longitudinal stability with a quantitative minimum speed versus stick force slope. Precise flight path control without continual pilot correction is the ultimate aim in this area, and there may be more acceptable ways to achieve this than as presently written in our requirements. We are actively engaged in simulator and flight research programs in the stability and control areas such as these. A clearer understanding of the term "attitude stability" may be gained by considering our present airplanes which utilize a "stick steering" feature of an autopilot, wherein the airplane maintains an attitude or other reference until otherwise commanded by the pilot. Following a pilot command, the airplane is established in a new trim position and has no tendency to return to the original trim point. Outside or environmental influences do not affect the trim point but, in a classic sense, the airplane does not exhibit static longitudinal stability, except as related to the pilot being required to institute an input in the proper sense to change the flight path.

Low Speed Steep Gradient STOL Airplanes

A new generation of airplanes, employing powered lift and capable of short field operation, are receiving national attention at this time. Again, these are new designs utilizing new and unique design innovations specifically developed for small takeoff and landing areas. Population concentrations and short route requirements have initiated an economic need for these transportation vehicles. Quite sensibly, the short field lengths to be operational in a congested area, dictate a steeper than usual takeoff and landing flight path to properly clear obstacles and, also, employ relatively low speeds to accommodate the shorter ground distances. The failure effects of these designs must be considered. It is anticipated that safety considerations such as minimum control speed with engine failure, and flight path guidance system failures in poor weather will pose new problems or require designed protection. Flying qualities also pose new considerations. Gusts, turbulence, crosswind, wind shear effects are amplified because, with average conditions, they present a much higher proportional disturbance when related to vehicle velocity. Control effectiveness, coupling of lateral directional stability modes and maneuverability at low dynamic pressures and with large thrust contributions to lift and control, all become paramount handling qualities areas for review and standards development.

These are special purpose vehicles which are selectively designed to operate between the helicopter and the normal fixed-winged flight regimes. Power-off stall speed, though a flight characteristic investigation item, no longer may be used as a performance or safety baseline. We are tentatively developing airworthiness standards for these airplanes. We are grateful for the contributions of the industry, military, operating organizations, and others in this task.

Maneuvering Requirements

Other than general references to controllability, present U.S. civil rules do not specify a level of required maneuverability or the characteristics involved in obtaining it. Required maneuverability varies with the particular use of the airplane, the operational envelope and its individual characteristics. In actual practice, the operational pilot cannot sense the values involving pitching moments at various angles of attack. Of prime concern to the pilot is his capability to adjust his flight path for collision avoidance, upset recovery, and to handle environmental effects in initial climb after takeoff, and during the landing approach and flare. Maneuvering the airplane in normal flight basically involves a measure of the effective static stability for the short period airplane motions, control system effectiveness, and the linearity or nonlinearity of the pilot's longitudinal control force to normal acceleration (F_s/g). The latter of these measures are of importance because, at forward C.G. the forces must be linear and low enough to allow the pilot (in most cases with one-handed effort) to properly maneuver and at aft C.G. to be linear and be high enough to eliminate the concern of overstressing the airplane on induce undesired oscillations. We all know these forces have varied in level over the years, from the extremes of absolutely necessary two-handed landing flare in some of our early four-engine piston transports to extremely light force requirements in cruising flight of our later jet transports. The manufacturer cannot vary the natural short period frequency of an individual airplane, but he can design the powered control system and where installed, the supplementary augmentation systems, to produce the desired airplane response and maneuverability in nearly all cases. Problem areas that may develop with this concept are the extremely tight places for control system actuators which will develop enough muscle to move the surfaces, hysteresis and friction resulting from extreme length of connecting systems from pilot controls to the actuators and the various failure effects of components within the systems.

We are moving into new phases of flight, requiring advanced thinking and systems to cope with supersonic operation and also with extremely low speed steep approach flight conditions. These extend and complicate our control systems for maneuvering the airplane in an acceptable manner.

Acceptable Flight Characteristics for Small or General Category Airplanes

A dramatic advancement has come about in this category of flying vehicles in the past few years. The old baseline generated around the Piper Cub and other airplanes of that type. In the present-day, many of our new light airplanes fly easily in operational envelopes not unlike those of World War II fighters and in the case of some high-performance turbine-powered machines, up to and very nearly supersonic flight. We cannot ignore the private airplane which is now in vast numbers and operates in the same airspace as our commercial jet transports with comparable complexity of systems. One area to be considered in the handling qualities of these airplanes is the basic premise that these, in a large percentage, are operated by airmen of average pilot skill and in some cases by persons of low experience level and dubious continuing proficiency. This means for the general aviation case, he must be provided with, if not a "forgiving airplane," an airplane which is relatively easy to fly. Consistent with this concept, a continuing upgrading of airworthiness requirements is necessary without unnecessary economic hardship on the small, uncomplex airplane manufacturer and operator.

Low-speed handling qualities including stall characteristics, minimum control speed with one engine inoperative in the multiengine airplanes, and general flying qualities are of paramount concern in the safety aspects of airworthiness in these vehicles. Some years ago, we dropped the severe spinning requirements in deference to good stall characteristics, and a tightening of the evaluation for inadvertent spinning tendencies. This, in conjunction with other characteristics related to average pilot skill, have produced an acceptable safety record.

High speeds are also attained with some of these airplanes which has brought on requirements for investigation of Mach number effects, overspeed warning systems, and more complex flutter analysis.

Flight Path Guidance and Flight Characteristics

The new flight director displays and innovations in flight path guidance are not a substitute for satisfactory handling qualities, but they do provide a valuable contribution to reduction of pilot workload and improve his ability to detect deviations from his desired flight path. An example of these advancements is the amplified scale of the pitch attitude indicator for supersonic transports. The resulting readability for flight phases, such as takeoff rotation, allows the pilot to precisely set pitch attitude to assure performance. Measurements to a half of a degree are important in this phase of flight, if acceptable margins for safety are to be maintained with practical limits on economical operation from existing runways. When you analyze why this is true, you find new departures in handling qualities related to performance. The lift/drag characteristics of these machines, coupled with the necessarily high thrust-to-weight ratios to obtain supersonic flight places the airplane in an operational area where it is extremely sensitive to pitch attitude and speed variations with an engine failure. With proper failure protection of these guidance devices, we must consider their contribution to the overall handling qualities picture.

Civil regulations within the terms of the Federal Aviation Act must contain minimum standards for safety. These standards should be general in nature so as to not inhibit advanced designs and only specific enough to provide for a degree of consistency in their application. Military standards are often quoted in the context of safety standards, however, it must be recognized that they have a much more complex objective. Military specifications are basically design standards oriented to military mission requirements. It is a common practice to waive or deviate from those standards without specific regards to economics. Commercial airplanes on the other hand must consider economics in a competitive sense. It becomes the responsibility of FAA safety inspectors to assure that the intent of the Federal Aviation Regulations has been met. This requires close coordination and policy guidance to obtain equal treatment between applicants. Flexibility is a must to obtain the required safety level and have a practical and viable commercial airplane. Research programs, study of existing and new designs, and good judgment are required to attain this goal.

LEAD DISCUSSION

by
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After the very interesting paper by Messrs. Sliff and LeSuer which covers very completely a very broad subject and gives a very clear view of a very complicated question, there is no need to add my own interpretations. I will only open the discussion by raising one major question and three minor ones.

Major Question: Mr. Sliff pointed out that progress in commercial transport aircraft has been faster than the adjustment of old regulations to the new types of aircraft. Does he think that this will lead inevitably to the need for a new philosophy of more flexible regulations replacing completely the old rules, or to a very large adjustment of the old rules?

Minor Question #1: Does Mr. Sliff think that the subsonic speed parts of the new tentative airworthiness standards for SSTs could apply to modern aircraft other than supersonic transports?

Minor Question #2: Mr. Sliff stated that center-of-gravity boundaries lead to new handling requirements. I think that they also lead to the complex problem of compatibility between the subsonic and supersonic c.g. boundaries (in terms of speeds and altitudes) for emergency descent and deceleration with the use of fuel transfer. This leads to the concept of envelopes associated with aircraft states as explained in the paper by Messrs. Carlson and Wanner.

Minor Question #3: The choice of stability criteria as an example of a bad concept which must be replaced is a very good one. Stability in itself has no meaning. It is only the pilot-aircraft loop which counts, whatever may be the pilot: human or automatic. The remaining problem is a question of redundancy and failure probability. This leads directly to the pilot rating criteria.

OPEN DISCUSSION

R.S. Sliff, FAA, USA

The first point was the regulations, as I said, on the very complex airplanes which are requiring considerable expansion and flexibility of requirements. The question was asked whether this would require a very large adjustment in the regulations themselves. My answer to that is No. The reason why I say that is the regulations are written in a qualitative and general sense. As I pointed out, the specific differences and complexities as they come up are handled in the terms of special conditions and requirements with the aircraft so that you can evaluate that product with an expert against a general requirement. This always lends itself to opinion and I don't know how to get away from that. Next, on applying SST standards to other aircraft, we definitely feel that most of the requirements with regard to a supersonic transport, with the exception of very few areas, are directly applicable to updating the rules and requirements for any modern transport aircraft. Only those which would be peculiar to either temperature, as affect by high Mach number or something peculiar to shock wave disturbance, or so on, for SST would be truly an individual requirement for an SST. We intended to update the overall transport standard in the same context that we have used to apply to supersonic transports.

On cg boundaries and failure concepts, we recognize that it is necessary to expand the cg envelope outside of that which is controllable in another regime of flight. In this particular case, you have to use a probability index such as TSS 5 or other to insure that you will have a safe airplane in face of failures that can occur.

There is only one way, I believe, that you can truly evaluate stability and you answered that question yourself, and that is through a pilot rating. We have long said that only as a guide would we use hard numbers such as 1 lb/6 knots for stick force versus speed. If it is half a pound and is suitable for that airplane it has to be qualitatively assessed.

REVISIONS TO V/STOL HANDLING QUALITIES CRITERIA OF AGARD REPORT 408

by

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SUMMARY

A brief review of selected handling qualities criteria for V/STOL aircraft shows that although a clearer understanding of the requirements for controversial areas such as roll control power, vertical flight path control, and transition is in hand, considerably more research is needed to refine these criteria for operational IFR activity. Because many items interact to influence the pilots' overall impression of the aircraft's behaviour, additional work of a systematic nature must be done to clarify this aspect. A better definition of a gust model which includes discrete gust effects is needed to firm up criteria for both hover and STOL operation.

1. INTRODUCTION

All of us who are closely associated with the use of aircraft can readily appreciate the need to continuously revise and update handling qualities. For V/STOL aircraft in particular, there are many reasons for this; for example, to reflect recent requirements of operational type aircraft, to give consideration for the peculiarities of operating with different types of lift-propulsion concepts, and to describe the effects of operation with novel control systems on closed-loop responses.

The first AGARD publication of V/STOL handling qualities recommendations, AGARD Report 408 (ref. 1), was based largely on NASA T. F 331 (ref. 2). Both of these reports have received criticism, not unexpected, on their scope and specific recommendations. They were directed primarily toward VTOL aircraft and did not adequately cover STOL aircraft, which utilize powered lift techniques. In addition, the recommendations did not adequately take into account the different requirements by the various lift-propulsion concepts or novel control systems. They were based mostly on results obtained from test bed type aircraft and helicopters and obviously could not reflect the requirements of operational type V/STOL aircraft. To a lesser degree, the same criticism applies to the revised AGARD Report 577 (ref. 3) because operational aircraft results were not available. Further, the consequence of providing only minimum acceptable values of each handling quality item was not fully appreciated by the user; a V/STOL aircraft that individually meets all recommendations could still be too demanding of the pilot's skill because several factors may interact to produce an overall unsatisfactory response.

In revising ref. 1 it was agreed that a more meaningful and useful document would include:

- Evaluation of the various handling qualities items in terms of *criteria* rather than requirements or specifications.
- A discussion section following each criterion to explain the purpose of the criterion.
- Data and reference material to back up the proposed criteria.

Criteria can be defined as evaluation standards based on numbers that are meant only to be typical and can vary depending on the particular mission and task. Meaningful criteria can serve as a guide in establishing specifications to be used by a contractor for the design and testing of a particular aircraft.

In the past, handling-qualities requirements have been presented without an explanation of why the pilot desires a particular characteristic; in many cases neither the purpose nor the interrelation of the various factors affecting the requirements were understood. Without an understanding of all possible tradeoffs, there may be a tendency to apply the requirements too rigidly to a particular aircraft design, thereby compromising its utility.

Finally, it is helpful to provide background data and reference material for each criterion. If the user understands the limitations of the data on which the criteria are based, he can evaluate the criteria with respect to their optimum application to his design, and, of course, the contractor can then provide more effective specifications.

In showing how the foregoing philosophy was carried out in preparing AGARD Report 577, examples in several controversial areas are given. The purpose is to point out how well the present criteria compare with the available flight results, review areas that need additional work, and indicate how these gaps in knowledge can be filled. Because of length restrictions, only the following areas will be covered:

- Roll control power
- Vertical flight path control
- Transition characteristics

2. RESULTS AND DISCUSSION

2.1. Roll Control Power

2.1.1. *General background.* One of the more controversial areas, which has persisted over the years, is a definition of how much roll control moment must be supplied for hover and STOL operation. Pilots have been more critical of the control of V/STOL aircraft

about the roll axis than about any other axis partly because the lateral positioning must be quick and precise and partly because of the effect of cross winds during landing. Precise control is essential during approach because even small bank angles will result in relatively large heading changes at low speeds. Undoubtedly, some of the difficulty in addressing this problem has arisen because several items interact to determine the overall roll response apparent to the pilot. These include:

Control needed for maneuvering
Control needed for trim
Control needed for upset (due to gusts, recirculation, ground effect, etc.)
Type of control system used
Control sensitivity
Aircraftft size (mission considerations)
Angular rate damping
Control lag
Turn entry characteristics (e.g., adverse yaw, yaw due to rolling)
Mechanical characteristics of control system (e.g., friction, breakout, force gradient)

The total amount of control needed is made up by a combination of these individual requirements; the first four are the major inputs. The pilot desires certain values of roll control for maneuvering, for trimming in sideward flight, and for controlling upsets due to turbulence or self-generated disturbances. Control power requirements depend on many factors: (1) the mission to be performed; (2) the susceptibility of a particular configuration to unsymmetric moments resulting from aerodynamic or thrust-induced crossflow as well as turbulence and ground-induced disturbances; (3) aircraft size, since in general, large aircraft are maneuvered less briskly, and because of their higher inertias they tend to be disturbed less by turbulence; (4) the type of control system used (more stabilized systems require less control power); and (5) the amount of angular rate damping available.

For trim in hover, various amounts of roll control moment are needed to maintain desired velocities in sideward flight. The amount differs for each VTOL concept because of the difference in magnitude of rolling moment introduced from both aerodynamic and engine-induced flow sources. For aircraft with inherently large rolling moments induced by side velocity, ample control moment is needed to avoid the development of excessively large bank angles, which may occur very abruptly with a sudden loss in altitude when the aircraft is suddenly turned sideward from a headwind approach. Some types of V/STOL aircraft require that any asymmetric rolling moments associated with powerplant failure be trimmed out Further, the amounts of trim required depend on the cross-wind magnitudes specified for a particular mission and VTOL concept.

The amount of control power available to counteract upset due to gusty air or self-induced flow effects in ground proximity (which are also configuration dependent) directly affects the precision of the approach and touchdown. In vertical takeoffs and landings, the pilot needs to adjust attitude rapidly to avoid excessive side drift. Bank angle excursions are undesirable in STOL approaches because of the tendency to induce large heading errors. In these cases, the pilot is interested primarily in returning to the initial bank angle in a given time. In addition, the type of control system used has a pronounced effect on control power requirements for upset. More sophisticated control systems, such as attitude command, automatically reduce or eliminate the need for the pilot to correct for the upset. Because corrections can be sensed and made more quickly by the SAS, large amplitude excursions in bank do not develop and there is a resultant savings in control power requirements.

Because of the foregoing considerations, the criteria for roll control power were broken into the factors listed in table 1. Although only examples of roll control power are presented here, a similar system has been used for the pitch and yaw axes. The chief purpose in breaking the requirements into separate parts is to force the user to examine how each one affects his particular aircraft design or flight evaluation. Different values of roll acceleration are given to take into account the type of control system used and the type of operation; i.e., VTOL or STOL.

Table 1. Roll Control Power Criteria

PARAMETER TO BE MEASURED	CONTROL POWER REQUIRED FOR:	TYPE OF CONTROL SYSTEM	MINIMUM LEVELS FOR SATISFACTORY OPERATION	
			HOVER	STOL
ROLL ANGULAR ACCELERATION, rad/sec²	MANEUVERING	ATTITUDE COMMAND	0.2 – 0.4	0.1 – 0.6
		RATE	0.2 – 0.4	
		ACCELERATION	0.3 – 0.6	
BANK ANGLE AFTER 1 sec, deg	MANEUVERING	ATTITUDE COMMAND		
		RATE	2 – 4	2 – 4
		ACCELERATION	2 – 4	2 – 4
ROLL CONTROL DEFLECTION AT ZERO ROLLING VELOCITY, in.	TRIM	ALL	SUFFICIENT CONTROL IN EXCESS OF MANEUVERING REQUIREMENTS TO TRIM OVER DESIGNATED SPEED AND C.G. RANGE AND FOR MOST CRITICAL ENGINE FAILURE	
TIME TO RECOVER TO INITIAL ATTITUDE OR CONTROL DEFLECTION, sec	UPSET (DUE TO GUSTS, RECIRCULATION, GROUND EFFECT, ETC.)	ALL	SUFFICIENT CONTROL IN EXCESS OF MANEUVERING AND TRIM REQUIREMENTS TO BALANCE MOMENT DUE TO A SPECIFIC GUST; FOR EXAMPLE, 30 ft/sec GUST	
			BUILDING UP IN 1 sec	BUILDING OVER A 100 ft DISTANCE
ROLL ANGULAR ACCELERATION, rad/sec²	TYPICAL RANGE OF VALUES USED BY V/STOL AIRCRAFT FOR MANEUVERING, TRIM, AND UPSET	ATTITUDE COMMAND	0.4 – 1.5	0.2 – 2.0
		RATE	0.8 – 2.0	0.3 – 2.5
		ACCELERATION	0.8 – 2.0	–

2.1.2. *Control needed for maneuvering.* Table 1 lists a range of values for maneuvering control requirements in order to reflect the mission requirements. In ref. 3 the criterion states that "... aircraft whose missions require extensive maneuvering should be capable of

at least the larger values indicated, while those for which maneuvering is only incidental to the mission and those for which direct side force control can also be used should be capable of at least the lower value noted." The validity of the values listed in table 1 is certainly open to question because ultimately the values must come from real operational experience with different classes of V/STOL aircraft. Until such results are available, we can only speculate, on the basis of limited data obtained primarily from nonoperational type V/STOL aircraft, some of which have attempted to simulate operational type maneuvers. There is the further problem of sorting out from data obtained during these maneuvers, the amount of control used uniquely for maneuvering and that which was used concurrently to correct for trim and upset due to gusts, turbulence, recirculation, etc. Perhaps the best answers can be derived from examining records of aircraft for which trim changes, by virtue of their engine and aerodynamic layout, are minimum. Further, if these aircraft use an attitude command type of control system, the effects of external disturbance are minimized. Results from two such aircraft, the VJ–101 and the DO–31, show that satisfactory operation in hover was obtained with values of 0.2 rad/sec^2 and 0.4 rad/sec^2, respectively. Further confirmation of the lower value of roll angular acceleration for STOL operation has been obtained from "flights" in a piloted motion simulator (ref. 4). A slightly higher value (0.6 rad/sec^2) was selected for the upper end of STOL operations to reflect the need for more agile maneuvering into confined areas.

2.1.3. *Control needed for upset.* The amount of control needed to take care of upset due to gusts, recirculation, ground effect, etc., is dependent chiefly on the magnitude and character of the disturbance. It is in this area that the proposed criteria are weak. Although improvements have been made in gust measurement techniques, data analysis, and prediction effects, a well-defined gust model suitable for hover and STOL operation still remains to be defined. The criteria for upset used in table 1 attempt to establish a base for firmer values. It was considered necessary to specify a discrete gust effect rather than the usual rms random noise type to provide meaningful results for control power assessments.

2.1.4. *Validity of roll control power criteria.* The range of values for total control power given in table 1 reflects the speculative nature of the criteria and permits flexibility in choice for design purposes. The values in the bottom row are typical ranges used by various aircraft and are not intended to represent firm numbers which must be met. An examination of flight test data and a discussion of how some of the aforementioned items interact to produce a given overall impression of roll response to the pilot follows.

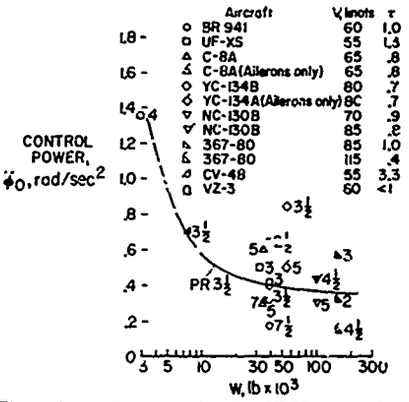


Fig. 1. Lateral acceleration for STOL operation; pilot rating next to symbol.

Figure 1 shows results of STOL aircraft tests (taken from ref. 5) obtained during approach and takeoff. The results are presented in terms of maximum angular acceleration obtainable as measured by the conventional roll reversal technique. For convenience, the data are presented as a function of gross weight which was used as a sizing formula $(W + 1000)^{-1/3}$ in AGARD Report 408A. Also shown are the pilot's ratings of the overall roll response for each aircraft. It should be recognized, however, that angular acceleration is only a convenient parameter to use as a yardstick and that it relates only indirectly to the pilot's impression of controllability. Further, when weight is used as a parameter, it only approximates the effects of size and, as noted previously, reflects maneuverability requirements and sensitivity to turbulence.

Note first that a large acceleration value does not necessarily indicate satisfactory pilot impression of roll response. For example, the VZ–3 aircraft has over three times the roll acceleration capability of the majority of the other aircraft and still has only a pilot rating of 4. The ability to maintain a desired bank angle while maneuvering in turbulence has been the most critical requirement for roll control of these STOL aircraft at takeoff and landing speeds. For example, in tests of the BR 941, less than 40 percent of the available control was used during extensive maneuvering. Remember that this aircraft requires little lateral trim for cross-wind operation and the propellers are interconnected to remove any engine out asymmetry trim requirements. The BR 941 is perhaps the most documented of these aircraft. It has been flight tested with several lateral control modifications and has been extensively investigated in piloted motion simulators. Flight tests with this aircraft in IFR operation and moderate turbulence (ref. 6) indicated that roll control was satisfactory with a control power of 0.4 rad/sec^2 under these more adverse conditions. Note that for a heavier aircraft, the NC–130B, poorer ratings are evident for this same control power value (based again on IFR operation in gusty air). The poorer overall roll controllability was due in part to low control sensitivity and to the fact that at 70 knots almost full roll control was required to trim for an inoperative engine. Therefore, too small a margin was left for maneuvering. The heaviest (and largest) aircraft tested was the 367–80 (707 jet transport) modified to incorporate a high-lift BLC flap system. With the combined aileron spoiler system, the roll acceleration produced by large control deflections was so large for that size aircraft that the pilot was concerned about possible structural damage. In the initial tests with this aircraft the ailerons were equipped with an aerodynamic tab control that was rated unsatisfactory (PR 4–1/2) because of high forces and nonlinear response characteristics. Changing to a hydraulic powered control system with essentially the same rolling moment capabilities improved the pilot rating because of the lower forces. These data show that an improved pilot rating resulted when a higher approach speed was used, even though less acceleration was available. In this case, the cross-coupling effects $C_{N_{\delta a}}$, C_{l_β}, C_{n_p} were greatly reduced at the lower C_L associated with the higher approach speed. A further example of interrelated effects is brought out by the results obtained on the BLC equipped YC–134A aircraft. Even though very large lateral acceleration was available with the combined spoiler and aileron combination, precise use of this capability was difficult because of nonlinear response. At approximately 30° wheel position, the region most frequently used in controlling the aircraft, the rapid increase in response and the large increase in force when the spoilers were engaged combined to produce an unsatisfactory characteristic that masked the control power ratings of this aircraft.

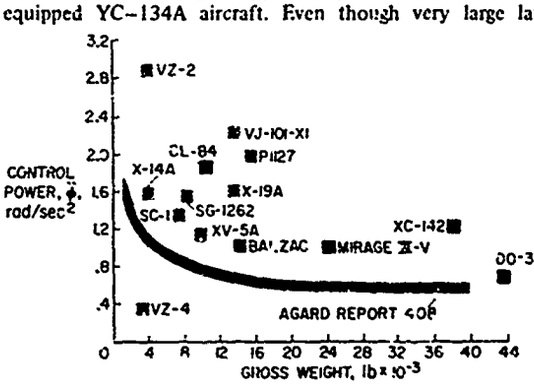


Fig. 2. Lateral acceleration for VTOL operation.

Figure 2 shows the same parameters for VTOL aircraft in hover. Note that a wide range of values exist for the various aircraft. These values are generally well above the former AGARD 408 sizing formula $(W + 1000)^{1/3}$, which was really meant to be a minimum maneuvering requirement. Because of lack of clarity in this respect, it was conveniently used in many paper designs (and for a few aircraft) as the total control power needed. It is obvious that a sizing rule is difficult to establish from these data for the reasons discussed in the following paragraph.

One of the first points to notice is that the X–14A is 1/4 the weight of the P.1127 but can get by with less control power mainly because the P.1127 requires a major portion of its available roll moment to trim for sideward flight. In fact, for the Harrier VTOL aircraft sideslip is restricted in forward flight by a warning device on the rudder pedals (ref. 7). Further, the aircraft would have required even more roll control power if the control sensitivity and the mechanical characteristics of the control system had not been optimized for low-speed flight. Other aircraft which also require a large percentage of available control power to offset rolling moments associated either with sideward flight in hover or sideslip in forward flight, are the XV–5A, SC–1, Balzac, and Mirage III–V. In fact, this particular trim requirement had been seriously overlooked in operational testing; consequently, all of the aforementioned aircraft (except the X–14A) have been damaged in accidents caused by this trim problem, some serious enough to be fatal. The major rolling moment contribution has come from induced flow effects associated with inboard locations of the jet engines.

Notable jet aircraft which are exceptions to the sideslip trim problem are the VJ–101 and the DO–31; both of these aircraft have the jet engines at the wing tips. This lack of trim requirement is reflected in the control power usage for the VJ–101 (ref. 8) which shows that only 0.25 rad/sec^2 was needed for roll control in typical takeoff and landing maneuvers. Similarly, with the DO–31, roll control power requirements for IFR approaches in gusty air showed that 0.4 rad/sec^2 was adequate. Both of these aircraft have larger roll control power available because of engine-out trim requirements.

2.2. Vertical Flight Path Control

2.2.1. *General background.* Vertical control of flight-path angle during approach, flare, and touchdown and during rotation and climbout is an important consideration for STOL operation because of the short field length requirements. Satisfactory routine operation from short fields with obstacles in the approach and climbout paths depends on precise control of flight-path angle. During STOL operation of V/STOL aircraft, vertical flight path cannot be controlled adequately by pitch control alone, and the pilot must use additional methods to develop normal acceleration.

Powered lift is used for flight path control in three general modes: (1) controlling rate of sink at flare and touchdown, (2) acquiring and tracking a particular flight path angle during approach, and (3) making gross changes in flight path for waveoff and turning flight. Satisfactory performance of these tasks depends on the amount of normal acceleration available from powered lift, the aircraft response time, and the degree of cross coupling. The values needed by the pilot depend on how critically the particular flight mode must be controlled. For example, altitude control during flare and touchdown must be precise and requires a short response time for this critical maneuver. It is equally important that cross-coupling effects between powered lift and aircraft rotation be minimized so that the pilot can precisely adjust rate of sink and aircraft attitude independently as required for optimum landing and takeoff performance.

Consideration of these points is given in the criteria presented in table 2.

2.2.2. *Criteria.* For satisfactory flight path control during all phases of STOL flight operation below V_{con} (including approach, landing flare, touchdown, and waveoff), the vertical aircraft response characteristics obtained at a constant attitude resulting from any combination of inputs from throttle, collective, and thrust vector controls should meet the values listed.

Table 2. Minimum Vertical Flight Path Control Characteristics in STOL Operation

ITEM	MODE*	PARAMETER TO BE MEASURED	LEVEL FOR SATISFACTORY OPERATION	MINIMUM LEVEL FOR ACCEPTABLE OPERATION
CONTROL POWER	A	INCREMENTAL NORMAL ACCELERATION	±0.1g	INSUFFICIENT DATA
	B	INCREMENTAL NORMAL ACCELERATION	±0.1g	INSUFFICIENT DATA
	C	STEADY STATE DESCENT ANGLE	6° OR 600 ft/min	200 ft/min
	ALL	INCREMENTAL DESCENT ANGLE	2° GREATER THAN SELECTED APPROACH ANGLE	INSUFFICIENT DATA
RESPONSE TIME	A	AIRCRAFT RESPONSE	ACHIEVE MODE IA IN LESS THAN 0.5 sec	INSUFFICIENT DATA
	B	AIRCRAFT RESPONSE	ACHIEVE MODE IB IN LESS THAN 1.5 sec	INSUFFICIENT DATA
	C	AIRCRAFT RESPONSE	ACHIEVE MODE IC IN LESS THAN 2.0 sec	ACHIEVE MODE IC IN LESS THAN 4.0 sec
CROSS COUPLING	ALL	PITCHING MOMENT	NOT OBJECTIONABLE	NOT OBJECTIONABLE

*MODE A. FOR FLARE AND TOUCHDOWN CONTROL WHEN LESS THAN 0.15g CAN BE DEVELOPED BY AIRCRAFT ROTATION USING PITCH CONTROL ALONE.

MODE B. FOR FLIGHT PATH TRACKING WHEN MORE THAN 0.15g BUT LESS THAN 0.30g CAN BE DEVELOPED BY PITCH CONTROL ALONE.

MODE C. FOR GROSS FLIGHT PATH CHANGES REGARDLESS OF THE NORMAL ACCELERATION DEVELOPED BY PITCH CONTROL

2.2.3. *Validation of data.* As noted in table 2, different modes of operation are specified for STOL operation of V/STOL aircraft depending on the precision of flight path control required. As expected, the pilot desires increased vertical response time and "g" from power the closer he gets to the ground. In order to determine whether the criteria for Mode A or B apply, the pilot performs abrupt longitudinal control steps at the appropriate trimmed flight path angle. Compliance with the criteria is demonstrated by steps performed with the flight path control device with the aircraft attitude maintained constant with the pitch control. Mode C applies equally to all aircraft regardless of the means used to produce the response.

In tests of the BR 941 aircraft (ref. 6) engine response to small throttle changes had a 0.5 sec lag plus a first-order time constant of 0.7 sec. There was no appreciable lag between vertical "g" and power changes (i.e., no aerodynamic, slipstream lag). It was possible with throttle alone to obtain more than ±0.1 g, which resulted in satisfactory flight path tracking down to about 50 ft. The pilot felt that longer engine time lags and time constants would have degraded his ability to track the ILS glide slope. This response was not adequate when he used power to arrest the sink rate at touchdown. In general, none of the STOL aircraft tested thus far (ref. 5) could be flared

by using engine thrust for several reasons: (1) engine response was too slow, (2) the aircraft had to be rotated for proper ground attitude, and (3) power changes produced undesirable changes in airspeed. As a result, g was obtained, as for conventional aircraft, by rapidly increasing aircraft attitude. The touchdown maneuver for STOL aircraft is, of course, similar to the height control problem for VTOL aircraft. In this respect, values of overall thrust response should not be greater than 0.5 sec, and 0.1 g should be available. The response for gross changes in flight path (away from the ground) is less stringent; for example, a 2.0 sec delay is considered satisfactory (see ref. 9).

2.2.4. *Additional data requirements.* Admittedly, the vertical flight path criteria, in their present form, are weak, and more firm quantitative values are needed for both control power and thrust response. As is true for control of other axes, cross-coupling effects and interrelated items affect the pilot's assessment of precision of control. Included are the following:

1. Static longitudinal stability
2. Short period and phugoid frequency and damping
3. Direct lift control
4. Effect of automatic power compensation
5. Ground effect on lift, drag, and pitching moment
6. Gust sensitivity (lift curve slope)
7. Power "backsidedness"
8. Trim change with power (magnitude and direction)
9. Thrust and control system response (lags)

A systematic evaluation of the foregoing items is a formidable task, and it is difficult to generalize on answers from specific aircraft because the significant parameters cannot be varied over wide enough ranges. Steps are under way to examine the effects of these parameters on vertical flight path control using a piloted motion simulator at NASA Ames, and at the RAE, Bedford, and by flight tests of the Bell X–22A aircraft.

2.3. Transition–Acceleration/Deceleration

2.3.1. *General background.* Good transition characteristics are essential for successful use of V/STOL aircraft for a number of reasons. First, it may be desirable to perform transitions quickly to minimize time spent in the terminal area. Second, transitions are usually performed in the critical landing approach phase of flight, where the pilot must be able to maintain precise control of flight path particularly for IFR operation. Finally, transitions occur during the pilot's peak work load, when he is involved with configuration changes, such as selecting landing gear and flaps, and starting lift engines, as well as communications and navigation duties. In the following paragraphs attention is given to those handling-qualities items that govern aircraft behavior in going from powered lift flight to aerodynamic lift regime and vice versa for both VTOL and STOL aircraft.

2.3.2. *Criteria.* VTOL aircraft should be able to accelerate rapidly and safely from hover to V_{con} in climbing flight or at constant altitude. From V_{con} they should be able to decelerate rapidly and safely at constant altitude or in a descent to the maximum approach angle required by the mission; to acquire and maintain both shallow and steep flight path angles; and to stop quickly and precisely over a preselected hover spot. Depending on the mission, acceleration and deceleration values up to 0.5 g in level flight are desired. In addition, it is desirable to be able to accelerate continuously from a rolling takeoff (RTO) to V_{con} and decelerate smoothly to a rolling landing.

STOL aircraft should be able to accelerate from V_{app} to V_{con} in level flight or climbing flight; to decelerate quickly from V_{con} to V_{app}; and to precisely acquire and maintain both shallow and steep flight path angles.

It should be possible to carry out the above maneuvers with the precision and performance specified for the mission without restriction due to control power, trim, stalling or buffeting, engine thrust, or response characteristics.

The pilot should be required to operate only primary flight controls, power setting, and thrust vector tilt. If other devices required for transitions are operated automatically, it should be possible for the pilot to monitor their performance easily, and inadvertent operation of any transition control should be prevented.

2.3.3. *Discussion.* The purpose of these criteria is to ensure that in going from powered lift flight to aerodynamic lift flight and vice versa, the pilot can perform the necessary maneuvers as expeditiously as needed without undue attention to aircraft attitude, angle of attack, airspeed, and trim factors that would compromise his ability to fly the aircraft accurately along a chosen flight path in all environmental conditions. Further, good control characteristics are needed for STOL operation when going in and out of ground effect because ground-induced recirculation may cause unsteady flow over the aircraft. In addition, the pilot should have the capability to decelerate as needed at any portion of the speed range to quickly attain a particular approach speed or to avoid overshooting a desired touchdown area.

The time required for making a transition can vary according to the mission; however, it is necessary from safety considerations that the rate desired by the pilot should not be governed by limitations in controllability about *any* axis. If the pilot must handle a large number of separate operations to accomplish the transition, his performance in terms of airspeed, angle of attack, and flight path angle control will suffer during this critical flight phase. Due consideration should be given to multicrew functions in transport configurations where, for example, lift engine startup and shutdown could be handled by a copilot.

2.3.4. *Validation of data.* Operation of various VTOL and STOL aircraft indicate that the V/STOL concept itself has certain built-in limitations on the acceleration/deceleration handling characteristics. Further, these characteristics vary depending on the direction of transition.

The P.1127 aircraft, for example, is equipped with a proportional-position, thrust vector control that operates only on the engine thrust vector. The magnitude and direction of the aerodynamic (lift and drag) vectors are controlled indirectly through changes in aircraft attitude. The pilot, therefore, can change the magnitude and direction of the engine thrust vector independently of the aerodynamic vectors. As shown in reference 10, the rate at which the proportional thrust vector control was moved related directly to the magnitude of the vector. When a large engine thrust vector is used as during takeoff, a rate of approximately 4°/sec was selected.

(Note that 90°/sec is available.) This provided an initial acceleration of approximately 0.2 g and an overall average acceleration (0 to 160 knots) of 0.43 g. A higher thrust vector rate would have produced higher accelerations but a loss in altitude since aerodynamic lift could not be gained rapidly enough to offset the change in vertical thrust. During a decelerating transition (160 knots to 0), however, the pilot commanded a thrust vectoring rate of approximately 45°/sec. This was possible, of course, because of the small magnitude of the engine thrust vector. A typical decelerating transition was initiated at 160 knots with +6.5° pitch attitude and a low power setting. From 160 to 80 knots, a maximum deceleration of 0.46 g was attained. At 80 knots the thrust vector was rotated from the 5° forward position to the vertical position after which the aircraft pitch attitude was then increased to +14° to decelerate from 80 knots to zero with an average deceleration of approximately 0.2 g.

In tilt-wing aircraft, such as the CL–84, the aerodynamic vector is rotated with the engine thrust vector The pilot, therefore, must command a thrust vectoring rate that is compatible with the magnitude of the aerodynamic vector and of the engine thrust. Further, maximum thrust vectoring rate is a function of wing angle and the direction of thrust rotation. The CL–84 wing could be rotated up at a rate of 6°/sec. The maximum downward rate of 12°/sec was linearly decreased to 2.63°/sec between wing angles of 45° and 5°. The pilot did not have direct control of thrust vectoring rate because his control was only an on/off switch. The approximate thrust vector rate desired could be achieved by intermittently turning the switch on and off.

In an accelerating transition the pilot commanded a vector rate of approximately 7°/sec, which produced an initial acceleration of 0.2 g. After a brief 2 sec period, the pilot commanded maximum thrust vector rate for the remainder of the transition. This produced a maximum thrust vectoring rate of approximately 10°/sec and a maximum acceleration of 0.44 g. In this accelerating transition, since the initial aerodynamic vector is small, a high thrust vectoring rate could be used without experiencing control coordination problems and in this respect the CL–84 is very similar to the P.1127.

Decelerating transitions of the CL–84 tilt-wing aircraft is completely different, however, because the pilot is required to manage the control coordination problem caused by tilting the large aerodynamic vector. This requires selecting a wing tilt rate that is compatible with the aerodynamic vector and the magnitude of the engine thrust. As stated in reference 11 this completely unfamiliar technique was difficult to perform. It was further complicated by the need to operate the wing-tilt switch intermittently to obtain a variable rate to match the lift required. Therefore, holding deceleration at any fixed rate was very difficult. A typical decelerating transition shows that the pilot commanded a thrust vectoring rate of 3°/sec for the major portions of the maneuver (15° to 60°) and then commanded a maximum available rate of 6°/sec for the remainder of the transition (60° to 80°). This produced a nearly constant deceleration of 0.15 g. The aircraft is capable of higher decelerations, but the pilot control coordination problems increase. Different characteristics are shown for the fan-in-wing XV–5 aircraft (ref. 12). At low speed, the wing fan louvers are used for height control, roll control, yaw control, and speed (thrust vectoring) control. In addition, the angle of the louvers determines the amount of roll control available to the pilot (roll control is phased out as a function of louver angle as speed and aileron control increase). Specific attention was required to ensure that a "rule-of-thumb" relationship of 2 knots of airspeed for each degree of louver angle was maintained to avoid a loss of lateral control power. A high degree of pilot attention was required to maintain the louver angle–airspeed schedule (a pilot rating of 5 was assigned). The maximum thrust vectoring rate built into the XV–5A aircraft was 3°–4°/sec. During an accelerating transition from hover, the pilot commanded an overall average thrust vectoring rate of 1.6°/sec and an acceleration of 0.13 g.

2.3.5. *Additional data requirements.* Sufficient data are available to show that one minimum or maximum rate will not satisfy all VTOL concepts, but insufficient data is available to establish a satisfactory rate for each VTOL concept. In addition, the limitations for IFR operation have not been clearly defined. It is to be expected that only relatively low deceleration values will be used to reduce pilot workload in the landing approach task. Early experience with the DO–31 aircraft indicate that deceleration values of 0.07 g were used to provide sufficient tracking time on the ILS to assess the approach and gain confidence to proceed to the landing. Further, real life operation is needed to assess the passenger comfort aspect for civil use.

3. CONCLUDING REMARKS

A brief review of selected handling qualities criteria for V/STOL aircraft shows that although a clearer understanding of the requirements for controversial areas such as roll control power, vertical flight path control, and transition is in hand, considerably more research is needed to refine these criteria for operational IFR activity. Because many items interact to influence the pilots' overall impression of the aircraft's behaviour, additional work of a systematic nature must be done to clarify this aspect. A better definition of a gust model which includes discrete gust effects is needed to firm up criteria for both hover and STOL operation.

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OPEN DISCUSSION

S.J. Andrews, A&AEE, UK

How can one design flying qualities to give high touchdown accuracy for short landing in view of the fact that the landing distance of the STOL aircraft is of the same order as the scatter of touchdown point of current aircraft?

S.B. Anderson, NASA Ames, USA

What we have tried to do with the vertical flight path control for STOL operation was to give you numbers that would specify how much vertical "g" was required for flight path control in combination with that required for pitching. This demands a certain value to be able to change flight path to hit the spot accurately, it demands a certain acceleration and rotation capability to get the aircraft in the right attitude for ground contact and also requires the proper response time for the power lift control. It is interesting to note that in all of the twelve or so STOL aircraft that we have tested we could not use power during flare and touchdown. There are two reasons for this: (1) the response time is too long and (2) the rotation of the lift vector was not sufficient.

R.S. Sliff, FAA, USA

Mine isn't really a question, but I thought I might be able to help the last question.

From the test work we have conducted at our experimental center in Atlantic City, with primarily two kinds of aircraft, the Twin Otter and Breuguet 941, we have found two primary things: (1) you cannot have a speed in excess of 70 knots on approach if you are talking about accuracies of 200-300 feet in the touchdown zone, and (2) you must have positive guidance. We used a microwave ILS system plus we were experimenting with vertical guidance in the form of a visual slope indicator. With these two devices we found that we could very easily set up touchdown zone of between 200-300 ft.

S.B. Anderson, NASA Ames, USA

One additional comment, if you have a landing gear which can absorb a lot more energy, like the Breguet 941 has, you just aim it and let it hit. This increases the touchdown accuracy immensely.

W.T. Kehrer, Boeing, USA

Seth, would you please comment on your opinion of the ability of commercial transport pilots to adapt a new and unusual control technique (if required) for STOL aircraft? I am concerned, of course, particularly with the landing approach mode of operation, where, for some STOL concepts, the pilot's control must vary somewhere between that required for a helicopter and that required for a conventional jet transport.

S.B. Anderson, NASA Ames, USA

There is no question that we are going to have to make the job easier than we've done for our test pilots. This will come about by the use of more augmentation, certainly auto throttle attitude command type of control systems, and improved display and guidance information. There is a lot of work to do to make these STOL aircraft acceptable to the ordinary routine pilot and to do it without raising the price too much.

W.T. Kehrer, Boeing, USA

Our STOL flight simulator work at Boeing indicates that commercial transport pilots generally will not adapt to "helicopter-like" control techniques, and in some cases when they have apparently adapted, they are seen to revert in times of stress to their old habit patterns - often with disastrous results.

J.E. Farbridge, D H, Canada

In response to two questions from the floor, I made some comments which the following may clarify:

Query 1: Someone commented about the apparent need for helicopter training with DLC. I wish to suggest "that consideration could be given to Direct Drag Control DDC for STOL operation in which the pilot control will be sensibly conventional. In particular, the augmentor-wing, as presently envisaged, uses a direct control of thrust vector which is essentially DDC on approach to land. This mode of control is extremely responsive and no change of power setting is required during approach and flare. Thrust vector control therefore replaces throttle control as a principal control, in conjunction with the stick."

Query 2: Someone asked how the dispersal of STOL touchdowns, which are presently of the order of STOL airfield lengths for CTOL approaches, are to be reduced. "Touchdown dispersal is also markedly reduced with high glide path angle approaches, and also partial flaring techniques, as well as the low speed already mentioned".

Prof. K.H. Doetsch, DFVLR, Germany

Not so much a question as trying to give an additional answer to the question just put on - how the average airline pilot should cope with V/STOL aircraft. I believe, based on German studies, that the pilot will require "unified" or "decoupled" controls in his hands for each degree of freedom of motion that is of major importance, even if this implies that this control operates for instance throttles and elevator (or other) controls simultaneously. The decoupling has to be done by automatic computers.

U.S. MILITARY V/STOL HANDLING QUALITY REQUIREMENTS

by

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SUMMARY

It is the purpose of this paper to describe the recently issued V/STOL handling qualities criteria specification, MIL-F-83300 (Ref. 1). The evolution of the specification is traced over the five year period of its development. Problem areas requiring additional work are pointed out as well as research efforts underway to address some of these problem areas.

THE NEED FOR CRITERIA

The V/STOL industry has needed a general flying qualities specification for several years. The lack of such a general set of requirements has resulted in the necessity to formulate detail specifications for each new procurement. For the low speed region, these specifications were, in general, blends of MIL-H-8501A, AGARD 408, and various degrees of experience on the part of the engineers defining the criteria; MIL-F-8785 was used, with some amendments, for higher speed flight. This state of affairs created problems not only for the procuring activity, who had to write these detail specifications, but also for the contractor.

The contractor usually had no chance to see the detail specification until the Request for Proposal was sent out for bids. Consequently, he had no solid basis for requirements during the initial phases of design.

In 1966 when the Air Force initiated the job of writing an adequate but not overly restrictive specification, it was realized that it would be a formidable job. A general specification having adequate requirements based on the latest data and operational experience and in a form which could be tailored to be used as a detail specification was the goal.

The requirements of the specification must be such that they are not so overly restrictive as to yield flying qualities in excess of those actually needed. This is very important for a V/STOL specification since meeting flying qualities requirements at very low speeds can have a large impact on vehicle performance. The weight of the mechanical and electronic components, and the thrust lost for control, must be the minimum necessary for good flying qualities, or the vehicle will lose performance capability needed for mission accomplishment. On the other hand, if inadequate flying qualities were provided for the sake of performance, the pilot would be unable to control the aircraft sufficiently well to perform the intended task.

The general specification should be easily tailored to a detail specification. In the initial phases of design of an aircraft; i.e., during feasibility studies, it is intended that the general specification, Reference 1, will be used. In the past, when no general specification was available, the contractor used his best judgment of the necessary flying qualities during initial design, but these were usually different from those seen later in the detail specification. This caused delays and design changes and was not an efficient design process. After the preliminary design process cycles for several iterations, the operational requirements and the handling qualities criteria are modified as necessary and desirable to arrive at a feasible vehicle. At this point, it is intended that a detailed handling qualities specification, a refined and simplified version of Reference 1, would be written and utilized in the procurement process. The Request for Proposal to the contractor would include this detail specification that the chosen aircraft contractor must meet. If the contractor disagrees with a requirement or its numerical values, he shows data justifying his request for a deviation when he answers the request. These deviations are reviewed by the Government technical staff and are approved, disapproved, or a compromise is reached. Finally, when a contractor is chosen to build the aircraft, the detail specification is complete, and this is what the contractor uses as the design goal for flying qualities.

Thus, it is seen that the criteria documents must be viewed as changing throughout the design process and not as rigid inflexible sets of rules. The general document must be based on the very best foundation possible and be broad enough in scope to include all or at least most configurations and missions. The design process must provide the flexibility needed to not unduly penalize a design without the license to the contractors to escape meeting necessary requirements just because they are hard to meet.

HISTORICAL DEVELOPMENT

In 1966, the U.S. Air Force Flight Dynamics Laboratory began a concentrated effort to improve the status of flying qualities criteria for V/STOL aircraft. This effort was a part of a larger effort of an Air Force advanced development program called the VTOL Integrated Flight Control System (VIFCS) program. As originally conceived, this program had four basic parts which can be briefly described as: (1) flight control system design, integration, and test including definition of the total flight control system criteria to meet VTOL requirements, and integration and fabrication of a total flight control system for control technology demonstration and validation in a modified XV-4; (2) analysis, design, development, and flight investigation of specific flight path display techniques suitable for all-weather operation and

their integration with the pilot-control system combination; (3) development of VTOL handling qualities design criteria; (4) modification of a jet VTOL airplane (the XV-4) for use as a variable stability test vehicle (the XV-4B).

Part 3 of this program, concerned with handling qualities criteria was performed by a large in-house effort by the Air Force Flight Dynamics Laboratory (AFFDL) supported by the Cornell Aeronautical Laboratory, Inc. (CAL) under contract. Under the contract, CAL's responsibilities included: (1) experimental simulator investigations into the handling qualities of VTOL airplanes; (2) developing techniques for analyzing and evaluating VTOL handling qualities; and (3) utilizing experimental data and analysis to generate VTOL handling qualities requirements and design criteria.

The initial effort during the first year of the program involved a survey of the VTOL flying qualities literature. In order to supplement the literature surveys, a series of meetings was held with representatives of airframe companies engaged in design, development, and manufacture of VTOL aircraft. At these meetings, held during the weeks of 10 October 1966, and 24 October 1966, at AFFDL, the attendees discussed their views, feelings and opinions on the applicability of existing handling qualities documents to VTOL aircraft, and the format and content of a future VTOL handling qualities specification.

Seventeen airframe industry companies were involved in individual meetings. The various governmental agencies concerned with these matters were in attendance. By providing a broad view of the overall V/STOL flying qualities picture, the literature surveys and meetings established a basis for more intelligent planning and coordination of the subsequent program activities. Reference 5 summarizes some of the results of the first year efforts.

To promote the attainment of the flying program objectives, CAL was authorized to issue subcontracts. These subcontracts were planned and coordinated so that the work devoted to preparing a V/STOL flying qualities specification would benefit from the experimental and analytical capability of other organizations known to have a direct interest in V/STOL. It should be mentioned that although the specification work originated as part of a broad Air Force program that included the development of the variable stability XV-4B, the unfortunate loss of this aircraft eliminated the possibility of fulfilling all of the VIFCS program objectives within the original timetables. Thus the subcontract efforts took on additional importance as a means of acquiring relevant data and information to use in formulating a flying qualities specification.

During the course of the program, four organizations participated as subcontractors: United Aircraft Research Laboratories (UARL), Systems Technology, Inc. (STI), Northrop-Norair, and National Research Council of Canada (NRC). Each subcontractor was selected so that, as shown in the following listing, V/STOL flying qualities could be systematically investigated by using different techniques and approaches to acquire and analyze data: UARL, fixed base simulation; STI, pilot model analyses; Norair, moving-base simulation; NRC, flight simulation with VSS helicopter.

Efforts in 1967 and 1969 were concentrated on formulating flying qualities requirements using the pertinent data in the literature and the data generated during the subcontracts as it became available. This work culminated in the publication in October 1968 of the first version of a proposed V/STOL flying qualities specification (Reference 6) along with an accompanying report containing related backup information and data (Reference 7). Both of these documents were submitted to industry for review. Review comments were received from eleven airframe contractors and a number of government agencies. A thorough study of the review comments along with continued data analyses followed during much of 1969. A revised specification was prepared in September 1969 (Reference 8). In October 1969, Reference 6 was jointly reviewed by representatives of the Air Force, Army, Navy and CAL. This latter review took place in order to screen Reference 8 prior to submitting it to a second cycle of industry review. Some changes were recommended and these changes were incorporated into the pertinent requirement paragraphs and resulted in the publication of Reference 9.

As a result of extensive in-house effort by AFFDL, an alternate requirement to the CAL response matching technique for specifying dynamic stability requirements was prepared. Reference 10, termed "Paper Pilot", describes this proposal.

A new document entitled Background Information and User Guide (BIUG) (Reference 11) was then prepared and in January 1970, these two documents (Refs. 9 and 11) were distributed to industry and Government agencies for a second review cycle.

Detailed review comments were received from 21 airframe contractors and from a number of Governmental agencies and from foreign agencies. On the basis of these comments, CAL prepared some suggested changes and in April 1970, distributed copies to potential attendees of an Air Force-Navy-Army review meeting. This review took place at the end of April 1970 and substantial agreement on a final version was obtained by the Air Force, Navy and Army representatives.

Resolution of final details continued until about 4 July 1970 when CAL published a new version. The Air Force made some final additional changes and printed a version which was distributed for the third and final review coordination (Reference 12). Detailed review comments were received from twenty airframe manufacturers. These comments were reviewed and several changes made to the specification requirements. The final version agreed to by the Air Force and Navy representatives on 11 December 1970, and submitted for adoption as MIL-F-83300. During development of the specification it was intended to cover all V/STOL aircraft, including helicopters, for the Air Force, Navy and Army. At this time the specification has been adopted by the U.S. Air Force for all V/STOL's, including helicopters. Formal coordination is proceeding with the U.S. Navy and U.S. Army with regard to the use of this document for helicopters procured by those services.

While Reference 12 was being reviewed, CAL prepared the draft of a new Background Information and User Guide (BIUG) for the specification. The purpose of the BIUG is to document the substantiating data

used in the specification and also provide notes and explanations which should help the user of the specification. The final version of the BIUG (Ref. 13) was published as of March 1971.

SPECIFICATION STRUCTURE AND PHILOSOPHY

General Outline

The V/STOL Specification, MIL-F-83300, contains six main sections: (1) Scope and Classification, (2) Applicable Documents, (3) Requirements, (4) Quality Assurance Provisions, (5) Preparation for Delivery, (6) Notes. As is usual with U.S. military specifications, the Index is at the end.

The bulk of the material is contained in the Requirements Section which is broken down into eight subsections: 3.1 General requirements, 3.2 Hover and low speed, 3.3 Forward flight, 3.4 Transition, 3.5 Characteristics of the flight control system, 3.6 Takeoff, landing and ground handling, 3.7 Atmospheric disturbances, 3.8 Miscellaneous requirements.

As the title implies, Section 1, Scope and Classifications, defines the scope and application of the specification. It also defines the framework for classifying the aircraft, the mission Flight Phases and the Levels of flying qualities. This section of the specification has been used to define a general framework which permits tailoring each requirement according to: (a) the kind of airplane (Class), (b) the job to be done (Flight Phase), (c) how good the flying qualities must be to do the required job (Level).

Figure 1 shows how these considerations are related and illustrates that use of this framework would permit stating 36 different values for a given flying qualities parameter, even after combining the Flight Phases into three categories. This detailed breakdown makes the structural parallel the U. S. military specification for conventional aircraft, MIL-F-8785B (Ref. 14), and helps the phasing into MIL-F-8785B at $V = V_{con}$, where V_{con} is the speed at which the requirements of the conventional airplane specification, MIL-F-8785B, begin to apply.

REQUIREMENTS

The Requirements section commences with a general statement. This provides a detailed explanation of the framework used to determine the conditions at which the requirements of the specification should be applied. The conditions of the aircraft which have to be considered are defined, and the framework for determining the corresponding flight conditions, primarily in terms of speed, altitude and load factor, is explained. In addition, a detailed explanation is given for applying the concept of Levels of flying qualities. The stability and response requirements are written for two flight regimes: (1) Fixed Operating Point Flight, (2) Accelerated Flight.

Fixed Operating Point (FOP) Flight

This is the name that has been used for flight consisting of maneuvering about a constant trim condition. For this condition, the techniques of linearized constant coefficient analysis, which have been used for years on conventional aircraft, seem to apply. As a result, the conventional techniques of understanding and specifying flying qualities have been extrapolated into the lower speed range. Quantitative requirements are placed on familiar concepts such as static stability, dynamic stability, control power, response to control inputs (sensitivity), and control lags. The requirements have to cover all speeds from hover to V_{con}. Within this speed range significant changes take place which make it necessary to change the flying qualities requirements. The reasons can be summarized as follows: (1) The characteristic modes of motion undergo substantial changes in form, as forward speed increases; (2) The change from direct lift to aerodynamic lift, as forward speed increases, results in changes in important stability derivatives, and necessitates changes in pilot control technique; (3) The parameters, and the specific values of those parameters, which adequately describe a level of handling qualities in hover, are inadequate or inappropriate to assure a similar level at high forward speeds.

It would be ideal if the requirements could be made a continuous function of some parameter such as speed. Unfortunately the existing knowledge of V/STOL flying qualities has not allowed this, and so a two part arrangement has been chosen with the division at 35 knots. There is nothing profound about 35 knots - it is a compromise chosen on the basis of our present understanding and includes the following considerations: (a) There is a substantial amount of published data resulting from experiments done in and around the hover condition. These experiments typically involved tasks in which the vehicle achieved translation velocities as high as 35 knots. (b) Many aircraft begin to develop "significant" amounts of aerodynamic lift above 35 knots, at which time there often exists a basic change in the dynamics. For example, one usually finds that hover approximations, such as effectively decoupled height mode, begin to break down at about 35 knots. (c) Along with the changing nature of the dynamics there is usually a change in the piloting technique.

Hovering over a spot at any angle to a 35 knot wind is a requirement of MIL-F-83300 (and others). Consideration was given to increasing the wind speed in which hovering capability is required. However, it was found that the probability of encountering winds greater than 30-40 knots did not justify a change. Certainly winds higher than 35 knots can be encountered, but it was assumed that the margin of the Service Flight Envelope over the Operational Flight Envelope will provide Level 2 hovering capability at speeds greater than 35 knots. Further margins may have to be demanded in special cases.

Since 35 knots is a satisfactory dividing speed from the point of view of both aircraft dynamics and operational considerations, it was convenient to group the requirements by speeds. If it had been decided that hovering capability was necessary up to some significantly higher speed such as 60 knots, then a more complex division of the dynamics and operational aspects would have been necessary and thereby created the need for a much more complicated specification structure.

With the step change at 35 knots, considerable care has been exercised to allow the requirements for speeds less than 35 knots to blend with the requirements for speeds greater than 35 knots, and to blend with the requirements of MIL-F-8785B at V_{con}.

Sections 3.2 and 3.3 then, provide requirements for Flight Phases which involve maneuvering about trim speeds in the range $\pm$ 35 knots and 35 knots to V_{con} respectively. For example, a STOL aircraft required to perform its landing approach at 60 knots would have to satisfy the requirements of 3.3 for that flight condition. A V/STOL which has to be able to perform tasks involving flight at 25 knots has to satisfy the requirements of 3.2 at that flight condition. An aircraft with an Operational Flight Phase which spans 35 knots has to satisfy 3.2 and 3.3 at the appropriate flight conditions.

Accelerated Flight

When considering the flying qualities of conventional aircraft it has been possible to virtually ignore the effects of acceleration (acceleration referring here to changing flight condition, particularly speed, rather than accelerations due to maneuvering) except for a few special conditions, such as passing through the transonic speed range. This happy circumstance is probably because the changes occur relatively slowly when compared to the frequencies of the rigid body modes. The acceleration capabilities of a V/STOL and the significant changes in dynamics and response which occur between zero speed and, say, 100 knots make it unlikely that we will be so lucky with V/STOL aircraft. It is desirable that a good understanding of the importance and extent of the transition problem be obtained as soon as possible.

Unfortunately the dynamics involved in a rapid transition are not yet well understood. For understanding, it is tempting to consider the dynamics of transition as though represented by a sequence of equilibrium or fixed operating points. Figure 2 shows how the longitudinal dynamics of the augmented X-22A change for such a sequence of points.

Clearly the changes in dynamics are considerable, so bearing in mind that the changes can occur in as little at 18 seconds, the question is how to interpret these changes. There is, as yet, no general answer to this question; however, some comments can be made.

First, if one does wish to treat the accelerated flight condition as a series of "frozen points" it is necessary to evaluate the aerodynamic characteristics for the appropriate aircraft state. An aircraft such as the X-22A can encounter a wide range of speeds and power settings, at a given conversion angle, depending on the rate of conversion and whether accelerating or decelerating (Reference 15). Such changes can have a very marked influence on the nature of the aerodynamic force and moment characteristics and hence on the "frozen dynamics".

Second, it is simple to show (Reference 15) that representing a time-varying system as a sequence of time-invariant systems can give misleading information about the nature of the dynamics. However, it is not a simple matter to put a quantitative measure on such effects or devise alternative techniques which can be used to understand the dynamics of a rapid transition. A notable attempt has been made in Reference 16 to develop such a technique, and some interesting trends are shown for simple variations of the derivatives (e.g., linearly proportional to speed). However the problem is by no means solved.

Now consider how this complicated dynamic situation has been accommodated in the specification.

Transition can be thought of as two basic parts:

1. Control of the speed and altitude as though the aircraft was a point mass.

2. Control of perturbations in speed, altitude and attitude from the desired values.

A knowledge of the first part can be obtained by controlling the aircraft with a very tight feedback loop. From this can be obtained a pseudo-trim for that particular transition. When flying, the pilot has to provide this pseudo-trim and also control the perturbations from the desired transition.

The difficulty of this task will be strongly dependent on how quickly the aircraft diverges from the desired nominal value. This will be a function of the rate at which the out-of-trim moments increase, and the basic dynamics of the aircraft. The difficulty of the task will also be influenced by how much effort the pilot has to exert to keep the aircraft within the transition corridor, i.e., within the permissible space of speed, conversion angle, power settings, and angle of attack. These are the factors to which attention has been directed in the requirements. Because of the current lack of knowledge concerning the dynamics in transition, these have not been prescribed. If an aircraft is designed to comply with the FOP requirements, it seems reasonable to assume that the resulting transition dynamics will also be acceptable or at least can be made to meet the qualitative requirements without excessive redesign. Some V/STOL aircraft (e.g., X-22A, XC-142) have flight phases which require FOP operation at most speeds below V_{con} and as a result will have to comply with the FOP requirements. Other aircraft, such as the Harrier, may have no flight phase which requires FOP flight at speeds between about 35 knots and V_{con}. Applying the FOP requirements between 35 knots and V_{con} might be unduly conservative for these aircraft and so the flight-phase flight-envelope structure has been arranged so that the FOP requirements are not imposed unless the mission requires such operation. This statement has to be slightly qualified because any aborted transition is in fact required to be safe. Of course, the manufacturer may still use the FOP requirements as a design guide, but research needs to be performed to determine whether or not the resulting transition characteristics are adequate, ultraconservative or deficient. If they are deficient, of course, even the vehicle which has to perform FOP flight will have unsatisfactory transition characteristics. This is a subject which needs systematic research.

A final point in this general discussion of transition; what is meant by "transition"? Reference 17 defines transition as "the act of going from the powered lift regime to the aerodynamic

flight regime and vice versa". For the purposes of applying section 3.4 of specification MIL-F-83300, the following definition is preferred: "transition is the act of changing from one fixed operating point to another". This latter definition reduces, in the limit, to the case of maneuvering about trim. However, since at the present time it is not possible to specify what level of acceleration is significant, it is not possible to be more definitive. Certainly consideration should not be restricted to complete conversions/reconversions, as implied by the first definition. Also, it is desired that aircraft which do not change configuration when they accelerate (e.g., helicopters) should also be required to satisfy the transition requirements. This intention is accommodated more clearly by the preferred definition since it does not involve any extraneous concepts such as having to define the limits of the powered lift regime.

The remaining requirements in the specification have been collected into four groups:

Characteristics of the flight control system. This section places requirements on mechanical characteristics such as control force breakout and gradients, and trim characteristics.

Takeoff, landing and ground handling requirements. Apart from convenience, this grouping does emphasize the fact that landing and takeoff are distinct flight phases, and that military aircraft can have missions other than takeoff and landing in the speed range below V_{con}.

Winds and turbulence. Some requirements are written in terms of a steady wind speed, in which case compliance with the requirement should be demonstrated in flight, in that wind condition. Other requirements are written with reference to operation in all potential atmospheric environments. In the future it is hoped to include a suitable turbulence model in the specification. For the present time the turbulence model and intensity to be considered will be chosen by the procuring activity, and compliance will be demonstrated by suitable analysis.

Miscellaneous requirements. Miscellaneous requirements that are equally valid at all speeds are collected together in the miscellaneous sections. Topics covered include: Warning and Prevention of Approach to Dangerous Flight Conditions, Pilot-Induced Oscillations, Cross-Coupling Effects, Transients Following Failures, and Control Following Thrust Loss.

THE BACKGROUND INFORMATION AND USER GUIDE (BIUG)

General Content of the BIUG

The BIUG, Reference 13, was published in support of Military Specification MIL-F-83300 "Flying Qualities of Piloted V/STOL Aircraft" (Reference 1). The intent of the document is to explain the concept and philosophy underlying the V/STOL Specification and to present some of the data and arguments upon which the requirements were based.

The material presented in the BIUG was obtained or generated following an extensive literature review and after many meetings and discussions with personnel from essentially all concerned civilian and governmental organizations. A number of studies were performed to obtain supplemental, experimental and analytical data. The results of these efforts have been published separately in References 19, 20, 21, 22, 23, and 24.

Section II of the BIUG outlines the historical development of the specification and acknowledges the many organizations, both industrial and governmental, that contributed comments, criticisms and suggestions in the form of review comments.

The philosophy and structure of the specification is outlined in Section III of the BIUG. This attempts to give the user of the specification an appreciation for the manner in which the requirements have been grouped; especially in distinguishing between the fixed operating point requirements and the requirements for the actual transition maneuver.

Section IV presents a review of the entire V/STOL Specification, in order, paragraph by paragraph. The format used is to present the pertinent paragraph, or group of paragraphs from the Specification, and then to follow this with a discussion of the requirement, a discussion of the theoretical background and experimental data on which the requirement is based, and a discussion of the possible limitations or inadequacies of the requirement. Where a similar requirement or design criteria existed before, the earlier version is mentioned to provide a basis for comparison.

PROBLEM AREAS REQUIRING ADDITIONAL RESEARCH

A considerable amount of V/STOL research work has been done in the past 15 years; the MIL-F-83300 Specification has been developed based on the results of these efforts. It is nonetheless safe to say that there are no topics which would not benefit from more and better data. It is hoped, and expected, that having a specification to test against, the various test activities will utilize the specification and publish data - thus broadening the data base. For test data to be of value in providing background for future development of a specification, it must contain the following information: (1) the aircraft stability and control parameters must be accurately identified and quoted - preferably with the records from which they were extracted; (2) sufficient pilot comment data must be included to be able to determine the answer to the question. If it met (or failed) a given requirement, was that particular characteristic satisfactory, unsatisfactory or unimportant? The lack of well documented data has been a continuing problem even where flight tests and simulations that should have been useful have been performed.

The biggest single need is for some operational experience. Anslysis, flight test, and extrapolation from airplane and helicopter experience has provided an initial base. We need better information on the way V/STOL capabilities can be used in service and the handling quality demands that result. Examples

are cross wind takeoff and landing, maneuvering in turbulence, thrust vector control, characteristics in engine failure conditions, etc.

Much more consideration needs to be devoted to IFR versus VFR flight. Very little guidance is provided in the available literature regarding the problems of handling qualities under IFR conditions. This may be attributable to the fact that it is virtually impossible to determine the required level of handling qualities without considering the nature of the information display provided for the pilot. In fact, the accomplishment of some tasks, for example IFR hover, may be limited not by the level of flying qualities but rather by the inadequacy of the information displayed. Considering the present rate of development of advanced information display concepts for all flight regimes, it is difficult to establish a philosophy to guide the formulation of IFR handling qualities requirements.

More thorough consideration of helicopters and STOL vehicles is needed. It is hoped that continued analysis, test, and evaluation will lead to more universal application of the requirements of MIL-F-8785B and MIL-F-83300 to these vehicles and their continued improvement and validation.

As pointed out in Reference 29 there is still a general problem in that there is no very tangible reward given to the contractor if he achieves a design with excellent handling qualities or achieves an optimum tradeoff of flight control system airframe characteristics. There is no effective penalty for doing a poor job. Some system of incentives based on "payoff" functions related to the general requirements must still be found and specified before the designer is going to insist on more than minimums.

The current specification still essentially treats each item separately. Combinations of minimums may well turn up poor or even unacceptable characteristics. This general problem is still with us and without more data and experience, cannot be rectified.

Following are discussions of several specific problem areas. This list is by no means inclusive. Additional discussion of various problem areas can be found in References 30, 31, and 32. It is interesting to note that many of the problem areas discussed in the older references such as 32, still remain as problems without any large improvement in the situation.

CONTROL POWER, CONTROL USAGE

Control power can be a very important design parameter. This is true in general, but can be particularly critical in and around hover where all the lift is obtained from power (or thrust) and, very often, providing control subtracts significantly from the lift available. It is, therefore, highly desirable to provide the minimum necessary control power.

A great deal of work has been done in investigating control power along with control sensitivity. Control gain (sensitivity or gearing) is relatively straightforward in the sense that one can be sure that whatever is provided, was really used. Control power is a very different matter. If a level of control power is provided and quoted in a report, one is seldom able to determine if the full available power was ever used, and if used, how often.

There is a need to increase the useful data base on control power usage. This means that data should be presented in the form of probability density function plots or cumulative probability plots, and power spectral density function plots. Sufficient information should also be given so that it is possible to distinguish the control used for trim from the control used to maneuver and to overcome upsets.

TRANSITION FLIGHT

Most of the quantitative research on V/STOL's to date has been done on the POP condition. The techniques developed for conventional aircraft seem to apply at such conditions and so have been used as the basis for flying qualities studies studies. Within this context a considerable amount of research has been performed, specifications have been developed, and can be reasonably substantiated, though there are of course still many areas where precise quantitative data need to be obtained. Unfortunately the dynamics involved in a rapid transition are not yet well understood. Obviously transitions can be flown, investigated or simulated and the pilot will know whether or not that particular maneuver or aircraft is satisfactory, acceptable or unacceptable. Unfortunately, without better understanding of the dynamics of transition, neither the pilot that flew the aircraft, nor the engineer who analyzed the results will be able to define mathematically what the characteristics were. Without such a definition the information cannot be applied to future aircraft, nor can flying qualities criteria be established.

HEIGHT CONTROL IN HOVER

There is a need to improve the precision with which VTOL aircraft can be hovered. Ideally a height control requirement would include the combined effects of T/W, engine thrust response, height damping (Z_w) and perhaps even the pitch and roll dynamics. This is certainly not possible at present, in fact, there are detailed questions about the current data base for even interpreting $T/W = Z_w$ boundaries. The problem hinges around the difference between natural or aerodynamic height damping, and height damping achieved by feedback to the thrust controls. The present specification accounts for the tendency of minimum T/W required to increase at low damping levels by requiring the capability to develop certain levels of incremental vertical acceleration from a 4 ft/sec rate of descent. As is pointed out in the BIUG this phrasing of the requirement has brought out the fact that there is a difference between artificial and inherent damping, since higher minimum T/W is required for compliance when damping is provided by augmentation. One would expect that from a piloting standpoint, it would be immaterial whether damping is inherent or artificial. Previous simulation testing and analysis provides little guidance since no distinction was made.

Another problem which has been virtually ignored in the literature to date is the time duration that vertical thrust increments are required for representative maneuvering situations. For example, some VTOL's

may be capable of achieving the required acceleration levels instantaneously by trading off stored kinetic energy in the propulsion system for vertical thrust. However, sustained thrust increments may be impossible because of the attendant deceleration of the propulsion system. This aspect of the problem should be addressed in future simulation efforts by including representative dynamic characteristics of VTOL vertical thrust systems.

LATERAL-DIRECTIONAL PROBLEMS

Several of the forward flight lateral-directional requirements in MIL-F-83300 are STOL and conventional flight oriented. For example, requirements 3.3.8, Roll-sideslip coupling, were derived empirically from test data generated from aircraft having conventional modal characteristics. These requirements, which are stated in terms of parameters such as ϕ_{OSC}/ϕ_{AV} and $\Delta\beta/\phi_1$, are all based on an underlying theme, which, briefly stated, is that in lateral-directional maneuvering roll control inputs are "primary" and that associated sideslip excursions are for the most part unwanted effects that can require complicated and objectionable rudder coordination in order to be suppressed. At higher speeds there is substance to this theme in the way of experimental flight test data. At lower speeds, the development of large sideslip angles during maneuvering does not appear to be as objectionable. Large sideslip motions are common at hover. Thus, somewhere between V_{con} and hover, the role played by sideslip excursions as a flying qualities consideration changes and perhaps the requirements should be phased accordingly.

The lateral-directional stability requirements in MIL-F-83300 were formulated using a data base that reflected low values of Dutch roll frequency but there is a need to obtain data for very low frequencies. In addition, the data base for the MIL-F-83300 stability requirements reflected neutral spiral stability and a well damped roll mode. Data on more stable spirals along with less damped roll modes is needed. Finally, there is a general need for data on configurations having stability augmentation systems with roll attitude feedback, heading hold and rate command control loops. Control mechanizations such as these are not represented in the data used to formulate MIL-F-83300 requirements.

DYNAMIC STABILITY - FIXED OPERATING POINT FLIGHT

The flying qualities literature gradually expanded from Control Power versus Rate Damping studies to more realistic models including the effects of derivatives such as M_θ, M_u, and X_u (and their equivalent in the lateral-directional plane). Such models have been investigated on fixed base simulators and moving base simulators and have also included the effects of wind, turbulence, and control system lags.

Attempts at correlating the results of these studies with parameters that can be used as flying qualities criteria have used techniques based on: (1) location, in the s-plane, of the roots of the system's characteristic equation; (2) on matching the time history of the response to a specified input; (3) by minimizing a performance index made up of parameters in an assumed form of loop closure around the model. Because they were still novel, methods (2) and (3) were set aside for further development and method (1) was adopted in the current version of MIL-F-83300.

It is realized that methods (2) and (3) offer advantages which should be exploited as soon as possible. These advantages include the ability to include the effects of control system dynamics along with the characteristic responses, and also the ability to be generalized to cover higher order systems.

In addition to the problem of obtaining correlation of the experimental data with a suitable flying qualities criteria, there is a need to verify that the experimental models contain all the important effects. Clearly a linearized constant coefficient model of a hovering VTOL is not exact, but it has been used on the assumption that it contains all the important features; a truly representative model is too complex to study in a generalized sense so has to be simplified to its essential features (though as complete a model as possible can always be used during design and evaluation of a specific design, it is difficult to apply the results of such a study to other configurations). An important area for research then, is to determine if the simple models on which criteria are being based really do direct attention to all the characteristics which need to be specified.

The Forward Flight section (3.3) of MIL-F-83300 addresses the "short-term response of angle of attack following an abrupt pitch control input". In the limit this will be the short period mode. The phugoid is covered by a blanket requirement on "all roots of the characteristic equation". It is expected that such statements are sufficiently general. However, there is a need to study all the aspects of longitudinal dynamics, and equilibrium, for the special conditions of STOL's.

Considerable effort should be spent on developing mathematical models which contain all the essential features of STOL aircraft currently being considered in preliminary design studies. Experimental investigations should then be performed to determine how the short term response dynamics and equilibrium characteristics (in terms of stick force and position gradients) interact with the multiplicity of factors involved and techniques such as closed loop analysis using pilot models may be useful in deriving better understanding. It may also be useful to try techniques such as response matching and minimizing the performance index, mentioned in the Hover and Low Speed discussion.

EQUILIBRIUM CHARACTERISTICS

Longitudinal equilibrium requirements are presently specified in terms of the pitch control force and displacement gradients with speed. Both stick force and position are required to be stable for Level 1 and for Level 2, IFR. For Level 2, VFR and for Level 3 a small unstable position gradient is allowed. These requirements are a constant source of contention between the military and the aircraft manufacturers. Demanding stick force and position stability throughout the speed range 0 to V_{con} will frequently necessitate a complicated control system with a series actuator. There is presently a scant data to substantiate the requirements, though qualitatively, most authorities will agree that they are desirable.

WIND AND TURBULENCE

Unlike MIL-F-8785 the V/STOL Specification MIL-F-83300 does not define the turbulence model which should be used in investigating the requirements. Many investigations have demonstrated that wind and turbulence is an essential ingredient of valid flying qualities simulator studies. The effects of discrete turbulence on V/STOL aircraft near the ground are especially important. During the last few years much work has been devoted to developing new and better turbulence models and incorporating these into simulator studies. It is essential that improved models be developed and applied to appropriate requirements.

CONTROLLERS

The control force and sensitivity limits are written for conventional stick (or wheel) and rudder pedals. They would be inappropriate for a side arm controller. The side arm controller may find its way into many types of aircraft. The Huey Cobra (AH-1G) already utilizes such a system for the front (gunner's) seat. There is a need therefore to develop suitable criteria for such controllers.

AUGMENTATION SYSTEMS

Augmentation systems of the complexity up to attitude systems have been considered in section 3.2 but there are no provisions to cover such systems as the velocity command system developed by MIT. In addition, aircraft having a significant degree of attitude augmentation may not be covered by the requirements of section 3.3 as they are written. This is particularly true in the case of lateral-directional augmentation, where heading hold or turn rate systems may or may not meet the requirements. In the longitudinal plane, velocity command systems are not covered.

CONFIGURATIONS OTHER THAN TILT TO TRANSLATE

The investigations into dynamic stability and control have been made for types of configurations which have to tilt to translate. It is not possible to say how applicable these would be for a type of configuration which had direct control of forces and used thrust vectoring (independently of attitude) for translation. There is an obvious advantage to designing an aircraft which does not have to tilt to translate/ the attitude can remain about constant and hence large attitudes can be avoided. This could be particularly advantageous in the terminal flight phases where large attitudes interfere with the field of view. The dynamics which would be desirable for such an aircraft will no doubt be different from the type studied to data. Hence, if preliminary design studies show such an arrangement to be feasible or desirable, then efforts should be made to cover them in the requirements.

RESEARCH PROGRAMS

To attack all of the above problems and the many others that need work to be performed, would involve a very large program and correspondingly, very large resources. Furthermore, many of these problems are not amenable to quick solution by mere application of manpower.

The U.S. Air Force has a three year program presently underway to refine and substantiate the requirements of MIL-F-83300. One phase of that program will be an investigation of attitude, speed and flight path control in the Forward Flight region during landing approaches, using both ground based simulation and in-flight simulation. A second phase will be a look at requirements on control lags, control mechanization and control power in the Hover and Low Speed region using fixed and moving base simulation. This program will involve in-house efforts within the Air Force Flight Dynamics Laboratory. Subcontracts with National Research Council of Canada and United Aircraft Research Laboratories are planned. In addition to this program there is a program to use the variable stability X-22A for various investigations. One of these investigations concerns the longitudinal dynamic response requirements in Forward Flight regions of MIL-F-83300. The X-22 programs are jointly sponsored by the U.S. Navy, U.S. Air Force, and NASA under the guidance of a steering committee and are performed by Cornell Aeronautical Laboratory.

Extensive in-house and contract work on further improvement and validation of MIL-F-8785, the handling qualities criteria document for more conventional regimes of flight, is continuing. This work, although not directly applicable to speeds below V_{con}, may be relevant to a degree and of course directly affects V/STOL vehicle design above V_{con}.

Some effort is being directed at the very large problem area of turbulence models and turbulence effects on aircraft. Contractors who have been or are at present involved in such work include University of Washington, University of Toronto, Northrop, and Princeton. Much more effort is required before this aspect of the problem can be properly treated.

The U.S. Air Force has a large integrated program underway concerned with the technology of STOL vehicles. It is expected that a number of the design study efforts to be performed will add considerably to the data base. Similarly, the large NASA program on STOL vehicles being established, should be very helpful. Results from Harrier tests and operational type use would also be of great value as they become available.

Work is continuing on pilot vehicle analysis for application to V/STOL handling qualities. In-house efforts of AFFDL on "Paper Pilot" are continuing (see paper by Anderson in this volume). Additional work is being performed by Systems Technology, Inc. (STI) under contract. A very ambitious analytical effort has been recently completed by STI for NASA, Reference 33. This effort involves prediction of pilot ratings for the complete multi-axis pilot vehicle system including displays. Other work by Bolt Beranek and Newman (BBN) has been completed or is underway in this area (Reference 34). Additional recent efforts on pilot-display research are discussed in References 35 and 36.

Even though we have reached a milestone in development of V/STOL criteria, we intend to continue our

efforts on about the same high level to further develop and refine the criteria. We will resist the temptation to relax in our efforts now that a reasonable set of criteria has been attained. It is to be expected, however, that our efforts for the next year or so will be directed at analyzing the basis of critical requirements and at improving the data base, before another attempt is made to generate a large scale change in the criteria.

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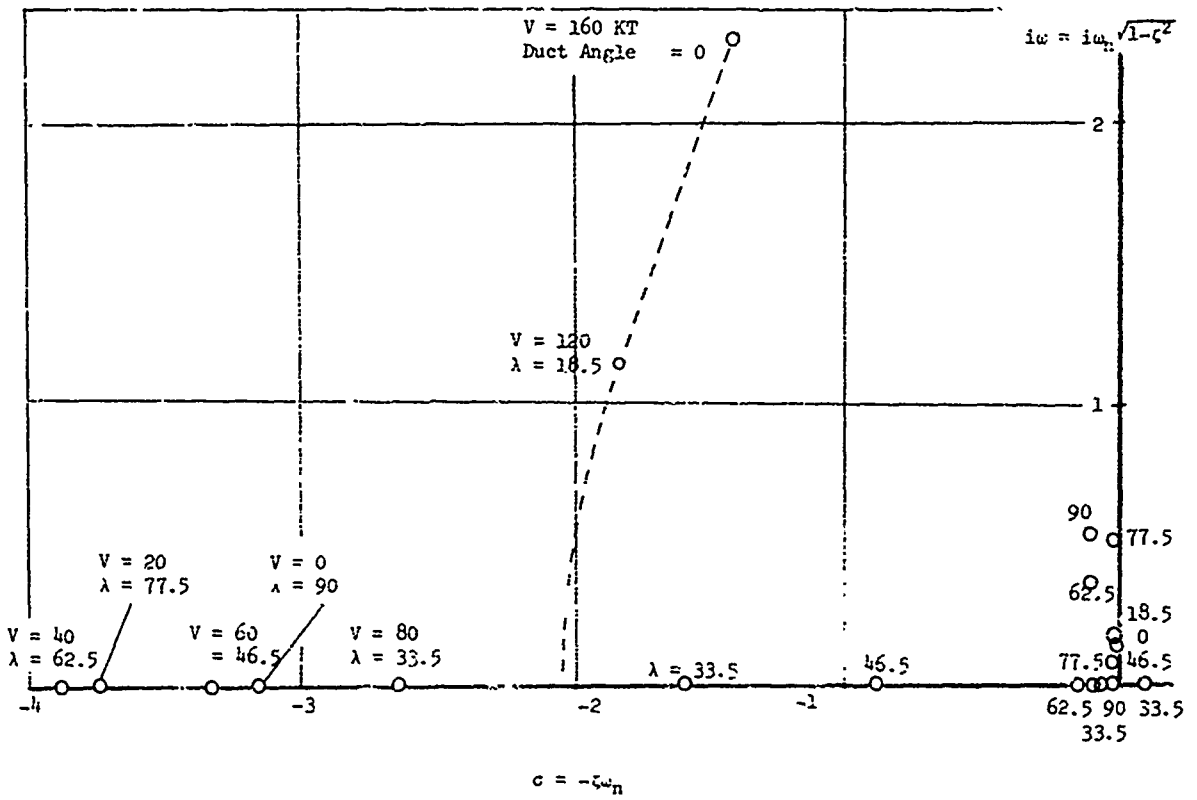
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Framework for Stating Flying Qualities Requirements

Class	Flight Phase Category	Level		
		1	2	3
I	A			
	B			
	C			
II	A			
	B			
	C			
III	A			
	B			
	C			
IV	A			
	B			
	C			

Figure 1



LOCUS OF X-22A FIXED OPERATING POINT ROOTS BETWEEN V = 0 AND

V = 160 KT (AUGMENTED) (DATA FROM REFERENCE 18)

Figure 2

LEAD DISCUSSION

by
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I think there will be general agreement among us that Messieurs Chalk and Westbrook deserve congratulations for having successfully produced a V/STOL flying qualities specification, MIL-F-83300, that has been accepted by the U.S. Air Force and I understand is likely to be accepted by the U.S. Navy and Army. A number of years ago I was a member of a committee of four that was commissioned by the Flight Mechanics Panel to produce a set of V/STOL flying qualities criteria for AGARD which became AGARD report 408. It was an interesting and most enjoyable task until we were suddenly faced with comments on the report from various agencies and industries following a meeting held for that purpose in Greece. The comments and ideas received were sufficiently diverse and conflicting that an easy way out was chosen. The solicited comments were all bundled together to form an appendix to AGARD 408 and republished as AGARD 408A, which fortunately one seldom sees in references. The authors of MIL-F-83300 were much more bold. Proposed specifications were submitted for review three times to interested agencies and industries and revised accordingly before the final document was submitted for approval to the U.S. Air Force. I think then that we are able to assume that the final version reflects the current view on V/STOL flying qualities of U.S. industries and government agencies concerned with aviation, at least as far as there is a consensus. For this valuable document we are indebted to the authors of this afternoon's paper.

I believe that they should be further commended for an innovation that was introduced along with MIL-F-83300 and MIL-F-8785. I am referring to the document titled Background Information and User Guide which reached its final revised version shortly after that of the V/STOL Flying Qualities Specifications. This report includes substantiating data used in formulating the specifications and as such collects together meaningful data and analysis. It is also an indication of the thorough manner in which the specification task was performed.

This afternoon's paper considered a number of problem areas where additional research effort or experience is needed to improve upon the specifications. I would like to make some comments on the particular area dealing with systems commonly referred to as attitude command and velocity command systems, the latter similar to that proposed by M.I.T. My concern is not that of being able to define better response criteria but rather that most such systems do not provide the pilot with useful, and in my opinion often essential information, regarding the amount of moment control about all three axes that has been used to trim and manoeuvre, or perhaps more to the point, how much moment control is still available after trimming and manoeuvring. It is certainly such information that allows the pilot to exploit the full potential of his aircraft when necessary. It can enhance safety considerably in that the pilot is able to make a better estimate of the control margin he needs to keep in hand for the particular circumstances of the moment.

In systems where cockpit control position is approximately linearly related to moment about the three axes the pilot is at all times aware of the control moment that is still available. Such is the case when the cockpit control is linearly connected either mechanically or hydraulically with control surfaces, cyclic pitch or other device producing the moment. An example of a system used in the past where this correspondence did not necessarily occur is the servo-tab type control. It has been necessary to take particular care in the design of servo-tab elevator controls where trim was achieved through incidence changes of the horizontal stabilizer to ensure that the cockpit control position reflected with reasonable accuracy the control margin available under different trim conditions.

In the case of stability augmentation systems where control surfaces or other moment producing devices move without corresponding movement of the cockpit control, the problem seems to have been adequately allowed for by specifying a limit to the authority of the system. Our present experience is nearly all related to systems which only augment angular damping derivatives and I'm not sure whether present specifications are sufficient for augmentation of some of the static derivatives.

In the case of attitude command systems and perhaps even more so with velocity command systems, cockpit control position is not related to the amount of moment control used in a manner that is interpretable by the pilot. I believe that the possible implications of this in these systems are such that considerable work is necessary before any attempt can be made to arrive at sufficient specifications.

OPEN DISCUSSION

R.S. Sliff, FAA, USA

Does the military specification 83300 consider community noise and any related operational problems?

C.B. Westbrook, AFFDL, USA

This aspect is not presently included into consideration when defining the requirements of MIL-F-83300.

D. McGregor, NRC/NAE, Canada

Do you see very significant differences between the military specification and the AGARD Handling Qualities Criteria that will be difficult to resolve so that both can reflect the same point of view?

C.B. Westbrook, AFFDL, USA

The military are customers as well as authors of the requirements and as a result we have the responsibility and authority to set the requirements we need. We did use inputs from the various NASA organizations to arrive at some of the requirements of MIL-F-83300. Dick Wasicko did coordinate some of this effort. We have been and will continue to evaluate the requirements of AGARD 577. Many of the requirements and criteria evolved out of the same data base and so have commonality to start with. I agree with you that AGARD 577 and MIL-F-83300 should come together at some point. However, AGARD 577 is not a specification but a document which presents criteria.

S.B. Anderson, NASA Ames, USA

It should be recognized that we tried to put out criteria instead of specifications and in this sense MIL-F-83300 and AGARD 577 are different.

I think there is room for closer collaboration in the work that Mr. Westbrook is undertaking in the future program. I hope we can work together a little more closely and make sure that there aren't so many differences.

APPLICATION OF V/STOL HANDLING QUALITIES CRITERIA TO THE CL-84 AIRCRAFT

by

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SUMMARY

This presentation reviews the design concepts and flight characteristics of the Canadair CL-84 tilt wing V/STOL aircraft as related to handling qualities and compares the achieved characteristics with the revised AGARD V/STOL Handling Qualities Criteria.

It is shown that the CL-84 characteristics are in general accord with the Criteria. While a few of the Criteria values appear inappropriate for the CL-84, it is concluded that the handling qualities of the aircraft would be improved if the aircraft met most of the Criteria in the areas where it presently falls short.

INTRODUCTION

Canadair Ltd., a wholly-owned subsidiary of General Dynamics Corporation, has been engaged in V/STOL research and development continuously throughout the past 15 years, with support from the Canadian Government. Almost from the outset, this effort was concentrated on the flapped, tilt wing concept and has, up to the present time, materialised in the design, development and flight testing of the CL-84 prototype and the CL-84-1 evaluation aircraft (Fig. 1).

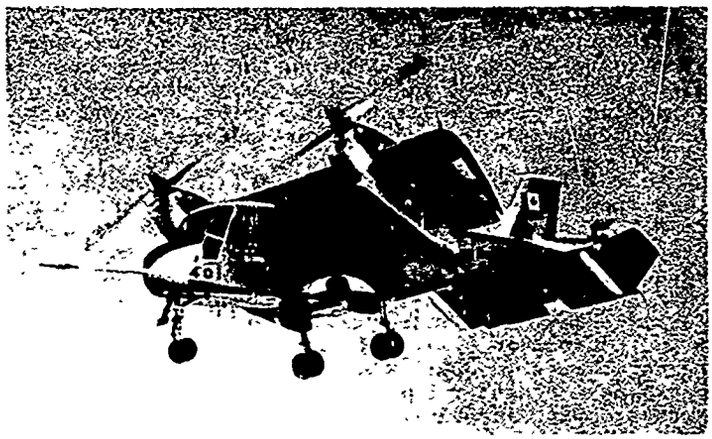


Fig. 1

It was evident at an early stage that the solutions to the problems of flight mechanics associated with the flapped, tilt wing concept in the V/STOL flight regime were not readily available. Thus, considerable effort has been expended in the past years at Canadair on the development of analytical methods, experimental techniques and control system concepts. Methods for predicting the aerodynamic characteristics were developed, and several thousand hours of powered model testing of flapped, tilt wing configurations have been completed in several wind tunnels and on the Canadair mobile rig. Control system designs, ranging from purely mechanical to "fly-by-wire" concepts, were investigated. It became increasingly evident from the aerodynamic studies that extensive control mixing and programming would be required, and that it would be necessary to evaluate the complete closed loop system comprising the characteristics of the flight sensor system, the human operator, the control system, including stability augmentation systems, and the uncontrolled airframe in order to obtain a valid assessment of the stability, control and handling qualities of an aircraft of this type. The degree of complexity involved in this closed loop assessment was judged to virtually exclude purely analytical means, and fixed base simulation was chosen as the most suitable method for solution of the problem. The Canadair fixed base simulation was supplemented by several programs undertaken by the N.A.E. Flight Research Section on their airborne simulator. References 1 and 2, and associated references, deal in detail with the early development of the flying qualities of the CL-84 prototype.

Flight test development of the prototype commenced following the first flight in May, 1965, and continued until the aircraft crashed in conventional flight in September, 1967. Although the exact cause of the accident could never be proven, the available evidence pointed firmly to a jam in the right side of the main propeller control system. An extensive accident investigation revealed several areas where design improvements, as related to reliability and maintainability, could be achieved, especially in the propeller control system. These improvements were incorporated in the CL-84-1 evaluation aircraft. Original plans called for the construction and flight development of three aircraft for evaluation by the Canadian Armed Forces (Reference 3). However, following flight of the first CL-84-1 in February, 1970, schedule delays and cost restrictions resulted in contraction of the program to the development of one aircraft by Canadair. It is the opinion not only of the Company, but of several visiting pilots, that the aircraft has proven itself worthy during the past six months and will be ready for evaluation at the end of the present Company program. It is hoped that the Canadian Government will decide to proceed with the evaluation program next spring.

It is appropriate that the applicability of V/STOL Handling Qualities Criteria to the CL-84 should be a subject at this Specialist Meeting. Throughout the development of the CL-84, the V/STOL handling qualities of the aircraft have received prime attention by the Company, and in the author's opinion, with reasonably gratifying results. While it must be admitted that there is considerable room for further development and improvements of the handling qualities of the aircraft, the greater desire expressed by most pilots for improvements in the conventional flight regime rather than in the V/STOL regime is perhaps testimony to the Company's attention to V/STOL handling qualities.

It is the objectives of this presentation to review the design concepts and characteristics of the CL-84 as related to V/STOL handling qualities, to compare the achieved characteristics with the revised AGARD criteria as given in Reference 4, and finally to assess the applicability of the criteria to the CL-84 aircraft.

DESCRIPTION OF THE CL-84-1

General

The CL-84-1 is a twin engined turboprop, tilt wing V/STOL aircraft with a design weight of 11,400 lbs. at a limit load factor of 4. Ultra-short take-off and landing performance can be achieved at weights up to 14,700 lbs. While designed primarily as a light transport, the capabilities of the aircraft make it useful for many other roles such as search and rescue, and ground support. The short span wing is essentially fully immersed in the slipstream from the 14 ft. diameter main propellers and can be tilted at any angle from 2° to 102° relative to the fuselage datum. The muscle of the wing tilt system is a single ball-screw actuator driven by two hydraulic motors from independent hydraulic supplies. The hydraulic motors are controlled by two independent electric actuators signalled from a two-way on-off switch on the pilot's power lever. The wing tilt motion actuates the full-span leading and trailing edge flap systems, which increase the lift capability of the wing at intermediate tilt angles, and the trim and control system gains of most of the aerodynamic trim and control surfaces.

The two Curtiss Wright four-bladed, fiberglass main propellers rotate in opposite directions and are interconnected mechanically by a cross-shaft mounted in the wing, and driven by two 1500 S.H.P. Lycoming T-53 free turbine engines through gearboxes. Overrunning clutches between the engines and the propeller gear boxes permit operation of the main power train and assures thrust symmetry in the event of one engine failure. A T-gearbox at the centre of the cross-shaft drives the dual two-bladed counter-rotating tail propeller via a tailshaft. The main function of the tail propeller is to provide aircraft pitch trim and control in V/STOL flights but the tail propeller also contributes significantly to the total lift in hover and low speed flight. A clutch, brake and aligner, operated by a cockpit master switch for conversion from V/STOL flight to conventional flight, permits stopping and alignment of the tail propeller blades in the minimum drag configuration for flight in the conventional regime, i.e. with the wing locked down. Thus, with the exception of the interconnected propellers. the aircraft operates as a conventional turboprop aircraft in the conventional flight regime.

The tail surfaces consist of a large horizontal tailplane with a part-span elevator mounted low on the aft fuselage; a central vertical fin with a rudder; and vertical fin surfaces end-plating the horizontal tailplane.

The long-stroke, tri-cycle landing gear is retractable and permits operation from unprepared fields.

Reference 5 gives a detailed account of the reasons for the selection of the CL-84 aerodynamic configuration.

Flight Control System

The flight control system of any V/STOL aircraft has a profound influence on the V/STOL handling qualities of the aircraft. This is particularly the case for the tilt wing concept where many of the aerodynamic surfaces provided for flight in the conventional flight regime are used for trim and control in the V/STOL regime.

The CL-84 cockpit has side-by-side seating with the pilot seated on the left. The flight controls are fully dualized, but a co-pilot is not required for operation of the aircraft. The cockpit flight controls are conventional both in configuration and in operation; longitudinal stick controls pitch, lateral stick controls roll and the rudder pedals controls yaw in all regimes of flight (See Fig. 2). Height, or thrust control is obtained by fore-aft movement of a power lever to the left of the pilot. A hand-and-arm rest is provided to aid precise height control in hover and low speed flight. All the cockpit flight controls are powered by servo actuators placed under the cockpit floor to ensure light feel forces and to prevent force feed-back from operation of the control and stability augmentation systems. Thus, the feel forces are entirely artificial. At present, a "two-feel" system is used which changes the light, constant force gradients used for V/STOL operation to higher, constant values for conventional flight when the conversion master switch is operated. The trim actuators are connected between the cockpit controls and the cockpit servo actuators, i.e. trim is obtained by re-positioning the main control surfaces in relation to a fixed cockpit control position.

The control system control runs consist of push-pull rods, bell-cranks and levers. In addition, for all the controls in the wing and nacelles, transfer mechanisms mounted close to the wing tilt axis permit the transfer of control motions from the fuselage to the wing at any tilt angle. Close tolerance, low friction bearings are used in all joints in the CL-84-1 so that, unlike the CL-84 prototype, no pre-loads are required in the control systems.

The "brain" of the V/STOL control system consists of a control mixing and programming unit mounted in the fuselage immediately behind the wing tilt axis. This "mixing box" contains programming cams and mechanisms, summing mechanisms and the stability augmentation system actuators. The programming devices are actuated mechanically by the wing rotation. The S.A.S. inputs are summed with the cockpit control inputs upstream of the programming and mixing units.

The longitudinal pitch control circuit connects the longitudinal stick directly to the elevator. The input from the longitudinal stick and the pitch S.A.S. actuators to

the tail propeller is programmed in the mixing box such that the gain varies from a maximum at 65° wing tilt to zero at 0° wing tilt. Thus, the pitch S.A.S. authority is automatically phased out for conventional flight. In addition to the control authority program, the tail propeller mixing box cam also provides a trim program with wing tilt such that the aircraft pitch trim remains essentially constant throughout transition from hover to conventional flight without any pilot trim input. A servo actuator at the tail propeller ensures low control circuit loads for normal operation. The required tail propeller pitch trim authority with wing tilt is minimized by programming both the full-span, single slotted trailing edge flaps and the horizontal tailplane with wing tilt angle. The wing tilt input is the only control input to the collective flap system and the tailplane so that neither collective flap deflections nor tailplane deflections are used in conventional flight. Both systems are redundantly powered by hydraulic servo actuators.

The roll control circuit connects the lateral stick to the main propeller blade angle controls and the trailing edge flap surfaces, which serve as ailerons as well as flaps. The lateral stick input to the mixing box, which is summed with the roll S.A.S. actuator output, gives one input to the differential flap/aileron circuit and another to the differential main propeller blade angle circuit. The gain of this input to each circuit is programmed with wing tilt angle by individual cams such that the moment reactions from differential flap/aileron deflections and differential blade angle deflections add about the aircraft roll axis and approximately cancel each other about the yaw axis at all wing tilt angles. The differential flap/aileron output from the mixing box is summed mechanically with the collective flap signal for each side of the wing by a mechanism mounted on the rear wing spar as shown in Fig. 2. (Note that the right flap/aileron control run and actuator has been deleted from this figure.) Similarly, the differential blade angle output from the mixing box is summed with the collective blade angle for each side by a summing mechanism mounted on the rear wing spar inboard of the right side nacelle. (Note that neither the differential blade angle output lever from the mixing box nor the control run to the summing mechanism are shown in Fig. 2.) The roll control power is essentially obtained from the differential thrust of the main propellers in hover and entirely from the flap/ailerons in conventional flight. The roll S.A.S. authority to the flap/ailerons in conventional flight can be retained at the option of the pilot.

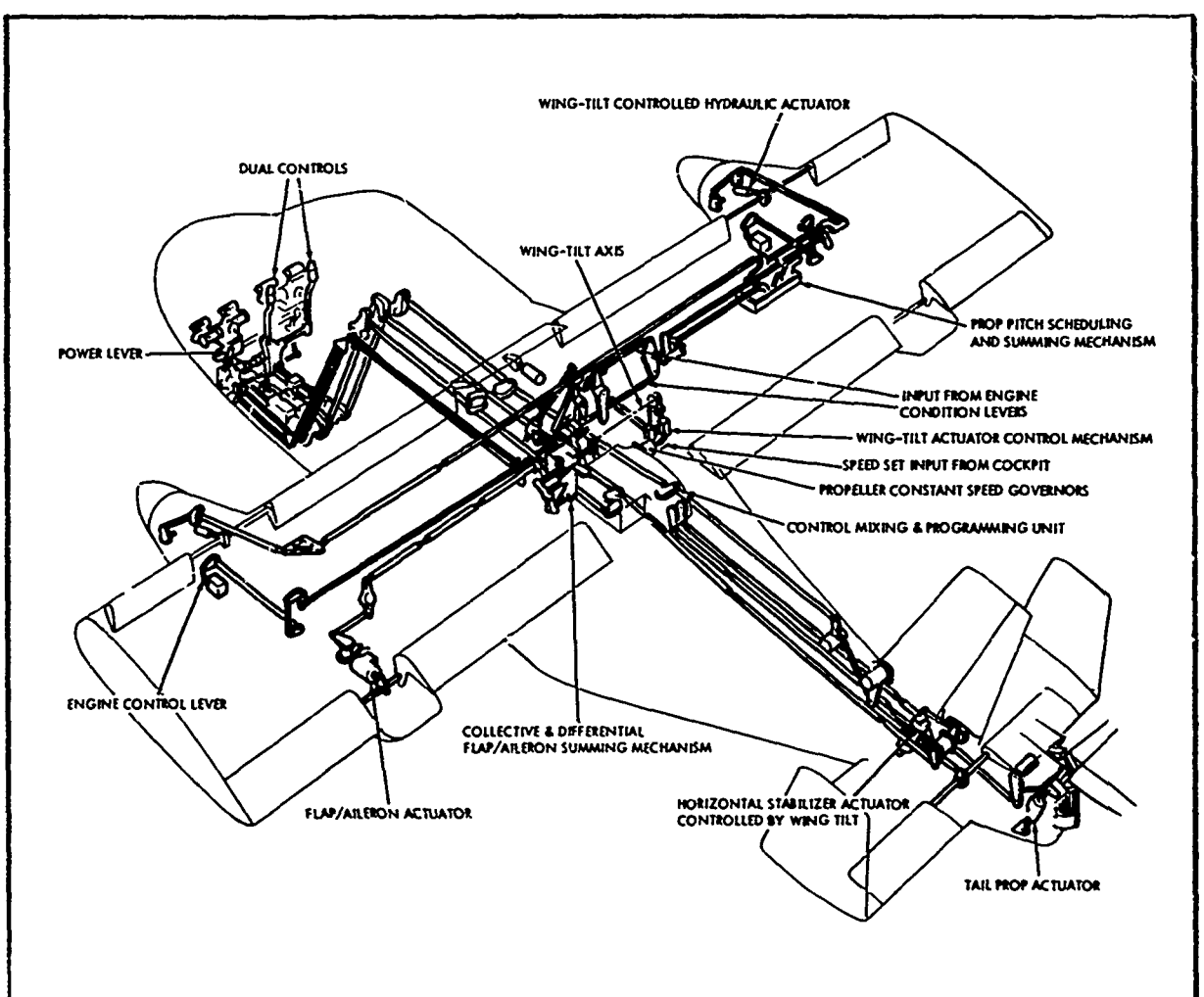


Fig. 2 CL-84-1 Flight Controls

The yaw control circuit is conceptually the same as the roll circuit with the exception that the rudder pedals are directly connected to the rudder. In this case, the programming cams are such that the moment reactions from the differential flap/aileron deflections and differential blade angle deflections add about the yaw axis and cancel about the roll axis. The summing mechanisms for the lateral stick and rudder pedal inputs to the differential flap/aileron circuit, and for the differential blade angle circuit, are located in the mixing box. The yaw control power is essentially obtained from the flap/ailerons in hover and entirely from the rudder in conventional flight. Thus, the yaw S.A.S. authority is automatically phased out for conventional flight.

The S.A.S. system consists of attitude stabilization and rate damping in pitch, roll rate damping, and rate damping with control augmentation in yaw. The pitch rate gyros and actuators are duplicated. The yaw control augmentation system counteracts the rate damping when the rudder pedals are displaced. All systems are self-monitored and self-centering following malfunctioning or failure.

The height, or thrust-power control system is in principle a conventional turboprop-direct power control-constant propeller speed governing system with propeller blade angle scheduling added. In normal operation, the two engine condition levers are ganged to the cockpit power lever so that the single power lever controls the power of both engines. In addition to the direct control runs to each engine, the sum of the condition lever motions gives a collective blade input to the two propellers. The gain of this input with power lever travel is shaped by a cam in the propeller scheduling and summing mechanism such that the power change required due to the collective propeller blade angle change is essentially equal to the change in power available from the engines when the aircraft operates at low speed. In order to prevent gross over-scheduling with increasing advance ratio, the scheduler cam is rotated by the motion of the constant speed governor actuator such that the overall gain from the scheduler is reduced with increasing advance ratio. Thus, for rapid power lever motions at constant airspeed, the system operates essentially as a direct blade angle control system with the propeller governor trimming the blade angles to exactly match the power available, while for changes in airspeed or selected propeller r.p.m., the governor system alone provides the changes required in blade angle.

The propeller governor system consists of a normal and an independent stand-by system with various underspeed, overspeed and switch-over devices.

The main propeller blades are operated by dualized pitch control units powered by redundant self-contained hydraulic supplies.

While it must be admitted that the CL-84-1 flight control system is not a simple system, the overall performance of the system to date has been good in all respects. Some development is presently needed in the flap/aileron circuit, notably for conventional flight, and compensation for the effects of structural deflections on the propeller control circuits may also prove desirable in the future.

CL-84 FLIGHT TEST EXPERIENCE

CL-84 Prototype

In the course of a two and a half year flight test program from 1965 to 1967, the prototype aircraft was evaluated by sixteen pilots and accumulated the following:-

- 405 total operating hours
- 145 logged flight hours
- 305 total flights
- 346 VTOL sorties
- 109 STOL sorties
- 151 transitions

Some highlights of these operations are:-

- VTOL operation in gusts to 35 knots
- World's first live simulated hover rescues by V/STOL aircraft over land and water
- STOL operation without wing angle restriction
- Conventional flight envelope to 300 knots and 3.0 g

Successful evaluations of the prototype aircraft were conducted by NASA and a U.S. Tri-Service V/STOL test team that included representation from the Navy, Air Force, Army and Marine Corps. It was also flown by RAF and Canadian Forces pilots. The following are abstracts from the official reports of the evaluations:-

a) NASA-TM X-1914

"In general, based on the limited evaluation performed, most of the flying qualities in the hover, transition, and cruise modes of flight were considered good".

b) USAAVLABS Technical Report 67-84 on Tri-Service Evaluation

"The tilt wing concept as exemplified by the CL-84 was considered to be suitable for search and rescue, surveillance, light transport and general utility mission applications. The aircraft was mechanically simple, generally easy to maintain, and easy to fly ... the deficiencies noted were not considered to be conceptual and were of a nature which can be corrected by hardware redesign within the state-of-the-art".

CL-84-1

To date (September 20, 1971), the following flight test experience has been accumulated on the CL-84-1:

- 166 total operating hours
- 60 logged flight hours
- 95 total flights
- 74 VTOL sorties
- 70 STOL sorties
- 52 transitions

Highlights of these operations are:

- Conventional flight envelope:
  - 3.65 g at 170 knots EAS
  - 2.15 g at 300 knots EAS
- V/STOL flight envelope:
  - 3.20 g at 130 knots EAS
  - 1.8 g at 60 knots EAS
- Operations off-base at Nicollet range; up to 3 flights per day
- Minigun firing on targets at speeds of 0, 40, 100 and 200 knots
- STOL and conventional flight operation with external tanks including tank dropping.

Preliminary flight evaluations of the CL-84-1 have been completed by pilots from the Canadian Forces, Royal Aircraft Establishment and the U.S. Navy. These pilots were unanimous in rating the handling qualities in hover and low speed as excellent, although some problems in conventional flight were noted.

COMPARISON OF CL-84 CHARACTERISTICS WITH AGARD CRITERIA

The design of the CL-84 prototype aircraft was originally guided by the Recommendations of AGARD Report No. 408. As the results of analysis and simulation studies became available, the design was increasingly influenced by these results rather than by the Recommendations, as might be expected. This is not to say that most of the findings disagreed with the Recommendations. However, Canadair's interpretation of the Recommendations at that time might have led the CL-84 program into difficulties if the Company had blindly considered the minimum requirements of the Recommendations as all that had to be met. A case in point is pitch control power and damping in hover and low speed flight. If the CL-84 had been designed to the minimum values given in the Recommendations, the aircraft would probably have crashed early in the flight test program during decelerating maneuvers near hover. The lesson to be learned from this is that no recommendations, requirements or specifications on flying qualities will ever excuse the aircraft designers from doing their homework properly.

In comparing the CL-84 V/STOL handling characteristics with the Criteria of AGARD Report No. 577, it was found impractical, even if it had been possible, to provide direct evidence from flight test records of all the characteristics of the CL-84. Therefore, emphasis has been placed on deriving the appropriate values for the CL-84 corresponding to the values in the tables presented in AGARD 577. All the values quoted were obtained either from analysis of flight test data, or where appropriate, from ground tests. Where values either vary, or are unknown, or where the data was obtained from a test condition which was not entirely appropriate, comments are included below the tables in an attempt to indicate whether or not the CL-84 meets the intent of the Criteria. Most of the data is derived from the CL-84-1, but in some cases CL-84 prototype data has been used. For the convenience of the reader, the section numbers, titles, table numbers and figure numbers of AGARD 577 have been used throughout. Where flight test time histories have been substituted in lieu of, or in addition to tables, the figure number(s) used is that of the appropriate table.

Section 1 CHARACTERISTICS OF THE CONTROL SYSTEMS

1.2 Control Breakout Forces

V/STOL Control Breakout Criteria: Acceleration System				
Control Axis	Normal, lb.	After failure of power control system, lb.	Normal,	After worst single failure of power control system, lb.
Pitch	0.5-1.5	5	1-1.25	Variable, but probably within criteria
Roll	0.5-1.5	4	1-1.25	
Yaw	1 -1.0	15	6-6.5	
height:				
Collective	1 - 3	5	Does not apply.	
Throttle	1 - 3	3	3-5	No change.

Table 1.1

After failure of the power control system (single failure), there is no significant increase in the breakout force other than that due to a small additional circuit friction which is variable with wing tilt angle. While not measured in any axis, pilot comments indicate that the values are probably within the criteria throughout the flight envelope. However, due to the valve travel in the inoperative cockpit actuator, there is a lost motion of approximately $\pm \frac{1}{4}$ inch at the pilot's control. In addition, spurious feed-back loads from the elevator to the longitudinal stick occur in hover, particularly in ground effect.

1.3 Control Force Gradients

The gradients after a single power control system failure have not been measured. However, excluding the effect of the elevator feed-back load in pitch, the gradients should not be changed significantly from those for normal operation in hover. In the STOL regime, the roll gradient remains the same as in hover, while the elevator and rudder hinge moments increase the longitudinal stick and rudder pedal gradients, respectively, with airspeed. While the pitch gradient may exceed 10 lb./in. for speeds above 100 knots, the yaw gradient is certainly well within the upper limit of the criterion throughout the V/STOL flight regime.

V/STOL Control Force Gradients: Acceleration System			
Control Axis	AGARD Criteria		CL-84-1
	VTOL* lb/in	STOL lb/in	V/STOL lb/in
Pitch	1 - 2.5	2 - 5	2.0
Roll	.5 - 1.25	1 - 3	2.0
Yaw	2.5 - 10	10 - 35	5.0

Tables 1.2 and 1.3

The values shown apply to normal operation only.

V/STOL Control Force Harmony Ratio			
Control Force Ratio	AGARD Criteria		CL-84-1
	Minimum	Maximum	V/STOL
Pitch/Roll	1	4	1
Yaw/Roll	4	8	2.5

Table 1.4

1.4 Control System Free Play

The CL-84-1 control system has very small values of backlash in normal operation. The only control circuit which may not be adequate in this regard is that of the flap/ailerons where the backlash is equivalent to $\pm \frac{1}{2}$ degree aileron movement.

After a single failure of the power control system, the free play is increased by about $\pm \frac{1}{4}$ inch at the pilots control.

1.5 Powered Control Systems

The only suspected deficiency in the present power control system is that of the flap/aileron actuator. As indicated in para. 1.4 above, a deficiency exists in the flap/aileron control system performance, but it is not known at this time if the problem is due to actuator performance, circuit free play, flexibility or a combination of these factors.

1.6 Trim Systems

It is believed that the CL-84-1 trim systems meet all the AGARD Criteria.

1.7 Height Control Systems

The only known deviation from these Criteria is the power lever friction device which can only be adjusted on the ground.

1.8 Thrust Vector Control

The wing tilt system of the CL-84-1 appears to meet these criteria in all respects. The wing tilt switch on top of the power lever demands rates programed with wing tilt angle and direction of wing motion such that the rates are compatible with the maximum performance of the aircraft. Criticism of potential inadvertent operation of the switch during ground taxi can be attributed to inadequate human engineering design of the power lever grip for operation in the low power regime. Since ground taxi power is well below the Flight Idle setting, this hazard is not present in flight.

1.9 Control Travel Limits

Cockpit Control Travel Limits		
Control Axis	AGARD Criteria ins.	CL-84-1 ins.
Longitudinal	± 4.0 - ± 0.5	3 FWD - 5 AFT
Lateral	± 3.0 - ± 0.5	± 4.0
Directional	± 2.5 - ± 4.5	± 3.0

Table 1.5

1.10 Augmentation Systems

The limited authority, high gain of the CL-84-1 S.A.S. results in sudden saturation of the pitch and roll systems in gross maneuvers at low speeds. While these characteristics have been described by pilots as mildly unpleasant, they have not prevented pilots, even with only one or two flights in the aircraft, from executing these maneuvers. The S.A.S. meets the Criteria in other respects.

Section 2 LONGITUDINAL STABILITY AND CONTROL

The data for the CL-84-1 in Tables 2.1, 2.2 and 2.3 were obtained from steady level flight at various wing angles with the fuselage level and 95% propeller r.p.m.

2.2 Pitch Control Power

Pitch Control Power Characteristics				
	AGARD Criteria		CL-84-1	
	Hover	STOL	Hover	STOL
Pitch Control Power Angular Acceleration Rad./Sec.^{2}	.4 - .8	.4 - .6	± 1.2	± 1.2

Table 2.1

With the high value of control power and high gain S.A.S., the maximum control power is difficult to measure in flight. The values shown have been derived from partial control inputs and extrapolated to full inputs by using the known tail propeller and elevator characteristics.

2.3 Control Sensitivity

Pitch Control Sensitivity: Acceleration System				
	AGARD Criteria		CL-84-1	
	Hover	STOL	Hover	STOL
Pitch Angular Acceleration per unit control deflection Rad./Sec.^{2}/in.	.08 - .16		0.3	0.3

Table 2.2

As a result of the non-linear variation of tail propeller thrust with blade angle, the pitch control sensitivity is not linear with stick deflection, but is higher for forward stick than for aft stick displacements. However, the change in sensitivity is essentially smooth.

2.4 Pitch Damping

Pitch Angular Velocity Damping: Acceleration System				
	AGARD Criteria		CL-84-1	
	Hover	STOL	Hover	STOL
Angular Velocity Damping, 1/Sec.	-.5 to -2.0	-1.0	-3.0	-3.0

Table 2.3

The pitch response of the aircraft is essentially dead beat and control reversals are not required as long as the aircraft operates within the saturation limits of the S.A.S. at trim and rate stabilization.

2.5 Control System Time Lags

A typical pitch response time history for the aircraft in hover is shown in Figure 2.. to illustrate the control system time lags. From a steady state condition with the fuselage nose down, the longitudinal stick is moved aft about 1.5 inches in about 0.15 seconds. The pitch acceleration, as measured by a sensitive accelerometer in the tail of the aircraft, shows that 63% of the maximum pitch acceleration is reached at about the same time as the longitudinal stick reaches its full aft travel. (The scale for the accelerometer is omitted since it does not show angular acceleration directly.) It is clear that the angular acceleration is in the commanded direction within less than 0.1 second and that the time required to reach 63 percent of the initial maximum acceleration for a true step input would be about 0.1 second. These values are well within those shown

in Table 2.4 of the Criteria. The maximum pitch rate is reached within 1 second after the control is fully applied. The reduction of the tail propeller blade angle following the initial peak is due to the S.A.S.

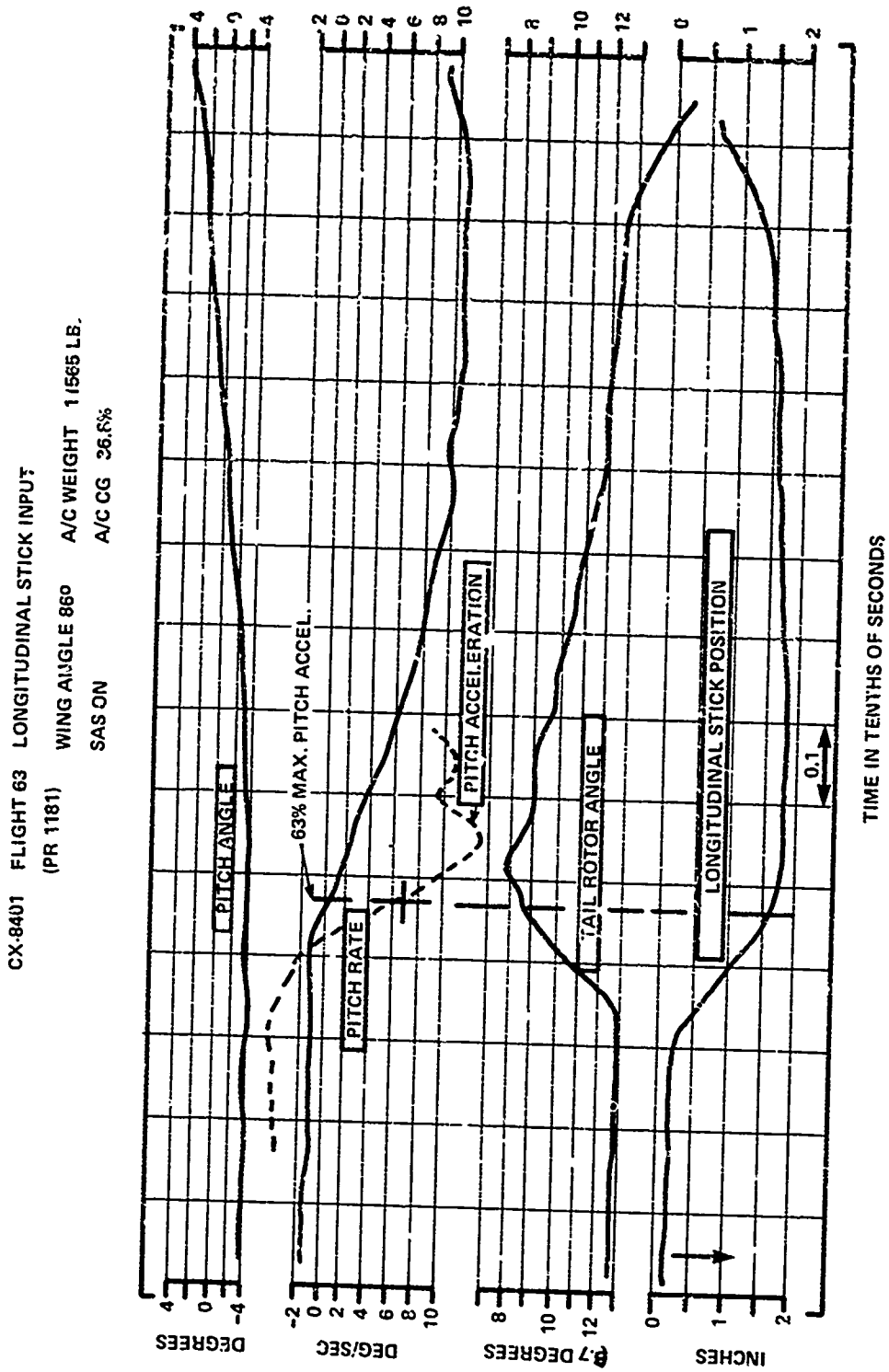


FIGURE 2.4 IN LIEU OF TABLE 2.4

2.0 Static Longitudinal Stability

2.0.1 Trim Speed Stability. Since zero control force corresponds to neutral stick position, this Criterion does not have much meaning for the CL-84.

2.0.2 Stability with Respect to Speed. The CL-84 does not meet this Criterion in normal operation for airspeeds between 30 knots and 60 knots. If a rapid aft stick pulse is imposed on the aircraft, the pitch attitude does not quite return to the original value, and a slow divergence of speed, attitude and angle of attack results. Since the response is not linear, the time to double amplitude increases as the speed decreases. For forward stick pulses, the aircraft is marginally stable in the 30 to 60 knots speed regime. The time to double amplitude with a single S.A.S. failure is not known, but pilots comments indicate that the divergence can easily be controlled.

2.6.3 Thrust Vector Stability. Wing tilt provides an exceptionally powerful means of controlling airspeed and the CL-84 is very stable in this regard.

2.7 Longitudinal Control Characteristics in Maneuvering Flight

The aircraft satisfies these Criteria in normal operation at constant power if the pitch S.A.S. authority limits are not exceeded. The stick force per g is about 15 lb. in the speed range from 30 knots to 70 knots. With a single S.A.S. failure, the turn rate for S.A.S. saturation is increased, but the stick force per g is reduced to about 5 lb. in the same speed range.

2.8 Dynamic Stability

The short-term pitch response of the aircraft is essentially critically damped throughout the V/STOL flight regime.

2.9 and 2.11 Longitudinal Control Characteristics in Take-off and Landing

While the CL-84 readily meets these Criteria, they are only considered of importance to the aircraft with respect to the requirement for adequate control power to maintain level attitude as the aircraft passes through ground effect. Aircraft rotation in the classical sense is not required nor used for STOL operation.

2.10 Longitudinal Control in Sideslip

For STOL operation from 40 knots to 90 knots, aft pitch control deflections of about 20% of full control are required at maximum sideslip. This corresponds to about 2 lb. pull force and is well within the limits of the Criteria. In hover, the requirements for pitch control inputs in yawing turns and lateral translations are negligible.

Section 3 LATERAL-DIRECTIONAL STABILITY AND CONTROL

3.2 Roll Control Power

Roll Control Power Characteristics: Acceleration System				
Parameter	AGARD Criteria		CL-84-1	
	Hover	STOL	Hover	STOL
Bank Angle after 1 Sec., Deg.	2 - 4	2 - 4	10	20
Roll Angular Acceleration Rad./Sec.^{2}	.8 - 2.0		1.5	1.2 - 2.7

Table 3.1

At speeds around 40 knots, the control power is limited by the power of the flap/ailerons. Control power could be increased by using a higher gain to the differential propeller blade angle, but pro-yaw coupling would inevitably result. The higher value in Table 3.1 corresponds to airspeeds around 100 knots.

3.4 Roll Control Sensitivity

Roll Control Sensitivity Characteristics: Acceleration System				
	AGARD Criteria		CL-84-1	
	Hover	STOL	Hover	STOL
Roll Angular Acceleration per unit control deflection Rad./Sec.^{2}/in.	.2 - .8		.375	.3 to .075

Table 3.2

The roll control sensitivity is essentially linear with control deflection in hover and high speed V/STOL flight. At speeds around 40 knots, the combined flap/aileron deflections are sufficiently large, at large control deflections, to cause up to 20% reduction in control sensitivity.

3.5 Cross Coupling

Figure 3.3 shows a time history of an uncoordinated bank-to-bank maneuver at 30 degrees wing tilt (corresponding to a speed of 55-60 knots). The maneuver was initiated from a 30 degrees banked, uncoordinated, descending turn to the left with about 14 degrees of sideslip. The bank angle is reversed in 2 seconds by application of full lateral stick for about 1½ seconds. The tendency for pilot-induced oscillations in arresting the

Cross Coupling Characteristics in STOL Operation (Yaw Control Free)		
	AGARD Criteria	CL-84-1
Maximum Sideslip to Bank Angle Ratio $(\Delta\beta / \Delta\phi)_{Max.}$	.3 - .5	.4
Maximum Sideslip Angle	20°	Variable

Table 3.3 (refer to Fig. 3.3)

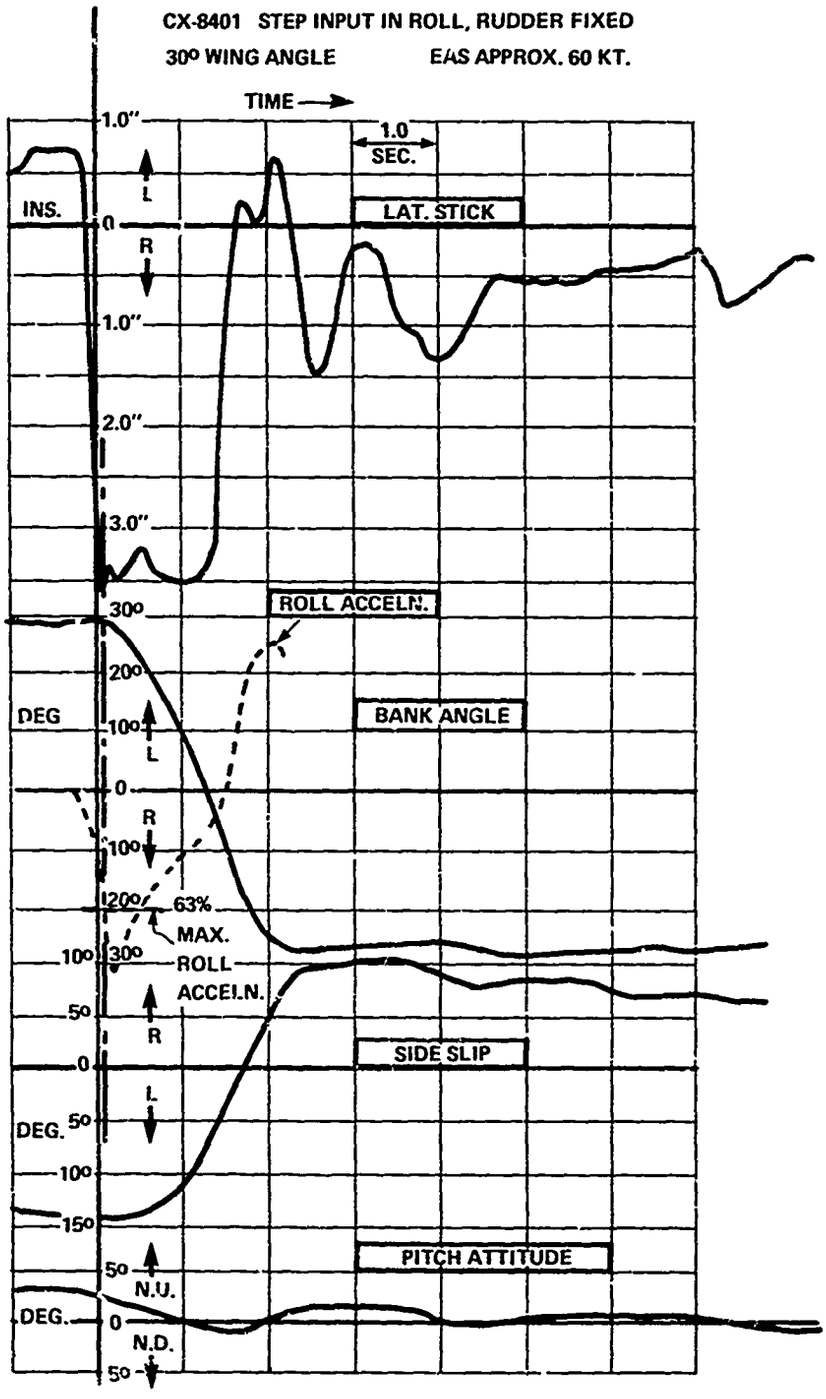


FIGURE 3.3

bank angle is indicated in the lateral stick trace. This is a result of the inadequate performance of the present flap/aileron circuit as discussed earlier. It will be noted that the sideslip angle follows the bank angle with about a $\frac{1}{2}$ second lag. A maximum of 10 degrees right sideslip is developed during the maneuver and the pitch attitude varies from about 3° nose-up to 1° nose-down. (The roll acceleration indicated in the figure was obtained from a wing tip accelerometer; the scale was omitted since it does not show angular acceleration directly.) In addition to the parameters shown in the figure, the test records show the following:

- A small, but detectable adverse yaw cross-coupling (less than 0.1 rad/sec^2) resulted from the lateral stick application.
- A forward longitudinal stick movement of $\frac{1}{2}$ inch accompanied the lateral stick application and resulted in an incremental normal load factor drop of 0.1 g.
- Throughout the maneuver, the total longitudinal stick movement was less than $\frac{3}{4}$ inches and the normal acceleration varied from 1.0 g to 1.2 g.
- Following stabilization of the right bank angle, the normal load factor varied between 1.0 g and 1.1 g.

The author confesses not to understand these Criteria as related to cross coupling about all axes following abrupt roll control inputs, as will be discussed later, and is thus unable to state whether or not the CL-84 meets the Criteria as evidenced by the above described test or any other test. However, it is clear from the CL-84 test data that roll control applications as such produce essentially roll moments with small or negligible effects in and along the other aircraft axes.

3.6 Roll Angular Damping

Roll Angular Velocity Damping				
Parameter	AGARD Criteria Minimum Levels		CL-84-1	
	Hover	STOL	Hover	STOL
Angular Velocity Damping, 1/Sec.	-2 to -4	-.5 to -3	-3.5	-3.3 to -6

Table 3.4

The present deficiency in the flap/aileron control circuit prevents assessment of the number of control reversals to stabilize for the CL-84-1. However, the CL-84 prototype met these criteria.

3.7 Roll Control System Time Lags

Roll Control Lags		
	AGARD Criteria	CL-84-1
Time from Control Input to 63% of Peak Angular Acceleration, Sec.	.2	.15

Table 3.5 (refer to Fig. 3.3)

Figure 3.3 shows that the angular acceleration is in the right direction within less than 0.1 second. For the ramp-type input of 0.2 second duration, 63 percent of the acceleration is reached at the same time as maximum control deflection, i.e. the lag to a zero-time input is 0.1 to 0.15 seconds and well within the limits of the Criteria.

3.8 Peak Roll Control Forces

The CL-84 meets these Criteria for both normal operation and single hydraulic failure throughout the V/STOL regime.

3.9 Spiral Stability

The aircraft is spirally stable in the classical sense throughout the V/STOL regime. However, in and near hover, an unstable lateral oscillatory mode is present, mainly as a result of the strong lateral speed stability (dihedral effect) of the aircraft. With the present normal value of roll damping, the period is about 12 seconds, and the time to double amplitude is about 30 seconds in the medium amplitude range.

3.10 Dihedral Effect

As indicated above, the CL-84 dihedral effect is more positive than desirable near hover. The dihedral remains positive throughout the V/STOL regime. In the speed range from 40 knots to 60 knots, 40-50 percent of full lateral stick is required in steady sideslips with maximum rudder pedal deflection. This corresponds to a force of about 5 lb. and is well within the Criteria.

3.12 Yaw Control Power

Yaw Control Power Characteristics				
	AGARD Criteria		CL-84-1	
	Hover	STOL	Hover	STOL
Time for 15° Heading Change - seconds	1.0 - 2.5	2.0	1.5	Variable, ≤ 1.5
Yaw Angular Acceleration Rad./Sec.^{2}	.35 - .8		.4	Variable, ≥ .4

Table 3.6

It will be noted that the aircraft yaw control power is marginal in terms of yaw angular acceleration, but meets the heading change criteria in hover. The yaw angular acceleration available increases with speed and is about 0.5 rad./sec.^{2} at 40 knots airspeed.

3.13 Yaw Control Sensitivity

Yaw Control Sensitivity Characteristics				
	AGARD Criteria		CL-84-1	
	Hover	STOL	Hover	STOL
Yaw Angular Acceleration per unit control deflection, Rad./Sec.^{2}/in.	.05 - .2	.05 - .10	.164	Variable .164

Table 3.7

The control sensitivity is essentially linear with control deflection in hover and at low wing tilt angles. For speeds from 30 knots to 60 knots, the sensitivity reduces by 10 percent to 20 percent for large control demands due to the reduction in effectiveness at large deflections of the down-going flap/aileron. A larger reduction can occur if opposed lateral-directional control is demanded.

3.14 Control System Lag

The yaw response of the aircraft to a ramp input in yaw in hover is shown in Figure 3.8 . It will be seen that the yaw angular acceleration is in the right direction within less than 0.1 second following the initiation of the control input and that 63 percent of the maximum acceleration is reached almost at the same time as the completion of the control input, i.e. in less than $\frac{1}{4}$ second. The equivalent time for a true step input would be about 0.15 seconds, which is well within the 0.3 seconds of the Criterion.

3.15 Peak Yaw Control Forces

With the present feel forces in the aircraft, the maximum pedal force falls within the Criterion for hover, but is appreciably less than that for STOL operation.

3.16 Cross Coupling

The cross-coupling effects in hover are based on maximum yaw control input turns. For STOL operation, the cross-coupling has been based on results from sideslip reversals, using full yaw control, as the aircraft passes through zero sideslip. The effect of yaw control applications on normal load factor is small and is not readily obtained from existing CL-84 data.

Yaw Cross-Coupling Characteristics			
	AGARD Criteria		CL-84-1
Parameter	Hover	STOL	Hover and STOL
Apparent Dihedral Rolling Moment Variation with Yaw Rate	Positive, but not more than 50% of roll control to trim for $\delta_{r_{max}}$		Positive 10-15% for $\delta_{r_{max}}$
Response about Pitch Axis	Pitch angle change less than 2°	Not objectionable pitch down with increase in sideslip	Negligible

Table 3.8

YAW RATES IN HOVER
CX-8401 FLT. 63 PR 998 → 1008
SAS ON A/C WEIGHT 11660 LB
A/C CG 36.7%

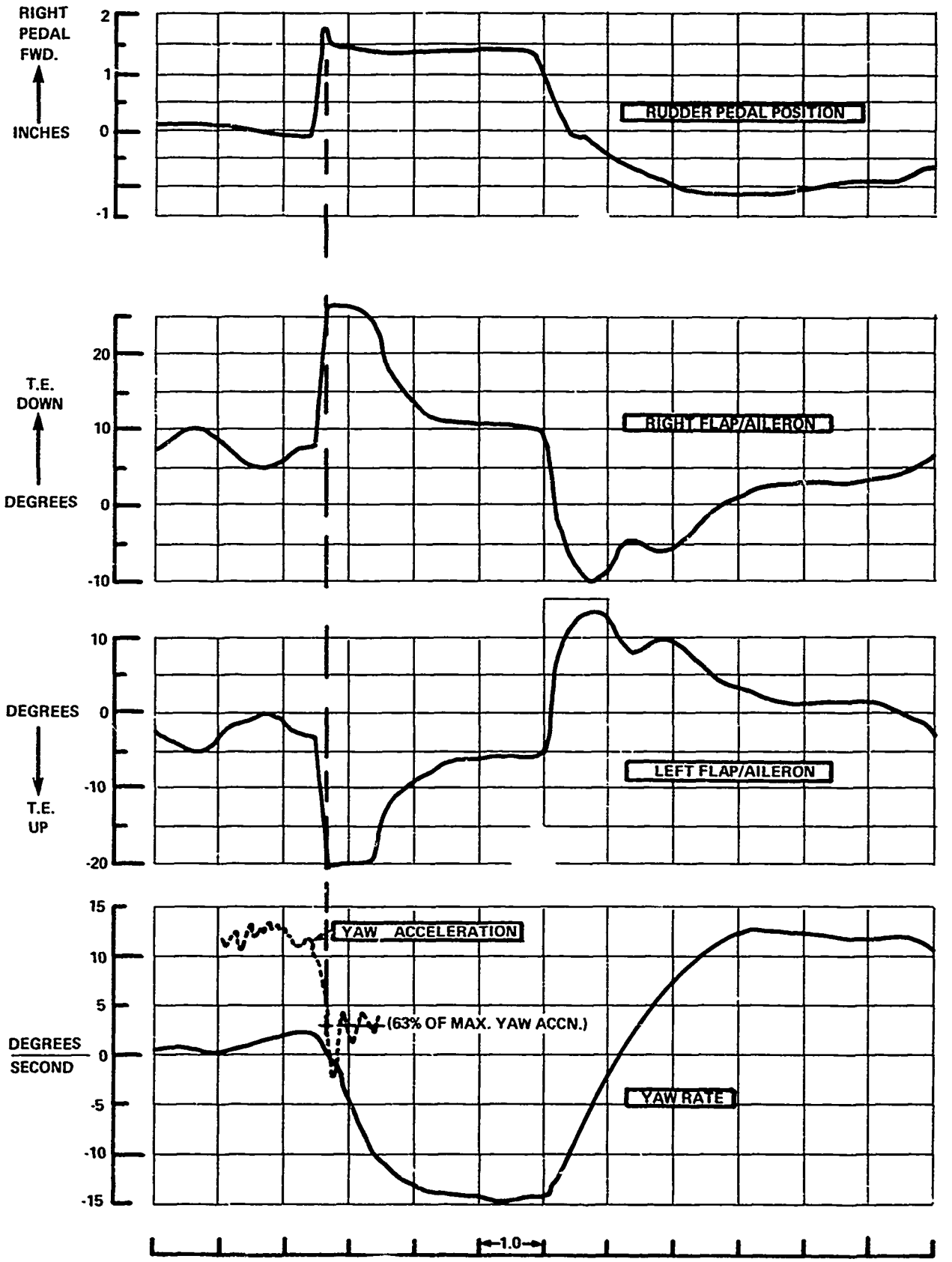


FIGURE 3.8

3.17 Directional Characteristics in Steady Sideslips

The aircraft meets these Criteria throughout the V/STOL flight regime.

3.18 Side Force Characteristics in Steady Sideslips

The side force due to sideslip is larger than desirable for the CL-84 and makes the aircraft rather gust sensitive in high speed flight. In STOL operation, the sideslip-to-bank angle ratio in constant heading sideslips is about 3 at 40 knots and about 2/3 at 100 knots.

3.19 Lateral-Directional Dynamic Stability

The roll-yaw oscillatory characteristics of the CL-84 are well damped in the STOL regime. At 60 knots, the frequency of the damped oscillation is approximately 2 rad./sec. and the product of the undamped natural frequency (ω_n) and the damping factor (ζ) is about 1.8. Referring to Figure 3.1 of Reference 4, it will be noted that this point falls outside the figure (above and to the left), but well within a natural extrapolation of the normal flight limit for satisfactory operation.

The unstable lateral oscillation in hover described in para. 3.9 does result in yaw excursions due to the effect of the directional stability of the aircraft in lateral translations. However, the yaw degree of freedom is not required to sustain this oscillation, and it appears inappropriate to refer to it as a roll-yaw oscillation.

Section 4 HOVERING AND VERTICAL FLIGHT PATH CHARACTERISTICS

4.2 Ground Effect

The ground effect characteristics of the CL-84 are favourable to performance from hover to about 15 knots airspeed and slightly unfavourable in the STOL regime. Recirculation makes the aircraft skittish in hover in close proximity to the ground, but no upset disturbances of appreciable magnitude about any axis are actually experienced. The recirculation disturbances reduce with decreasing wing tilt and increasing speeds and are not evident at speeds above 30 knots. In STOL operation, a small loss of lift, an appreciable reduction in drag and a nose-down pitch trim change is evident when entering ground effect. With one exception, significant difficulties due to operation in proximity of the ground have not been experienced in any part of the V/STOL flight regime, either in normal operation or in operation with simulated S.A.S. or hydraulic system failures. The exception refers to rapid deceleration to hover at low heights above ground (10 to 20 feet); when the aircraft can experience loss of lift in catching up with its own recirculation under certain wind conditions. Such operation is generally avoided unless a larger-than-normal thrust margin is available.

4.3 Vertical Flight Path Control

Vertical Flight Path Control in STOL				
Item	Mode	Parameter	AGARD Requirement For Satisfactory Operation	CL-84-1
Control Power	A	Incremental "g"	± 0.1 g	+ 0.3 g *
	B	Incremental "g"	± 0.1 g	Negative increment limited by buffet boundary
	C	Steady State Rate of Climb	6° or 600 fpm	1600 fpm *
	All	Incremental Descent Angle	2° greater than F/P angle	See buffet boundary curves
Response Time	A	Aircraft Response	0.5 sec	0.3 sec
	B	Aircraft Response	1.5 sec	
	C	Aircraft Response	2.0 sec	Not determined
Cross Coupling	All	Pitching Moment	Not objectionable	Nose up with ‡ increased power

Table 4.1

* Measured on approach (30° wing tilt, approx. 60 Kt. I.A.S.) at Maximum VTOL Weight ($T/W_{HOV} \simeq 1.05$). Rate of Climb available at STOL weight should exceed 1000 f.p.m.

‡ Typically, 1" forward stick is required on a full power overshoot from an approach with 30° wing tilt.

4.4 Hovering Precision

The CL-84 has demonstrated adequate hovering precision for rescue work. It is believed that the precision requirements of the Criteria cannot be met by any existing VTOL vehicle under moderately adverse wind conditions unless a fully automated control system is employed.

4.5 Vertical Thrust Margins

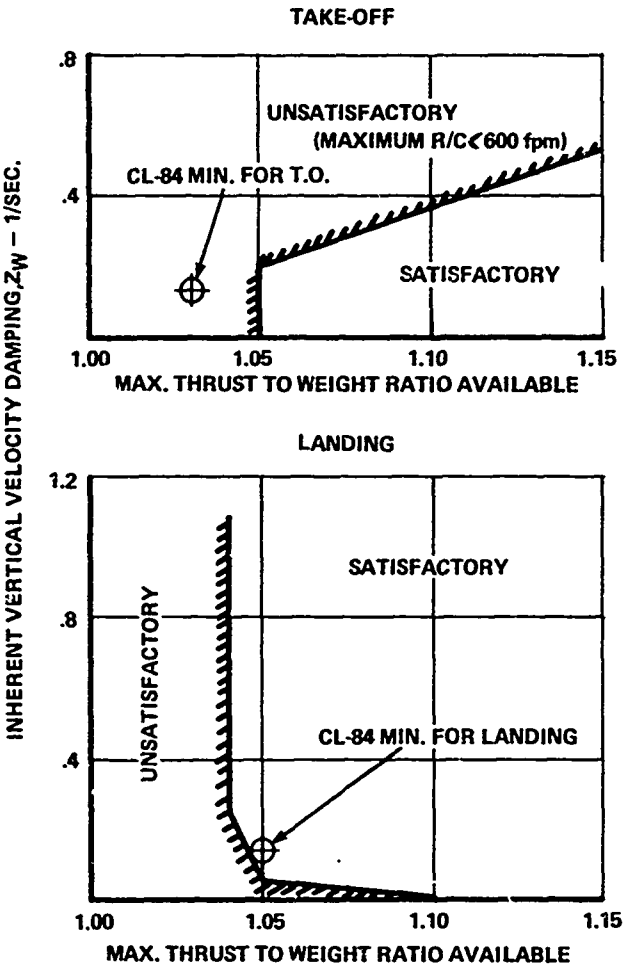


FIGURE 4.1 VERTICAL HEIGHT CONTROL CHARACTERISTICS

The minimum thrust margins used for normal operation of the CL-84 are shown in Figure 4.1. It is noted that the margin used for take-off is less than that called for by the Criteria. The aircraft has performed vertical take-offs and landings with no margins available for hover out of ground effect.

4.6 Vertical Velocity and Thrust Response

Vertical Velocity and Thrust Response Characteristics			
Parameter	AGARD Criteria		CL-84-1
	Minimum	Maximum	
Height control sensitivity "g"/in	.1	.4	.25
Vertical velocity response R/C (after 1 sec), fpm	150	775	450
Thrust response, first order time constant, sec.	Not greater than .5 sec.		.15

Table 4.2

The values for the CL-84 would appear to be optimum relative to the Criteria for vertical velocity and thrust response.

Sections 5 and 6 TRANSITION AND MISCELLANEOUS CHARACTERISTICS

The Criteria of these Sections are mainly qualitative and no attempt has been made to compare the CL-84 characteristics paragraph by paragraph with these Criteria. Instead, a brief description of the general transition characteristics of the aircraft is given with particular emphasis on the few areas where more development is needed.

A typical accelerating transition is shown in Figure 3 . The particular time history shown was obtained from the CL-84 prototype in 1966, but this maneuver was satisfactorily performed early in the prototype flight test program so that not much improvement would be evident from present records. The maneuver is normally terminated at 15 degrees wing tilt where the large longitudinal acceleration is converted into a rate of climb and the landing gear is retracted. As can be seen from the time history, the cockpit control activity level is moderate and more than adequate control remains in all axes to cope with upsets or to terminate the maneuver at any point. On the Harper-Cooper handling qualities rating scale (Reference 6), the current rating (HQRS) is about 2 for this maneuver (See Reference 7).

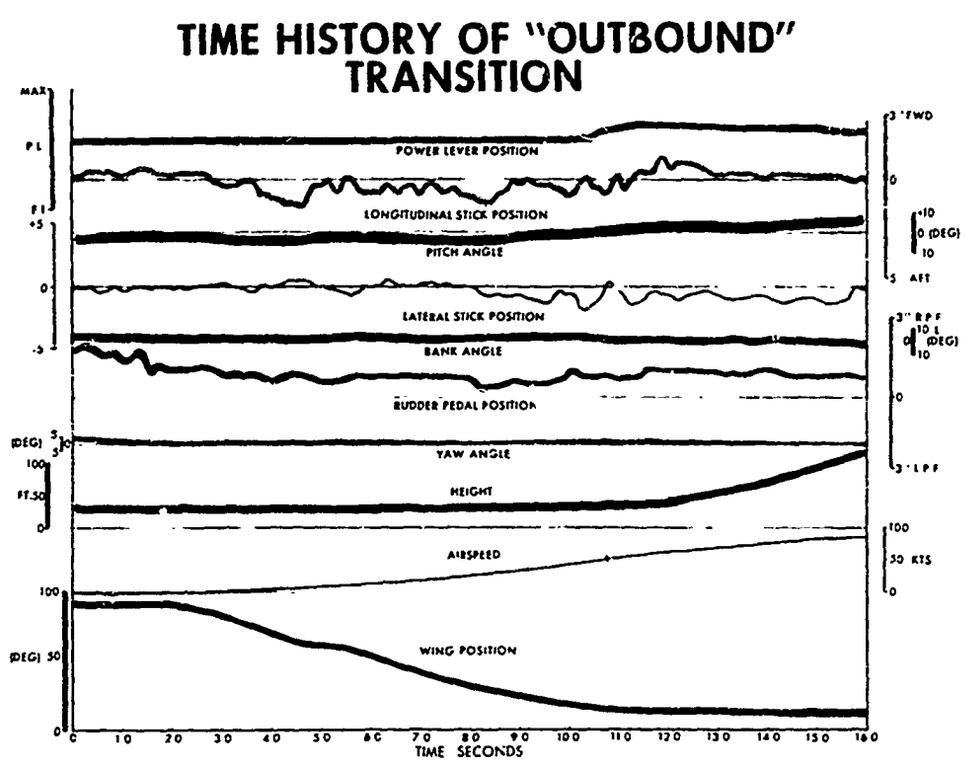


FIGURE 3

A decelerating transition time history is shown in Figure 4 . This data als s from the CL-84 prototype, but following some development of the thrust control sys The control activity levels indicate that this maneuver is not as readily performed the accelerating transition. This is primarily a result of operating "up the back end of the power required curve". In order to decelerate, the wing tilt angle must be increased, and the thrust reduced to prevent "ballooning". As the speed reduces, the thrust-power required increases. Thus, the pilot must find the matching rates of wing tilt angle and power increases to perform a smooth, level deceleration. Obviously, this requires training and familiarity with the aircraft. While the improved thrust control system of the CL-84-1 aids in this regard, the maneuver is not straight-forward and programming of power with wing tilt angle may prove necessary to make this maneuver simple and repeatable enough for operational use under I.F.R. conditions. The present HQRS rating is about 3.

Based on pr type experience, the approach to maximum lift during rapid, decelerating transitions not accompanied by a buffet warning. However, a strong nose-down pitch trim change is evident as maximum lift for a given power is approached, and this may prove adequate as a warning in the future. Maximum lift is not reached before the level deceleration rate exceeds 0.3 to 0.4 g's, except near hover.

The decelerating, descending transition is perhaps the most difficult transition maneuver to perform accurately with the CL-84. While a flight path accelerometer instrument has been devised for the aircraft to aid the pilot in determining his limiting combinations of deceleration rate and descent angle, the maneuver requires considerable coordination of the figure controls. This difficulty results from operation on the back side

of the power required curve combined with a low rate of lift increase with angle of attack, corresponding to a low height rate damping, a rapid variation of drag with angle of attack, and a low value of angle of attack pitch stability. Increased pitch attitude stabilization does not appear to be a solution to this problem since the angle of attack changes rapidly with rate of climb or descent without any change in pitch attitude. In the author's opinion, this handling qualities problem area is the only significant one which definitely requires improvement in order to make the CL-84 an operational I.F.R. V/STOL aircraft. It is perhaps a tribute to the CL-84 control system that the handling qualities rating for this maneuver currently rates no worse than 4.

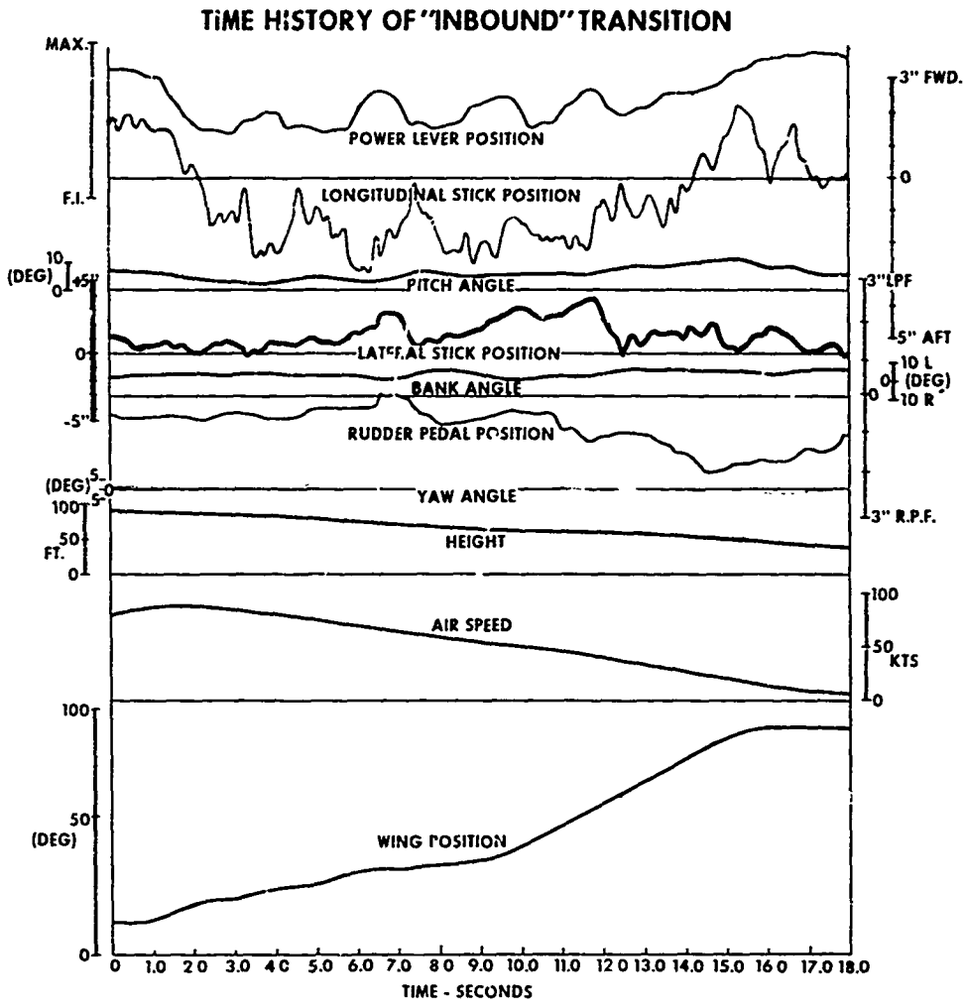


FIGURE 4

In descending flight in the STOL regime, the descent angles and rates are limited by a light buffet. Unfortunately, the CL-84-1 exhibits a much earlier onset of buffet than that for the CL-84 prototype. The reasons for this deterioration are not known at present, but clues may be found in the fact that the CL-84-1 operates at higher weights with an appreciably farther aft center of gravity than did the prototype. Figure 5 shows a comparison of the buffet boundaries for the two aircraft. It is evident from the values of the rates of descent for the two aircraft that the CL-84-1 must be improved at least to the level of the prototype to be operationally useful. The curve for the prototype represents a minimum descent angle of 12 degrees at 30 degrees wing tilt, corresponding to an approach speed of about 50 knots. The possibilities for improvements are indicated by the maximum penetration boundary achieved for both aircraft without loss of control.

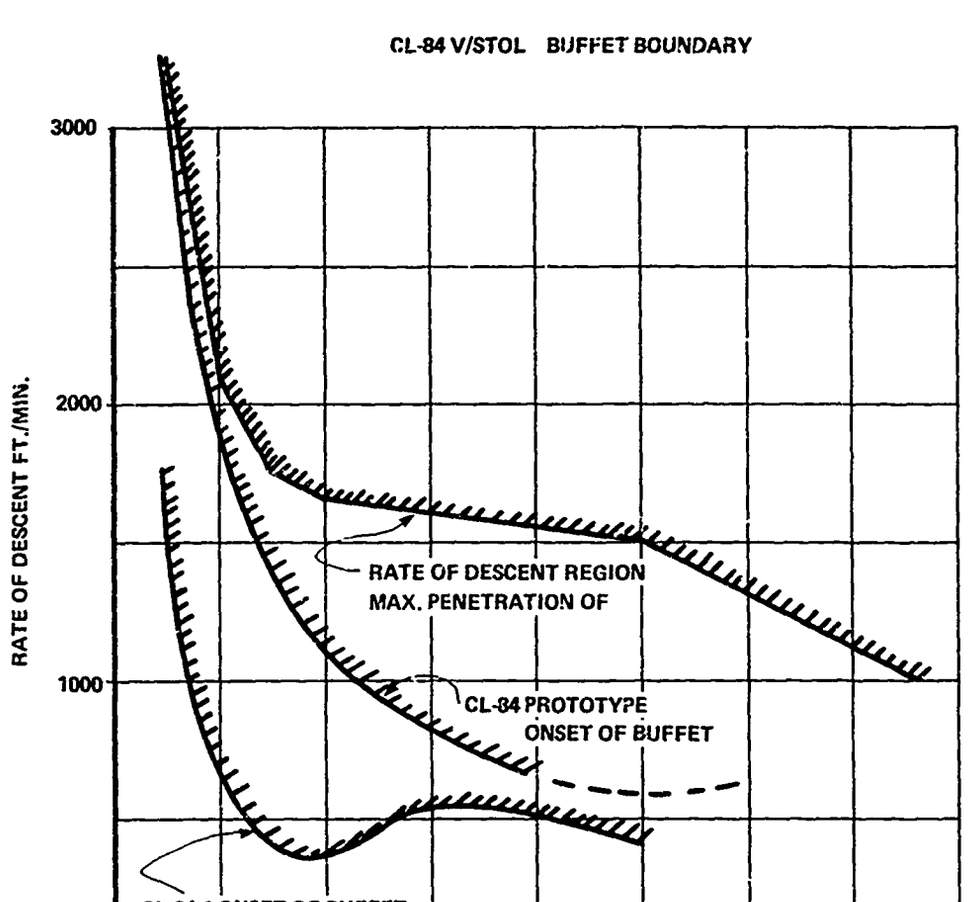


FIGURE 5 BUFFET BOUNDARY TRANSITION MODE

CRITIQUE AND CONCLUSIONS

GENERAL

In philosophizing on how to conclude his dissertation on the application of the V/STOL handling qualities Criteria to the CL-84 aircraft, the author realized that he was faced with the unenviable task of criticizing (a) the CL-84 characteristics for failing to meet all the Criteria; (b) the Criteria for not agreeing with those characteristics of the CL-84 already found to be satisfactory or (c) both the CL-84 characteristics and the Criteria. Having completed the comparison, such as it is, he decided that the honest task was option (c). This choice was made easier by the fact that the CL-84 characteristics are, in general, in good agreement with the Criteria.

In the assessment made in this part of the presentation, the author has attempted to determine:

(i) whether the CL-84 needs improvement, or whether the Criteria are too demanding or not applicable in those cases where the CL-84 does not meet the Criteria,

and (ii) where the Criteria appear to be too lenient in light of the CL-84 flight test experience.

In addition, a few suggestions are made where it is felt that the Criteria could be clarified or improved. In the many cases where no mention is made of a particular set of Criteria, the author is either in agreement with the Criteria, or considers himself not knowledgeable enough to comment.

CONTROL SYSTEM

The high breakout force of the CL-84-1 power lever has received unfavourable pilot comments and requires reduction. The Criterion is judged appropriate.

Both the roll and yaw control force gradients of the CL-84 have been described as too high in hover. With respect to the roll gradient, this is in agreement with the Criteria. However, the Criteria allows twice the CL-84 yaw gradient in hover and seven times this gradient for STOL operation. It is certain that these upper limits would be unacceptable for the CL-84. The present CL-84 yaw gradient has been judged satisfactory for STOL operation, but is only one-half the minimum of the Criteria. It is recommended that the minimum be lowered. Similarly, the optimum control force harmony ratio for yaw-to-roll in the Criteria appears to be too high based on the CL-84 experience.

LONGITUDINAL STABILITY AND CONTROL

The minimum levels of pitch control power and damping for satisfactory operation given by the Criteria are certainly too low for the CL-84 in and near hover. On the other hand, these levels are probably quite satisfactory for large V/STOL aircraft or for aircraft with high wing and disk loadings, such as jet lift aircraft. It is appreciated that it is virtually impossible to specify general requirements that will prove satisfactory for all concepts and sizes of aircraft. The discussion of the Criteria in AGARD 577 makes this point, but it is questioned if the point is emphasized strongly enough.

The CL-84 does not meet the Criteria for stability with respect to speed. While the aircraft could be modified to meet these Criteria by increasing the S.A.S. attitude stabilization gain, it is doubtful if this would enhance the handling qualities of the aircraft significantly. The main problem with the aircraft in decelerating, descending flight in the speed range from 30 knots to 60 knots is a speed-vertical velocity problem rather than a speed-attitude problem, as discussed previously. It is proposed that mild speed divergence (10 to 15 seconds to double amplitude) be accepted.

Since many V/STOL aircraft are capable of gross maneuvers at low speed far in excess of what may be needed for fulfilling their mission requirements, the Criteria for longitudinal control characteristics in maneuvering flight should be restrained to a normal maneuver envelope as required by the mission. For example, this would make the CL-84 acceptable as a utility transport, but not as a ground support aircraft with the present S.A.S. saturation limits. In addition, the criteria should be restricted to constant power and constant air speed since it will prove impracticable (and probably unimportant) to demonstrate compliance with the Criteria for all conceivable rates of change of power, airspeed and normal load factor.

LATERAL STABILITY AND CONTROL

The cross-coupling Criteria for abrupt-roll control inputs are not understood. For any finite bank angle in uncoordinated roll maneuvers, the sideslip developed depends on the normal load factor history as well as on coupling due to the application of roll control and the roll rate. If the initial condition is 1 g level flight, and the longitudinal stick is fixed during the roll control application, the sideslip developed depends on the bank angle reached even if no coupling exist with roll control and rate. It would appear that the Criteria may be meaningful if the ratio of the rate of change of sideslip angle with time to the roll rate is obtained as the aircraft passes through zero bank angle in a full roll control reversal. This is not the way the appropriate test is des-

cribed in the Appendix of AGARD 577. It is suggested that this Criteria and the appropriate test be clarified in the report.

The yaw control power of the CL-84 is close to the lower limit of the Criteria. This is in agreement with pilot opinion which classifies the hover yaw control power as marginal.

The peak yaw control force limits for STOL operation are considered too high from the CL-84 experience. This is perhaps because the control power is relatively low and consequently large pedal movements are required.

While the author believes that he understands the yaw cross-coupling Criteria better than the roll ones, additional clarification of the Criteria and the appropriate test would be helpful.

HOVERING AND VERTICAL FLIGHT PATH CHARACTERISTICS

The hovering precision Criteria are considered unrealistically demanding for moderately adverse wind conditions such as 15 knots gusting to 25 knots.

While the CL-84 operates successfully in take-off with a vertical thrust margin less than that of the Criteria, the values in the Criteria are considered reasonable.

The first order time constant limit for acceptable thrust response should probably be made a function of the natural height rate damping of the vehicle. The value of 0.5 seconds may be satisfactory for a lightly loaded helicopter, but would prove disastrous for the CL-84.

TRANSITION AND MISCELLANEOUS CHARACTERISTICS

The mainly qualitative Criteria given in these sections appear both appropriate and comprehensive. While the CL-84 may not meet all the Criteria at the present time, particularly as a result of the restrictive buffet boundary of the aircraft, it is difficult to take issue with the principles of any of these Criteria or to argue that they need not be met by an operational aircraft.

CONCLUDING REMARKS

In reviewing the AGARD V/STOL Handling Qualities Criteria and their applicability to the CL-84 aircraft, the author has been impressed with both the style and thoroughness of the Criteria. In the author's opinion, the Criteria represent about the right blend of quantitative and qualitative requirements to make them useful for both design and evaluation of most V/STOL concepts. It has been accepted by the authors of the Criteria that it is impossible at this time to fully quantify all the V/STOL handling qualities requirements and expect them to be applicable to the large variety of V/STOL vehicles under consideration.

In comparing the CL-84 characteristics with the Criteria, it is evident that the Criteria are appropriate for this type of V/STOL aircraft. While a few of the numbers in the Criteria do not appear to be appropriate in the light of the CL-84 flight test experience, there is no doubt that in most cases where the CL-84 does not meet the Criteria, the aircraft would exhibit better V/STOL handling qualities if it did.

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LEAD DISCUSSION

by

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Recommendations, Criteria, proposed Requirements on the Handling Qualities of V/STOL Aircraft have been given since a number of years and many problems have been focused.
Flight Tests of V/STOL Aircraft, ground simulations and in-flight simulations through hovering rigs and variable stability helicopters have given a basic contribution to the formulation of the most recent criteria, like those of the AGARD Rep. No. 577.
In this respect the CL-84 was particularly valuable, taking into account that several pilots were able to fly it and to try different control modes.
Nevertheless many aspects of the V/STOL Handling have not been yet clarified or have not achieved a defined numerical evaluation.

Surely further flight tests experience and the continuous comparison of the existing aircraft characteristics, like those of the CL-84, provided with variable stability and different control system modes, with the formulated handling criteria will allow to go more in depth in the knowledge of the criteria still uncertain.
Moreover the use of the aircraft in operational trials will allow to enlight some aspects of the handling criteria related to special missions which now are not supported by any evidence.

To my opinion, in order to be effective, the flight tests or simulations should be oriented towards the solution of those V/STOL handling qualities problems still open or awaiting further refinements; therefore I would suggest guided researches, not a random collection of tests results and pilot's opinions.

A possible list of V/STOL handling problems worthwhile to be discussed and, if necessary, investigated is here commented.

- The aircraft response and maneuver requirements have been defined in different ways, like the maximum angular acceleration available from control power and the angular damping, the attitude change within one second of control application or the time to get an attitude change of 30°.
  A better definition of what is the complete aircraft response to control inputs the pilot aims, will be much more helpful in designing for instance the Command Stability Augmentation Systems.
  By acting on the controls, pilots are looking to attitude changes, angular rates, translational speeds, load factor variations behaving within the limits of satisfactory time histories whose definition could represent a synthesis of the handling problems.

- The allowed or desired level of coupling of one and another aircraft response should be clarified, as in the case, for instance, of a STOL aircraft where a throttle displacement, affecting the thrust, the lift and the pitch moment, requires not desired coordinated maneuvers of the other controls, whilst in the case of a STOL lateral control an advisable dynamic coordination between yaw rate and bank angle is still to be defined.
  The longitudinal control of a STOL aircraft in approach appears to be of great actuality and deserves extensive investigations covering also the techniques of thrust and aerodynamic vectoring together with problems of the speed stability and the flight path control.
  The CL-84 should have in this respect the provisions to carry out interesting research activity by flying with intermediate tilt wing.

- From the past flight experience a conflict appears between the aircraft maneuvering performance and its stability or damping. This argument, for instance, has been used several times against, or not, the attitude control system.
  An optimum compromise between the two requirements could be realized in a maneuver demand system by using non-linear techniques, like saturation of the control in large maneuvers or non-linear wash-out related to the maneuver amplitude.
  The non-linear technique would allow to design aircraft with reduced control power available for maneuvers and therefore with reduced bleed from the lift power.
  I wonder if the CL-84 experience in this area could be enlarged or considered exaustive, with the aim not much to identify the possible non-linear control systems but to define their limits, such as allowed overshoots or required responses according to the maneuver amplitude.

- The adoption of complex Command and Stability Augmentation Systems, changing remarkably the static and dynamic response characteristics of the aircraft, raises the problem of the safety in case of failures.
  In these cases there is not only a problem of defining the allowable transient amplitudes due to possible runaways, but the capability of a pilot to change suddenly his compensation technique in controlling the aircraft itself.
  Having for instance a triplex control system with manual reversion it could be better for a pilot

to revert deliberately to manual control after the first failure not affecting CSAS characteristics, to avoid the risk of a second unpredictable critical failure changing the aircraft response and which he could not be able to cope with.

- The design of the aircraft control power is defined by the needs of trimming and maneuvering the aircraft as well as to cope with the external disturbances.
  What is not yet clear is how the control power required to maneuver can be matched to that required to control the disturbances.
  By assuming, for instance, that no correlation exists between maneuver and gust, the total required control power could be computed by the square root of the sum of the squares of the two control powers.
  A more valid criterion could result by an ad-hoc programme of research.

- A number of V/STOL aircraft belonging to different classes have flown till now and their operational experience should give an indication of different handling criteria according to different aircraft classes or tasks or missions.
  In this connection the new US Military V/STOL Requirements MIL-F-83300, presented by Mr. Westbrook at this meeting, could be a good basis to correlate the different flying qualities requirements to the different aircraft classes and flight phase categories.

- A further aspect of Handling Qualities, I like to draw the attention, is the definition of advisable margins which the aircraft must hold during the partially powered flight regimes. In fact on one side the maximum usable lift coefficient, limited by stall, pitch or roll moment divergence, buffet level is a function of the power setting, the angle of attak and the aircraft configuration, while on the other side the disturbances like an engine failure or a gust excitation can result in large sideslip, airspeed and angle of attack changes owing to the slow flight speed.
  A consequence it is not easy to coordinate so many variables in a sensible way.

- Anyhow, to conclude, I fully realise that if it is easy to raise controversial problems on V/STOL handling, the aircraft designer will have to make guesses on their solution for long time before sound and complete handling criteria are derived from flight and simulation experience.

V/STOL HANDLING QUALITIES CRITERIA COMPARED WITH FLIGHT TEST RESULTS OF THE V/STOL-SUPERSONIC-FIGHTER VJ 101C AND THE V/STOL-TRANSPORT-AIRCRAFT DO 31E

by

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SUMMARY

After a short description of the two aircrafts, their cockpit controls and their Stability Augmentation Systems the main features of the take-off and landing procedures are presented. The Handling Qualities of the two aircrafts in hover and transition flights are compared with the recommendations of the AGARD-Rep. 577. Furthermore the influence of the Stabilisation System and its characteristics on the used control power and the effects of the jet induced downwash and of the hot gas recirculation are shown. Finally some comments to the new Recommendations of the AGARD-Rep. 577 are given on the background of the flight experience with the VJ 101 and the Do 31.

1. DESCRIPTION OF THE AIRCRAFTS

1.1 General

The VJ 101C is a VTOL-Supersonic fighter aircraft with a maximum VTOL-Take-off weight of 17.600 lbs (Fig. 1). The aircraft has four cruise engines RB 145 R with afterburners which are installed in movable wing tip pods, two in each pod, and two lift engines RB 145 which are mounted in the fuselage behind the Cockpit. Between 1962 and 1971 with two prototypes a total of 457 tests were performed. These tests include 15 Take-off transitions, 32 Landing transitions, 50 Hover flights and various partial transitions aimed at optimising the Handling Qualities in partially converted configuration.

The Do 31E is a VTOL-Transport Aircraft with a maximum VTOL-Take-off weight of 45.000 lbs (Fig. 2). The aircraft is powered by two Bristol Pegasus 5-2 lift and cruise engines with swivelling nozzles and 8 Rolls Royce RB - 162 Lift engines, which are installed in wing tip pods, four engines on each side. In addition to the flight tests with the two hovering rigs the VTOL-prototyp Do 31E3 has performed about 150 flights with 60 Vertical take-offs, 85 Vertical landings and nearly 160 landing transitions.

1.2 Cockpit Controls

Both aircrafts use the main control levers in conventional as well as in hovering and transition flights. Fig. 3 shows the cockpit view of the VJ 101. The centre stick is used for roll and pitch by means of thrust modulations during hovering and transition, ailerons and elevator during aerodynamic flight, pedals for yaw by differentially swivelling the cruise engines during hover and transition and rudder for aerodynamic flight and a collective thrust lever for total thrust control.

Two switches on the collective thrust lever are for selection of cruise engine rotating direction up/down and the speed of rotation zero, slow, medium and fast.

All engines are started by means of six individual gas levers bringing each engine up to idle. From this position all engines are commanded by means of the collective thrust lever. Also reheat is selected by cocking the collective thrust lever. The lift engines mounted in the fuselage directly behind the cockpit are scheduled by the cruise engine rotation angle δ so that they come up from idle to the thrust commanded by the collective thrust lever as the cruise engines are swivelled. The control law of the lift engine thrust is therefore

$$T_{Lift} = T_{Cruise} \sin \delta$$

Fig. 4 shows the cockpit view of the Do 31. A center stick, - no wheel for safety reasons in an ejection case - is used to control the pitch axis by elevator and a bleed air thrust nozzle at the rear part of the fuselage, and the roll axis by ailerons and thrust modulation of the lift engines. The yaw axis is controlled by pedals which actuate the rudder and the swivelling nozzles of the lift engines. In aerodynamic flight only the control surfaces are actuated and the VTOL-control devices are switched off. In VTOL-flight the aerodynamic control surfaces remain connected to the VTOL control devices.

In addition to these conventional control levers the pilot uses cruise engine throttles, a cruise engine nozzle control lever as well as a single lever to start the eight lift engines and to control their thrust level.

1.3 Control System

The primary flight control system of the VJ 101 is a Commanded and Stability AugmentationSystem (CSAS) in Fly-By-Wire technique. The control laws are:

- hovering: attitude control in roll and pitch, rate control in yaw
- transition: blending from attitude to rate control scheduled with cruise engine angle of rotation δ
- aerodynamic flight: normal damper type system

The primary flight control system of the Do 31 is a mechanical System with an Stability Augmentation System (SAS) differentially linked which is switched off in the conventional flight. There is no blending during transition. The characteristics of the SAS are:

- attitude control about roll and pitch axis with an additional damper in the roll axis
- rate control about yaw axis
- pitch attitude preselect equipement
- roll damper in conventional flight.

The pitch attitude preselect equipement gives to the pilot the possibility to preselect a certain pitch angle by a switch and engage this pitch attitude by pushing a button at the control stick.

The main features of the two control systems which influence the Handling Qualities are given in Table 1 in comparison with the recommended values due to AGARD-Rep. 577.

	ROLL			PITCH			YAW		
	AGARD-Rep. 577	Do-31	VJ 101	AGARD-Rep. 577	Do 31	VJ 101	AGARD-Rep. 577	Do 31	VJ 101
VSTOL Breakout Force lbs	0,5 - 3,0	2,1	1,65	0,5 - 3,0	3,3	1,65	1,0 - 10,0	19,3	4,4
Control Force Gradients lb/in	0,5 - 1,5	2,7	2,7	1,0 - 3,0	3,6	3,0	2,5 - 10,0	12,9	30,3
Peak Control Force lbs	15	12,2	16,5	push 15 pull 25	20,0 23,0	20,0 24,0	15 - 50	46	130
Max. Control Travel in	3,0 - 6,5	±4,65	± 5,5	4,0 - 6,5	±5,2	±6,0	2,5 - 4,5	±2,05	±3,15
Attitude change per unit control deflection deg/in	3,0 - 5,0	7,0 non-linear	3,6	3,0 - 5,0	6,0 non-linear	3,16	-	-	-
Max. Attitude change at max. control deflection deg	-	± 18	±20	-	± 22	± 19	-	-	-
Time to 90 % of the deranded attitude change, T_{90} sec	1 - 2	2 - 3	2,0 1,8=1)	1 - 2	2 - 3	1,8 1,5=1)	-	-	-
Natural frequency of the Control Systen rad/sec	-	2,5	3,0	-	2,5	3,0	-	-	-
Damping ratio	-	1,0	0,5 0,75=1)	-	1,0	0,8 0,9=1)	-	-	-
Rate change per unit control deflection deg/sec/in	-	-	-	-	-	-	-	8,5 non-linear	2,2
Max. Rate change at max. control deflection deg/sec	-	-	-	-	-	-	-	14,5	7,0
Time for 15° Heading change sec	-	-	-	-	-	-	1,0 - 2,5	1,1	2,2
Time constant sec	-	-	-	-	-	-	-	1,3	2,5

=1) with afterburners

Table 1 Characteristic Datas of the Control and Stabilisation Systems

Most of the values correspond to the Recommendations. The main deviations are the following:

- Both aircrafts have a higher control force gradient, perhaps due to the fact that for an attitude stabilized vehicle otherwise the pilot could disturb the SAS too easily.
- The control forces of the VJ 101 in Yaw are higher and the dynamic behavior is

slowlier, due to dynamic structure problems of the heavy swivelling engine pods.

- The dynamic attitude response of the Do 31, described by the T_{90}, is less fast than recommended by AGARD Rep. 577 and realised at the VJ 101. This higher T_{90} corresponds to the heavier transport aircraft.

1.4 Take off and landing procedures

The Take-Off-Procedure is normally a compromise between several problems, which influence the Vertical Take-Off (VTO): hot gas recirculation, skidding of the aircraft on the ground, damage of runway surface by the jets, pilot workload and fuel consumption.

For the VJ 101 damage of the runway is the most important problem on the ground. Therefore the take-offs are performed in two manners:

- From deflectors. The aircraft is positioned over the deflectors, all engines are started, flaps selected for take-off (at the same time the engine inlets are automatically opened to low speed configuration), the cruise engines are swivelled into vertical, reheat selected and power advanced to full thrust. Full thrust can be selected since the CSAS has a so-called minus-control-capability. A priority control system reduces the total thrust only to the level which at each moment is necessary for the stabilisation of the aircraft.

- From normal runways it is not possible to take-off absolutely vertical, since the reheat would damage the runway surface; therefore a slightly different technique is used. Again all engines are started and the flaps are deflected for take-off. During the last part of engines rotation brakes are released and at an angle of 75° reheat is selected and power advanced rapidly. The aircraft does take off after about 3 - 4 meters from brake release.

For the Do 31 avoiding of hot gas recirculation is the most important problem at vertical take-offs. From many tests the following procedure was found as an optimum:

After starting the cruise engines the thrust is advanced to a medium level and the cruise engine nozzles are swivelled into the take-off position of 75 degrees. Then the lift engines are started to idling, the cruise engine power is advanced to take-off thrust and the aircraft finally is lifted off the ground by increasing the lift engine thrust to the take-off level. This whole procedure is done within 35 seconds, so that the pilot workload in this phase is high.

In comparison to the VTO the following transition to the aerodynamic flight is easy to control for both aircrafts. Fig. 5a shows in principle the procedure for the VJ 101. The pilot selects the swivelling direction and chooses a tilt speed of the cruise engine pods so that no height is lost. At the same time gear up is initiated. After being airborn (approx. 180 KIAS) the pilot shuts down the lift engines and closes the lift-engine-door. Flaps are retracted and then automatically the high speed intake configuration is selected.

Fig. 5b shows the procedure of the landing transition with the VJ 101. The lift-engine-doors are opened and the lift engines are started by windmilling. Flap selection again shifts the air intake into low speed configuration. The undercarriage is lowered, park brakes checked, reheat selected at very low thrust setting. By selection the "up"-direction for engine rotation the engines are slowly rotated into vertical to maintain a nearly constant sink rate of about 500 to 1000 ft/min. During the approach the pilot checks that he does not leave the two limits of his transition corridor (Fig.6).

As only straight-in transitions have been performed, the pilot did not maneuver in roll but only compensates side wind effects by small roll inputs. The forward velocity during the final part of the transition is commanded via pitch attitude, the direction by yaw and the sink rate by the thrust level.

Fig. 7 shows in principle the take-off and landing procedures of the Do 31. The flight path of the take-off transtion is mainly controlled by swiveling the nozzles of the cruise engines. If the pilot swivels the nozzles so fast that the aircraft just does not loose altitude, than the maximum acceleration occurs and the transition is finished in less than 20 seconds. Normally the pilots swivels slowlier to have higher flight path angles in the beginning of the transition. The average time for a take-off transition was 30 seconds.

The most effort of the Do 31 flight testing was spent upon the problems of the landing transition. It was very soon found out that from all possible aims of optimizing the landing transition the most important factor was to reduce the pilot workload. An optimizing of the fuel consumption by reducing the transition time is not possible without changing the actual control system by adding an automatic sinkrate system for instance.

Therefore the landing transition is a procedure, which can be done by the pilot with a reasonable effort of maniability. The first step is the start of the lift

engines during a nearly stationary horizontal flight. The descent begins at a certain point, for instance at the interception of the ILS-beam, by changing the pitch attitude, lift engine thrust and cruise engine nozzle position. This will lead to a decelerating descent along a straight flight path. Corrections, if necessary, are done by pitch attitude changing or lift engine thrust modulations. The flare and the final deceleration is done by enlarging the pitch angle and corresponding to that the lift engine thrust. The final descent to the vertical landing is controlled by the lift engine thrust. The thrust of the cruise engines is not changed during the whole maneuver. If the aircraft touches the ground the thrust of the lift engines and the cruise engine nozzle angle must be reduced at once to avoid recirculation problems. With this procedure the average time for a landing transition from the start of the lift engines till touch down was between 2 - 3 minutes.

Fig. 8 finally shows the differences between the used acceleration and deceleration values during typic l take-off and landing transitions of the Do 31 and the theoretically possible values. It can be seen, that for a take-off-transition these optimal values are nearly used during the whole transition whereas there is a big difference between possible and used deceleration for a typical landing transition. Furthermore it can be seen, that the recommended 0,5 g acceleration and deceleration values of the AGARD Rep. 577 is too high and was used neither for the Do 31 nor for the VJ 101 during landing transition.

2. HANDLING QUALITIES

2.1 Control Accelerations

Fig. 9 shows the envelope of used control accelerations during Hover and Transition flights for both aircrafts. The statistical evaluation showed no significant differences between the values of hover and transition, so this Fig. is valid for both flight phases, exept for the Do 31 in pitch, as in pitch large trimming moments occur during transition. This will be shown next. The figure shows the envelopes of the used control accelerations in percentage of the used test dates. For instance: 90 % of all ever used values of control acceleration about the roll axis are for the Do 31 between zero and 0.14 rad/sec^2 and for the VJ 101 between zero and 0.31 rad/sec^2.

The Fig. demonstrates also the influence of the size of the aircraft on the used control accelerations as the type of the SAS is the same for both aircrafts. Therefore from this Fig. it can be concluded that the lower limit of the recommended control accelerations of AGARD Rep. 577 corresponds good to larger aircrafts and the upper limit good to smaller aircrafts. The exeption is the yaw control power of the VJ 101, these values are smaller than expected due to dynamic structure problems of the heavy swivelling engine pods. Of course the maximum available control power about the different axis is much higher, due to the fact, that an engine failure has to be trimmed out. Table 2 shows these values for normal conditions in Hovering flight:

	ROLL $\dot{p}$ [rad/sec^2]	PITCH $\dot{q}$ [rad/sec^2]	YAW $\dot{r}$ [rad/sec^2]
DO 31 E	0.76	0.27	0.40
VJ - 101 C WITH VARIABLE ENGINE RPM	3.0	1.7	0.40
VJ - 101 C WITH CONSTANT ENGINE RPM	1.0	0.6	0.40

Table 2 Max. available control power

As mentioned above large trimming moments occur at transition flights with the Do 31 which consume a large amount of the available control power (Fig. 10). These large trimming moments are due to jet induced effects, as will be described next and due to the aerodynamic pitching moment depending on the actual angle of attack, the dynamic pressure and the center of gravity position. The Figure shows also the maximum amount of additional control moment which was used to control disturbances. It has to be said that the given datas describe the worst of all cases and that there was no difficulty due to this problem during the flight test period. The critical period is passed very fast and if the necessary trim moments would have been larger than the available control moment, the aircraft would have pitched up and enlarged the angle of attack. Due to this the aerodynamic pitching moment would have been reduced and the aircraft would have come to a new steady state.

2.2 Effects of the SAS on the used control accelerations

Fig. 11 gives an interesting result concerning the problem of the effects of autostabilization on the used control moments for maneuvering, which was found by chance during the flight tests of the Do 31. At this flight the pilot forgot to engage the SAS and did that only when more than half the transition was passed. It can be seen that by engaging the SAS the used control moments are reduced significantly.

Fig. 12 shows the influence of the SAS characteristics on the necessary thrust for control about the roll axis which was found by flight tests of the VJ 101. As the flight experience had shown that during actual transitioning and maneuvering towards the landing spot the pilot only very seldom uses the roll control it was tried to enlarge the T_{90}, time to reach 90 % of the commanded attitude, to save thrust. Test with tethered pitch and yaw axis showed that for step inputs and a T_{90} = 2 sec 5 % of the installed cruise engine thrust was needed. Using a T_{90} = 2,2 sec this value dropped to 3 %. Even with this higher value of T_{90} = 2,2 sec, the aircraft was as well handled by the pilots as with the T_{90} = 2 sec, but the take-off weight could be increased considerably. At the same time the sensitivity of the pilots to overshoots was reduced.

2.3 Dynamic Characteristics

Fig. 13 shows the well-known diagram of the control system characteristics, which are found from moving base simulation. From this results it was found that the system would have good dynamic characteristics if the natural frequency was about 5 rad/sec and the damping nearly aperiodic. From flight tests with the VJ 101 - and the results were quite similar for the Do 31 - it was found, that the natural frequency should be lower and the damping ratio should be higher than found by the simulator tests. This tendency is even stronger for the pitch axis. The large distance between pilot position and the axis of rotation makes the pilot more sensitive in pitch than in roll due to the fact, that pitch angular accelerations produce additional vertical accelerations at his seat.

Furthermore it was found from the flight tests, as already mentioned, that the T_{90} can be higher than recommended by AGARD Rep. 577 and that this value is of no great importance for the pilot opinion of the system dynamics, Tab. 3. From flight tests with the VJ 101 it was found that it is more important that the time from control input to angular acceleration on-set (dead time) does not exceed about 0.05 sec, that the time to reach 63 % of peak angular acceleration does not exceed 0.2 seconds and that very little or better no overshoot or change in acceleration on higher order systems occurs. The last two points are very important since overshoot combined with a high time constant will lead to PIO.

	AGARD-REP 577	VJ-101C	DO 31E
T_{90} [sec]	1 - 2	2-3	2-3
TIME TO 63% OF PEAK ACCEL. [sec]	< 0.2	< 0.2	no datas
DEAD TIME [sec]	< 0.1	< 0.05	no datas

Table 3 Control system time lags

The limit cycle experienced in flight tests with the VJ 101 was objected by the pilots as soon as it would exceed about $\pm$ 0,3° and 1 Hz or $\pm$ 0,5° and 0,3 Hz in the pitch axis. In the roll axis again they were less sensitive and would not object limit cycles up to $\pm$ 0,5° and 1 Hz. Here also the strong influence of the vertical acceleration can be seen.

For higher order closed loop attitude systems it is very important to check for "reversions in the sign of accelerations". Fig. 14 gives some results of a comparison between two types of pitch attitude response for a stick step input. The slight overshoot was not objected by the pilot but the superimposed oscillation was objected and the behaviour was judged "unacceptable".

2.4 Control System Failures

Failure investigations using the VJ-101 showed, that changing from attitude control to rate control as a failure mode can be handled by the pilots if this happens

only in one axis. Simultaneous reversions in both axis roll and pitch posed severe difficulties to the pilots and can result in too high side velocities. Reversions from attitude control to acceleration control, in the case of the VJ-101 accompanied with a time lag of about 0,2 seconds for acceleration built-up, could not be handled for any reasonable time to ensure safe landings.

As the SAS of the DO-31 is only a one channel system with an additional damper in the Roll axis the effects of a system failure were very early investigated by tests on the pedestral and in flight. It was demonstrated that the pilot was able to control the aircraft in Pitch and Yaw without any stabilization, in Roll it was possible only with the roll damper engaged or if the yaw and pitch axis were stabilized. But even then there was a PIO of $\pm$ 5 degrees amplitude.

2.5 Sensitivity to disturbances and side step maneuvers

As the necessary lift in hover and transition of both aircrafts is generated mostly by the engine thrust and not aerodynamically by the wing the sensitivity to disturbances is very low. It was even found for the Do-31 that the aircraft is more sensitive to disturbances in conventional flight than in transition.

Also, on the contrary to other Jet lift-VTOL configurations there are no instable rolling tendencies at side step maneuvers. The reasons for this good behaviour are the endplate-effect of the lift engine jets in the case of the Do-31 and the cruise engine jets of the VJ-101 and the large available control accelerations in the roll axis. With both aircrafts side step maneuvers up to 5 degrees of bank angle are performed without any difficulty.

Nevertheless it seems to be dubious whether side step maneuvers are of great practical importance as side wind effects could also be controlled by a heading change.

3. JET INDUCED EFFECTS AND HOT GAS RECIRCULATION PROBLEMS

The jets of the engines induce a flow which produces forces and moments on the surfaces of the aircraft. The most important effects are the lift losses and the jet induced pitching moments.

Due to the special arrangement of the engines in the case of the VJ-101 the jet induced pitching moment is automatically trimmed without any significant reduction of the available control moment. In the case of the Do-31, as this jet induced pitching moment has to be trimmed out by bleed air thrust, there is a significant reduction of the available control moment in pitch. Fig. 15 gives some information about the values, which are evaluated from Do 31 flight tests and which correspond sufficiently to the windtunnel test results. The most important parameters are the thrust level of the engines and the nozzle angle of the cruise engines. This explains the difference between the values of take-off and landing transitions. The lift losses can reach values of more than 10 % of the total weight at medium transition speeds or within the ground effect and the jet induced pitching moment consumes more than 50 % of the available control moment at lower transition speeds. Within the ground effect the jet induced pitching moment changes its sign so that the autostabilization system needs large control momentums at touch down.

Hot gas recirculation occurs, when the hot exhaust gases are reflected on the ground and are rising again by the so called fountain-effect. These hot gases could then be re-ingested by the engines, which lead to thrust losses due to the higher inlet temperatures, to overheating problems of the jet pipes and, if it occurs suddenly, to pumping of the compressor. So the actual used take-off - and landing procedures described before are developed to avoid recirculation as far as possible. Flying within the ground effect and that means within the recirculation area which begins below 40-50 ft altitude is not possible for both aircrafts.

Fig. 16 gives some ideas of the recirculation and jet induced effects on the touch down sink rate of the Do 31 in relation to the initial sink rate out of the ground effect. The inlet temperature of the cruise engines is increased at normal vertical landings between 20 and 40 centigrades. The nozzle angle of the cruise engines at touch down depends on the forward speed and is normaly between 95 and 110 degrees. Due to these effects, which both increase the sinkrate, the initial sink rate out of the ground effect should not be more than 1 m/s to avoid too high gear loads.

4. REMARKS TO THE AGARD-REP. 577

4.1 General

The new AGARD-Rep. 577 concerning the Handling Qualities of VSTOL-Aircrafts is a remarkable improvement in comparison with the old Rep. 408 A. This could be seen also from the flight test datas of the presented aircrafts. Nevertheless there are some remarks from a project engineers standpoint, which can make the Report even more usefull for the design of a new aircraft.

One of the most important purposes of Recommendations like these should be to give to the project engineer in the early state of a project some information how much thrust he has to install to guarantee resonable performance and flying qualities. Furthermore the lay-out should depend from the required missions, the configuration and size of the aircraft and the effects of an engine or system failure. For instance the importance of Flying Qualities in hover flight for the lay-out of a VTOL-aircraft the main tasks of which are rescue missions or other mainly hover tasks will be much higher in comparison to another aircraft, whose VTOL capability is only used to avoid the use of a ground fixed runway. So, for the latter the recommended maneuvering capabilities could be of a lower level for instance. The size and configuration influence was demonstrated in this paper and the effects of engine or system failure is mostly a lay-out criterion for multi-engine types of V/STOL-aircrafts. The thrust to weight ratio (T/W) after an engine failure in combination with a certain emergency amount of control power will lead to the values of thrust or to the numbers of engines which should be provided for the project. So especially this point should be handled in detail within VSTOL-Handling Qualities Recommendations.

An easy way to regard all these different points could be the definition of certain "Levels" for the recommended values similar to the USAF-MIL Spec. for Handling of V/STOL-Aircrafts. For instance: Level 1 for mission tasks, Level 2 for normal flight and Level 3 for emergency like engine or system failure. With these levels the influence of the special missions and of the configurations could be better accommodated.

4.2 Special remarks

From flight experience and project layout investigatiors we would like to give some special comments to several detailed points.

- Recommendations for thrust to weight ratios (T/W) at simultaneously actuated control devices especially for an engine failure case are missed in the Report. A proposel could be: T/W = 1 should be possible at the most critical engine failure with simultaneously actuated control devices for maneuvering up to the half of the lower limit of the control power for moneuvering in addition to the trim moments.

- Recommendations for a system failure could be more specified in the following manner: Control system failures should not lead to large changes in control law e.g. reversions from attitude to rate control should happen in only one axis and from attitude to acceleration control should not be possible for any axis.

- For the attitude control systems in pitch and roll there seem to be discrepancies between the criterias for the dynamic behaviour and the damping criterias.

- For a rate control system in yaw more characteristic recommendations seem to be necessary, for instance values for max. rate change at max. control deflection or a definition of a permissible heading failure at the end of a yawing maneuvre after a zero rate command.

- The recommended acceleration and deceleration value of 0.5 g seems to be too high for normal transitions and should be replaced by 0.3-0.4 g. At the same paragraph the "simultaneous level flight" should be replaced by "without height loss which can not be subsequently recovered".

- Flight in recirculation is not an absolute necessity and should be replaced by safe penetration of the recirculation region.

- The initial response e.g. onset of accelerations should have low values, whilst the T_{63} for angular accelerations is only of interest as far as the stability of the closed loop system is concerned.

- As already mentioned above the control lags are only of importance when accompanied with overshoot that is poor velocity damping.

- The catalogue of the "Maneuvers for V/STOL aircraft handling-qualities evaluation" in the Appendix is too extensive for a practical use und from our standpoint it overvaluates the hovering capabilities which are for the handling of the VJ 101 and the Do 31 not as important as the transition techniques or the behavior of the total system with the characteristics of the SAS included. Therefore from the actual experience of simulation and flight testing it must be possible to revise this Appendix to give a more practical guideline for the simulation and flight test work.

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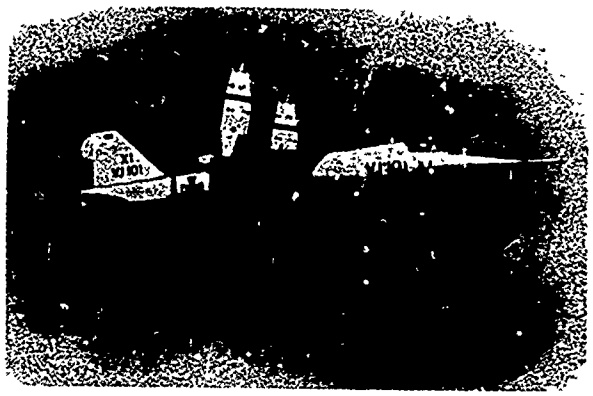


Fig. 1 VJ – 101 C

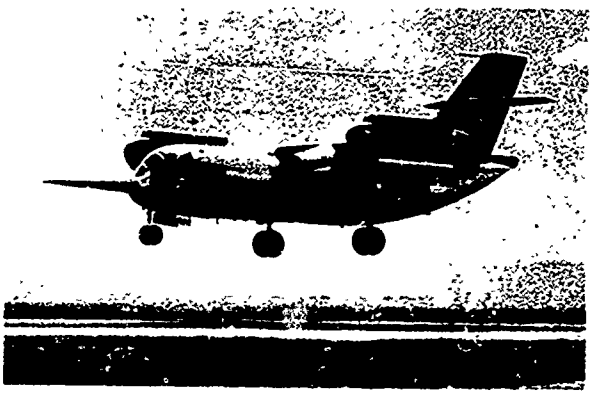


Fig. 2 DO – 31 E3

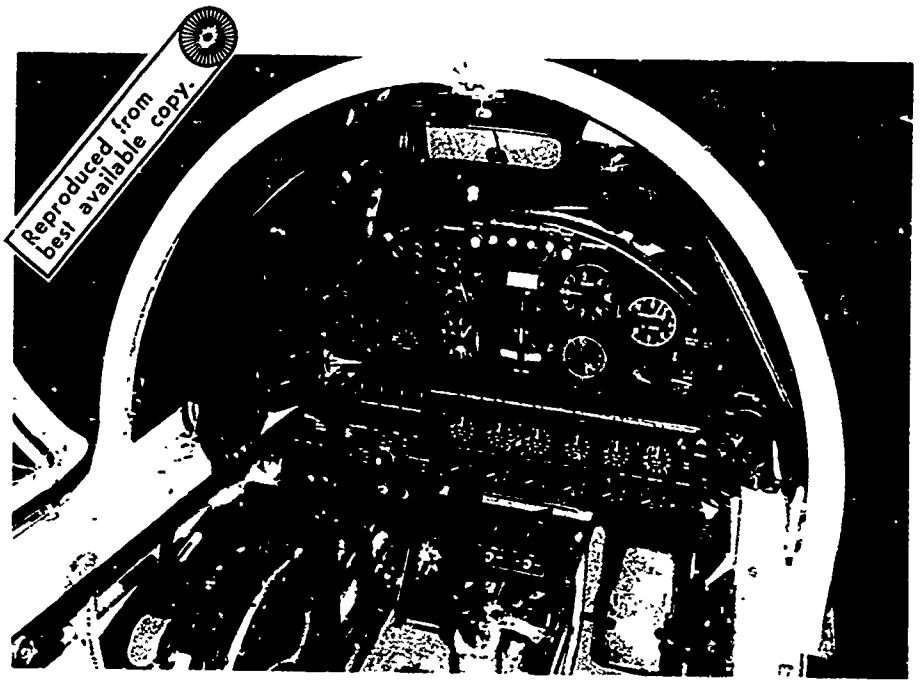


Fig. 3 VJ – 101 Cockpit View

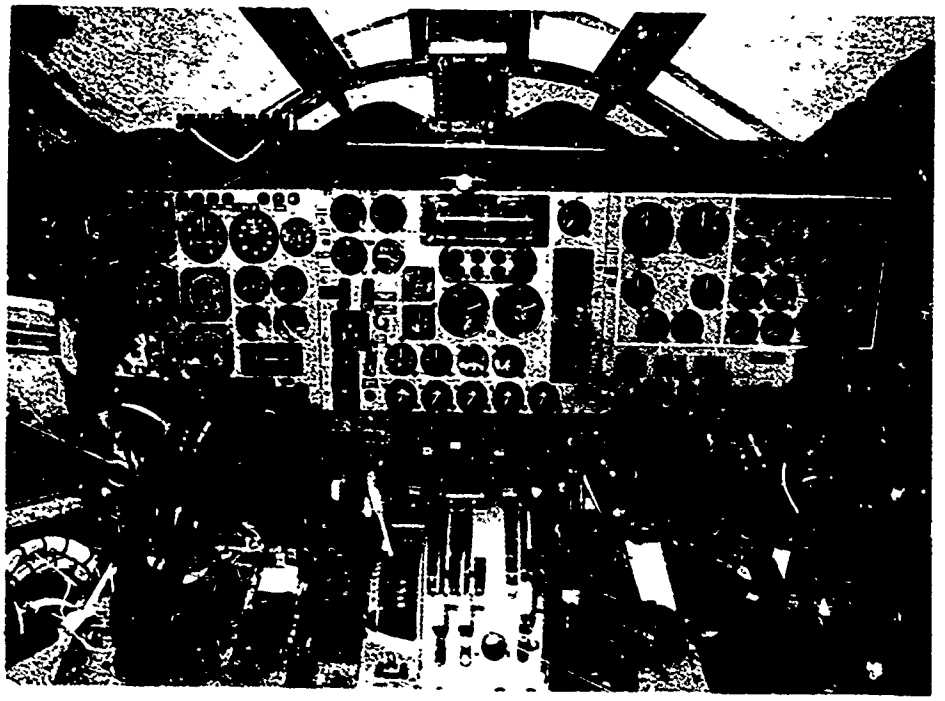


Fig. 4 DO – 31 Cockpit View

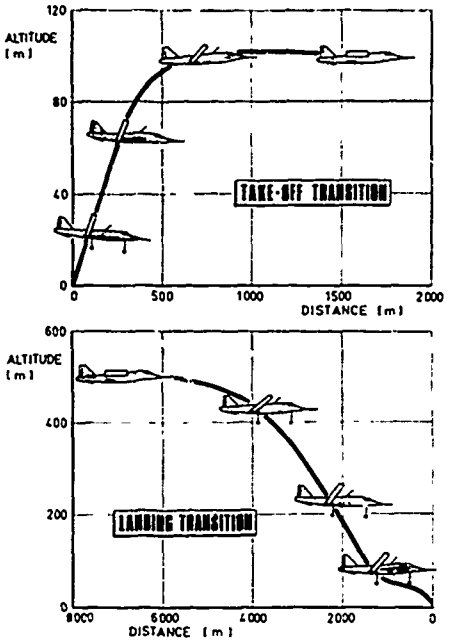


Fig. 5 Transition procedures of VJ – 101

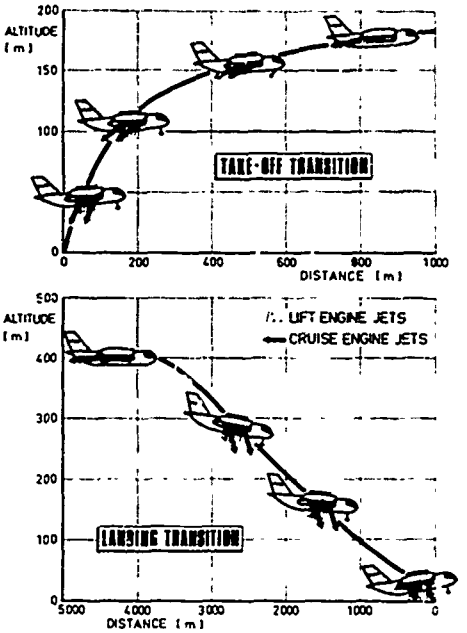


Fig. 7 Transition procedures of DO – 31

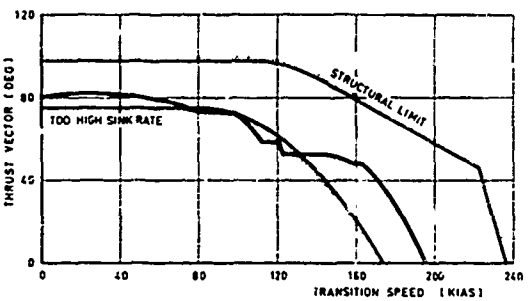


Fig. 6 Transition corridor of the VJ – 101 and used values of a typical landing transition

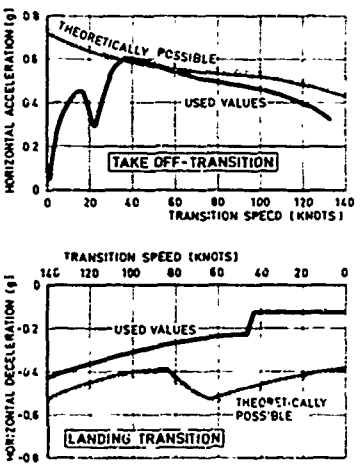


Fig. 8 Horizontal accelerations and decelerations in transition flights with the DO – 31

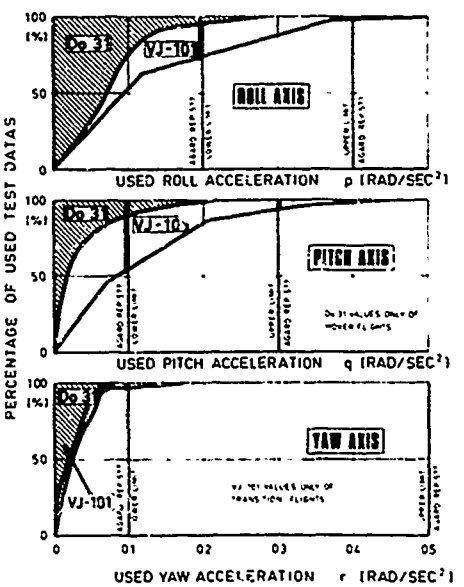


Fig. 9 Envelopes of used control accelerations in hover and transition flights

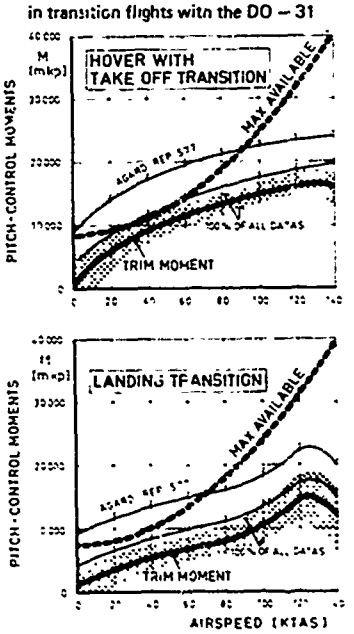


Fig. 10 Used and max. available pitching moments in transition flights with DO-31

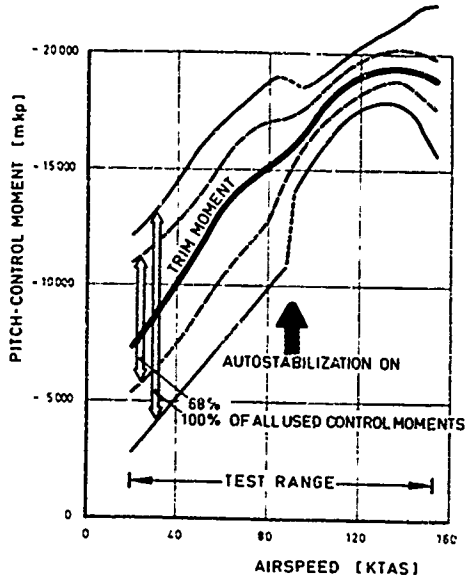


Fig. 11 Effect of autostabilization on the used pitching moments in a typical take-off transition with the DO – 31

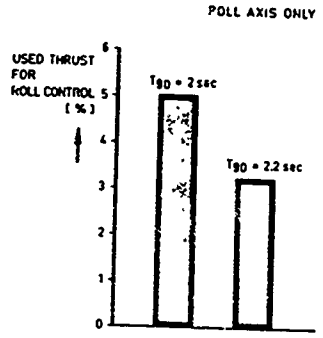


Fig. 12 Effect of T_{90} on used thrust for stability and control

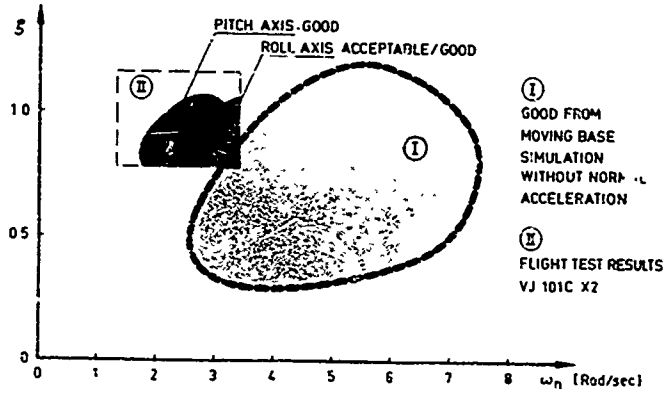


Fig. 13 System dynamics: comparison simulation vs flight

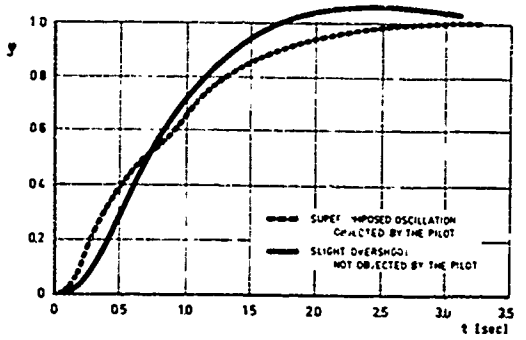


Fig. 14 Pitch attitude response for a stick step input

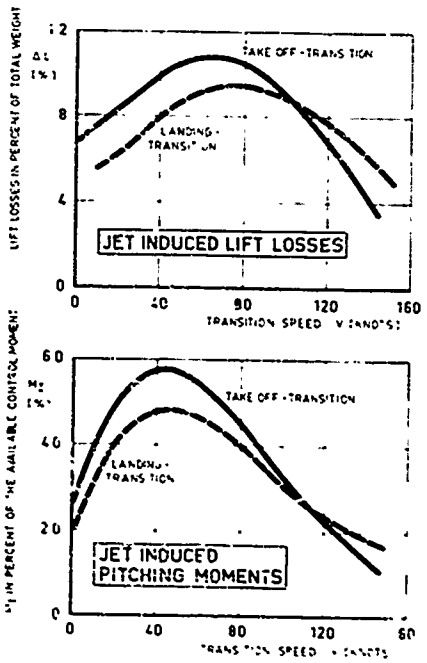


Fig. 15 Jet induced effects in transition flights with DO–31 at typical VTO and VL-transitions

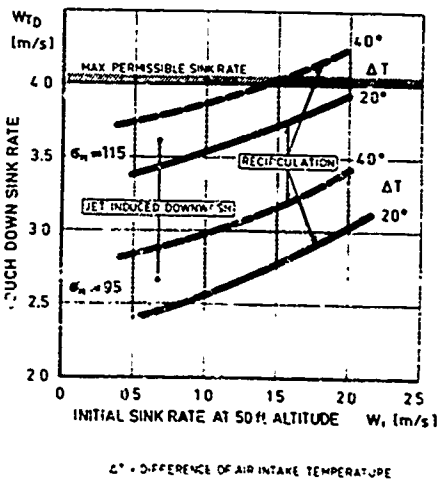


Fig. 16 Influence of recirculation and jet induced downwash on the touchdown sinkrate of the DO – 31

LEAD DISCUSSION

by

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Before powered-lift V/STOL aircraft can be utilized commercially, several important questions must be answered. What performance and safety margins are required? What operational limitations must be established for routine commercial operations? But first and foremost - What handling qualities must these V/STOL aircraft have to permit slow, steep terminal area flight patterns under instrument as well as visual flight conditions?

The Federal Aviation Administration (FAA) has only recently undertaken its own R&D programs to obtain solutions to some of the civil aircraft handling qualities problems which have been identified as important to civil aviation. Since 1967, the FAA has worked in close cooperation with NASA and the U.S.A. military services in R&D utilizing the most modern experimental facilities for handling qualities research. We have sponsored, and are now jointly supporting handling qualities research using the Princeton variable-stability Navion, the Air Force-Cornell T-33 and TIFS variable-stability airplanes, the NASA-Ames S-16 and the new FSAA moving-base simulators, and the NAVAIR X-22A variable-stability V/STOL flight research aircraft.

The objectives of this work are to develop quantitative and qualitative flight characteristics criteria for aircraft system design and for civil certification to define optimum characteristics, to evaluate tradeoffs in design factors and to establish minimum standards for airworthiness certification. This work is intended complement research by NASA and by the military services, but directed toward civil aircraft configurations and regulatory applications. We like to believe that we are making useful contributions to the body of knowledge needed for new aircraft design and certification, and to assure safe, routine operation of advanced civil aircraft of all types.

Reading the paper on V/STOL handling qualities criteria for the VJ-101C supersonic fighter, and the DO-31E transport aircraft - one is impressed not only by the ingenuity of these design concepts, but also inevitably by the commonality of experience reported for these V/STOL designs and of nearly all of the other V/STOL aircraft developed thus far. Almost all have experienced major accidents during their flight operations. Very few of these accidents have been directly attributed to the handling qualities of those designs. Many have been one-or-two-of-a-kind vehicles, relative low-budget, intended for exploratory research, and utilizing relatively unproven power plant or flight control concepts. The DO-31 is perhaps unique in that flight testing was terminated by choice rather than by necessity. As noted in the Committee's latest report on V/STOL handling qualities criteria, AGARD Report No. 577, the preponderance of the results of flight tests of these vehicles relate to performance and flight safety considerations. Only limited data relevant to the development of V/STOL handling qualities criteria are available, and much additional research remains to be done to resolve the critical handling qualities problems associated with low-speed flight regimes - approach and touchdown, hovering, transition or conversion, and related emergency flight conditions.

A new set of stability and control design problems has emerged for V/STOL aircraft. For conventional airplanes, control power frequently has been equated with good handling qualities, especially where rapid maneuvering dominates mission requirements and critically affects structural weight and payload. With most V/STOL research vehicles, however, maneuvering control power has not been the problem. Indeed, experience with the VJ-101 and the DO-31 indicates that maneuvering control requirements were easily met - but trim and stabilization requirements such as trim changes in ground effect require the capability for rapid response to control application. It appears that adverse ground effects are going to be a fact of V/STOL life, and certification and operational criteria are bound to be influenced drastically thereby. Satisfactory touchdown characteristics may be more critical and harder to achieve than good approach handling qualities - which heretofore has generally been the critical low-speed design problem.

Moving ground plane tests of heavy-wing-loading STOL transport airplane configurations indicate large lift and drag reductions plus nose-down trim changes as the airplane approaches the ground in the powered-lift landing configuration. Some unpublished simplified three-degrees-of-freedom analyses of a constant-power, open-loop, elevator flare maneuver, varying flare rate and flare initiation height are indicated in Figure 1. Typical values of powered-lift STOL transport aircraft characteristics, stall margin, approach speed, powered-lift effects and longitudinal control characteristics were assumed. Touchdown sink rates appear to be very sensitive to flare initiation altitude and wing position. The results indicate an inability with elevator alone to arrest completely the sink rate, and only a narrow range of flare initiation heights to achieve minimum sink rates at touchdown.

Additional direct lift control could be used to fully arrest the sink rate. It would appear that the assumption of constant power is valid in this case because of the short-time period involved in the flare maneuver and probable flare engine time constant which would require very precise power control action by the pilot in addition to his other duties.

A related control problem which not yet received its due attention is that of rolling and yawing moments resulting from asymmetric jet-induced interference effects near the ground. It is only touched on in AGARD Report No. 577 on V/STOL handling-qualities criteria. Sideslipping near the ground or operation in crosswinds can impose very significant lateral control power requirements for aircraft designs with high effective dihedral. Even with a VTOL aircraft, it is not always possible to head into the wind to avoid crosswinds. Likewise, yawing moments resulting from differential inclination

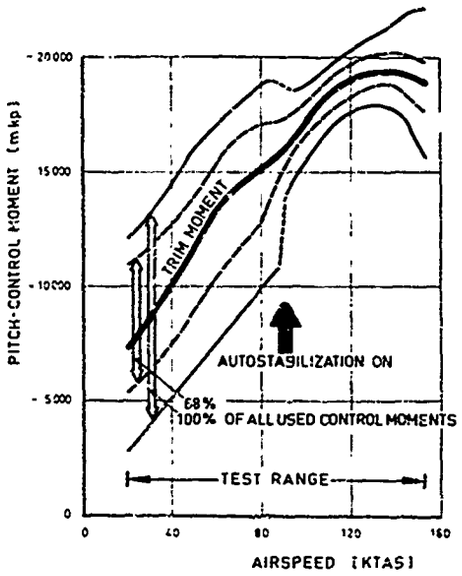


Fig. 11 Effect of autostabilization on the used pitching momen.s in a typical take-off transition with the DO – 31

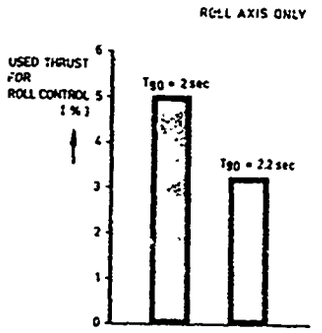


Fig. 12 Effect of T_{90} on used thrust for stability and control

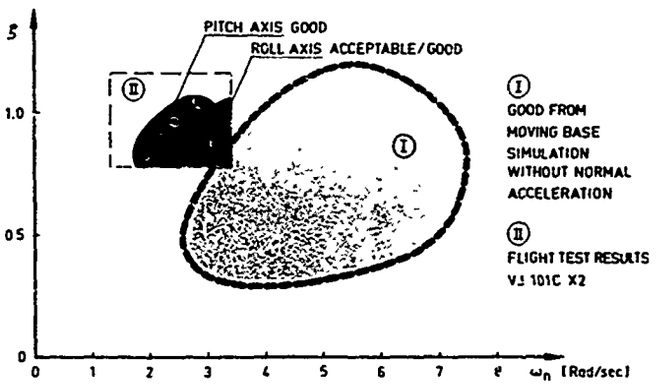


Fig. 13 System dynamics: comparison simulation vs flight

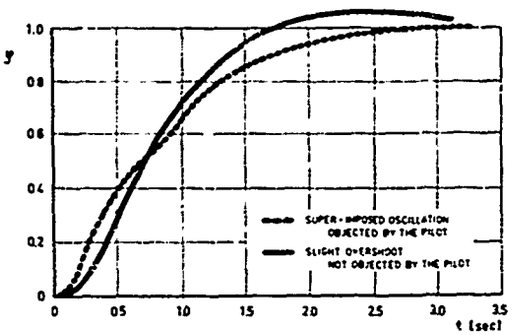


Fig. 14 Pitch attitude response for a stick step input

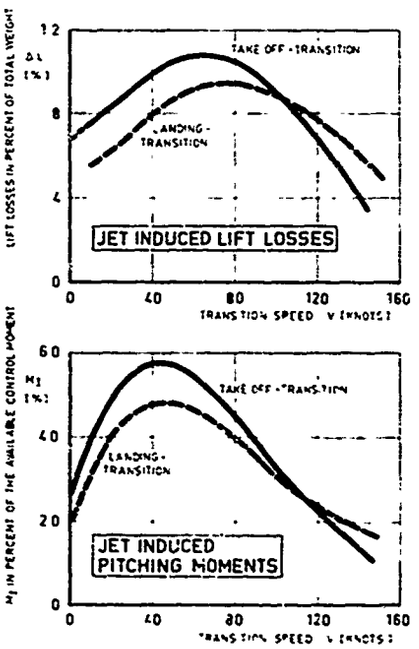


Fig. 15 Jet induced effects in transition flights with DO–31 at typical VTO- and VL-transitions

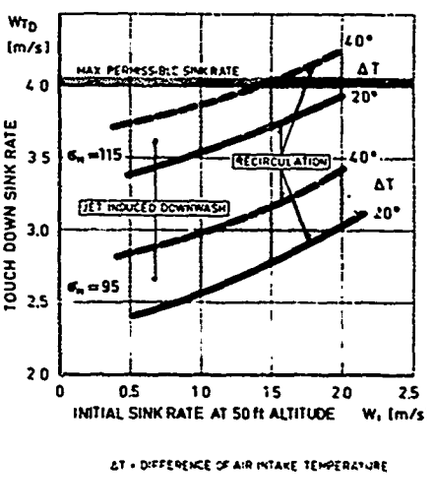


Fig. 16 Influence of recirculation and jet induced downwash on the touchdown sinkrate of the DO – 31

and magnitude of the lift vector with banking in ground effect can exceed the available yaw control power. Here mechanical interconnects or control mixing may be particularly troublesome if automatic stabilization is not available, if control system lags are high, or if control response is sluggish. NASA tests of the XC-142 indicated that available yawing moment control to counteract asymmetric yawing moments, near the ground, are exceeded above the bank angles of about 8 degrees (see Figure 2).

Related problems due to ground presence - recirculation and ground erosion due to jet exhaust are of course well known - and were described to be severe for both the VJ-101 and DO-31. Afterburners for takeoff as available with the VJ-101 may be useful under very special circumstances, but impose drastic operating restrictions. Recirculation problems may be alleviated somewhat by making takeoffs and landings at low forward speeds rather than vertically, and with minimum time spent in ground effect. Immediate shutdown of lift engines after touchdown is required to avoid high inlet temperatures, thereby increasing the pilot's workload. For the DO-31, NASA reported that the effects of suckdown due to pressure forces and engine thrust loss due to exhaust gas ingestion combine to result in an incremental downward acceleration of about 0.1g, and an induced impact of about 8 feet per second during a typical vertical landing. The NASA tests (Reference 2) indicated that below about 35 feet, the landing commitment is definite because of concern over reingestion and power availability.

The VJ-101 and DO-31 VTOL tests confirm that the pilot workload during transition or conversion and during landing represents a most difficult challenge to the VTOL control system designer. The variety of conversion concepts available to the VTOL designer such as to tilt the thrust unit, to swivel the nozzles, or to use separate or additional propulsion systems for hovering and cruising, require additional operations to be carried out by the pilot, and very likely require new or unusual flight-path control techniques.

Both the VJ-101 and DO-31 employed sophisticated command control and stability augmentation systems for use below transition. Attitude stabilization was considered mandatory by the NASA pilots for VTOL operation of the DO-31 because of the workload involved in power management. With the attitude-command control system about the pitch and roll axes, the DC-31 could be comfortably flown down to breakout at about 200 feet and flare initiation. The control and attitude stabilization systems allowed the necessary attention to be paid to power management, because of the pilot's capability to readily arrest the sink rate. With the tilt-wing, propeller-driven XC-142A VTOL,low-gain attitude stabilization plus a power-command flight director allowed pilots to concentrate on powered-lift management problems involved in backside operation, and resulted in much improved ILS tracking performance over that with a rate stabilization system. See Reference 3. At the slow approach speeds, typical of VTOL aircraft and without attitude stabilization, the pilot's total workload during precision approaches will very likely be excessive because of the lack of strong acceleration cues to warn the pilot of attitude divergence.

Achievement of desirable handling qualities, even for the unsophisticated small airplane, has proved to be extremely difficult by aerodynamic design treatment. Aerodynamic improvements to an aircraft design are rarely made solely to optimize handling qualities or to reduce pilot workload, but rather to provide for minimum satisfactory or acceptable handling characteristics to exploit the intended performance or mission effectiveness. Experience thus far with the various V/STOL aircraft concepts indicates that stability and control augmentation will be required to compensate for inherent deterioration in handling qualities because of weight and speed factors. We should increase our handling qualities to research on advanced flight control system concepts to learn the types and levels of augmentation and command responses that optimize pilot-vehicle performance for the various flight mission phases. We also need to continue to develop related design and analytical techniques for the flight control systems as well as for the basic airplane.

The traditional approach to handling qualities research has been to relate the pilot's descriptive evaluation of relative handling quality to the dominant parameters describing the aircraft response. With the command augmentation system, the command model is the dominant characteristic and pilot's evaluation of the augmented aircraft response must be in terms of its closed-loop characteristics. With modern data processing techniques, it is possible to devise suitable quantitative measures of quality to replace subjective pilot opinion. Pilot workload or closed-loop task performance in the context of the mission requirements is readily measured and analyzed by machine data processing. Quantitative measures of handling quality must be developed to eliminate the problems of test pilot variability because of differences in training, experience, technique, personality, bias, etc.

Mr. Wunnerberg suggests an interesting variation of the U.S.A. handling qualities MILSPEC approach to the "levels of flying qualities." He would accept Level 2 for "normal" flight, reserving Level 1 for mission tasks, and reverting to Level 3 for emergencies. The MILSPEC defines level of flying quality in terms of adequacy for mission flight phase - but includes all the usual flight phases as "normal" flight. Level of flying quality is related directly to failure state and the operating point in the operational or service flight envelope. Level 1 is specified in the MILSPEC as the normal state within the operational flight envelope.

A matter of special concern to the FAA is the relation of the pilot opinion rating scale and the level of flying quality to the so-called "minimum acceptable level" of safety for civil aircraft certification. The United States enabling statute, the Federal Aviation Act of 1958, calls for the highest possible level of safety in scheduled airline operations, Sec. 601(b), but paradoxically requires only such minimum airworthiness standards for aircraft as are reasonably required in the interest of safety, Sec. 601(a)(1). The FAA transport airplane certification requirements implementing the statute, Federal Aviation Regulations Parts 21 and 25, imply FAA determination of a level of safety and requires consideration of probable system failures in the establishment of that minimum acceptable level of safety in operations. This philosophy adopted for civil certification may be closer to Mr. Wunnerberg's suggested Level 2 than the Level 1 of the military specification.

It is difficult to relate the civil "minimum acceptable level of safety" quantitatively to the MILSPEC "level of flying quality" and to "airplane failure state." The Cooper-Harper pilot opinion rating

system recognizes that the combined rating degradation caused by two or more poor flying quality parameters can be significantly worse than the degradation caused by any one of them, but this problem has not been studied to any great extent by the military services. The MILSPEC sets Level 2 as having a numerical pilot opinion rating 3½ to 6½ (descriptively as having deficiencies which warrant improvement). Level 3 carries a pilot opinion rating above 6½ - characterizing deficiencies which require improvement or excessive pilot workload. The MILSPEC specifies a reasonably probable (Level 2) failure as occurring with a probability of 10^{-2} per flight within the operational flight envelope, and 10^{-4} within the service flight envelope.

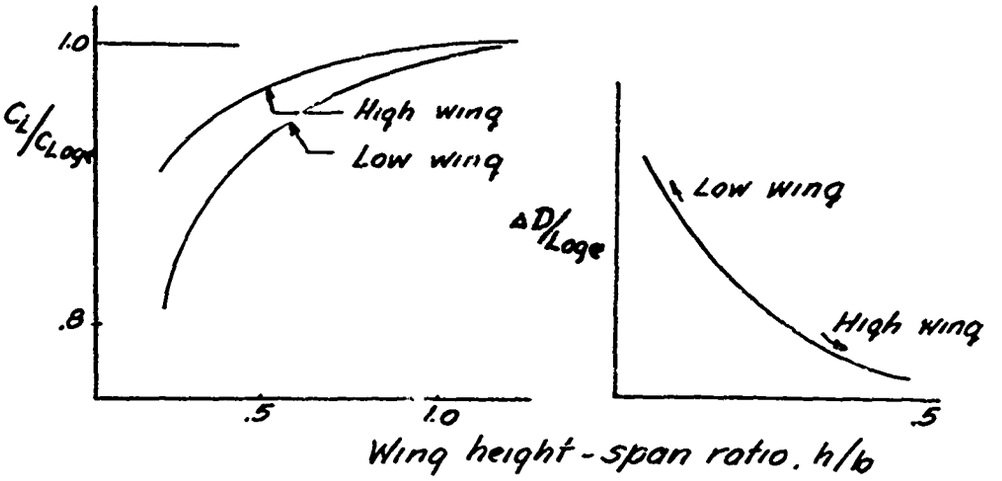
There are no similar failure probability values similar to the military values established in the civil requirements. The civil requirements, on the other hand, primarily relate to effects of system failures on performance rather than on handling qualities. The differences in criteria and intended application make detailed comparison of the civil and military requirements not always feasible. This is only one facet of the FAA problem in applying the criteria derived from MILSPEC - related handling qualities research to the establishment of civil airworthiness regulations. We have made a start on this, however, and we hope soon to begin to investigate the problem of multiple degraded characteristics on minimum acceptable level of safety, under carefully controlled-conditions, which is possible with the use of available ground-based and in-flight simulators.

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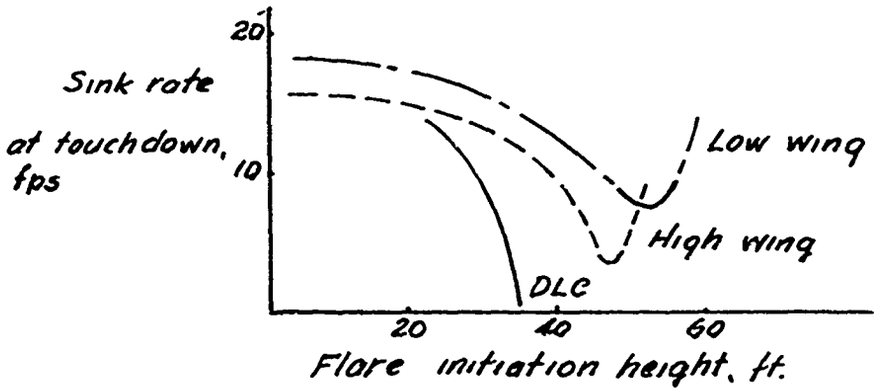
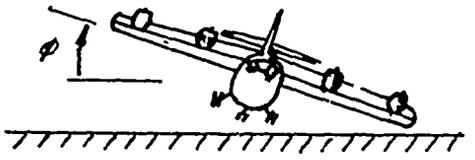


Fig. 1.- Powered-lift STOL transport ground effects.



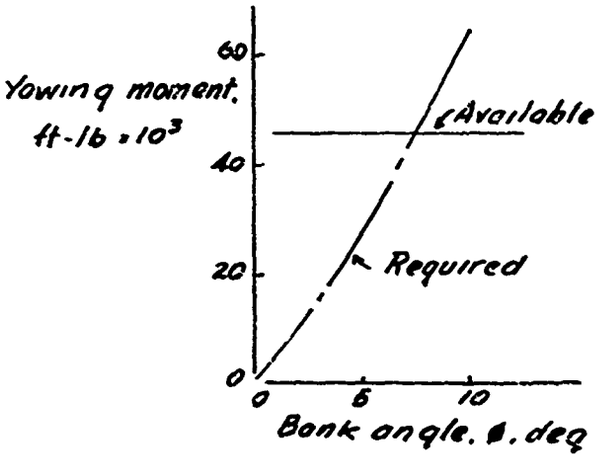


Fig. 2.- Effect of bank angle on yawing moment.

CRITERIA TRENDS OBTAINED FROM ANALYSIS OF CURRENT AIRCRAFT

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INTRODUCTION

At the Air Force Flight Test Center, we are actively involved in the test and evaluation of USAF aircraft. In the past, the criteria used for our flying qualities evaluations have been, for the most part, the design criteria. Evaluating an airplane against design requirements is certainly essential. But we have often found that an evaluation which is limited to only design criteria is incomplete and leaves many unanswered questions. First, there is the problem of correlation of the requirements with the adequacy or suitability of the airplane, particularly for those cases for which the design criteria are not met. What is needed, at least for certain cases, are parameters which can be more directly correlated with aircraft flight phase tasks. Secondly, there are some requirements which are not readily translatable into either design or test guidance; e.g., the requirement that an airplane be spin resistant is a qualitative one which really furnishes no guidance to either the designer or the flight test evaluator.

This paper discusses the need for developing additional criteria specifically for evaluation purposes. Also included are discussions of several other topics in the flying qualities area which have been recurrent items of interest in our recent evaluations of high performance aircraft. Included are comments on high angle of attack criteria, an overview of the results from evaluations of aircraft equipped with control augmentation systems, and a summary of our limited experiences in applying MIL-F-8785B (reference 1).

CORRELATION OF CRITERIA WITH MISSION TASKS

One of the major problems confronting us today is the task of evaluating the effectiveness of an aircraft in terms of its mission. Regardless of the mission of the airplane, the flying qualities and performance of the air vehicle comprise the foundation upon which the fighter, bomber or cargo weapon or support system is built. Personnel in the flying qualities field often assert that when a choice must be made between improvements in either performance or flying qualities at the expense of the other, performance is the inevitable winner. If this is true it is because performance criteria can be more directly correlated with mission accomplishment. Expressing performance capabilities in terms that are meaningful is a relatively simple task; deficiencies in takeoff performance, airplane range, maneuvering performance or engine out performance are easy to relate to mission effectiveness. The significance of not meeting a flying qualities requirement such as roll rate, stick force per g, or damping ratio is somewhat less obvious.

Past stability test programs have usually consisted of a quantitative evaluation of the airplane against flying qualities design criteria as well as a pilot qualitative evaluation of handling qualities. As a result it has been difficult to convince program managers that improvements are needed when specifications are not met unless a deficiency can be unequivocably tied to safety of flight. These remarks should not be construed as being critical of program managers. On the contrary, test and evaluation procedures and criteria must be refined to relate flying qualities more directly to mission capabilities. The parameters must be directly correlatable with mission effectiveness. We must provide program managers with direct evidence that improving flying qualities in a given area is a worthwhile investment, and will result in an improved weapons system. In other words, our recommendations for improvement must have a more substantive base than failure to meet design criteria.

There are those who argue that meeting the specification criteria is synonymous with providing flying qualities that are adequate for the mission. While this may be true, at least insofar as the Level 1 requirements of reference 1 are concerned, the converse certainly does not always apply. We do not know, a priori, what the consequences of not meeting the requirements are, at least insofar as mission accomplishment is concerned. The Level 1 requirements of MIL-F-8785B, by definition, represent flying qualities that are clearly adequate, whereas the Level 3 flying qualities are such that the airplane can be controlled safely, but pilot workload is excessive or mission effectiveness is inadequate, or both. The extremes of the spectrum are easy to evaluate, but the need for improvement for the cases between Levels 1 and 3 - the large "gray" or marginal area - can only be determined in many instances by using a standard other than the design criteria.

There is another problem in using the design criteria of MIL-F-8785B as the only evaluation criteria. The design criteria are, of necessity, specified on a piecemeal basis. Taken individually, the requirements are necessary but not sufficient conditions for flying qualities which range on a qualitative scale from optimum to marginal. In evaluating the airplane, care must be taken not to focus too heavily on a

piecemeal evaluation to the exclusion of really performing a good evaluation of the aircraft in terms of the tasks it will be used for operationally. All too often, the classical, historical flying qualities evaluation has been a piecemeal approach. For the most part, only one axis has been evaluated at a time, at a series of fixed flight conditions. In so doing not enough attention has been paid to the criteria in toto. Combined effects must also be assessed under highly transient conditions and a certain degree of pilot preoccupation must be added. To do this effectively we must concentrate far more heavily on evaluating the aircraft in mission-oriented tasks. Examples of such tasks are various highly transient air combat maneuvers such as gun firing (simulated and actual) during high g decelerating turns, the highly transient air-to-ground weapons delivery maneuvers, the previously mentioned ground controlled approach, and so forth. Obviously, the findings from each evaluation must be used to refine the design criteria for subsequent procurements. To do this, the parameters measured must again be separated and isolated. This is no simple task as those who have worked on updating MIL-F-8785 are well aware.

How can we orient a portion of our flying qualities testing more directly towards flight phase tasks? Let's use an air superiority fighter as an example. For this type of aircraft, the ability to maneuver to a lethal position for the employment of missiles and/or a gun is of primary importance. The process of maneuvering into position is currently called the conversion process. Conversion capability in an airplane is a function of flying qualities, performance, and visibility when human factors (pilot skills) are eliminated. In the flying qualities area, what is the relative importance of each of the following: lift-limited capabilities (instantaneous g available), roll rate, roll response, longitudinal stability and control (e.g., damping, force gradients), lateral-directional stability and control? It is essential that the relative importance of each factor be known to eliminate lost motion during the development cycle and when making improvements to later models of a given airplane type. Recent studies by the NASA Flight Research Center at Edwards Air Force Base have demonstrated that handling qualities deficiencies as related to air-to-air tracking can be identified and isolated by performing tracking tasks using a fixed reticle gunsight which is photographed, and then observing the pipper motion relative to the target aircraft. As an example, in a case in which a lateral-directional problem caused degradation of the tracking task, the pipper moved across the target with side-to-side motions, in spite of the pilot's best efforts to effect precise tracking. Likewise, vertical motions of the pipper were evident with a problem in the pitch axis and irregular circular patterns existed when wing rock was encountered.

Tracking tasks were used by the Air Force Flight Test Center to evaluate various flight control system configurations on a specially modified airplane with a developmental control augmentation system (reference 2). Pilot opinion ratings, combined with a quantitative assessment of the ability to track, were used to optimize the system.

There are other illustrations of the need for this task-oriented approach. In two recent evaluations, test personnel were not certain of the magnitude and severity of problems that could arise from marginal power approach configuration speed stability characteristics until mission-oriented tests as well as classical piecemeal flying qualities evaluations were completed. Traditional tests had indicated a potential problem area, which could not be assessed in terms of airplane effectiveness until mission-oriented tasks were performed. For one airplane, the magnitude of the problem was apparent when angle of attack excursions of several degrees were experienced when attempting minor corrections during a ground-controlled approach. In another airplane, aft cg landing characteristics were evaluated during approach and landing by a number of pilots in calm and turbulent air. The original objective of this evaluation was to determine an aft cg limit for stability augmentation system off operation as classical stability tests had indicated marginal longitudinal stability characteristics. The pilots found, however, that directional rather than longitudinal characteristics were the major area of concern with the stability augmentation off. The directional mode perturbations tended to mask the low longitudinal static margins during the aft cg landings. Further, the pilots noted very little difference in the aircraft approach and landing characteristics with all stability augmentation on and with only the pitch augmentation off. The point here is that evaluation personnel arrived at two different recommendations relative to improvements in longitudinal stability and these recommendations were meaningful only because of the insight provided by performing mission-oriented tasks. In addition, the mission-oriented tasks had been preceded by compehensive stability tests using the traditional approach. In retrospect, it would have been better to accomplish the mission-oriented tasks early in the test cycle to better identify problem areas.

The AFFTC has initiated a program to develop and refine test techniques which will provide a rapid means for evaluating handling characteristics as they effect precise maneuvering requirements in accomplishing the primary mission. The program should develop evaluation procedures to quickly isolate those portions of the flight regime where the airplane is deficient. A detailed investigation of the causative factors can then be made using more conventional flight test techniques. This is in contrast to past programs where we have tested throughout the flight envelope at a number of altitudes and speeds, comparing flying qualities with specification design criteria. When the criteria were not met, we were frequently unsure of the real need for improvement.

CONTROL AUGMENTATION SYSTEMS

The design trend, over the past 15 years for high performance aircraft, has been toward a steady increase in the relative contribution of the augmentation system in meeting flying qualities requirements. The trend has been made possible by major advances in flight control system technology. The trend has been made necessary by an ever-increasing flight envelope.

In the past several years, this evolutionary process in flight control system design has progressed to control augmentation systems, where aircraft response, rather than control surface position is commanded. With this type of augmentation system it is possible to achieve certain "optimized" uniform flying qualities through a wide Mach number, angle of attack and airplane cg range. In so doing, the inherent aerodynamic response characteristics are masked to a high degree.

The ability to suppress or mask the basic aerodynamic characteristics has some disadvantages as well as advantages. On the positive side, it is possible to mask undesirable aerodynamic characteristics. These systems have provided some rather spectacular improvements in flying qualities when incorporated on airplanes which had previously been equipped with more conventional stability augmentation systems. As an example, on one airplane, transonic "dig-in" tendencies were essentially eliminated, by suppressing the basic aerodynamic characteristics which are, of course, changing markedly with Mach number in the transonic speed range. The net result was that it was possible for the pilot to maintain precise control of the airplane in a high g decelerating turn. With the production configuration it would not have been possible to perform a precise tracking task in the transonic region. With the control augmentation system, it was possible to provide maneuvering stick force gradients, which were highly linear and which did not vary significantly with Mach number or angle of attack.

A control augmentation system can also stabilize the longitudinal and lateral-directional oscillations normally associated with high angle of attack flight making it possible to effectively use a larger angle of attack range. From an operational viewpoint, this is a desirable feature for maximum combat maneuvering effectiveness and precision air-to-air and air-to-ground weapons delivery.

There are disadvantages associated with the ability to mask certain undesirable aerodynamic features. With a conventional system, the pilot usually has cues resulting from a gradual degradation in flying qualities with cg movement, or with increasing angle of attack as he approaches a stall. When flying qualities continue to be good even through the airplane is being flown into an area of degraded basic airplane stability characteristics, the possibility of inadvertently maneuvering into a potentially hazardous area exists. In several cases this has led to inadvertent flight at conditions well outside safe angle of attack limits and, in another instance, well aft of a safe cg limit.

The ideal combination of these features, of course,is to retain the excellent flying qualities through a large envelope but at the same time provide the pilot with positive cues when he approaches a limit, or insure that he does not inadvertently exceed safe limits. Since many of the cues which were, in the past, provided by the basic aerodynamic characteristics of the vehicle have been eliminated, attention must be given to insuring that adequate substitutes are provided. The high angle of attack case will be discussed separately.

As was noted earlier, many of the stringent flying qualities criteria have been satisfied in recent airplanes through augmentation systems rather than as a result of basic airframe aerodynamic characteristics. There are a number of people who believe that this is an unhealthy trend. However, some of the features considered to be highly desirable, e.g., certain optimized uniform flying qualities throughout a wide Mach number, angle of attack and cg range are very difficult, if not impossible to achieve aerodynamically since aerodynamic characteristics do vary widely with each of the aforementioned parameters.

In summary, with a few exceptions, the control augmentation systems currently in being are covered by the current flying qualities criteria. The problem lies with insight in application as the criteria have, for the most part, evolved from evaluations of classic aerodynamic characteristics.

HIGH ANGLE OF ATTACK CRITERIA

Loss-of-Control Prevention

In our design criteria, we legislate against departures and spin susceptibility with the requirement that "neither post-stall gyrations nor spins shall be readily attainable for (a variety of entry conditions) except by prolonged gross misapplication of controls". (Reference 1) How often have these criteria been met in recent fighter-type designs? Let's assume that we have an airplane which has poor aerodynamic stall warning, or the warning is masked by a high authority stability augmentation system, coupled with a lack of departure and spin resistance. What courses of action are available? Basically there are two - the designer can attempt to make aerodynamic refinements or he can artificially provide the necessary warning and loss-of-control resistance. Artificial stall warning devices are generally accepted today; however,

there is still considerable resistance to the use of spin resistance or loss-of-control prevention devices. A loss-of-control prevention device is the only positive means of eliminating aircraft losses due to stalls, post-stall gyrations and spins in high performance fighter-type aircraft that are not highly resistant to departure. There are two basic types of loss-of-control prevention systems; one which activates the control stick such as a stick pusher, or one in which control is applied through the stability augmentation system to the control system itself. The choice of which means to employ depends, to a large extent, on the type of stability augmentation system in the airplane. If predictive studies indicate that the airplane will not be departure-resistant the development of a loss-of-control prevention device should be initiated early to prevent costly delays and hardware changes in case initial flight test results prove that the device is necessary.

There is a real need to meet the departure-resistance criteria in a fighter type aircraft. Artificial angle of attack limiting is not an ideal solution but it is much better than no solution. Similarly it would be preferable to be able to provide excellent flying qualities throughout a wide flight envelope without having to resort to a high authority stability augmentation system. However, stability and control augmentation are accepted as means of meeting the flying qualities criteria in our specifications, except when it comes to providing a high level of departure resistance. The use of a loss-of-control prevention device is no different in principle than permitting the use of stability augmentation to satisfy other criteria which would otherwise not be met.

Artificial Stall Warning

For those cases in which aerodynamic stall warning is inadequate, a suitable artificial stall warning system must be provided to satisfy the stall warning criteria of MIL-F-8785B. What constitutes adequate aerodynamic warning is described in detail in the specification. Suitable artificial devices are not addressed. It has been our experience that, for a fighter type airplane, a device which provides positive stall warning without reference to a cockpit instrument is essential. Lights are unacceptable for fighter applications. Rudder pedal shakers have proven to be inadequate for several reasons. The shaker is often masked by a wide band of airframe buffet, or offset with external stores, gunfire vibrations, and the shaker requires that the pilot's feet be firmly on the rudder pedals. Stick shakers have proven to be acceptable artificial warning devices.

STALL/SPIN FLIGHT CRITERIA

In the fall of 1970, the AFFTC was tasked with preparing a replacement specification for MIL-S-25015 (USAF), Spinning Requirements for Airplanes (reference 3). The previous specification was considered to be outdated because it did not place enough emphasis on the angle of attack range between maximum usable lift and the point at which the aircraft enters a fully developed spin. In 1970, a test program was accomplished by the AFFTC on an F-4E. During this program, a detailed investigation of the post-stall, pre-fully developed spin region was made. This test program, which was reported on in a previous AGARD paper (reference 4), provided much of the experience upon which the new specification, (reference 5), was based.

Rationale Behind The Specification

The flight test demonstration maneuvers required in the new specification are shown in Table I, taken from reference 5. This table is a structured matrix of four test phases, designed in logical test progression from initial stalls with immediate recovery attempts, to stalls with aggravated control inputs, and from there to aggravated inputs with delays.

Each test phase includes both one g and accelerated stalls. Additionally, stalls are accomplished both by slowly increasing angle of attack, and by abruptly increasing it. The degree of the abruptness is increased commensurate with the phase. For fighter-type aircraft and certain types of trainers, stalls are accomplished from tactical entries; e.g., from the types of maneuvers that would be associated with air combat maneuvering in an air superiority fighter. The degree of resistance to departures and spins is associated with the specification test phases as is shown in Table II, taken from reference 5. The table represents a qualitative definition of departure and spin resistance.

COMMENTS ON SPECIFIC MIL-F-8785B CRITERIA

Air Force Flight Test Center personnel recently completed a test on an aircraft equipped with an experimental control augmentation system (reference 6). This system provided a dramatic improvement in tracking capability but the test results in several areas showed only minor improvements when comparisons were made with MIL-F-8785B. The changes in the specification parameters were not indicative of the dramatic improvement in tracking capability, which has occurred. In fact, in several key areas which would appear to relate to tracking capability, the aircraft fell outside or on the boundaries of the specified limits, i.e., stick force per g gradients were low, short period natural frequency was too low for the corresponding ratio of load factor to angle of attack, (n/α), and roll-yaw coupling requirements were not met. A majority of the stick force per g gradients were below the MIL-F-8785B minimum of 3 pounds per g; however,

the gradients were highly linear. When evaluated during tracking tasks, the low gradients were not considered to be objectionable, on the contrary the flying qualities were considered to be excellent.

In the User's Guide for MIL-F-8785B (reference 7), it is recognized that airplanes with certain type of stability augmentation systems, such as maneuver command systems, have zero gradients of longitudinal control force and position with speed yet can be quite stable with respect to external disturbances. In evaluating an aircraft equipped with an augmentation system which functioned as an autotrim device, it was found that the absence of any trim requirements accompanying an airspeed change was a desirable feature, particularly for highly transient maneuvers where speed was changing rapidly. This eliminated the need for continuous trimming by the pilot and he could concentrate on the task.

In MIL-F-8785B, the nonterminal flight phases (other than takeoff, landing, and associated maneuvers), are broken into two categories, the Category A tasks that require rapid maneuvering, precision tracking or precise flightpath control, and the less demanding Category B tasks that are normally accomplished using gradual maneuvers and without precision tracking. There are operational flight envelopes associated with each Category and the appropriate flight phase task(s) for the airplane. As an illustration, for an airplane with a ground attack mission, the stringent MIL-F-8785B requirements for flight phase Category A apply up to limit load factor and up to medium altitude. However, above a medium altitude the requirements apply over a much smaller envelope in terms of normal load factor (0.5 to 2.0 g's). For an aircraft with a ground attack mission, this can, depending upon interpretation, result in very few requirements above an altitude of roughly 20,000 feet and at load factors greater than 2.0. This has already been found to be a potential problem area in applying the specification.

In summary, except in the limited areas previously mentioned, we have not yet evaluated an airplane against the criteria in the new flying qualities specification (reference 1), but will do so in the near future when we begin our evaluations of the F-15, A-9, A-10, and B-1A. In another two to three years, we will be in a better position to judge the adequacy of these criteria.

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TABLE I

FLIGHT TEST DEMONSTRATION MANEUVERS

TEST PHASE	MANEUVER REQUIREMENTS	
	CONTROL APPLICATION	STALL/DEPARTURE ENTRY CONDITIONS
A Stalls	Pitch control applied to achieve the specified AOA rate, roll and yaw controls neutral or small lateral-directional control inputs as normally required for the maneuver task. Recovery initiated after the pilot has a positive indication of: a. A definite g-break or b. a rapid, uncommanded angular motion, or c. the aft stick stop has been reached and AOA is not increasing d. sustained intolerable buffet	1) Slow AOA Rate Abrupt AOA Rate (normal and accelerated stalls) 2) Tactical (aircraft attitude the AOA rate appropriate to the simulation)
B Stalls with Aggravated Control Inputs	Pitch control applied to achieve the specified AOA rate, roll and yaw controls as required for the maneuver task. When condition a, b, or c from above has been attained, controls briefly misapplied, intentionally or in simulated response to unscheduled aircraft motions, before recovery attempt is initiated.	
C Stalls With Aggravated and Sustained Control Inputs	Pitch control applied to achieve the specified AOA rate, roll and yaw controls as required for the maneuver task. When condition a, b, or c has been attained, controls are misapplied, intentionally or in simulated response to unscheduled aircraft motions, and held for several seconds before recovery attempt is initiated.	
D Spin Attempts	Pitch, roll and yaw controls applied as required for the maneuver task. When condition a, b, or c has been attained, controls applied in the most critical positions to attain the expected spin modes of the aircraft, and held for an extended time before recovery attempt is initiated. (This Phase required only for training aircraft which may be intentionally spun and for aircraft in which sufficient departures or spins did not result in Test Phases A, B, or C.)	1) Abrupt AOA Rate 2) Tactical

TABLE II

SUSCEPTIBILITY/RESISTANCE CLASSIFICATION

(determined by Test Phase in which departures/spins first occur)

	CLASSIFICATION	
	Departures	Spins
A - Stalls	extremely susceptible	extremely susceptible
B - Stalls with aggravated control inputs	susceptible	susceptible
C - Stalls with aggravated and sustained control inputs	resistant	resistant
D - Spin attempts	extremely resistant	extremely resistant

OPEN DISCUSSION

M.D. White, NASA Ames, USA

In connection with the talk of stall entry control application, is there any indication from evaluating pilots as to whether the appropriate cut-off level for control application may be set below the most aggravated case as a function of airplane mission, operational experience, etc?

C.E. Adolph, AFFTC, USA

It is our opinion that for fighter aircraft you want to go to full pro-spin controls. This may not be true for cargo aircraft but it is true for fighter aircraft, because sometime in service some pilot will get into these conditions and you want to be able to tell him how to recover. You must take the test in steps, not just forcing it into a spin. There are cases where during the post stall gyration and departure, corrective measures could be made to prevent the spin.

A.G. Barnes, BAC, UK

Mr. Adolph says that several aircraft were flown with stick force per g less than the 8785B minimum of 3 lb/g and were well liked by pilots. The military requirements of UK (AvP 970), France (AIR 2002c), and Sweden all allow a minimum of approximately 2 lb/g. The McDonnell analysis of F-4 data supports this, and our flight experience with Lightning and Jaguar confirm it.

Designing to a high minimum stick force per g for an aircraft with a large cg range usually means that very high stick force per g will appear at forward cg - perhaps 12-15 lb/g at operational conditions, unless complexity is added to the flight control system.

Thus there is evidence for a reduction in minimum levels, and a design penalty if it is not reduced. Perhaps I should address Mr. Westbrook. What is the mechanism by which MIL-8785B is changed?

C.B. Westbrook, AFFDL, USA

If the problem arises during the development of a particular system, then Mr. Carlson of the particular SPO would be involved. In setting up the requirements we have tried to include a mechanism by which requirements can be changed. These changes can be during the design stage or later. The process, which requires coordination with other organizations, could be done in three to six months.

Sqn Ldr D.C. Scouller, RAF/ETPS, UK

You have said that you have found in military aircraft acceptance testing that while using the mil specs as the general basis, you now find it necessary to compare the aircraft's behaviour against its mission. This vividly illustrates the danger of checking an aircraft against mil specs as though they were a shopping list. I would argue that you must write your test schedules so that the ability of the aircraft to perform its mission is the primary aim of your investigation.

You spoke of the use of artificial methods of stall prevention. I would like to stress that it should be impressed upon the design staff that good natural stall behaviour is the best solution and that artificial methods should be a fallback solution.

While endorsing your new approach to stall/post stall/spin investigation I could not see the purpose of classifying spin resistance in tabular form. I think a verbal description, e.g., "prone to spin" is better.

C.E. Adolph, USAF, USA

The table is nothing very profound it is just an attempt on our part to qualitative come up with a set of vocabulary which is consistent.

With regard to your second question, I agree with you one hundred percent.

On your first point, I agree, but the Air Force test agency or contractor must determine whether the contractor has met the design criteria. This is a powerful mechanism for getting changes made to the vehicle to meet criteria.

A.L. Byrnes, Lockheed, USA

I'd like to offer a partial reply to Mr. Barnes question on how specification deviations are negotiated. In U.S. military contracts, specification amendments are negotiated along with the contract. The agreed on deviations become part of the contractual document. The contractor is then financially liable for any requirements not met.

Comment on Mr. Adolph's paper. As an aerodynamicist responsible for aircraft design, I am very much concerned over the practice of defining a required angle of attack range as done in Reference 5 of your paper, rather than specifying the desired maneuver capability. I'd also like to point out that for many years now we have relied on a very excellent stall and spin prevention device, the pilot, who, with proper training, has done an excellent job. It is hard to follow the logic of ruling out the rudder pedal shaker as an ineffective stall warning device because the natural airframe buffet is so heavy it masks the shaker. It seems to me we should seriously question the cost effectiveness of encouraging fighter pilots to use tactics which result in loss of aircraft from deliberately exceeding the airplane design envelope and then attempting to correct the "problem airplane".

R.J. Woodcock, AFFDL, USA

We have had cases of fighter aircraft which start buffeting at a comparatively low angle of attack, with maneuver capability remaining at higher angles of attack. Pilots will use this higher angle of attack in air-to-air combat, although they then have no good cue to the angle of attack margin remaining before loss of control.

In the USAF we write the handling qualities requirements into each contract, paragraph by paragraph, rather than merely calling out 8785B. This practice promotes a thorough review for each specific case, also affording an opportunity to incorporate later results.

We hope that there is some relation between the design flying qualities requirements and operational use. We value very highly flight test comments on the relevance or irrelevance of the 8785 requirements. Realizing the need for a closer tie between design requirements and operational needs, we are continuing research. Ron Anderson will discuss tomorrow one form this work is taking.

SIMULATION AND ANALYSIS IN ESTABLISHING FLYING QUALITIES CRITERIA

BY

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INTRODUCTION AND SUMMARY

This paper illustrates the application of simulation and analysis in establishing flying qualities criteria of piloted airplanes. The discussion draws on published work which has been used to create the existing military specification MIL-F-8785B (ASG), and other published information on in-progress work to improve the subject specification in certain areas. It is presumed in the discussion that the reader has access to Specification, MIL-F-8785B(ASG) and to the Background Information and User's Guide for MIL-F-8785B(ASG).

Two areas are identified where better criteria are needed in the specification; the effects of turbulence and the impact of control system dynamics on flying qualities. A detailed discussion is presented on a program in which ground-based simulation and pilot-in-the-loop analysis are employed in an attempt to better define the impact of turbulence on flying qualities. A similar discussion is presented of a program in which inflight simulation and pilot-in-the-loop analysis are employed to determine a method of specifying total system requirements rather than control system and airplane modal characteristic requirements.

Attention is drawn briefly to some of the shortcomings of ground-based, and inflight simulation. The possibilities are discussed of overcoming these shortcomings using more advanced systems such as the Northrop Large Amplitude Flight Simulator with a wide-angle visual display (LAFS/WAVS), the USAF Total Inflight Simulator, and the proposed USAF Fighter, Inflight Simulator.

LIST OF SYMBOLS

s – Laplace Operator
Z – Normal Force
M – Pitching Moment
V – Velocity
w – Vertical Velocity
M_w – dM/dw
$M_{\dot{w}}$ – $dM/d\dot{w}$
M_q – dM/dq
q – Pitch Rate
δ_e – Control Surface Displacement
Δn – Incremental Load Factor
$\omega_{n_{sp}}$ – Short Period Natural Frequency
α – Angle of Attack
F_s – Stick Force
Z_w – dZ/dw
$Z_{\dot{w}}$ – $dZ/d\dot{w}$
Z_{δ_e} – $dZ/d\delta_e$
n_L – Limit Load Factor
K – A Constant
ζ – Damping Ratio
$|\phi/\beta|_d$ – Bank Angle to Sideslip Ratio
ϕ – Bank Angle
β – Sideslip Angle
N'_p – Primed Yaw Rate Due to Roll Rate Derivative
N'_{δ_A} – Primed Yaw Rate Due to Aileron Deflection
ADI – Attitude Display Indicator
θ – Pitch Angle
r – Yaw Rate
p – Roll Rate
ψ – Heading Angle
δ_{β_g} – Incremental Side Gust
Y_ϕ – Pilot Describing Function
K_ϕ – Pilot Gain in Roll Closure
K_q – Pilot Gain in Pitch Rate Closure
ω_{BW} – Bandwidth
a_{Y_p} – Lateral acceleration at the pilot station

Other symbols are defined where used.

SIMULATION AND ANALYSIS IN ESTABLISHING CRITERIA

A review of the section of Military Specification MIL-F-8785 (ASG), entitled "Flying Qualities of Piloted Airplanes"[1] relating to the longitudinal maneuvering requirements and some of the material from the Background

and User's Guide for MIL-F-8785B (ASG)[2], will serve to illustrate the role played by various forms of simulation and analysis in establishing criteria. Let us consider first the requirement on short period frequency and acceleration sensitivity (Section 3.2.2.1.1 of the Specification). The short-period undamped natural frequency $\omega_{n_{sp}}$ must be within the limits shown in Figures 1, 2 and 3 of the Specification. If suitable means of directly controlling normal force are provided, the lower bounds on $\omega_{n_{sp}}$ and n/α of Figure 3 may be relaxed if approved by the procuring activity.

The Category 3 flight phase requirement of Figure 3 of the Specification is shown in Figure 1 of this paper, and can be used to illustrate how a combination of analysis and simulation was employed in generating the requirement.

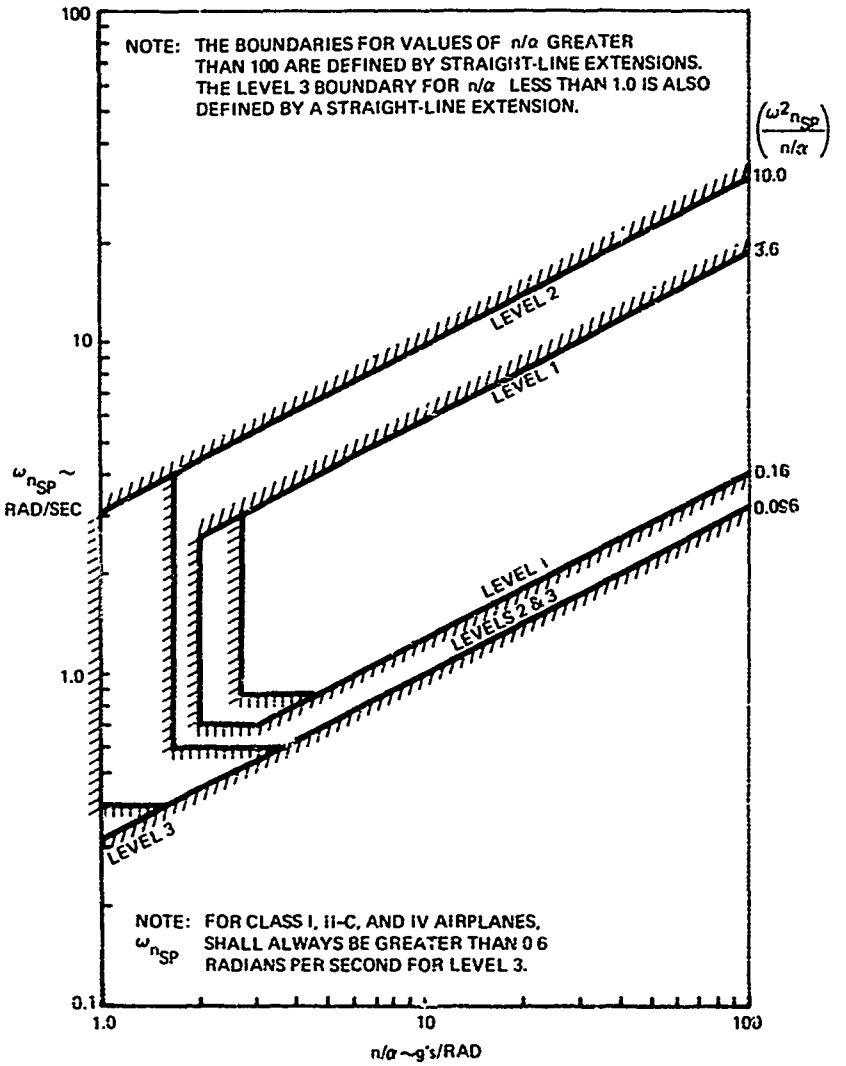


FIGURE 1. SHORT-PERIOD FREQUENCY REQUIREMENTS (FROM REFERENCE 1)

In formulating the criteria in the manner of Figure 1, it was argued[3] that a pilot during in-flight simulation tests had encountered conflicting requirements, both at the lower and higher values of short-period natural frequency when selecting the best compromise between stick sensitivity (M_{FS}), and steady-state stick-force gradients (F_s/n). A simple analysis can be used to illustrate the problem.

Consider the attitude response to longitudinal controls of an airplane flying at constant speed. The equations describing the motion can be[3] written

$$(s - Z_w)\, w - Vq = Z_{\delta_e}$$

$$-(M_{\dot{w}}\, s + M_w)\, w + (s - M_q)\, q = M_{\delta_e}$$

The solution of these equations for the steady-state response to control inputs will yield

$$\frac{\Delta n}{\delta_e} = \frac{Vq}{g\delta e} = \frac{V}{g} \cdot \frac{\left(Z_{\delta_e} M_w - M_{\delta_e} Z_w\right)}{\omega_{n_{sp}}^2}$$

$$\frac{\Delta\alpha}{\delta_e} = \frac{1}{V} \cdot \frac{W}{\dot{e}_e} \doteq \frac{M_{\delta_e}}{\omega_{n_{sp}}^2}$$

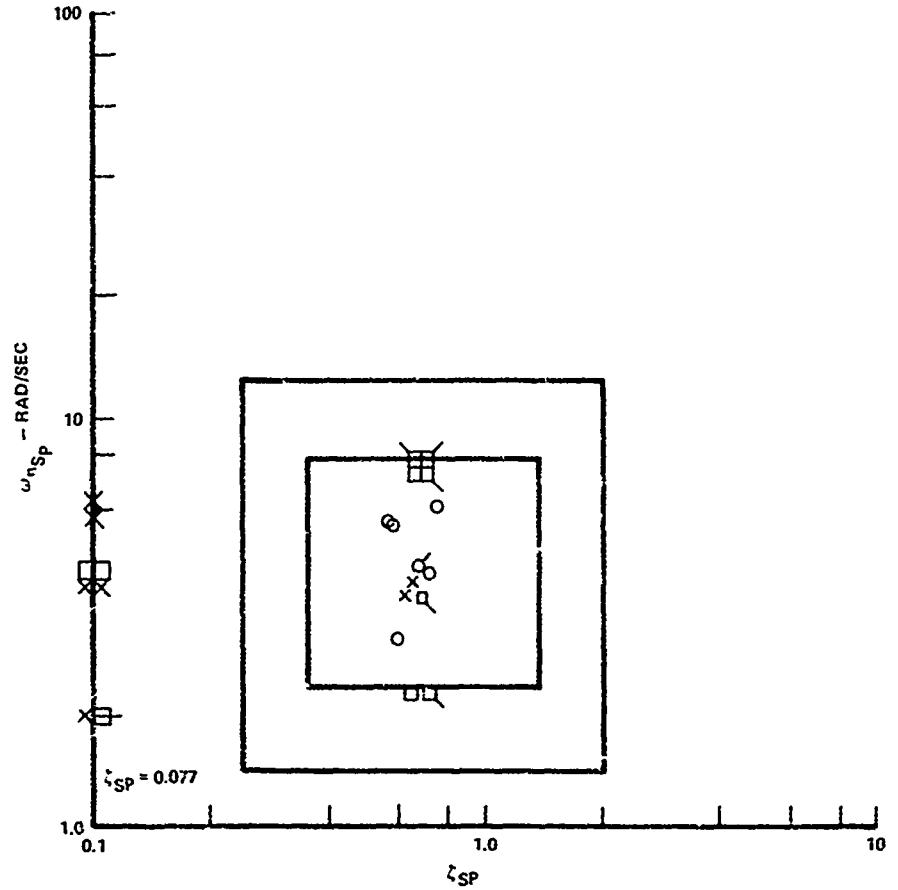


FIGURE 2. TYPICAL DATA FROM IN-FLIGHT SIMULATION (FROM REFERENCE 3)

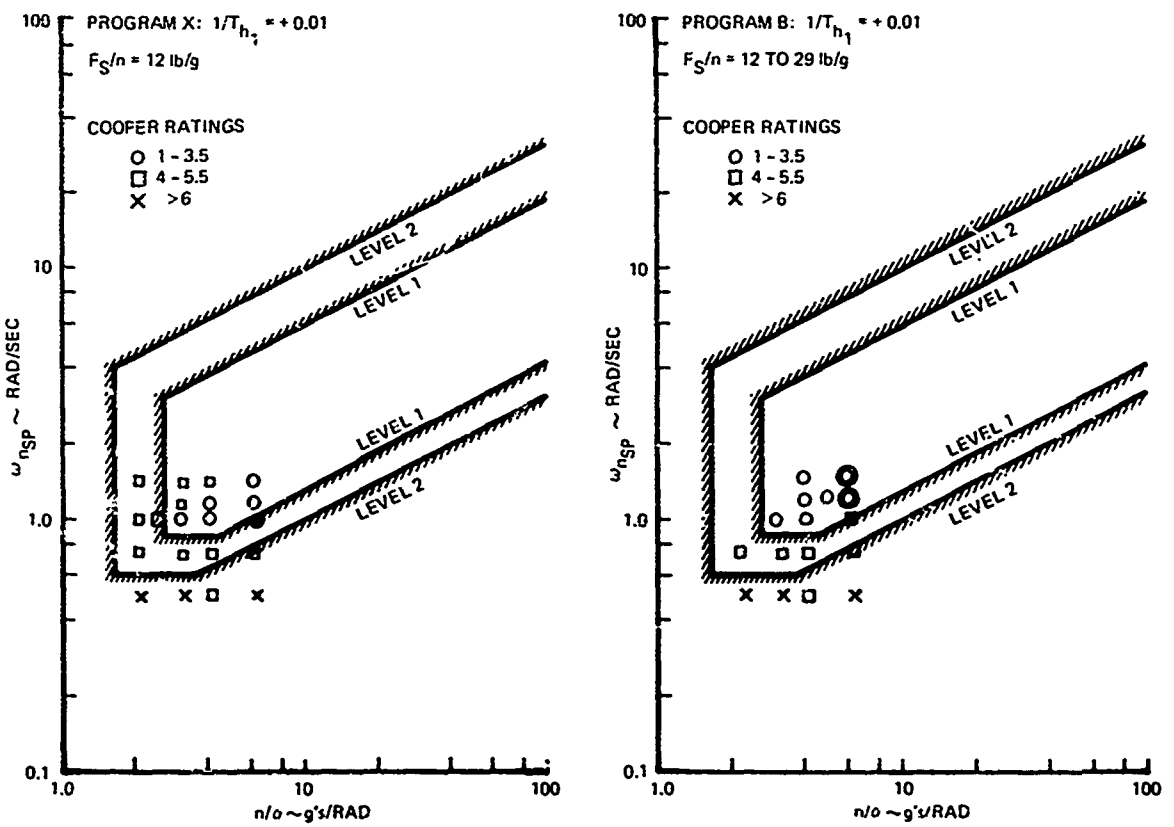


FIGURE 3. TYPICAL DATA FROM GROUND-BASED SIMULATION (FROM REFERENCE 3)

also

$$\frac{F_s}{\Delta n} = \frac{1}{\left(\frac{\Delta n}{\delta_e}\right)\left(\frac{\delta_e}{F_s}\right)} = \frac{\omega^2_{n_{sp}}}{\frac{\delta_e}{F_s} \cdot \frac{V}{g} \left(Z_{\delta_e} M_w - M_{\delta_e} Z_w\right)}$$

These algebraic equations can be manipulated to get

$$\frac{F_s}{\Delta n} = \frac{\omega^2_{n\,sp}}{M_{FS}\,(n/\alpha)}$$

where $M_{FS} = M_{\delta_e} \delta_e / F_s$, or the initial pitch acceleration per pound of stick force.

Written differently,

$$\frac{F_s}{n} \times M_{FS} = \frac{\omega^2_{n_{sp}}}{n/\alpha}$$

We can see that a lower and upper bound can be established for the parameter $\omega^2_{n_{sp}}/n/\alpha$ by arguing that values of the parameter could be found where a satisfactory compromise between sensitivity and steady-state forces might not be possible. This possibility has been demonstrated during inflight simulator tests by Cornell.[2] The pilots compromised in the selection of elevator-to-stick-force gearing on the basis of sensitivity and accepted light stick forces during steady-state maneuvers, but rated the configuration unacceptable. At the other extreme, in the same tests the pilots who compromised on steady-state forces by selecting low sensitivity to avoid abrupt response and by accepting high steady forces were obliged to rate the configuration unacceptable. Acknowledging the validity of the above argument and using data similar to that shown on Figure 2 from inflight simulation tests, the requirement on natural frequency as a function of n/α has been written[2] in a manner to bound the parameter $\omega^2_{n_{sp}}/\frac{n}{\alpha}$ as shown on Figure 1 of this paper.

Thus we have seen how inflight simulation data and simple analysis have been employed to establish part of the criteria of Section 3.2.2.1.1 of the Specification.

We see also on Figure 1 that there are lower bounds on $\omega_{n_{sp}}$ and n/α. Reference 3 indicates that pilot-in-the-loop analysis has established that there are, in fact, lower limits on

1. $\omega_{n_{sp}}$, for tasks requiring precise control of pitch attitude.
2. $\omega_{n_{sp}}$, n/α for tasks requiring precise control of pitch attitude and flight path.

In the first case, to maintain constant performance the pilot must supply phase lead as $\omega_{n_{sp}}$ decreases; this results eventually in degraded pilot rating. In the second case, the same argument holds for $\omega_{n_{sp}}$; and, further, as n/α decreases, more angle of attack change is required to control flight path, and the pilot ends up needing to overdrive the pitch attitude of the airplane, with resulting degradation of pilot rating. Closed-loop analysis had been used to formulate a rationale for lower bounding $\omega_{n_{sp}}$ and n/α, but before it could be used to define criteria some validation was provided by moving-base simulation using the Grumman ground-based simulator. The experiments were conducted for Class I and IV airplanes during carrier approaches, and Figure 3 shows how the data were used to validate the lower bounding of $\omega_{n_{sp}}$ and n/α.

This demonstrates the use of the pilot-in-the-loop analysis techniques and ground-based simulation in formulating criteria.

Another criterion pertaining to short-period response is the "short period damping requirement" of Paragraph 3.2.2.1.2, which states that the short-period damping ratio shall be within the limits of Table IV. Table IV is reproduced here as Figure 4. This criterion was based on extensive inflight simulator data similar to the data of Figure 2. It is interesting for this discussion in that engineering judgment rather than analysis was used in determining upper and lower limits on damping ratio. Further, arbitrary increments were added to account for turbulence. It is significant that validation of this criterion, discussed later, infers that the criterion leaves something to be desired, and suggests the need for testing to better define the effects of turbulence on acceptable damping ratio.

Consider the requirements on "Control Forces in Maneuvering Flight," Paragraph 3.2.2.2.1, which specifies that at constant speed in steady-turning flight, pull-ups, and push-overs, the variations in elevator-control force with steady-state normal acceleration must be approximately linear. In general, a departure from linearity is considered excessive which results in local gradients that differ from the average gradient for the maneuver by more than 50 percent. All local force gradients must be within the limits of Table V (reproduced here as Figure 5), etc.

This criterion is formulated from data from both ground-based and inflight simulator tests; while no mathematical analysis is involved, a sound engineering rationale is applied. It is argued that a pilot tends to select a constant value of stick force per g, (F_s/n), at high values of the load factor parameter (n/α), but constant-stick-force angle-of-attack gradients, (F_s/α), at low values of the load factor parameter in (n/α). It is suggested[3] that this is due to the pilot's concern shifting from structural integrity at high n/α to pitch attitude control at low n/α. On the basis of these concerns, the limits on F_s/n were expressed in the form $\frac{K}{n/\alpha}$ at low n/α, and $\frac{K}{(n_L - 1)}$ at high values.

LEVEL	CAT A & C FLIGHT PHASES		CAT B FLIGHT PHASE	
	MIN	MAX	MIN	MAX
1	0.35	1.30	0.30	2.0
2	0.25	2.00	0.20	2.0
3	0.15	———	0.15	———

FIGURE 4. SHORT-PERIOD DAMPING RATIO LIMITS (FROM REFERENCE 1)

When ground-based simulator data and inflight simulator data were reviewed, it was observed that the values $\frac{21}{n_L - 1}$ and $\frac{56}{n_L - 1}$ from the MIL-F-8785 bounded the Level 1 data points at the higher n/α, thereby suggesting their use as criteria (Figure 5). At the low values of the load factor parameter, the pilot rating data and comments suggested $F_S/n = \frac{240}{n/\alpha}$ would serve well as the Level 1 upper boundary (Figure 5). Because of the limited amount of low load factor parameter data, the lower limits of F_S/n were made constant for all values of the parameter n/α. It was also agreed that an upper bound probably existed for F_S/n at very low n/α; thus a fixed value of F_S/n as a function of n_L was established at values of n/α less than the lowest value used in the simulator tests which was approximately an n/α of 8 g's per radian. The following section on validation of this criterion, using flight test data obtained during the development and certification of the F-4 and F-5/T-38, will demonstrate in a general sense the soundness of the above method of using simulator data and engineering judgment in establishing criteria.

CENTER STICK CONTROLLERS		
LEVEL	MAX GRADIENT $(F_S/n)_{MAX}$	MIN GRADIENT $(F_S/n)_{MIN}$
1	$\frac{240}{n/\alpha}$ BUT NO MORE THAN 28.0 NOR LESS THAN $56/n_{L-1}$*	THE HIGHER OF $\frac{21}{n_{L-1}}$ AND 3.0
2	$\frac{360}{n/\alpha}$ BUT NO MORE THAN 42.5 NOR LESS THAN $85/n_{L-1}$*	THE HIGHER OF $\frac{18}{n_{L-1}}$ AND 3.0
3	56.0	3.0
*FOR $n_L < 3$, $(F_S/n)_{MAX}$ IS 28 FOR LEVEL 1, 42.5 FOR LEVEL 2.		

FIGURE 5. ELEVATOR MANEUVERING FORCE GRADIENT LIMITS (FROM REFERENCE 1)

FLIGHT TEST ANALYSIS IN ESTABLISHING CRITERIA

An important analysis process in improving Military Specification MIL-F-8785B (ASG) is the application of data taken during the development of airplanes, and certification of the airplanes to MIL-F-8785 (ASG). Such an endeavor requires the researching of past records, the conversion of pilot ratings from one scale to another, the analysis of pilot comments, and the redefining of the airplanes flying qualities in the parameter format of the new military specification.

Such an activity has been undertaken by McDonnell Douglas Aircraft using F4 flight test data[5] and by the Aircraft Division of Northrop Corporation using F-5/T-38 flight test data.[4] Both of these activities are being funded under contract by the Control Criteria Branch of AFFDL.

Figure 6 shows a comparison of Northrop T-38 data with the short-period frequency and the acceleration sensitivity criterion discussed in the preceding section. While there are no pilot ratings available, the airplane does meet the Level 1 and Level 2 requirements and has favorable handling qualities in the flight conditions shown. This tends to confirm the soundness of the method of applying simple and pilot-in-the-loop analyses to data taken from ground-based and inflight simulators.

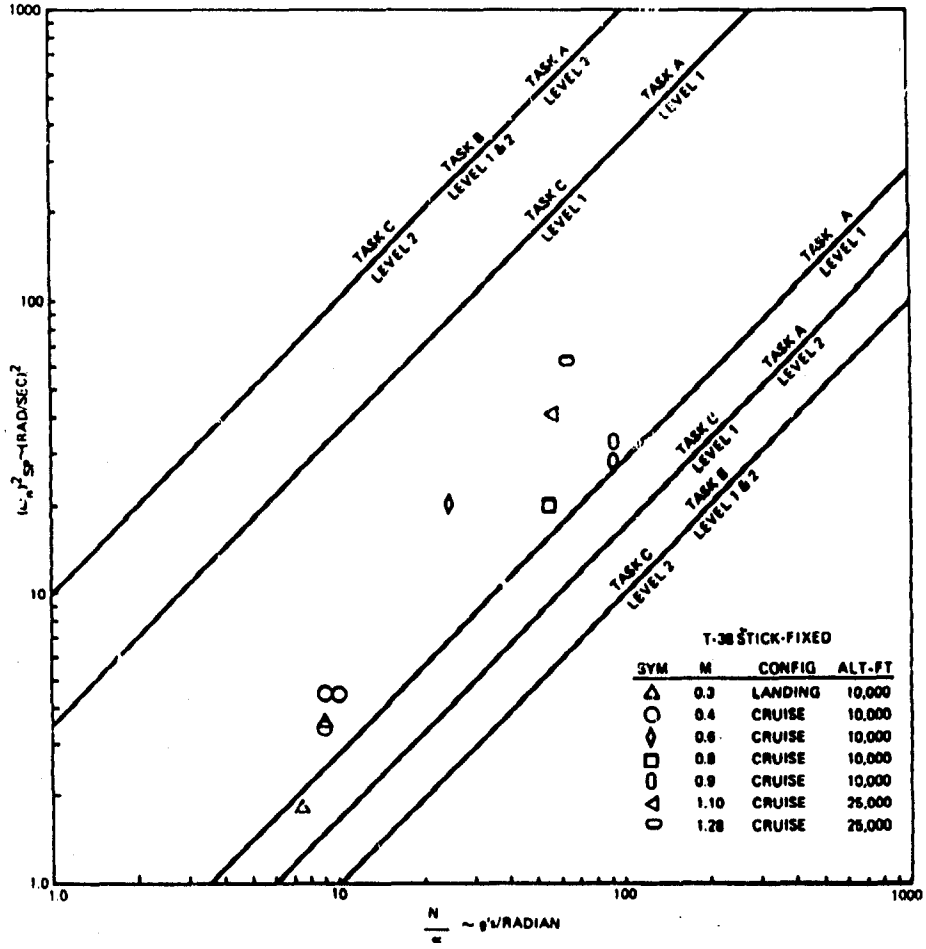


FIGURE 6. COMPARISON OF FLIGHT DATA WITH REQUIREMENTS (FROM REFERENCE 4)

The damping requirement does not fare so well in the validation process. The T-38 data on Figure 7 show that the airplane does not meet the requirements of Paragraph 3.2.2.1.2; yet the dynamic characteristics have been well received by pilots in evaluations. A similar conclusion was arrived at by McDonnell Douglas[5] when the F-4 was shown to have lower damping ratios than required by the specification under conditions where its flying qualities were acceptable.

The "control forces in maneuvering flight" requirement of 3.2.2.2.1 at Levels 1 and 2 are reasonably validated by the F-4 data of Figure 8, although little trend of F_S/n variation with n/α is apparent in the data. F-5/T-38 data in Reference 4 better confirm the soundness of the criteria for F_S/n as a function of n/α. It seems reasonable to assume, considering the amount of data from inflight and ground-based simulators used in formulating the requirement, that the F-4 and F-5/T-38 data should be consistent with the requirements, which they are.

The portion of the requirement stating that the local stick force gradient shall not differ by more than 50 percent of the average gradient during the maneuver is questionable. In the case of the T-38/F-5, the control system has non-linear gearing and force-to-stick deflection characteristics required to yield satisfactory flying qualities as well as to

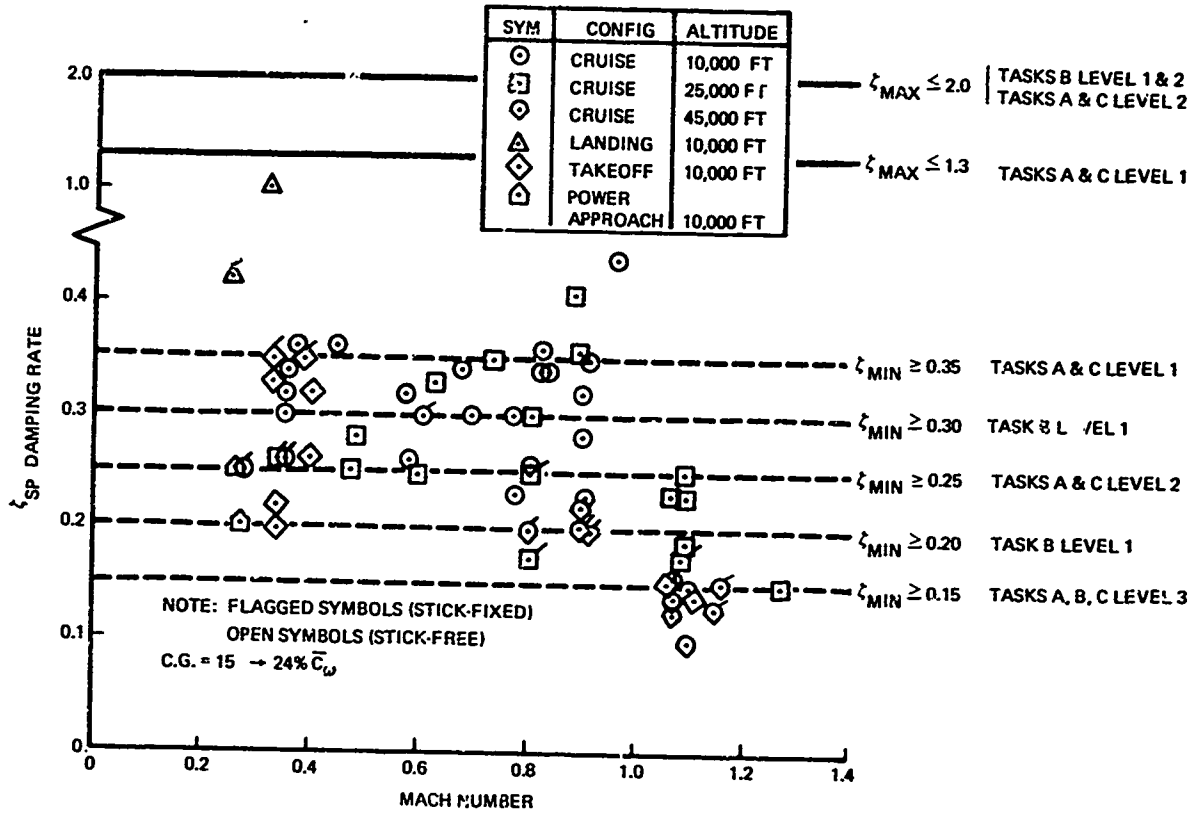


FIGURE 7. COMPARISON OF FLIGHT DATA WITH DAMPING REQUIREMENTS (FROM REFERENCE 4)

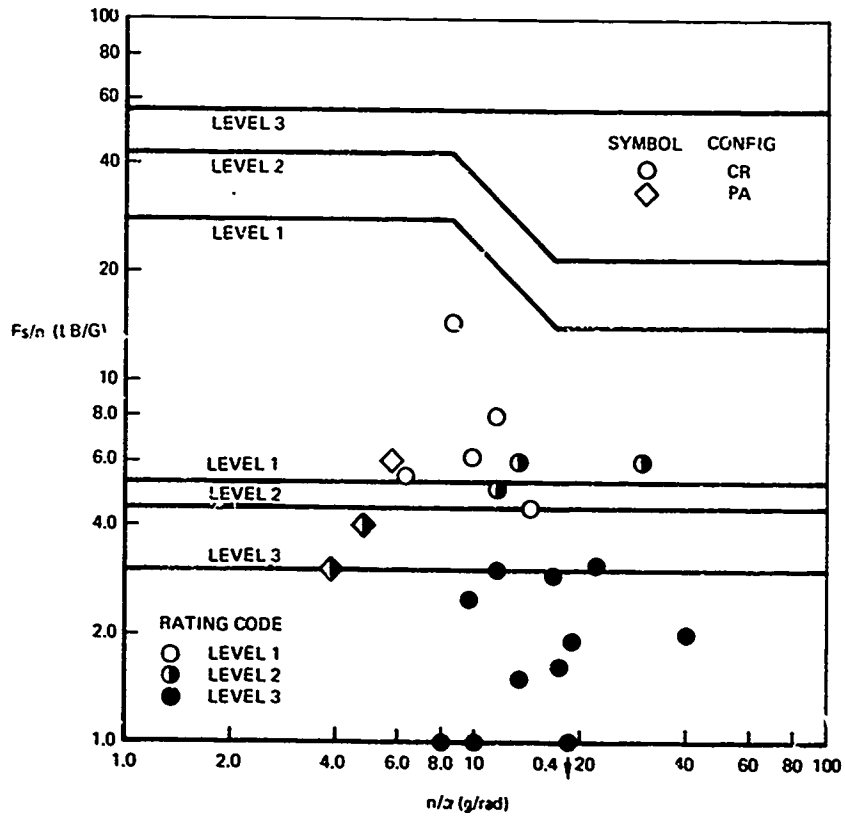


FIGURE 8. COMPARISON OF F-4 DATA WITH REQUIREMENTS
(FROM REFERENCE 5)

provide PIO protection. The basic system under static ground conditions has a ratio of maximum to minimum force-to-tail relationships which exceeds 2.0, and therefore even with linear aerodynamics the ratio of force gradients would be greater than 2.0 for all conditions of flight. Notwithstanding this, the aircraft's flying qualities in this regard are acceptable.

In the process of establishing and validating criteria, the interaction of the control system characteristics with the airplane short-period modal characteristics, and also the effect of turbulence on flying qualities, are identified as requiring better specification. For example, in Section 2.2.2.1, [3] in justifying the use of conventional-short period modal parameters as criteria, the following argument is made: "The control system specification of Section 3.5.3 will normally require the natural frequencies of the control system to be appreciably higher than the short-period natural frequency. The result will be no interaction between the control system dynamics and the airplane short-period mode." It is unlikely that this observation will be true as the Control-Configured Fighters with the control-augmented flight control systems come into being. The Control Criteria Branch, acknowledging[3] that what are desirable are criteria which are based on the response of the total system and independent of identifying certain modes of motion, has been funding inflight simulator tests and analyses at the Cornell Aero Labs to develop such criteria. [7]

The short-period damping ratio requirement, Section 3.2.2.1.1 of the military specification, is typical of the manner in which turbulence effects are handled. Substantial volumes of flight test data were reviewed and upper and lower limits were chosen for the damping ratio. Although some of the data had been collected in turbulence, when the specification levels were established, an incremental damping ratio was applied to the data to cover turbulence effects. The result of this is a specification of damping ratio which is overly stringent. In an attempt to better quantify turbulence criteria, the Control Criteria Branch at AFFDL has been funding ground-based simulator tests and analyses at Northrop.

The ground-based simulator tests and analyses of Reference 6 will be discussed to show how pilot-in-the-loop analyses and ground-based simulation can contribute to establishing more quantitative criteria for turbulence effects on flying qualities or to validate existing criteria. The inflight simulator tests and analyses of Reference 7 will be discussed to demonstrate the contribution of inflight simulation and analysis to the definition of criteria relating to flight control systems and their impact on flying qualities.

GROUND BASED SIMULATION AND ANALYSIS

Unpublished work conducted by Mehas at Northrop, and reported briefly, [9] has demonstrated that ground-based simulation of the lateral-directional motions of Class IV airplanes in the Northrop Large Amplitude Flight Simulator is comparable with inflight simulation. This has provided Northrop with a powerful tool with which to study the effects of turbulence on the lateral-directional handling qualities of Class IV airplanes. To complement this, Onstott[6] cleverly combined the techniques of multiloop analysis and pilot modeling with work by AFFDL personnel on statistical analysis, then developed a method of predicting pilot-airplane dynamic response to turbulence. The method could also be used in estimating the dynamic performance of the pilot-airplane system in compensatory tracking situations. Onstott's work was sufficiently general so that it could be applied to the longitudinal and lateral directional degrees of freedom, as he is currently extending the lateral-directional work of Reference 6 to the longitudinal case.

The Northrop Large Amplitude Flight Simulator (Figure 9), described in Reference 9, was used in the research to validate the performance prediction technique and to provide pilot ratings on the flying qualities of the airplanes simulated. An automated version of the prediction technique capable of analyzing the system typified by Figure 10 was developed and used in the research.

The airplanes used in the simulator and analysis were a selection of the airplanes used in the inflight simulation tests of Reference 8, plus the Northrop F-5. The airplanes characteristically had good dutch roll frequency and damping, and a neutrally stable spiral mode. The $|\phi/\beta|_d$ ratio, roll subsidence time constant T_R, $N'_{\dot{p}}$, and $N'_{\delta_A}/L'_{\delta_A}$ ratio were varied in the simulator experiment.

The pilot performance in four tasks was evaluated during the simulation as follows:

Task 1, maintaining zero bank angle in the presence of turbulence. Side gusts were introduced to the airplane model, and the bank angle error was displayed on the vertical command bar of the ADI. The pilot's task was to minimize the bank angle error without the application of rudder.

Task 2, compensatory tracking of a random bank angle. Filtered white noise was used to provide the commanded bank angle. The difference between this signal and the actual bank angle was used to drive the vertical command bar on an ADI. The pilot's task was to keep the needle centered by controlling bank angle without the application of rudder.

Task 3, compensatory tracking of a random heading signal. Filtered white noise was used to provide the commanded heading angle. The difference between this signal and the actual heading was used to drive the vertical command bar on the ADI. The pilot's task was to keep the needle centered by use of ailerons without the application of the rudders.

Task 4, maintain zero heading in the presence of turbulence. Side gusts were introduced and the heading error was displayed on the vertical command bar of the ADI. The pilot's task was to minimize the heading error without the application of rudder.

Figure 11 shows the typical block diagrams for the first two tasks. The remainder of the discussion will concern itself with these tasks since they will be adequate to show the use of simulation and analysis in establishing criteria.

Analytically, it is required (1) to obtain transfer functions for the bank angle to gust disturbance, and (2) the bank angle to bank angle command with the proper loop closures. Noting that all the appropriate loops are to be closed, the following equations are used to describe the airplane.

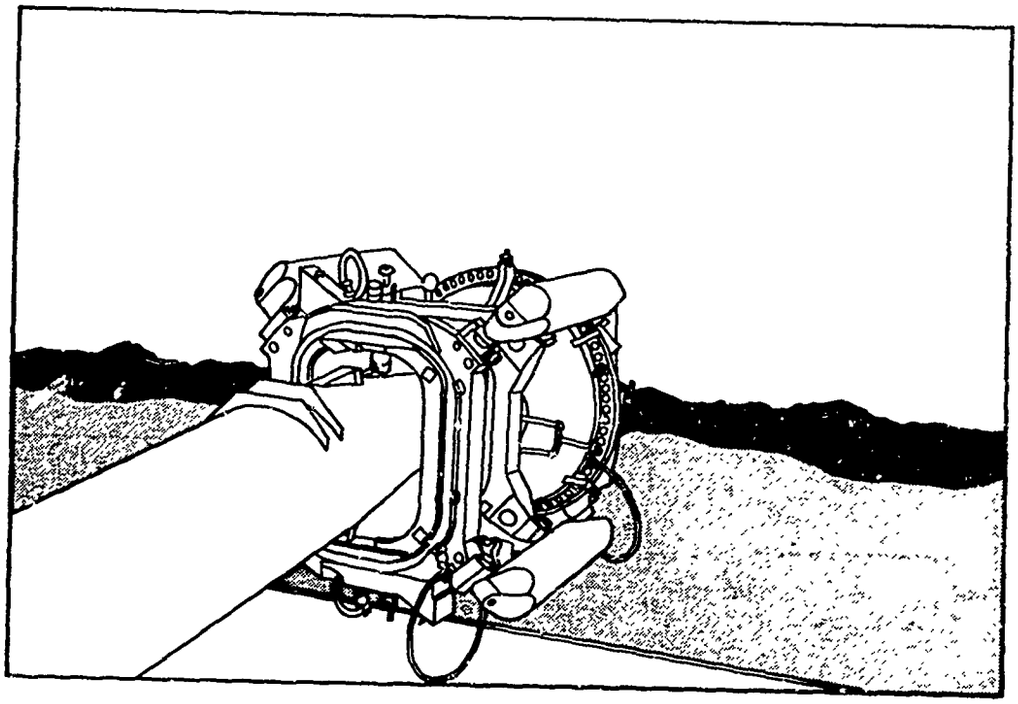


FIGURE 9. NORTHROP LARGE AMPLITUDE FLIGHT SIMULATOR

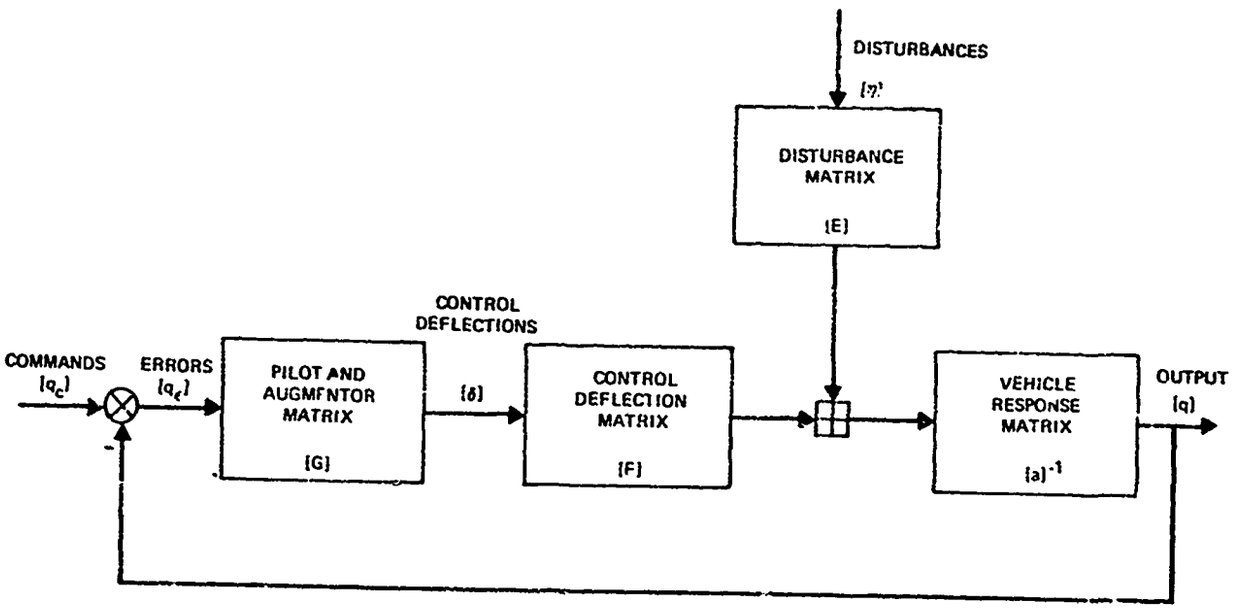
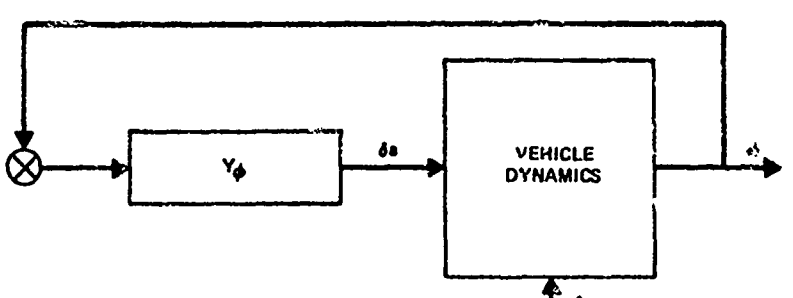


FIGURE 10. MULTILOOP BLOCK DIAGRAM (FROM REFERENCE 6)



BANK ANGLE CLOSURE IN TURBULENCE

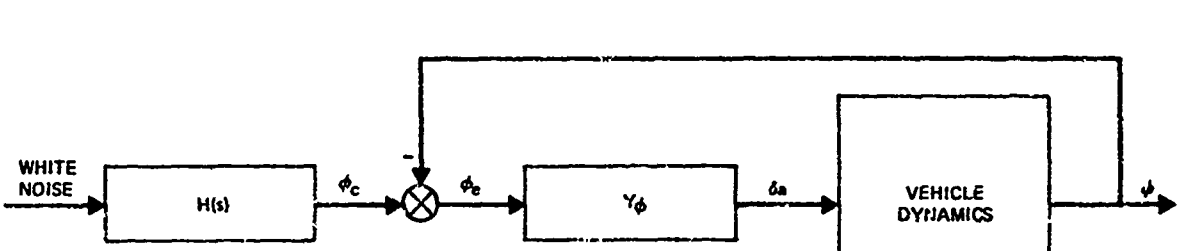


FIGURE 11. BANK ANGLE CLOSURES (FROM REFERENCE 6)

$$\left(-\frac{g}{U_o}\cos\theta_o\right)\phi + \left(1-\frac{g}{U_o}\sin\theta_o\frac{1}{s}\right)r + (s-Y_v)\,\beta = Y^*_{\delta_A}\,\delta_A + Y^*_{\delta_R}\,\delta_R + Y_v\,\delta_{\beta_g}$$

$$s(s-L'_p)\,\phi + (-L'_r)\,r + (-L'_\beta)\,\beta = L'_{\delta_A}\,\delta_A + L'_{\delta_R}\,\delta_R + L'_\beta\,\delta_{\beta_g}$$

$$(-sN'_p)\,\phi + (s-N'_r)\,r + (-N'_\beta)\,\beta = N'_{\delta_A}\,\delta_A + N'_{\delta_R}\,\delta_R + N'_\beta\,\delta_{\beta_g}$$

$$\left(\frac{1}{s}\sec\theta_c\right)r = \psi$$

Based on the technique of Reference 6, the following expression for the ϕ/ϕ_c and ϕ/δ_{β_g} transfer functions are obtained:

$$\frac{\phi}{\delta_{\beta_g}} = \frac{N^{\phi}_{\delta_{\beta_g}} + Y_\psi\,N^{\phi}_{\delta_{\beta_g}}\,\frac{\psi}{\delta_A} + Y_\beta\,N^{\phi}_{\delta_{\beta_g}}\,\frac{\beta}{\delta_R} + Y_r\,N^{\phi}_{\delta_{\beta_g}}\,\frac{r}{\delta_R}}{\Delta''}$$

$$\left|\begin{array}{l} r\to\delta_R \\ \beta\to\delta_R \\ \phi\to\delta_A \\ \psi\to\delta_A \end{array}\right.$$

$$\frac{\phi}{\phi_e} = \frac{Y_\phi\left(N^{\phi}_{\delta_A} + Y_r\,N^{\phi}_{\delta_A}\,\frac{r}{\delta_R} + Y_\beta\,N^{\phi}_{\delta_A}\,\frac{\beta}{\delta_R}\right)}{\Delta + Y_\psi\,N^{\psi}_{\delta_A} + Y_p\,N^{r}_{\delta_R} + Y_\beta\,N^{\beta}_{\delta_R} + Y_\psi\,Y_\beta\,N^{\psi}_{\delta_A}\,\frac{\beta}{\delta_R}}$$

$$\left|\begin{array}{l} r\to\delta_R \\ \beta\to\delta_R \\ \phi\to\delta_A \\ \psi\to\delta_A \end{array}\right.$$

The N-symbol polynomials (i.e., $N^{\psi}_{\delta_A}$___) are computed by evaluating the proper determinants, and detailed expressions, with rules for deviation, are given in Reference 6. Typically, the N-symbol polynomial will have the form

$$N^{\phi}_{\delta_{\beta_g}} = (-L'_\beta)\,s^2 + (L'_\beta\,N'_r - N'_\beta\,L'_r)s$$

and

$$N^{\phi}_{\delta_{\beta_g}} \; N^{\psi}_{\delta A} = \sec \theta_o \left(- L'_{\beta} \; N'_{\delta_A} + L'_{\beta} \; L_{\delta_A} \right)$$

The pilot transfer functions typically will take the form of the ratio of polynomials

$$Y_{\phi} = K_{\phi} \frac{P_{\phi_1}}{P_{\phi_2}} \cdot \frac{D_{\phi_1}}{D_{\phi_2}}$$

Onstott (6) has developed some clever rules for the manipulation and evaluation of the above transfer functions and N-symbols, and the reader is referred to this work for more specific details than are possible in this paper.

Since the pilot does not act on heading or sideslip, in the particular case of Task 1, the pilot models Y_{ψ} and Y_{β} are set to zero, and the total system transfer function of bank angle to δ_{β_g} is written

$$\left. \frac{\phi}{\delta_{\beta_g}} \right|_{\phi \rightarrow \delta_A}$$

and, if H(s) is the transfer function of the random gusts (in this case of the Dryden form), then

$$\text{rms } \phi_e = \hat{\phi}_e = \frac{1}{2\pi j} \int_{-j\infty}^{j\infty} \left| H(s) \cdot \left. \frac{\phi}{\delta_{\beta_g}} \right|_{\phi \rightarrow \delta_A} \right|^2 ds$$

This expression can be evaluated digitally employing the method described in FDCC TM 65-17 for a given root mean square gust level.

In the case of Task 2, the open loop transfer function $\phi/\phi_e \big|_{\phi \rightarrow \delta_A}$ can be used to obtain

$$\phi_e = \phi_c - \phi_c \left[\frac{\left. \phi/\phi_e \right|_{\phi \rightarrow \delta_A}}{1 + \left. \phi/\phi_e \right|_{\phi \rightarrow \delta_A}} \right]$$

and, if H(s) represents a normalized random appearing command signal,

$$\text{rms } \phi_e = \hat{\phi}_e = \frac{1}{2\pi j} \int_{-j\infty}^{j\infty} \left| H(s) - H(s) \left(\frac{\left. \phi/\phi_e \right|_{\phi \rightarrow \delta_A}}{1 + \left. \phi/\phi_e \right|_{\phi \rightarrow \delta_A}} \right) \right|^2 ds$$

This can be evaluated in the manner of FDCC TM 65-17.

This, then, provides a process for calculating the performance expected of the pilots in the simulator experiments. Figure 12 shows typical data from the computerized form of the above method, where a pilot describing function

$$Y_{\phi} = K_{\phi} \; (.5\, s + 1)\, e^{-.3\, s}$$

is used for Task 1 and

$$Y_{\phi} = K_{\phi} \; (.5\, s + 1)\, e^{-.44\, s}$$

is used for Task 2. The variation of $\hat{\phi}_e$ with pilot lead T_L is typical for all the cases tested, and is offered as justification of the use of a value of 0.5 for the leadtime constant T_L. Employing this value of the leadtime constant, the predicted tracking performance is taken to be the minimum attained as K_{ϕ} is varied in the manner of Figure 12.

Figure 13 shows a comparison of the predicted and measured performance during the tracking-in-gust task and, being typical, attests to the accuracy of the prediction techniques.

For clarity in the remainder of the discussion, the following code is used to distinguish the airplane configuration tested: "Configuration A B 2.6," where A refers to the $|\phi/\beta|_d$ ratio, B the roll time constant T_R, 2 the value of yawing moment due to roll rate N_p, and 6 the value of the ratio of yawing moment to rolling moment due to ailerons. Further,

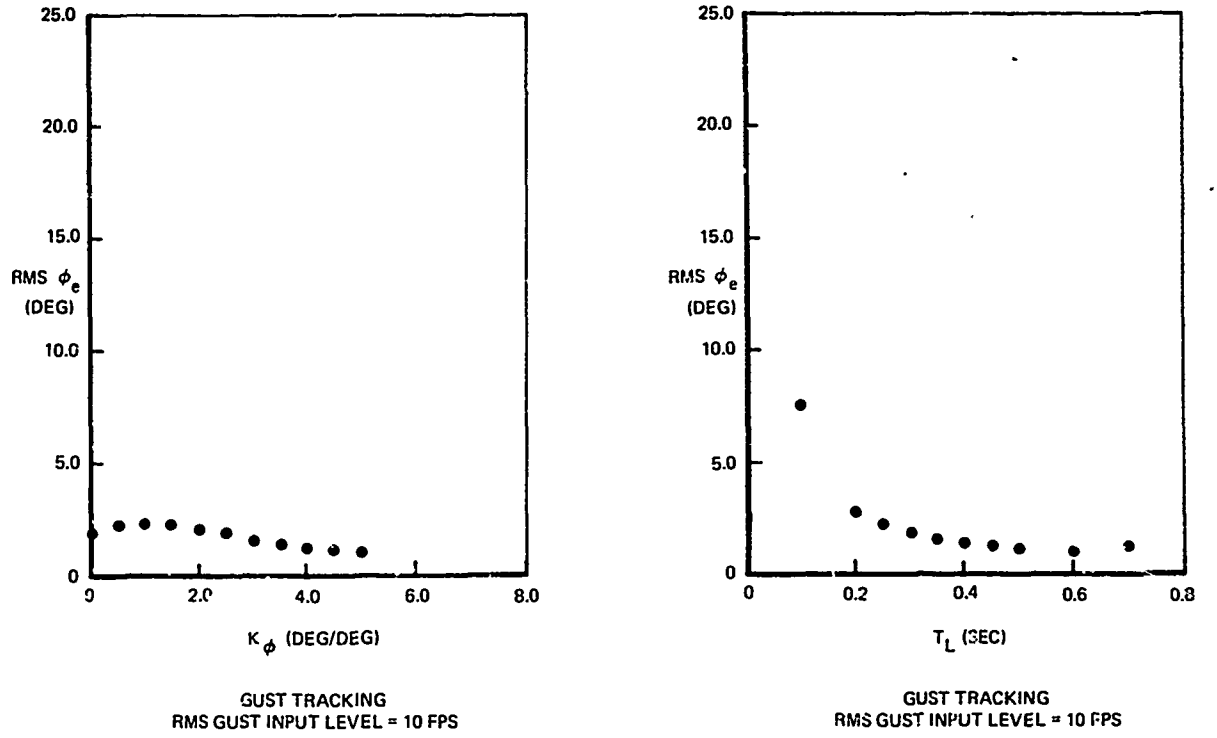


FIGURE 12. COMPUTED TRACKING PERFORMANCE WITH PILOT LEAD AND GAIN VARIATIONS (FROM REFERENCE 6)

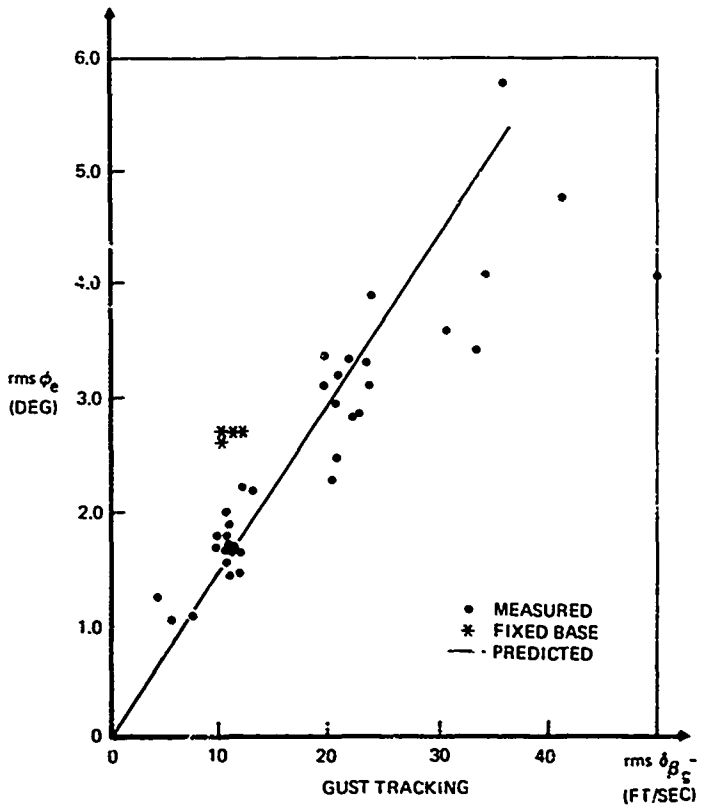


FIGURE 13. COMPARISON OF COMPUTED AND MEASURED PERFORMANCE IN SIMULATED T-33-AB2.6. (FROM REFERENCE 6)

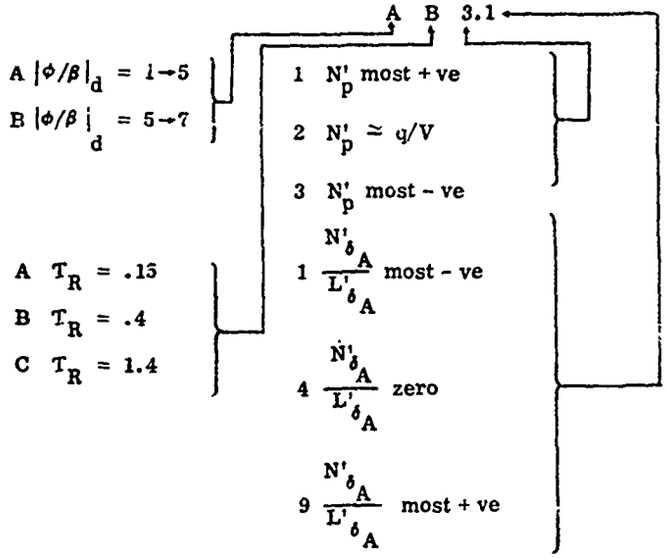


Figure 14 shows the predicted Task 1 and Task 2 pilot performance in nine airplane configurations. Superimposed on the graph is the pilot rating assigned during Task 1 in different turbulence levels. If we use the following reasoning (see next paragraph), then the data on this figure further validate the applicability of the analytical model.

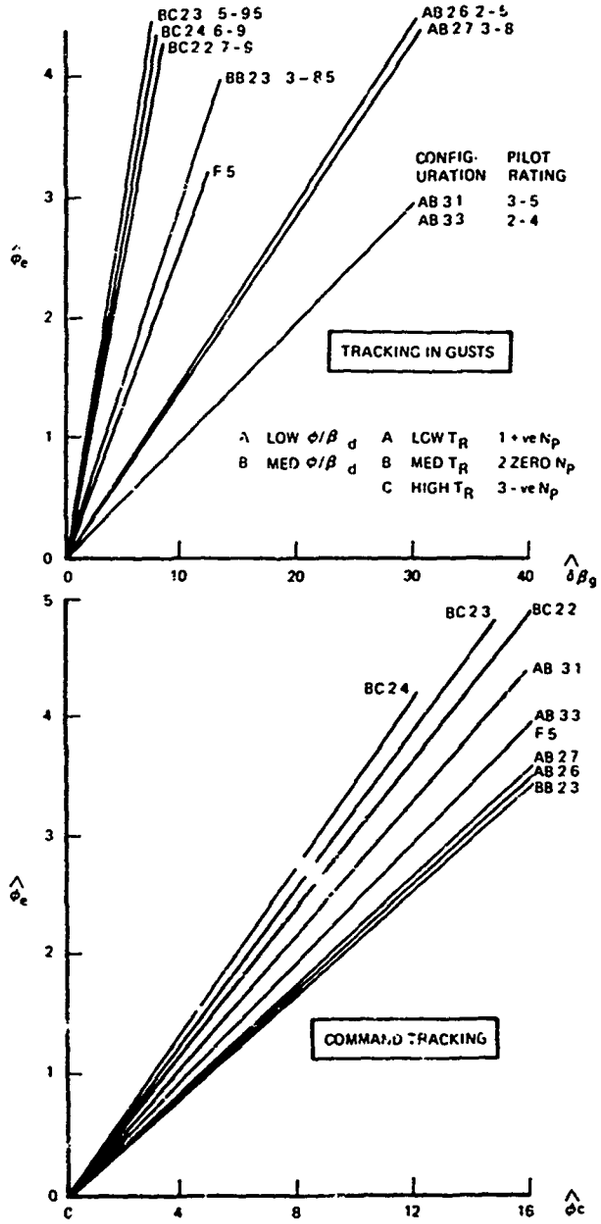


FIGURE 14. EFFECTS OF CONFIGURATION ON COMPUTED PERFORMANCE

In the case of Task 1 we might expect the configuration with the highest $|\phi/\beta|_d$ ratio to have the highest bank angle errors in turbulence because of the high bank angle disturbances caused by β gusts. This is confirmed by the data on Figure 14. Also, it may be expected that the configurations with the lowest roll damping (highest T_R) would have the highest $\hat{\phi}_e$, and this is again confirmed by the data on Figure 14. Rather less obvious, we may expect that within a configuration group, configurations with positive N'_p would exhibit the highest bank angle errors. The rolling rate induced by the sidegust would tend to aggravate the amount of sideslip, hence increasing $\hat{\phi}_e$. On Figure 14, the highest $\hat{\phi}_e$ for Configuration AB occurs at the more positive N'_p.

Comparison of the data for Task 1 and Task 2 (lower and upper graphs, respectively) indicates an important finding of the work, namely, that a configuration with the best performance in compensatory tracking BB2.3 is not necessarily the best configuration for holding bank angle in turbulence.

So much for performance alone. We have demonstrated that we have an excellent means of predicting performance, which is configuration- and task-sensitive. The ideal thing then would be to have some means of predicting pilot rating with similar accuracy. Criteria could then be specified in the manner of MIL-F-8785B(ASG), where levels of flying qualities are specified which are combinations of pilot work load and mission effectiveness. It has not at this time been possible to predict pilot rating, or to establish a rating that is a combination of performance and pilot work load. The work is not complete, and a great deal more data have been acquired through further analysis and simulation. It does seem that such a prediction may be possible, and Figure 15 will be used to illustrate the kind of thinking involved.

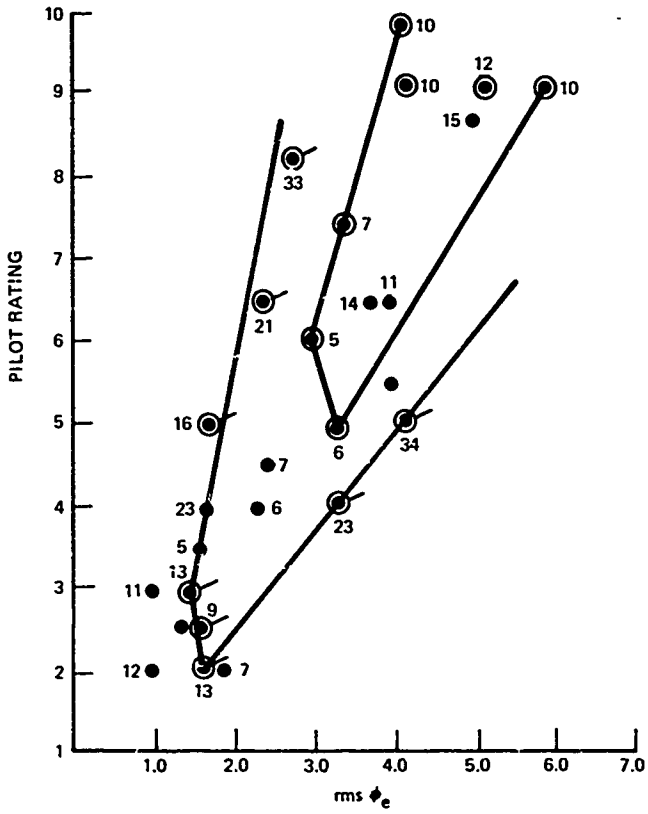


FIGURE 15. RELATIONSHIP BETWEEN PILOT RATING AND TRACKING ERROR

On Figure 15, the pilot ratings of Task 1, the holding bank angle in turbulence task, are plotted against bank angle error. Superimposed on the data is the rms gust level for each case. The first observation is that the configurations with the higher $|\phi/\beta|_d$ ratios have the worst pilot ratings and in turbulence of much lower levels than the lower $|\phi/\beta|_d$ ratio configurations. This indicates a strong configuration-dependence on $|\phi/\beta|_d$ ratio at constant ω_{n_d} and ζ_d. In fact, this is consistent with the reasoning behind the requirement of Paragraph 3.3.1 of the Military Specification, where increased dutch roll damping is required as a function of $\omega_n^2 |\phi/\beta|_d$.

The material in the Paragraph 3.3.1 of the Military Specification follows from work by Ashkenas in which he analyzes data where pilot rating was obtained by curve-fitting flight data obtained during investigations of airplane dutch roll characteristics. In fact, the criterion was specifically created to accommodate the effects of side gust on roll acceleration. It is possible that through a review and an extension of the work of Ashkenas, and through application of the results of the current experiments, a better criterion for the effects of turbulence can be established.

A further observation from the data of Figure 15 is possible by comparing the AB2 configurations. The prediction technique would indicate (Figure 14) that we may have expected the $\hat{\delta}_c$ for a given δ_{β_g} to be similar for AB2.6 and AB2.7. This is not the case, as shown on Figure 15. It is possible that the pilot worked harder to maintain lower tracking error on AB2.7 than on AB2.6. The increased work load would account for the higher pilot ratings assigned the AB2.7 configuration. If this is the case, as the data on Figure 15 imply, it may be possible to analyze the data in the manner of Anderson[10] and to establish a criterion that involves performance and pilot work load.

I have tried to illustrate in some detail the kind of work that can be accomplished by judiciously employing ground-based simulation and analysis. The ground-based simulator is ideal for this kind of work since turbulence can be produced under controlled experimental conditions, something which has been difficult in the past to achieve with inflight simulators. Inflight simulators historically have possessed inadequate means of producing simulated side acceleration in flight. The coming on the scene of TIFS, with its direct lift and sideforce producers, makes possible accurate inflight gust simulation. The combined use of TIFS and ground-based simulators such as the Northrop Large Amplitude Flight Simulator may be necessary to completely resolve the question of specifying flying qualities requirements in turbulence.

INFLIGHT SIMULATION AND ANALYSIS

It has been noted in a previous section that existing flying qualities criteria require simplifying assumptions on the impact of the control system dynamics on other airplane modal characteristics. Some work conducted to provide information to eliminate the need to identify modes of motion was conducted by Cornell and serves to illustrate the application of inflight simulation and analysis in establishing flying qualities criteria. An interesting thing about the analysis is that, like the work of Onstott and Salmon, it leans heavily on the work of STI for the general rules of manipulation, but Neal and Smith felt that the STI techniques were not specific enough for this application. The same motivation had led Onstott and Salmon to use a statistical format for their analysis.

Figure 16 shows a block diagram representation of a typical Flight Control System-airplane combination employed in the tests. The FCS consisted of a real pole-zero combination close to the $T\theta_2$ zero of the airplane and a complex pair of poles that varied from values close to the short period poles to $\omega_3 = 75$ rad/sec. The variable-stability T33, Figure 17, was used as the inflight simulator for the experiment. The feel system characteristics were held constant at a spring gradient of 22 lb/inch, and the elevator/stick force gradient was selected by the pilot for each flight. The same compromise discussed earlier between steady-state stick force per g and stick sensitivity had to be made on each flight in order to eliminate stick force as a variable in the evaluation.

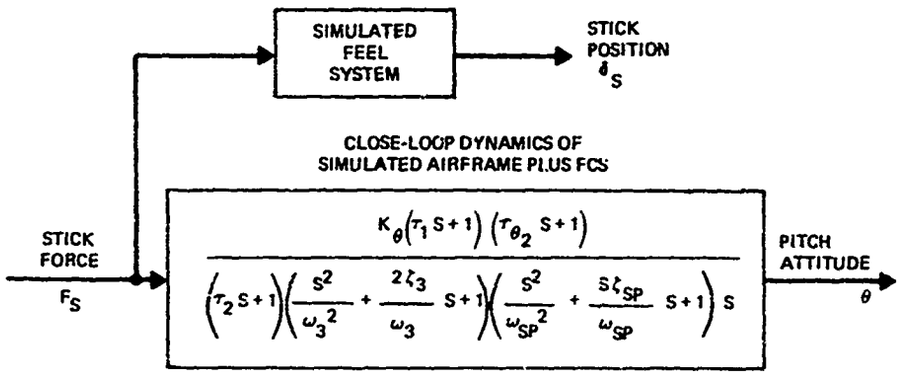


FIGURE 16. BLOCK DIAGRAM FOR BASIC CONFIGURATIONS SIMULATED (FROM REFERENCE 7)

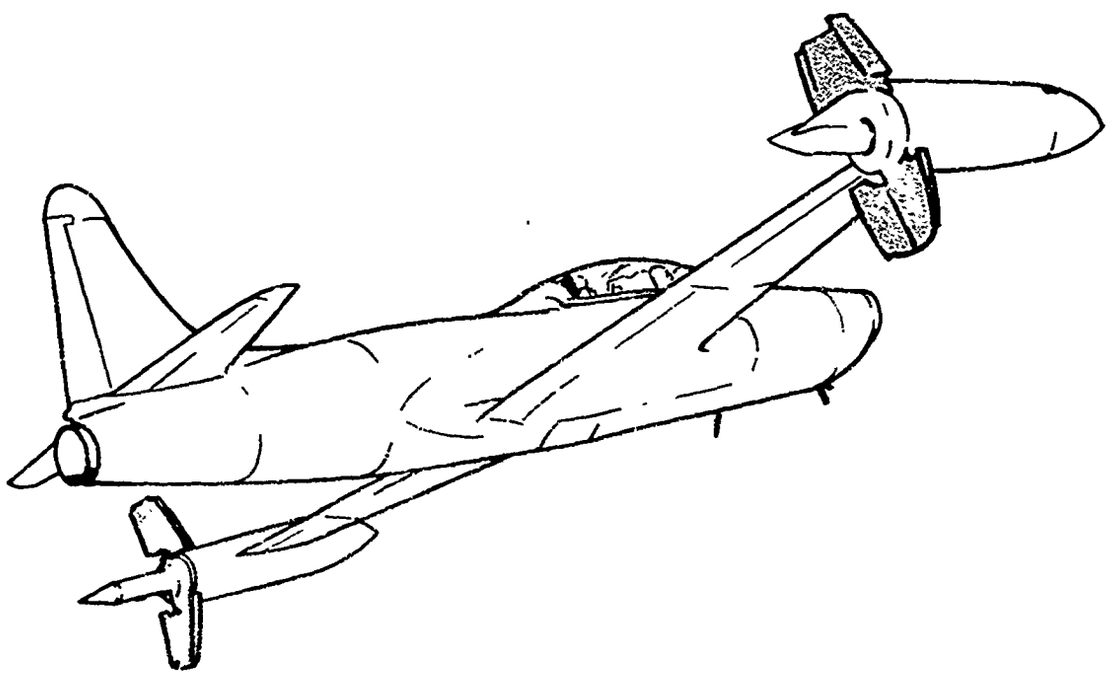


FIGURE 17. T-33 AIRPLANE WITH L/D DRAG PETALS EXTENDED TO FULL OPEN POSITION

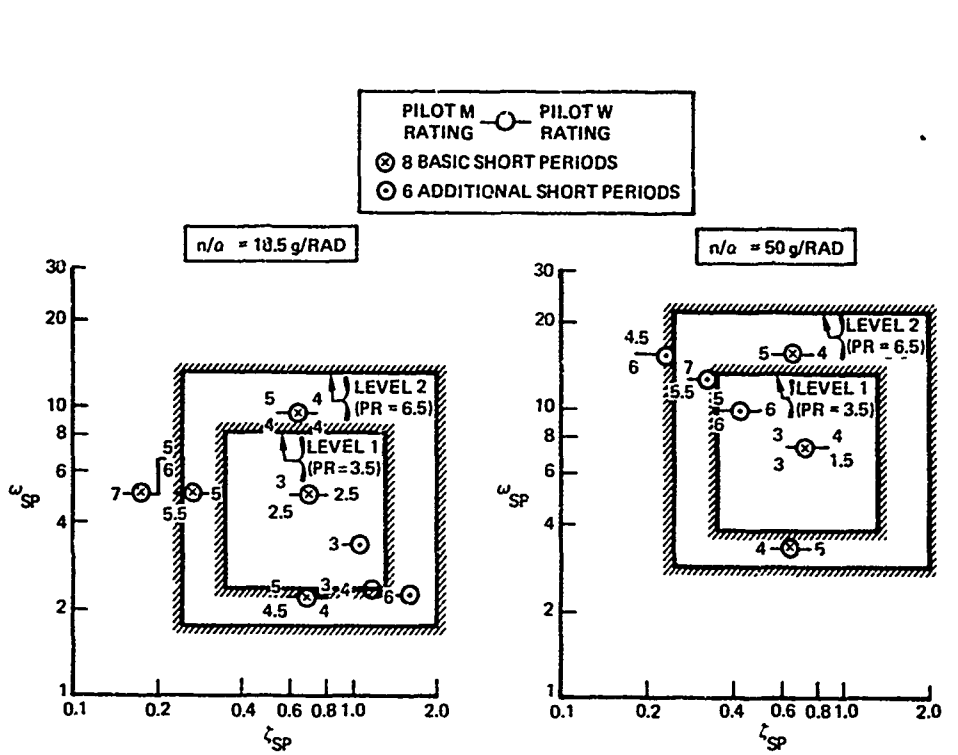


FIGURE 18. CORRELATION OF PILOT RATINGS WITH MIL-F-8785B – (FROM REFERENCE 7)

The tasks employed in the simulation were typical of Class IV airplanes in the air combat mission and included VFR and IFR maneuvering and tracking. Pilot rating and PIO rating data and pilot comments were the only data taken.

The basic short-period characteristics of the airplanes simulated are shown on Figure 16, along with the associated pilot ratings for conditions where no FCS effects were included. The correlation with MIL-F-8785B(ASG), Section 3.2.2.1, is good for the two n/α values investigated, with the exception of the high-frequency cases at n/α = 50 g/rad. For the cases where the FSC effect were included, the data are plotted on Figure 19 as pilot rating versus control surface phase lag at the short-period natural frequency. The correlation with the MIL-F-8785B(ASG) Section 3.5.3 requirement shown on Figure 19 is very poor indicating a shortcoming in the requirement for the configurations studied. The attitude of the Cornell researchers was that a criterion could be established which was based on the characteristics of the total response. They tested the validity of the well known C* criteria and the equivalent Second-Order System criteria and concluded that these were not appropriate, the first because it lacked generality and the second because of the insensitivity of certain parameters. The authors then developed an analysis procedure based on standard frequency response techniques and the pilot closure rules of Ashkenas and McRuer. Essentially the method involved:

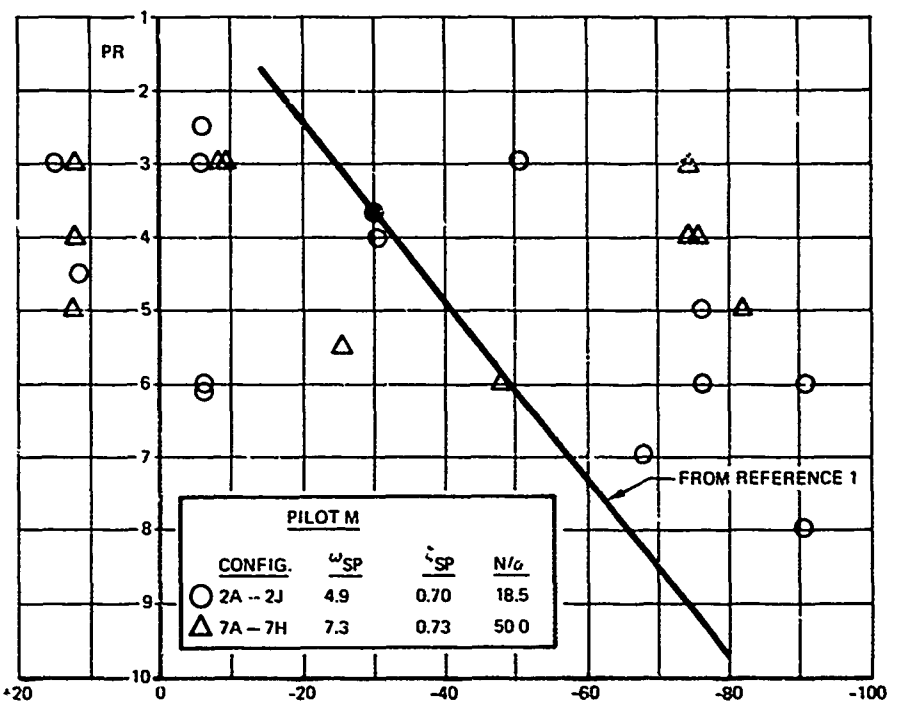


FIGURE 19. VARIATION OF PR WITH CONTROL SYSTEM PHASE ANGLE AT $\omega = \omega_{SP}$ (FROM REFERENCE 7)

1. Providing a mathematical model of the closed loop tracking task.
2. Establishing a series of performance measures describing a "standard of performance" which the pilot tries to achieve.
3. Develop a method of converting open loop characteristics to closed loop characteristics.
4. Establish a method for determining how the pilot is likely to apply compensation to achieve the performance standards.
5. Develop a method of relating tracking performance and pilot compensation to pilot opinion.

The form of the tracking performance standard was specified as follows:

1. A minimum bandwidth for the total closed loop system of 3.5 rad/sec
2. A maximum low frequency droop of -3db at frequencies below ω_{BW}
3. A closed loop resonance θ/θ_c which is a function of the pilot compensation required.

The pilot compensation is the phase relation between the pole and zero in the assumed form of the pilot transfer function

$$\frac{Fs}{\theta e} = Kp\, e^{-.35} \left(\frac{\tau_{p1} s + 1}{\tau_{p2} s + 1}\right).$$

and pilot compensation is take : to be

$$\angle_{pc} = \angle \left(\frac{j\omega\tau_{p1} + 1}{j\omega \tau_{p2} + 1}\right) \omega = (BW)_{min}$$

Employing an interesting open-to-closed-loop transformation technique using Nichol's charts, the authors computed the pilot compensation and closed-look resonance for each condition tested. The correlation of the computed values of these parameters with pilot opinion provides the criterion boundaries shown on Figure 20. The correlation is sufficiently good to suggest the use of the method to specify flying qualities criteria for Class IV airplanes.

While the details of the methods of analysis and inflight simulator experiments have not been presented, it is hoped that the use of inflight simulation and analysis in attempting to establish criteria has been adequately demonstrated.

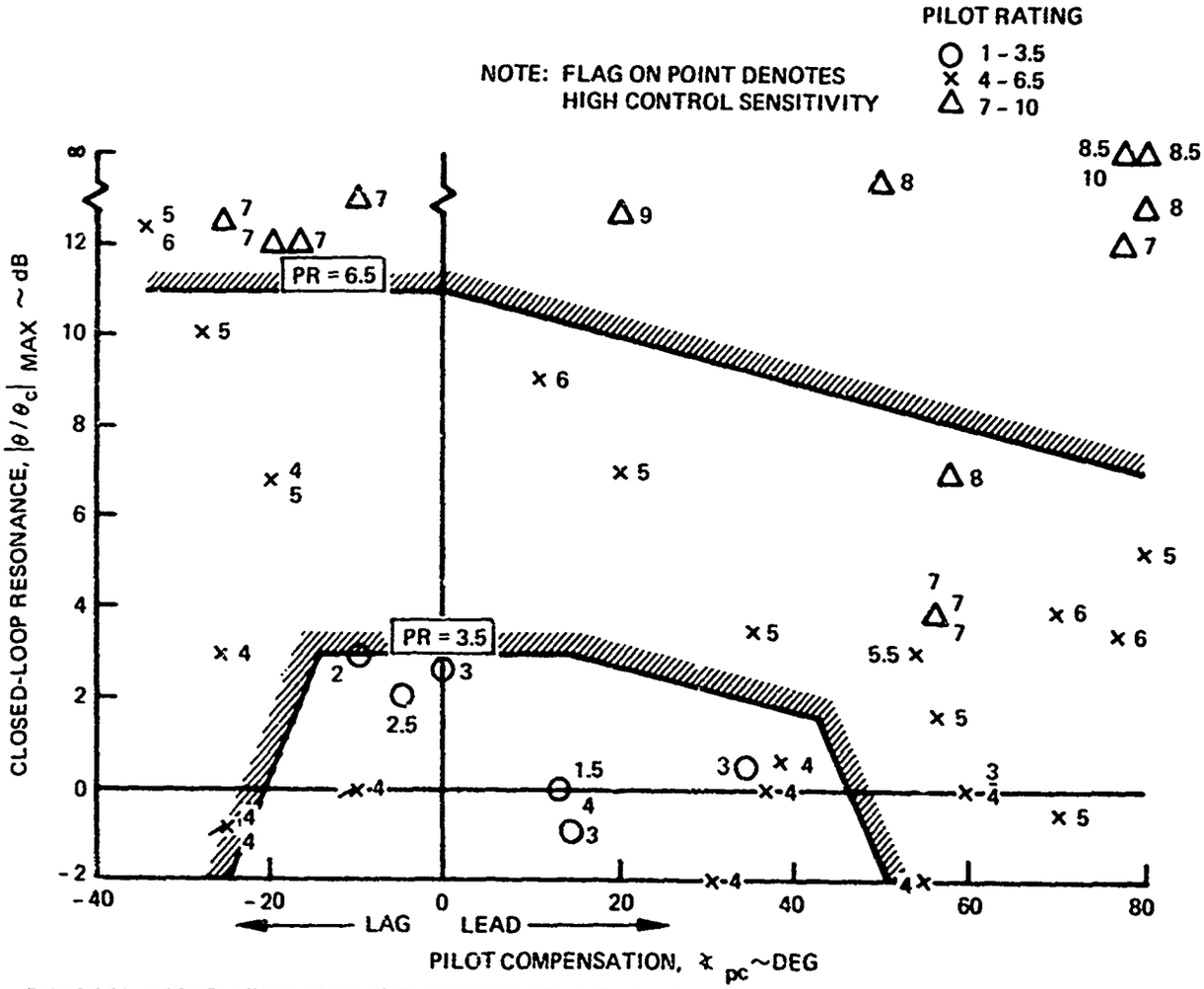


FIGURE 20. CORRELATION OF PILOT W RATING DATA WITH CLOSED-LOOP PARAMETERS (FROM REFERENCE 7)

TOWARD IMPROVED SIMULATION CAPABILITY

In discussing the use of simulation and analysis in establishing criteria, no indication has been given of the adequacy or inadequacy of the reproduction of the motion and visual cues involved.

There are significant imperfections in ground-based simulators in the quality of motion reproduction. Consider the comparison of model acceleration, and model roll rate, with simulator acceleration and roll rate shown on Figure 21. It is clear that while the response to turbulence of the model and simulator is close, the response to step control inputs is grossly affected by the simulator motion system. Of course this is only a small part of the complete story, and it is possible by proper mixing of the visual and motion cues[9] to achieve a synthetic environment in which correct pilot response can be achieved. One might think of ground simulators as good fixed-based visual displays carried on adequate motion systems. The demand from the motion system is mainly to provide adequate motion onset cues with an unavoidable minimum of associated improper motion cuing within the perception level of the pilot. Figure 22 shows the Northrop Large Amplitude Flight Simulator and a wide-angle visual display (LAS/WAVS) which will be used in the continuing research on the effects of turbulence on flying qualities of piloted airplanes. This simulator has been developed to allow realistic simulation of most tasks required of Class IV airplanes, including air-to-air combat, and will be available to complement in-flight simulators in the determination of flying qualities criteria for piloted airplanes.

It is probable that until inflight simulators are available with high load-factor and Mach number performance, simulators such as the LAS/WAVS will play an important part in research on the flying qualities of air-to-air combat airplanes. The inflight simulator which might be used in the development of flying qualities criteria has technology difficulties of a similar nature to the ground-based simulator. Consider Figure 23, which shows in block diagram form the key aspects of ground-based and inflight simulators. In ground-based simulators, we can work on the simulation of visual and motion cues independently.[9] On inflight simulators, the visual cues are inseparably involved with the motion cues. If the motion response on the inflight simulator to inputs is improper, then the visual cues will be inadequate and the inflight simulator will cease to respond like an airplane. This is characteristic of certain inflight simulators in use today and may be characteristic of model-following variable stability systems. The Cornell TIFS, Figure 24, provides an excellent opportunity to explore the problems of simulating the VFR environment and operation of airplanes and of developing a procedure for the proper reproduction of motion and visual cues in flight.

An airplane that would expand the research capability in the area of flying qualities of Class IV airplanes is a variable stability version of a high-performance Class IV airplane. The airplane shown in Figure 25 is typical of what could be accomplished. Canards, flaps, and direct side-force producers could be used in conjunction with the usual control surfaces to provide simulation in all degrees of freedom. Careful application of response feedback and model-following techniques could overcome the problem of improper visual and motion cues in large-angle, rapid, flight path changing maneuvers. The result would be an excellent high-performance inflight simulator.

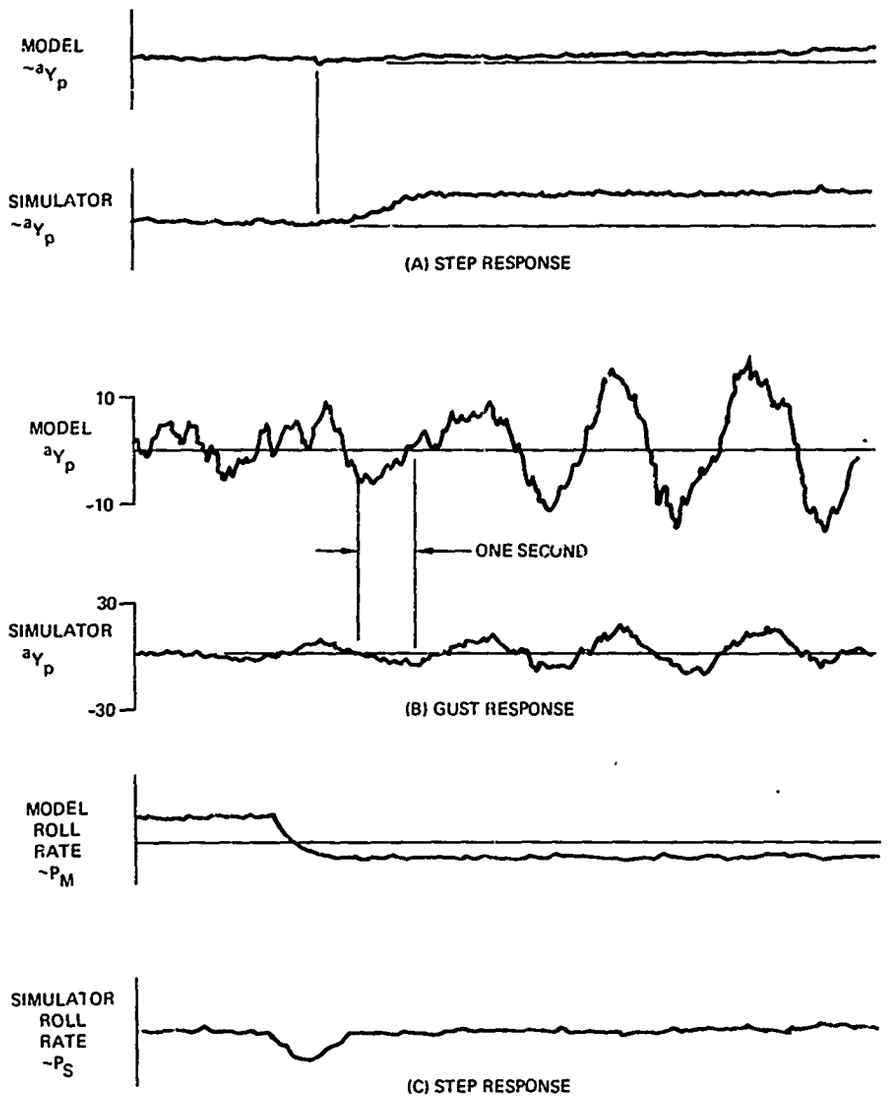


FIGURE 21. COMPUTED AND MEASURED ROLL RATE AND LATERAL ACCELERATION

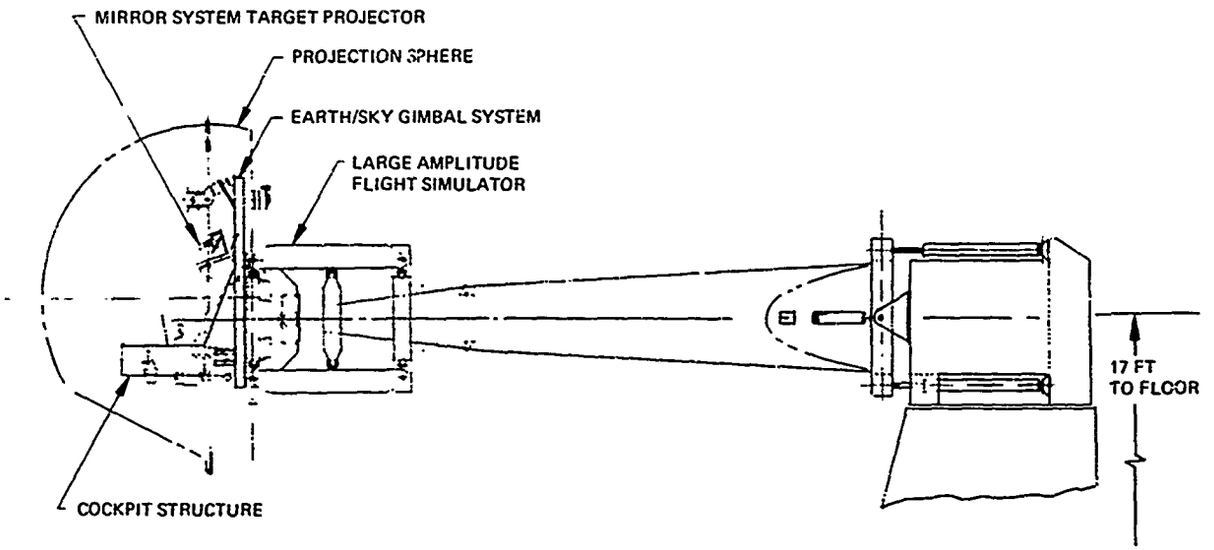


FIGURE 22. LARGE AMPLITUDE SIMULATOR/WIDE ANGLE VISUAL DISPLAY

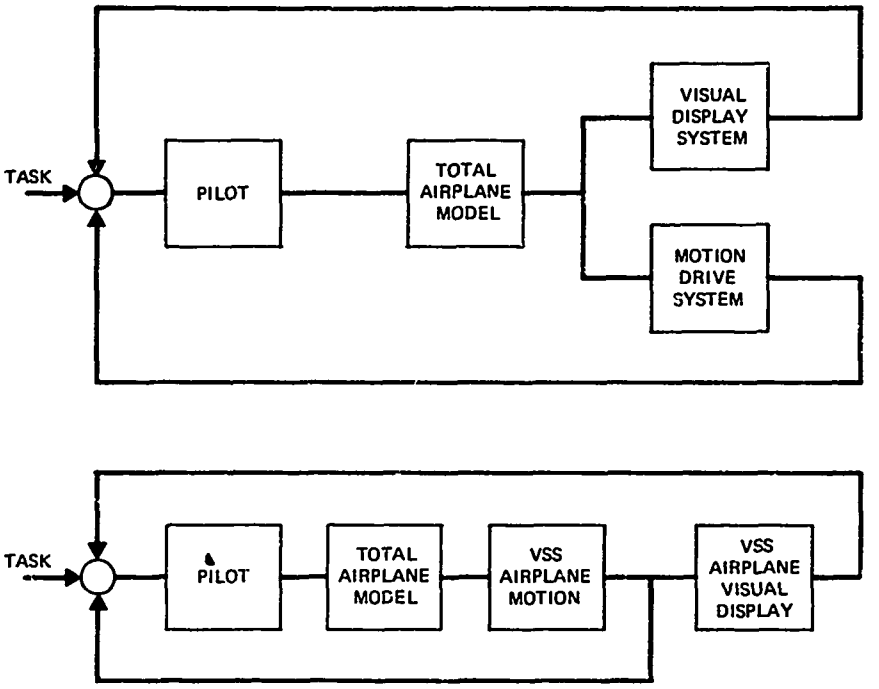


FIGURE 23. MOTION AND VISUAL CUING IN SIMULATORS

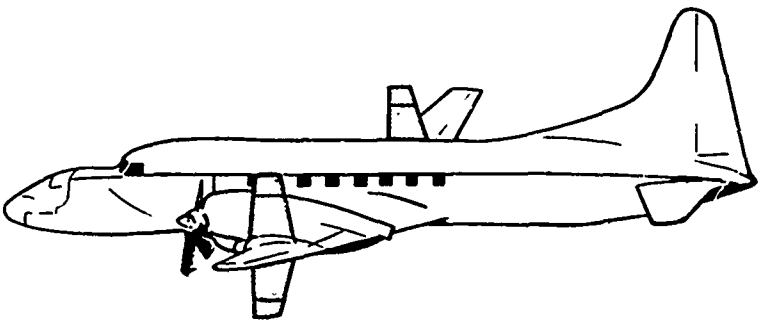


FIGURE 24. USAF/CAL TIFS AIRPLANE IN FLIGHT (FROM REFERENCE)

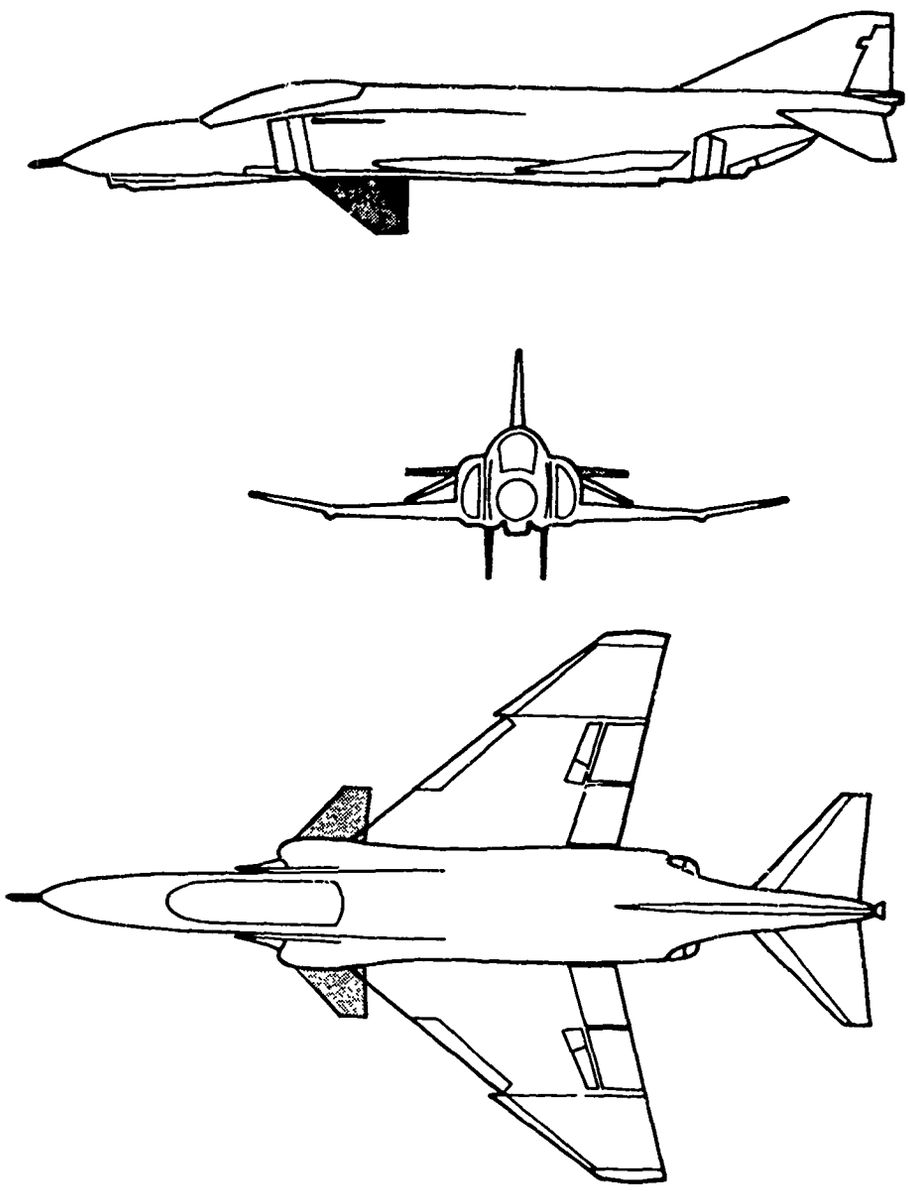


FIGURE 25. FIGHTER IN-FLIGHT SIMULATOR

CONCLUSION

Existing flying qualities criteria specified in MIL-F-8785B (ASG) have been established using open- and closed-loop analysis techniques, ground-based simulation, inflight simulation, and experience from flight testing in-service airplanes. While the specification is comprehensive, there are areas where the requirements need improving. The two more obvious areas are associated with the effects of turbulence on flying qualities and the interaction of control system dynamics with airplane characteristics. It has been demonstrated that ground-based simulation and analysis hold the promise for better specification of turbulence effects, and inflight simulation and analysis may be useful in specifying total system flying qualities criteria. Improved inflight and ground-based simulator facilities necessary in this research can be provided with current technology.

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LEAD DISCUSSION

by
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Bedford, Beds
England

Mr Gallagher's main thesis is that handling criteria should be developed from a foundation of simulation and analysis, and should then be validated using operational experience. This is now received doctrine and is respected as such, so that most of my comments will be concerned with the details of his paper rather than its basic principles. However, it is perhaps worth emphasising a general point that is implied rather than spelled out in the text, namely the importance of synthesis in the development of criteria - by this I mean the process of drawing together the threads of all relevant items of research into a consistent pattern: a classic example of synthesis in this sense is the monumental "Background Information ...." of Chalk and his associates, to which Mr Gallagher refers. I make this glaringly obvious point only because there has sometimes been a tendency to formulate 'instant criteria' on the basis of a single experiment, plus a hunch, and to give other relevant material insufficient consideration, usually with rather unsatisfactory results.

I would like to turn now to some of the detailed points raised in Mr Gallagher's paper.

I found the arguments put forward for an upper, as well as a lower, bound of natural frequency at a given n/α were quite persuasive. However, the situation seems less satisfactory when it comes to translating these arguments into quantitative limits: for example, the upper frequency limits of Mil.Spec. 8785 B for Category C flight phases do not seem to be well-supported by the in-flight simulations on which they are supposed to be based - indeed the upper frequency limits of the experimental data for Category C were typically about one-half the local upper limits for Level 1. There is, in fact, reasonable supportive evidence from ground-based simulators for the upper frequency limits relating to Level 1, Category C (for example, the Studies made by A G Barnes of BAC), but the situation is less clear in the case of Category A flight phases where, it seems to me, we need additional experimental data before the upper frequency limits can be properly established.

I agree with Mr Gallagher that the minimum damping limits shown in Fig. 4 are too high and, in the case of Level 3, much too high. To give a better feel for the 'miss distances' involved would Mr Gallagher give us some more information about Fig. 7 - for example, do all the data labelled "cruise" relate to Category B flight phases and were all the configurations rated at Level 1. His point is well taken, however, that this problem arises partly because we still lack a rational method of dealing with the handling qualities required for flight in turbulence - a corollary of this is that we require adequate models of the turbulence itself as a starting-point and we look forward to an interesting discussion on this topic tomorrow.

I fear I am not sufficiently familiar with the work of Onstott and Salmon to comment in much depth on the next section of the paper, though, bearing in mind the recent work on the non-Gaussian nature of turbulence (see paper 14 by J G Jones), one must ask if these and other experiments based on simulated turbulence having Gaussian distributions give a sufficiently accurate approximation to "real life"; furthermore one must question the adequacy of root-mean-square error as a measure of pilot performance - the evidence suggests that we need a measure that takes particular note of the occasional large disturbances, to which the pilot is particularly sensitive.

Turning to Figure 15 of the paper, Mr Gallagher's comment that the 'BC' configurations, with their high $|\phi/\beta|$ ratios, received less favourable pilot ratings is correct, but it should also be mentioned these configurations had inferior roll control as well, (in the sense of having higher τ_R) which would, presumably, have influenced assessment in the "wing-levelling" task. The differences shown in Fig. 15 between the similar configurations AB 2.6 and 2.7 seem rather anomalous and, to me, very puzzling. What indicators of pilot effort would Mr Gallagher suggest as being sufficiently different between the two cases to outweigh the presumably beneficial effect on rating of the better performance obtained with AB 2.7? On an allied topic, I had thought that a classic response of the pilot when confronted with a task of increasing difficulty was, initially, to maintain a nearly constant performance at the expense of working harder and so worsening his ratings; beyond a certain level of task difficulty his performance deteriorated fairly abruptly and this sometimes coincided with the rating rising through 6.5: this is very much the type of variation shown for configuration AB 2.7, whereas AB 2.6 shows a quite different form. I would like to ask, firstly, if Mr Gallagher can explain these differences and secondly, if the pilot behaviour just described is the more typical, what indicators of performance will also prove sufficiently sensitive as indicators of pilot rating?

I get the impression from his Section on 'In-flight Simulation' that Mr Gallagher, like many of us, wishes to see a move away from the somewhat indirect form in which many of the present American requirements are cast. The Cornell experiments he takes as an example of in-flight simulation, illustrate one of the directions that such a move might take, though I do not believe that the deductions from these experiments have yet been brought to the point where they can be used as criteria. The pilot compensation and the associated resonance peak are both very sensitive to the value assigned to the closed-loop bandwidth, and Neal and Smith found it necessary to associate different bandwidths with different groups of data in order to bring the latter into line with each other. Clearly, before this approach can flourish it will be necessary to establish convincingly, the rules that may govern these postulated variations in bandwidth. In my view we are still a long way from being able to do this; moreover the task seems likely to prove more complex than might appear on the surface, because pilots do not behave consistantly - examples of this appear throughout the literature, including the Neal and Smith experiments, in which, for example, a given configuration was given widely differing ratings by one pilot on different occasions, apparently because,

on one occasion, he flew the aircraft "more aggressively" (i.e., aimed for greater bandwidth) and encountered P.I.O. problems in consequence. The problem is thus not only to establish the appropriate range of forms and stategies for our pilot model in a given task, but also to establish the probability that the pilot will adopt a particular form and strategy. It seems to me that the "pilot model" approach can only be used properly in some statistical sense like this, in view of the unpredictability of individuals: the problems appear formidable.

I have a final question for Mr Gallagher. Would he please tell us more about the large amplitude simulator he shows in Fig. 22? In particular what problems, if any, have been encountered with the structural modes of the motion system and what steps have been taken to deal with them?

OPEN DISCUSSION

R. Deque, Aerospatiale, France

It seems difficult to derive absolute handling criteria for new types of aircraft from ground based simulators (and not only trends). This is because limitations of simulation we know by experience. We can give two examples: (1) Pilot ratings can be changed by only modifying cockpit environmental conditions without changing the aircraft dynamics; (2) We have found that pilot behaviour on a given simulator can change largely depending on if he works on the simulator before or after he has been flying the real aircraft which is simulated.

J.T. Gallagher, Northrop Corp, USA

For one thing, ground based simulation may be all that you have and it is better than nothing.

With regard to the pilot's behavior after having flown the real aircraft, that is to be expected, because after flying the real aircraft the pilot has a better feel for the real environment that you were trying to simulate. Knowledge of this makes you a better user of simulators.

S.B. Anderson, NASA Ames. USA

Perhaps Mr. Deque is referring to one of our tests on the FSAA, where the pilot on the fixed base simulator used much larger amplitudes of control motion but when he had motion those large amplitudes produced some physical discomforts. The pilot thus found that in the motion case that either the large control amplitude produce discomfort or the simulation was not a true representation of the characteristics that existed in the moving base simulation.

R.P. Harper, Cornell Aero Lab, USA

It seems that bank angle error alone is an insufficient parameter for forecasting pilot ratings. Things like sideslip excursions and roll acceleration excursions, etc, are influencing the pilot, his control activity, etc. Neal and Smith were able to correlate the pilot rating results from actual in-flight simulations with a close loop analysis of pitch angle tracking. I agree with Mr. Bisgood's point that this theory needs to be subjected to further test before it is accepted as good criteria.

I.L. Ashkenas, STI, USA

Mr. Bisgood's statement that a pilot can perform with a very bad airplane, get good performance and still rate it as an unacceptable airplane is a very important point and has been lacking from some of the previous discussions. Performance is not the sole factor, we must consider the pilot effort required to achieve that performance.

HANDLING QUALITIES CRITERIA FOR SUPERSONIC TRANSPORT

by

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INTRODUCTION

These informal notes are offered for discussion in place of the French Aerospatiale paper that was originally scheduled for presentation. The aerospatiale paper was titled "Criteria for Supersonic Transport Certification." These substitute discussions will not attempt to recommend specific criteria to be adopted for SST certification. Instead, comments will be presented concerning the influence of handling qualities criteria specifications on the aircraft design; and some examples will be given of criteria that were employed to guide the design of the Boeing United States SST configuration.

The development of criteria to govern the design of the United States SST involved a period of several years of study, and considerable experimentation with various flight simulator facilities. During this period, all existing criteria were reviewed, and much thought was given to the adoption of new approaches to enhance the aircraft design with regard to safety, performance, and flying qualities. The recently revised U.S. military flying qualities specification, MIL F 8785B, and its background and user's guide played a significant roll in the development of the Boeing criteria. Throughout all of this study and experimentation work, the considerable experience of The Boeing Company in the design, certification and selling of large commercial jet transport aircraft dominated the decision making process in the criteria selection. These studies culminated in the publication of a sizeable Boeing document entitled 'Stability and Control, Flight Control, Hydraulic Systems and Related Structures Criteria for the Supersonic Transport."

DISCUSSION

Figure 1 outlines some thoughts on what should be the content and tone of a criteria specification for commercial transports. First and foremost, a criteria must insure safe handling qualities for all regimes of flight operation. In addition to the normal flight operations, operation to the extremes of the flight envelope, and operation in severe turbulence must be specified. Also to be considered are flight operations with systems failures. A criteria specification must also consider the critical combinations of these items that have a reasonable probability of occurrence. For example: the airplane must be able to operate safely in turbulence of some specified level following flight controls systems failures.

The criteria specification must also provide for demonstration of compliance. This is often difficult to do but should be a controlling consideration in the development of each criterion.

Finally, the criteria should avoid dictating the design detail of the aircraft and its systems. For example, instead of specifying numerically the required levels of stability or maneuvering control force gradients, it would be preferable to word the requirement in more general terms, such as:

> "Control system/pilot compatibility must be maintained throughout the speed/altitude envelope to ensure adequate control response and maneuverability with reasonable control forces, linearity of response, and protection against structural damage due to overcontrol."

HANDLING QUALITIES CRITERIA
FOR SUPERSONIC TRANSPORT

- CRITERIA SHOULD ENSURE SAFE HANDLING QUALITIES
  - FOR NORMAL OPERATION
  - FOR OPERATION TO EXTREMES OF FLIGHT ENVELOPE
  - FOR OPERATION IN SEVERE TURBULENCE
  - FOR OPERATION WITH SYSTEMS FAILURES
- CRITERIA SPECIFICATION SHOULD PROVIDE FOR DEMONSTRATION OF COMPLIANCE
- CRITERIA SHOULD AVOID DICTATING AIRCRAFT AND SYSTEMS DESIGN DETAIL

Figure 1.

This approach to a criteria specification places the responsibility on the designer to provide a satisfactory configuration, but gives him freedom to select, design and optimize the airframe/systems combination to meet the specification.

Let us now examine a few of the criteria that were developed to guide the design of the Boeing SST configuration and its flight control system. Figure 2 presents some examples of the criteria developed for longitudinal stability. It shows criteria adopted for normal operation of the aircraft, and criteria employed for minimum safe systems operation. Minimum safe operation refers to the most degraded levels of aircraft handling qualities that still permit safe operation. Time does not permit detailed discussion of each criterion listed. Instead, the criteria that will be discussed are those that differ significantly from past approaches to the specification of longitudinal stability. For example, for normal systems operation response characteristics are specified in terms of pitch rate time response boundaries. These boundaries are expressed as the ratio of pitch rate-to-steady state pitch rate as a function of time following a control input. These boundaries provide more specific guidance for design of the flight control system than do criteria specified in terms of frequency, damping and n_{z_α}.

For minimum safe system operation, a wide range of maneuver force gradients is permitted, but it is still required that the aircraft maneuver response be stable. Speed stability, in terms of control force versus speed, is not required. Instead, the airplane is permitted to be unstable, and then we specify the maximum level of instability that is permitted. The permitted level of instability is stated in terms of time to double amplitude of the unstable root of the longitudinal equations of motion. It is required that the unstable root must not double amplitude in less than six seconds.

Most of the other longitudinal stability requirements listed on the chart are conventional in nature. However, the specification permitting static instability is a new approach to aircraft design. This approach was taken to improve the airplane longitudinal balance, reduce aircraft weight and aerodynamic drag, and thus improve payload/range performance.

Figure 3 shows the relationship between longitudinal handling qualities and time to double amplitude of the unstable root. It is a summation of pilot ratings obtained as a function of the level of airplane instability. The curved line on the graph summarizes the mean pilot rating as a function of time to double amplitude as obtained from various experiments on fixed-base simulators, moving-base simulators and variable-stability aircraft. It is seen that pilots can safely control the airplane with time to double amplitude as low as three seconds. This is indicated on the graph by the pilot rating 6-1/2 intersection with the curve. At pilot rating 6-1/2, the aircraft handling qualities are objectionable, but the pilot can still retain safe control of the airplane. The criterion of six seconds to double amplitude was based upon experimentation of this type, and the consideration to provide a comfortably safe margin for commercial aircraft design.

LONGITUDINAL STABILITY REQUIREMENTS

NORMAL SYSTEM OPERATION

- STABLE MANEUVER CONTROL FORCE AND DEFLECTION GRADIENTS (25 TO 45 LBS/g).
- SPECIFY MANEUVER RESPONSE CHARACTERISTICS, Q/Q_{SS} VS TIME BOUNDARIES.
- STABLE SPEED STABILITY (CONTROL FORCE VS SPEED) FOR FLIGHT WHERE PROLONGED OPERATION OR PRECISE AIRSPEED CONTROL IS NECESSARY.

  MAXIMUM GRADIENT 1 LB/KNOT.
- SPECIFY DYNAMIC DAMPING.
- NO LOCKED-IN PITCH UP.

MINIMUM SAFE SYSTEM OPERATION

- STABLE MANEUVER FORCE GRADIENTS (8 TO 100 LBS/g).
- SPEED STABILITY NOT REQUIRED

  LEVEL OF INSTABILITY LIMITED TO UNSTABLE ROOT MUST NOT DOUBLE AMPLITUDE IN LESS THAN 6 SECONDS
- SHORT PERIOD DAMPING RATIO NOT LESS THAN .15.
- NO TENDENCY FOR SUSTAINED OR UNCONTROLLABLE OSCILLATION.

Figure 2.

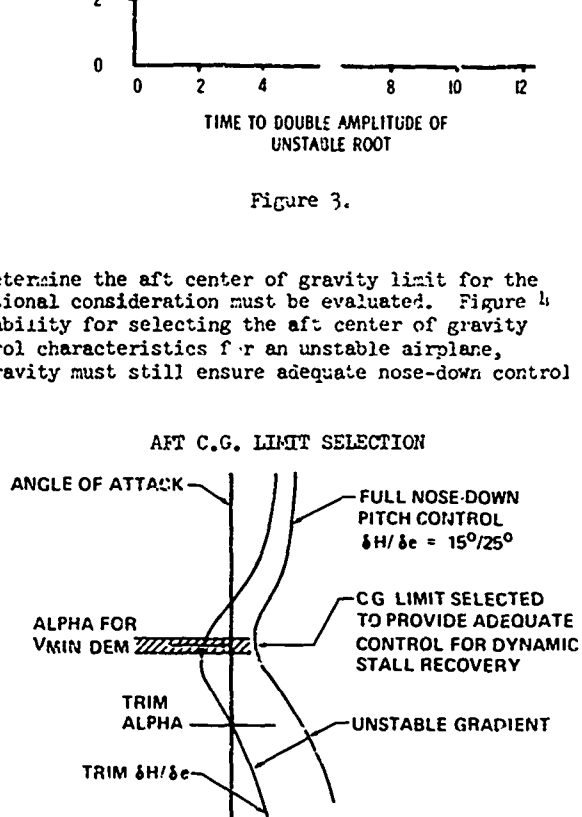


Figure 3.

The time-to-double amplitude criterion may determine the aft center of gravity limit for the airplane. If it does not determine the limit, an additional consideration must be evaluated. Figure 4 graphically states an additional criterion of controllability for selecting the aft center of gravity limit. Shown here are the limiting stability and control characteristics for an unstable airplane, wherein the most aft permissible operating center of gravity must still ensure adequate nose-down control throughout the operating angle of attack range.

Figure 5 specifies high-speed longitudinal control requirements. Criteria are stated for normal operation and for minimum safe operation. These criteria are shown more graphically on Figure 6 in a plot of maneuver load factor vs speed. The shaded area shows the required maneuver-load factor envelope for control. This load factor envelope is seen to be well inside of the structural design load factor envelope. Boeing studies have shown that these levels of maneuver capability provide safe operation throughout the flight envelope. For example, a load factor capability of 2 g's at maximum operating speed decreasing to 1.5 g's at maximum dive speed has been shown to provide a satisfactory level of control for recovery from dive upsets. It should be noted that this maneuver capability is required in either symmetrical or rolling maneuvers; the intent being that application of roll control must not compromise the longitudinal maneuver capability below the levels specified.

Figure 4.

HIGH SPEED LONGITUDINAL CONTROL REQUIREMENTS

NORMAL SYSTEMS OPERATION

- o DEVELOP LIMIT ANGLE OF ATTACK OR LOAD FACTOR 2g WHEN TRIMMED FOR 1g FLIGHT AT ANY SPEED UP TO V_{MO}/M_{MO}
- o DEVELOP n = 1.5g AT V_D/M_D WHEN TRIMMED FOR 1g FLIGHT AT V_{MO}/M_{MO}

MINIMUM SAFE SYSTEMS OPERATION

- o DEVELOP n = 1.5g* WHEN TRIMMED FOR 1g FLIGHT AT V_{MO}/M_{MO}
- o DEVELOP n = 1.25g AT V_D/M_D WHEN TRIMMED FOR 1g AT V_{MO}/M_{MO}.

* At transonic speeds this requirement is reduced to 1.25g total load factor capability.

Figure 5.

LONGITUDINAL CONTROL REQUIREMENTS FOR NORMAL OPERATION

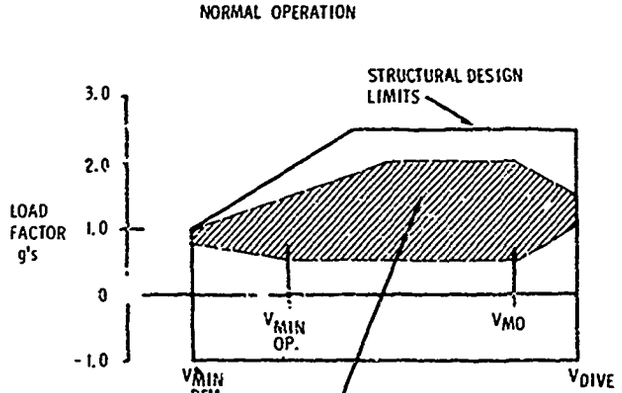


Figure 6.

A critical design area for sizing the longitudinal control of SST aircraft may lie in the low-speed flight regimes. Figure 7 illustrates a requirement established for low-speed longitudinal control capability in the landing flare. Through a series of flight simulator experiments a criterion was developed to relate pitch attitude acceleration requirements to the incremental lift or sink produced by the control input. The graph shows the acceptable boundary of pitch attitude acceleration versus the incremental normal acceleration (g) produced by the pitch control input. A negative value of g indicates the sink produced with control inputs. It is typical of short-coupled, tailless aircraft that pitch control inputs generate relatively large sinking forces relative to the nose-up control moments produced. The boundary then establishes a need for increasing pitch attitude acceleration for the more short-coupled aircraft.

LANDING LONGITUDINAL CONTROL REQUIREMENTS

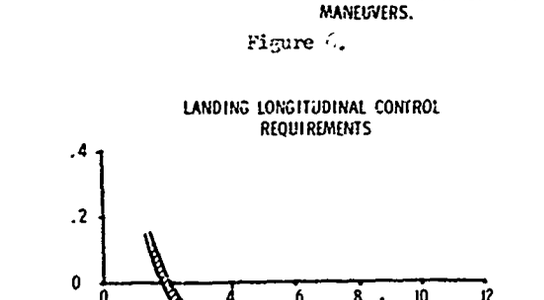


Figure 7

Figure 8 summarizes some of the more critical requirements for the lateral control system. The criteria used for the Boeing SST specified roll performance requirements in terms of time to bank, as will be shown on the following chart. Additional requirements are that the aircraft should be able to perform landings in 35-knot, 90-degree crosswinds using no more than two-thirds of the lateral control, and that roll control power be sufficient to prevent structural contact during the landing when encountering a 20-foot per second step lateral gust at or near the touchdown point. It is further required that bank excursions be held to no more than 30 degrees during the transients experienced for the most severe propulsion system failures that can be expected to occur in supersonic flights. The dynamic roll response characteristics are specified in terms of the ratio of roll rate acceleration-to-average roll rate following control input. It is also specified that the roll rate must never reverse following a roll command.

Shown in Figure 9 are the roll performance requirements specified as the time required to achieve a given bank angle. It is required, for example, during take-off and landing that the airplane achieve a 30-degree bank in no more than 2-1/2 seconds with all systems operating normally. This requirement is relaxed to 30 degrees in 4-1/2 seconds for the minimum safe condition. It will be noted that the roll performance requirements shown for the clean configuration at speeds up to maximum operating speed and speeds up to the maximum dive speed are low relative to some current specifications for large aircraft. The SST roll performance requirements were determined through a considerable amount of flight simulator experimentation, and review of the roll control capabilities of current commercial jet aircraft. This work was aimed at establishing reasonable levels of roll performance in up-and-away flight. The lowest roll performance specified appears to be the maximum required for commercial transport operation.

LATERAL CONTROL

- SPECIFY TIME TO BANK
- HANDLE 30 KNOT 90° CROSSWIND LANDINGS WITH NO MORE THAN 2/3 LATERAL CONTROL
- PREVENT STRUCTURAL CONTACT DURING LANDING WITH 20 FT/SEC STEP LATERAL GUST AT TOUCHDOWN
- HOLD BANK ANGLE EXCURSIONS TO 30° OR LESS DURING MOST SEVERE PROPULSION SYSTEM FAILURES
- SPECIFY DYNAMIC RESPONSE, SUCH AS $P_{OSC.}/P_{AVG.}$
- ROLL RATE SHALL NOT REVERSE FOLLOWING A ROLL COMMAND

Figure 8

LATERAL CONTROL

ROLL PERFORMANCE REQUIREMENTS SPECIFIED AS TIME TO ACHIEVE A GIVEN BANK ANGLE.

CONFIGURATION	NORMAL SYSTEMS	MINIMUM-SAFE SYSTEMS
TAKEOFF & LANDING	30°, 2.5 sec.	30°, 4.5 sec.
CLEAN CONFIG. UP TO V_{MO}	60°, 7 sec.	30°, 6 sec.
CLEAN CONFIG. AT V_D	60°, 11 sec.	30°, 11 sec.

Figure 9

The foregoing discussions have cited some examples of handling qualities criteria developed as a result of one designer's attempt to review critically and improve upon existing criteria. The objective of this criteria development work has been to assure a safe and satisfactory aircraft design, and, wherever possible, evolve criteria that ease the design constraints imposed by previous approaches to flying qualities specifications. In this regard, the supersonic transport studies have shown that substantial benefits are to be derived in the areas of flight safety and aircraft performance.

A specific example of the performance benefits that can accrue is seen in the new approach taken in the establishment of longitudinal stability criteria. As noted earlier, this approach permits location of the aft center of gravity limit aft of the stability neutral point, and requirements are then specified to limit the maximum permitted levels of instability. These requirements assure that the longitudinal balance of the aircraft and the design of its flight control system will provide a safe airplane even in the most degraded operating state. Figure 10 illustrates the benefits of adopting this approach to the specification of handling qualities criteria for the longitudinal axis. For the Boeing SST, the acceptability of the unstable airplane was attained through the development of a stability augmentation system that was labeled HSAS. This chart shows the payload/range benefits derived from the improved performance achieved for the airplane designed to these criteria. It is seen that a range improvement of 225 nautical miles was attained with the HSAS airplane. Or, more significantly, that a reduction in payload of 30 percent would be required to attain the same range without the HSAS concept.

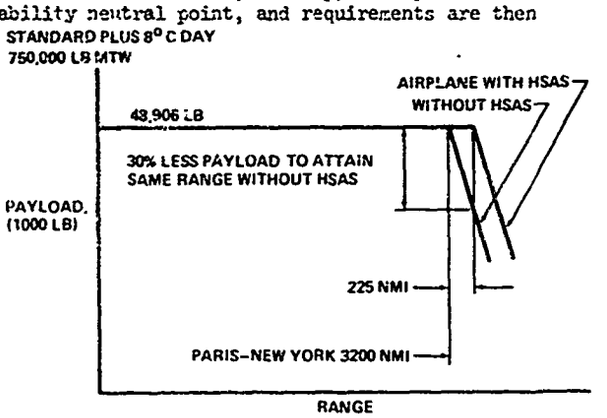


Figure 10

The achievement of performance benefits of this magnitude should be a strong incentive to develop new approaches to the specification of handling qualities criteria for Supersonic Transport certification. Every effort should be made to assure that the final specification does not inhibit the inventiveness or design capability of the aircraft designer. It is concluded that careful composition of the specification can assure safe handling qualities for all regimes of flight operation and at the same time provide the designer with the opportunity to develop new design approaches that contribute significantly to improved aircraft safety and economics.

OPEN DISCUSSION

R.P. Harper, Cornell Aero Lab, USA

Regarding the plot that you showed of the allowable instability, what was behind that plot? Was the pitch damper with the hard SAS and furthermore, did you find that without hard SAS, did you get a different result?

W.T. Kehrer, Boeing, USA

That's a good comment; it should be pointed out that that chart is very specifically our airplane with its damping characteristics and its control characteristics both in terms of control power and feel. Also, the visual display plays a very important part in that chart. I would not want to imply that that chart could be applied across the board to new transport aircraft.

D.P. Davies, ARB, UK

While the Certification Authorities can promise to be flexible and cooperative in terms of SST certification, it must be understood that eventually firm requirement levels must be established for quantitative handling requirements.

As one example, the following roll rates are offered as reasonable minima:

normal operation	10°/sec
single failure case	6°/sec
double failure case	5°/sec

Mr. Kehrer's suggestions in the failure cases fall well short of the above proposals. His value of 3°/sec at M_D (presumably all engines operating) is short by 100%.

W.T. Kehrer, Boeing, USA

We had a great deal of uncertainty about those roll rates, and here possibly is a limitation of the flight simulation facility. Some of our pilots were telling us that for this corner of the envelope the only requirement was that when he puts in full wheel the aircraft should roll in that direction. That is how we arrived at that low level of 30° in 11 seconds. However, when you examine a time history of the rolling maneuver, you will see that following the initial rise time in the roll response, the roll rate will stabilize at a value slightly over 5 degrees per second, to achieve the 30° bank in 11 seconds criterion.

THE ROLE OF PILOT RATING IN THE DEVELOPMENT OF HANDLING CRITERIA

by

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Introduction

Since the earliest days in the development of the airplane the quality of handling has played an important role. The success of the Wright Brothers, where so many others had failed before, was in large part due to their successful blend of performance and controllability. Throughout the development of the airplane success has seemed to lie with those who blended these two ingredients - maximum performance consistent with adequate handling. Performance is something that is usually specified in terms of objective measures of the aircraft motion capabilities. The quality of handling however, is difficult to define in a fashion which can be directly measured in what is normally termed an objective manner. It is easy to make the general statement that the handling quality should be good, but it is more difficult to set forth specific measurements which if made will demonstrate that the handling is good or adequate.

The handling qualities are characteristic of the combination of the airplane plus pilot - handling implies the pilot's control of the airplane. To measure the quality of the handling one must characterize the behavior of the pilot/airplane combination. In those cases where the pilot's use of the controls is known, and the effect of this use is also known, a direct measurement can usually be made of the achievement of a level of handling. An example might be the measurement of minimum nose wheel lift-off speed as one of the elements affecting the quality of handling during takeoff. The pilot's use of elevator and throttle controls can be specified allowing either a direct measurement of the lift-off speed or, in the design stage, a calculation of that speed. Through our engineering understanding of the takeoff maneuver, the relationship of that speed to the takeoff speed bears on the adequacy of pitch controllability during takeoff.

There are many more maneuvers performed by the pilot/airplane combination, though, where either the use of the pilot's controls is unknown or the effect of the required control use is unknown. An example here might be use of the elevator to pull "g" in air combat maneuvering. In pseudo-steady-state flight conditions we can measure the normal acceleration as a function of elevator stick position, but we don't know how the pilot will apply the elevator stick when a change in g is required. Since we do not have adequate analytical models of the role of the pilot as a controller, we must use a real pilot. When the pilot does pull g in air combat maneuvering, we can measure the time history of the elevator motion. We can also measure many characteristics of the airplane motions during the maneuvering but unless we can relate these measurements to combat success, they are not of much direct value in judging the quality of handling. This we do by asking the human intelligence present in the control loop to judge the probable combat potential. To do this, he must view the maneuvering capability which he has seen in the light of the control activity required to achieve that maneuverability and come up with a quality judgement of its handling.

Pilot rating is an index which reflects the pilot's judgement as to the quality of the handling and is one portion of his total evaluation. The other part of his evaluation is commonly referred to as pilot comment data and should contain commentary on the nature of his objections to and difficulties with the handling. Pilot rating is not a rating of pilots, it is a rating of the quality of handling given by the pilot controller.

The role, then, of pilot rating is to provide a means of defining the quality of handling in those control situations where a direct measurement cannot be made which will provide a meaningful judgement of that quality. Generally the rating itself is of limited meaning without the associated commentary as to the nature of the objections which led to the rating. The combined commentary and rating data are referred to here as the pilot evaluation. It should be mentioned, too, that the pilot comment data is incomplete as evaluation material without the pilot rating since the latter provides a weighted, overall value judgement as to the effect of the various objections noted in the commentary.

A pilot rating scale for use in the evaluation of handling qualities was presented to the AGARD Flight Mechanics Panel in 1966 by Cooper and Harper (Reference 1) and after some revision was published (Reference 2) as NASA TN-D-5153. The pilot rating scale presented in Reference 2 seems to be in general use, among the NATO countries at least. The use of pilot rating in the evaluation of aircraft handling qualities is discussed in that reference.

Pilot Evaluation - A Discussion of Certain Problems

Probably the greatest difficulty with pilot ratings has to do with the attendant need for accurate pilot comment data as to the nature of his objections to the handling. A carefully designed and executed experiment is required in order to obtain accurate and complete pilot comment data. By its very nature, this commentary is almost always lengthy and cumbersome to deal with. Engineers who are pressed for time and who must produce answers often neglect or even completely eliminate pilot comment data from their data collecting experiment. The problem is not that they wish to ignore the pilot comment data - the problem is to digest its meaning and summarize the findings in a reasonable length of time. How do

we - or how should we organize our experiments and question our pilots so as to ferret out the important material in a significantly less burdensome manner?

For one thing, we continue to need a better understanding of the dynamic behavior of the pilot/airplane system in order to ask better questions and comprehend the answers with fewer words of explanation on the part of the pilot. This understanding will require more concentration and research into the nature of the pilot/vehicle system. We should improve our analytical models (understanding) of the pilot and how he operates as an airplane controller - in the multiple variable, multiple input control situation of the real airplane. To do this, we need measurements of the pilot's dynamic control behavior in the actual flight phases, so that we can better understand his objections. We need pilot ratings to go with those measures of his control behavior, and we need pilot commentary to assess his view of his control problems. With these data, we can formulate more meaningful models of him as a controller and begin to predict his evaluation results in new situations.

Even without analytical models of the real pilot, we need to develop improvements in our methods of obtaining pilot comment data. The manner in which this is presently done is that the engineer (with the help of the evaluation pilot or someone who represents his view and experience in the flight phase) formulates questions based upon his understanding of the evaluation that is to be conducted, and his a priori knowledge of the results for which he is looking. Free commentary by the evaluation pilot is solicited in order to cover those aspects of the evaluation results which were not anticipated or adequately covered in the questionnaire. It is our experience at CAL that even with the revision of questionnaires following a preliminary evaluation phase, the pilot commentary is long and drawn out. Good, solid, substantial, important information is present in these comment data but it requires careful reading and analysis, re-reading and re-analysis of the pilot commentary to ferret out the important information.

Thus it is basically a communication problem. We don't know enough to ask the correct questions before we conduct the experiment. In his commentary the pilot must answer or is forced to answer our inept questions and in addition has to communicate his unanticipated piloting difficulties and observations to the engineer. The pilot sees and must describe the pilot/airplane combination to the engineer who fundamentally thinks in terms of the airplane alone. This difficulty is further compounded by the fact that the pilot (hopefully) describes that which he sees in a language familiar to him - one that is sometimes unfamiliar to the engineer. Clearly an improved understanding of the pilot/vehicle system will greatly aid the engineer in the formulation of his questions and in the analysis of the pilot commentary.

Improved understanding of the pilot/vehicle system is not the entire answer,however, for if we knew the pilot/airplane system well enough to ask all of the proper questions, there would be little need for the conduct of the evaluation experiment. We must therefore live with some lack of understanding of the pilot/vehicle system. It is in this situation that we should seek an improved means by which the pilot is aided in logically communicating his (unanticipated) observations and objections to the engineer. The author of this paper solicits the attention of the audience (and readers) to this area of need. New ideas and approaches are needed.

As mentioned earlier, the difficulties which are often encountered with pilot comment data can lead the engineer to set aside or ignore the comment data and concentrate on the pilot ratings. Ratings are numbers (at least in current rating schemes) which the engineers can feel, weigh and manipulate - and plot. The pilot rating numbers tell the story of how the pilot weighed what he has seen, but no amount of manipulation will extract from the numbers the reasons which cause the pilot to select that number.

Since one overall rating does not give us the nature of the pilot's objections, some researchers have been led into a number rating system for each of the areas of evaluation upon which the engineer wants the pilot to comment. The elevator stick forces, the pitch damping, the roll control power and so forth are each weighed on a scale of goodness from 1 to some number. Frequently the pilot rating scale of Reference 2 is used to quantify each comment.

There are pro's and con's to this practice. In one sense the objective of standardizing the pilot's evaluation language is a commendable one. For example, if the elevator stick forces were referred to as light in one evaluation and good in another evaluation, are these comments really different? Obviously one cannot tell without more information. If, however, the pilot had used a standard set of descriptors to characterize his quality evaluation of the elevator forces, this uncertainty would not exist. But on the other hand, misuse of such numerical descriptions can be troublesome and logically difficult. If numbers are used does one average the numbers to arrive at a conclusion? If the scale of Reference 2 is used to quantify comments, is it possible to have the elevator stick forces rated poorer than 6.5 but arrive at an overall rating of the configuration better than 6.5? It would seem to be an unnecessary complication to introduce multiple uses of the same scale in one experiment.

The terms pitch damping and lateral control power were introduced above to point out the fact that engineers often ask questions about the airplane - alone characteristics, without specifying that the evaluation pilot perform a specific test to permit evaluation of that characteristic. Without this direction on the part of the engineer, the pilot will likely perform some combined pilot/airplane operation and comment on some observable characteristic of this combined behavior. He thus may be answering the question which the engineer did not ask.

Some Troublesome Aspects of Pilot Rating Data

In the earlier days of handling quality evaluations, the most controversial aspect as to the role of pilot rating in the development of handling criteria was centered on whether pilot evaluations were any more meaningful than man-on-the-street opinion. This concern has been suppressed by the expert evaluator concept of the evaluation pilot. The evaluation pilot is not a man-on-the-street opinion giver. He

is an expert subject conducting a flight task for which he is well trained. It is his job to evaluate the combined pilot/airplane capability for the use and to describe his difficulties with and objections to the particular set of characteristics.

This is not to say that all skepticism as to the validity of pilot evaluations and pilot rating data have been laid aside. In fact the skeptics frequently point to the different ratings given by different pilots when supposedly evaluating the same configuration. If the pilots don't agree in their evaluation results, how then can we put much stock in their answers?

Let it be said that in the author's experience pilot rating results are reliable and in good agreement both among pilots and with one's self in repeated evaluations of the same characteristics. This opinion presupposes a carefully planned and executed experiment. Significant differences in pilot rating should serve as warning flags to alert the engineer to potential deficiencies in his experiment. If pilot rating differences do occur, several sources for these differences should be examined. First, be sure that the characteristics which are being evaluated are actually the same. Although mistakes are generally rare, they do occur - switches get thrown the wrong way, knobs are set wrong and so forth. For these reasons, calibration data should be recorded for each configuration under evaluation which may be retrieved later and compared. Next, be certain that the pilots are conducting the same experimental evaluation - that they envision the same intended use and examine the same combination of piloting tasks, that they envision the same evaluation situation in terms of environmental conditions, number of crew members, turbulence and so forth. Look at the apparent weighting given by the individual pilots to the particular elements of the evaluation.

If the above considerations do not offer reasonable explanations for rating differences, look for other causal factors and classify these as to their relevance in the experiment. One area which is often pointed to as a source of pilot rating differences is the experience and backgrounds of the pilots. Since in most evaluation experiments the set of evaluation subjects is small, one might expect significant differences in experience and background among the subjects. Therefore any rating differences could be expected to correlate with these differences in background. Such correlation is often meaningless and can hide real causes of rating differences. Pilot rating differences can be on occasion attributed to evaluation pilot attitude or set. One example is the tiger who has a feeling that he can fly anything - that all airplanes are good, some are just more demanding than others. Other subjects may not be tigers in that sense but do not have the range of evaluation experience to realize that airplanes can be made better than those particular ones which they have flown. Both of these attitudes lead to pilot ratings of a quality better than would appear to be justified. These attitudes can almost always be favorably affected by seeing to it that the evaluation pilot experiences early in the evaluation program a range of flying qualities from good to unflyable. The tiger is forced to admit there are some things that even he can't fly, and the under-experienced or highly specialized evaluator has his eyes opened through experiencing handling qualities different than he had ever imagined.

Even with careful attention to these details of experimental design, one will still experience some variability in the pilot rating results. This variability which remains should be carefully examined, for it may represent a sensitivity of the handling qualities to normal variability in the capabilities, techniques, and strategies of the subject pilot population which the evaluation pilot hopefully represents. One set of handling characteristics is not necessarily of the same quality when mated with the full range of variability of the subject pilot population. Some sets of handling characteristics may well be more sensitive to this variability in the pilot population than others, and this sensitivity information is an important characteristic of the handling qualities.

Almost nothing is presently known about this sensitivity to pilot variability. One might expect that it would have its greatest effect near the limits of pilot capability - that is, in the control of configurations which would be rated at the unflyable or lower end of the pilot rating scale. It is here that pilot skill and technique may have a significant effect on the safety and controllability of the pilot/vehicle combination. Most evaluation pilots implicitly consider this factor in that they consider variations in the piloting capability - variations, at least, in their own capability when tired or otherwise degraded in ability. The full extent of the effect of pilot variability can probably only be determined by experiment. A relatively large sample size and a representative sample which includes the extremes of pilot variability would be required. The difficult thing is to assure that one in his sample has a really meaningful range of pilot capability.

This brings us to a final area of pilot rating to be considered here. The region of the pilot rating scale of Reference 2 below (worse than) the rating of 6 involves the handling qualities region where the evaluation pilot considers the airplane inadequate for the intended use. The scale really considers two possibilities:

1. The objectionable characteristics are such that the configuration is considered inadequate for the intended use but controllability is not in question.

2. The objectionable characteristics are such that the configuration is inadequate for the intended use and the controllability is in question.

If controllability is not in question, the rating 7 is assigned. The ratings 8-10 are assigned according to the amount of pilot compensation required when controllability is in question. Controllability in this region of the scale (above 10 but worse than 6) is such that the precision of control is inadequate for the flight phase with a tolerable pilot workload. When controllability is in question (ratings 8 and 9) substantial pilot compensation is required to accomplish the task safely. Thus adequacy in control is assumed to be a level of quality higher than minimum safe control in that either better precision of control is achieved, or that significantly less compensation is required on the part of the pilot. Questions have been raised at CAL during evaluations in the landing flight phase as to what constituted adequacy as compared with minimum controllability. Isn't the adequacy limit (PR=6.5) the same as the controllability limit (PR=9.5) for a landing? Although there is a difference in most pilots' (and passengers') minds between

an adequate landing and a minimum controllable one, the answer is largely in the amount of pilot compensation required, and the dependence of the landing success upon the presence of that amount of compensation. This method of categorizing inadequate configurations has, as far as the author is aware, provided a logical basis for handling evaluations to date. The possibility exists, however, that among the organizations using this scale, other experience may be contrary and should therefore be brought to light.

One concept which the rating scale of Reference 2 does not treat is the probability of loss of control. In the ratings 8, 9, and 10, controllability is treated in terms of the pilot compensation required for control. For the ratings 8 and 9 successful control can be retained to accomplish the intended tasks but substantial pilot compensation is required to accomplish it. For the rating 10 the amount of pilot compensation required is such that the evaluation pilot believes control will be lost during some portion of the required operation.

The difficulties for the evaluation pilot in applying this scale can best be illustrated by considering the landing task in turbulence. A rating of 7 might be given because too much compensation is required on the part of the pilot to obtain an adequate landing performance. The rating 8 or 9 would be assigned when substantial pilot compensation is required for control, and control here would be such as to achieve a safe landing. If less pilot compensation was supplied or if the magnitude of the disturbances were quite unusually large, there would be some expectation or probability of exceeding the sink rate at touchdown limits, for example, and sustaining actual aircraft damage.

As noted above, extreme variations in pilot capability could also result in structural damage for airplanes rated 8 or 9. The judgement as to these probabilities is left to the evaluation pilot, primarily for the lack of any known better way of handling these probabilities or these uncertainties.

Two other factors are important in the rating 8, 9, and 10 portion of the scale. One factor is the state of training of the pilot to whom these handling characteristics are subjected. This judgement, too, is left to the evaluation pilot but is certainly one to ponder and carefully define in setting up the experiment. Another factor to be defined is the circumstance under which the pilot is given these flying qualities. For routine handling qualities experiments for criteria development, concentration is upon the circumstance that the airplane under evaluation comes with these characteristics. The pilot does not generally assume that he is suddenly confronted with these characteristics under conditions of large initial disturbance. Therefore one must be cautious in the application of these general results to specific problems concerning sudden failure of flight control systems. In the absence of more definitive data for those specific circumstances, one would probably require characteristics of the rating 7 level if at all possible.

In summary, it might be said that although substantial improvements have been made in the evaluation of pilot/airplane dynamics, there are a number of troublesome areas in the execution of handling qualities experiments, and in the analysis and application of the resulting data. Several of these problem areas have been noted here, and while some discussion has been offered, too few solutions are presented. It is hoped that these problems and others will be discussed at this meeting and a stimulus given toward the solution of these problems. It is likely that total solutions will not be rapidly forthcoming; however, an evolutionary improvement is both desired and foreseen.

References:

1. Harper, Robert P., Jr.; and Cooper, George E.: A revised Pilot Rating Scale for the Evaluation of Handling Qualities. AGARD C.P. 17, Compilation of papers presented to AGARD Flight Mechanics Panel Specialists' Meeting, Sept. 20-23, 1966.

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LEAD DISCUSSION

by
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On reading the paper by Bob Harper yesterday I was very disappointed. I had no questions to ask him. I totally agreed with his point of view. It is a very unpleasant position for a discussor! So, I shall make only some comments on his very interesting paper and leave the discussion, if necessary, to the audience.

My first remark shall be about the use of the Cooper-Harper scale. We cannot use this scale to rate anything. We use some scales in order to rate for instance the work of pupils at school, the performance of ski jumpers at Olympic games, the taste of cakes if necessary, but all these scales are not Cooper-Harpor scales. We have to be very careful to use the Cooper-Harper scale only as an index for evaluating the pilot workload and nothing else - namely not for evaluating the effectiveness of a pitch damper or the validity of lateral control power. We can only use the Cooper-Harper scale to evaluate the modification of workload due to a modification of a damper or due to a modification of the control power.

I think it is also very important to insist as a point related to the last one that rating seven or ten does not mean that the aircraft is unacceptable - it means only that the index qualifying the workload is seven or ten and nothing else. In certain cases the rating ten can be acceptable if the corresponding tested flight case is highly improbable and the rating four can be unacceptable if the tested flight case corresponds to a daily situation.

And now let us have a look at the problem of divergence between pilots.

When I gave my definitions of controls, selected and true configurations, state of the aircraft, state of the atmosphere, state of the runway and task, it was precisely to be sure that the pilots were doing exactly the same jobs. As you have said, it is possible to record a number of parameters in order to be sure that the task is the right one. It is true for checking the selected configuration, the failure situation, the mass and the c.g. location, even for checking the state of the atmosphere by making some turbulence measurements for instance. But there are two things that we cannot check by a record for the moment.

The first is the definition of the objective of the subphase. When I say "the definition of the objective" I speak mainly about the tolerances. Remember that the objective of a subphase is given with tolerances, taking into account the possibility of performing the next subphase. Generally these tolerances are not strictly specified to the pilots, and they can be estimated differently by them. It is evident then that the workload can be different if the pilots are trying to obtain different precisions of control.

Another thing which cannot be checked by records, at least for the moment, is the flight technique. In the definition of the task we have included the flight technique, which is the relationship the pilot tries to maintain between various parameters such as speed, altitude, angle of attack, bank angle, and so on. It is fundamental to describe clearly and precisely what flight technique is to be used, since some confusion can arise if different flight techniques are used by different pilots.

Another remark you have made concerns the psychology of the pilots. You have spoken only about one type of tiger - the tiger who gives only good ratings. I know of another type - the tiger who gives only bad ratings thinking that he has been able to land the flying machine only because he is so clever and skillful! I think, like you, that it is necessary to make a precise choice through the test pilots, taking into account these psychological factors. We have, I think, an equivalent problem for simulation pilots who have to accept the artificial situation of the simulator. The evaluation pilots have to evaluate the workload and not evaluate their own skill. I think that a serious psychological training effort is necessary to obtain this result.

A great number of things could be said about the problems of training and experience of evaluation pilots, but we do not have enough time and I prefer to spend some time on the interpretation of the scale. When a pilot is fulfilling a task he has two objectives:

- First, he has to observe what I call the immediate safety of the aircraft. In other words, he has to maintain within the limits the different flight parameters like attitudes and angle of attack; if any one of these parameters crosses the limit there is an immediate risk of an accident.
- Second, he has to observe what I call the short-term safety, in other words the tolerances of the objective of the subphase. If he cannot observe these tolerances there is another risk of an accident since he cannot begin the next subphase in good position.

Some experiences have shown that when we artificially increase the workload of the pilot, for instance by modifying the apparent inertial and aerodynamic characteristics using a variable stability aircraft, the pilot can observe the two types of safety until a certain level of degradation is reached. Then he leaves the observation of the short-term safety to observe only the immediate safety. For a second level of degradation the pilot cannot even observe the immediate safety and looses control of the aircraft.

To my mind the first level of degradation corresponds to the rating 6.5; or, more precisely, to the jump from the one-to-six range to the seven-to-ten range, because 6.5 means nothing. Indeed, we could use letters instead of numbers and I don't know exactly the meaning of F.5. Similarly, the second level of degradation corresponds to the jump from the six-to-nine range to the ten rating.

I think that what I have said is exactly the same thing that Bob Harper has presented in his paper, but not with the same words. So, for ratings from one to six the pilot's workload is increasing but he can fulfill

the task. From seven to nine the pilot provides his maximum work and has to leave a part of his objectives in order to control his aircraft. For a rating of ten, the pilot cannot even control the aircraft.

To sum up, the scale from one to six is an index for workload increasing from near zero to one hundred percent. The scale from seven to nine is an index for the difficulty the pilot has in controlling the aircraft and a rating of ten means that the pilot has lost control.

To obtain a rating from the pilot we have to ask him three questions:

- First question - Have you lost control of the aircraft? If the answer is yes, the rating is ten. If the answer is no, we ask the next question.
- Second question - Have you observed the tolerances of the objective of the subphase? If the answer is no, the rating is seven, eight or nine. The choice between these three values depends on the hesitation of the pilot to answer the two questions. If he has answered no to the first question with hesitation (it was a "no but") the rating is nine. If he has answered no to the second question with hesitation (it was again a "no but") the rating is seven. If there was no hesitation for both the first and second questions the rating is eight. And now if the answer to the second question is yes the rating is in the one-to-six range and we have to ask another question to precisely establish the workload.
- Third question. I think it is here that the main difficulty occurs with the evaluation scale. We can use descriptions of the workload as they are used in the scale proposed by Messrs. Cooper and Harper. Personally I think it is difficult to make a choice between six possible cases. So I would propose, although I have not for the moment good reasons to demonstrate that it is a better way, that we ask the following question - Was the workload higher than the maximum workload admissible for daily use? With the answers of yes, no, and no but possible, it is then possible to further subdivide the first range of the rating scale into three parts corresponding to the ratings from one to six. The main problem is to be sure that every pilot agrees on the meaning of maximum workload admissible for daily use.

I think that I have spoken enough for now and that it would be the right time to open the discussion with the audience.

OPEN DISCUSSION

A.G. Barnes, UK (to Mr. Wanner)

The suggestion of Mr. Wanner that pilot rating is only a rating of workload is superficially attractive, but seems to me to be unduly restrictive. It prevents the pilot from including in his rating his background experience, and his ability to extrapolate to the circumstances for which the rating is needed. For example, in still air, with decreasing aircraft stability we would still get good ratings. For the same aircraft in turbulence, the aircraft would be bad (the pilot rating would reflect turbulence level). If the pilot only rated workload for a set task (and he is probably a poor judge of workload) then we would lose that part of the pilot's judgment which says that "in this case I was able to perform well, but I could not do it every time".

Mr. Wanner, French Air Force, France

I totally disagree with your point of view. I think that we can't ask the pilot to imagine what the aircraft would be like in another condition. For your example the pilot could not imagine what could be the handling qualities with turbulence, if he has never flown the aircraft in these conditions.

Sqn Ldr D.C. Scouller, RAF/ETPS, UK

I think it is necessary to distinguish between pilot opinion and performance. You yourself cite the case of the "tiger" pilot who distorts the results. I submit that, provided one uses objective evaluation pilots, carefully defines their task, and gives them some training in that task, they should give similar opinion ratings, but their performance may be different.

R.P. Harper, Cornell, USA

It is advisable to give a pilot a complete range of conditions at the beginning of the program to handle the "tiger" pilots who say they can fly anything. This will force them to admit that there are aircraft that they can't fly and 10's will result. There are many things that go into an experiment and there is a need for a lot of planning prior to the experiment.

CRITERIA FOR STALL AND POST STALL GYRATIONS

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SUMMARY

The handling requirements as laid down by the B.C.A.R. are described, problem areas associated with the interpretation of the regulations are discussed.

1. INTRODUCTION

The purpose of this note is to outline some of the problems associated with the handling characteristics during approaches to, and excursions beyond, those operational limits of present day commercial aircraft which are related either to their stall characteristics or, for certain configurations, such as slender configurations, to their rate of climb capabilities.

In normal operation satisfactory handling qualities are primarily assessed on the niceness of control which is based objectively on the overall stability and control characteristics and subjectively on collective pilot opinion; it is implied that a high degree of safety is incorporated once the handling aspects are acceptable. However, in the stall and post stall regimes, or alternatively in the neighbourhood of a minimum flight speed condition, safety is paramount, hence stringent airworthiness requirements have evolved which are aimed at ensuring satisfactory dynamic behaviour for virtually all possible high angle contingencies: handling qualities are deemed satisfactory when recovery from post stall gyrations has been adequately demonstrated. Therefore, a description of the handling qualities in the stall environment leads directly to a discussion of the stall requirements as they are applied in flight test procedures and in operational flying.

As already stated the emphasis is on commercial aircraft. outlining in the main the attitude in the U.K., as reflected in the British Civil Airworthiness Requirements of the Air Registration Board. It is hoped that points of divergence from other countries will arise in the discussion at this conference.

It is easy to appreciate why the stall requirements continue to present problems. Airworthiness requirements incorporate past experience, which by now is not inconsiderable, whilst endeavouring to meet current trends. But modern configurations cover a wide range in shape and size from the swept conventional aircraft, often with its ill defined stalling characteristics, to the slender aircraft, when conventional stall no longer occurs, to the V/STOL breed of aircraft where power and aerodynamics are inextricably bound up together. Necessarily the stall requirements can only be phrased in qualitative terms and often it is in the interpretation of these requirements for specific aircraft that difficulties arise.

No one will dispute the basic philosophy of relating the airworthiness requirements and those operational limitations applicable to the low speed flight of the stall condition, or to some alternative minimum flight speed. Factors are applied to fix the operational limitations which then permit adequate margins for manoeuvring, to allow for probable speed variations, and to prevent reasonably probable meteorological disturbances from stalling the aircraft. In the rare events that take an aircraft inadvertently beyond its low speed operational limitations then unmistakeable stall warning must be present to inform the pilot of what is happening, and in the even rarer event of excursion beyond the stall, ability to recover, relatively quickly, is imperative. In practice safety factors appear to be well chosen from the point of view that a satisfactory level of safety has been achieved in low speed flight; typical quoted figures suggest that the probability of reaching the stall warning is of the order of 1 in 10^3, while the probability of occurrence of stall is of the order of 1 in 10^5.

Understanding of the reasons for the effectiveness of the various safety factors is not in any way complete; the overall factors have been empirically established over the years but the breakdown into proportions which allow individually for manoeuvring, speed variability, and turbulence is not available; this gives rise to difficulty in formulating equivalent factors for new configurations which follow novel operational procedures.

The definition of the datum for the minimum speed in steady level flight, the specification of the factors of safety, the demonstration of satisfactory dynamic behaviour in inadvertent excursions beyond the operational limits have important repercussions in the design stages. If flight tests show inadequacy in meeting any airworthiness stall requirements, the consequences can be expensive and time consuming for the traditional remedies of 'quick fixes' are increasingly difficult to achieve, major modifications may be required. Ideally the aim must be to acquire at the design stage all the information necessary to predict the aircraft behaviour at low speeds and at high angles of attack, prototype flight tests should then be made to check out and quantify the predicted trends, not to investigate unknown conditions.

2. IDENTIFICATION OF THE STALL AND MINIMUM SPEED CONDITION

Identification of the stall and minimum speed condition is an important aspect in the programme of test flying on a prototype commercial aircraft. But the stall identification is not a straightforward matter, for even one basic configuration operates over a wide weight and height range, while in the low speed regions the effects of the full range of slat and flap settings must be considered. Even Mach numbers, at low speeds, can have a not inconsiderable effect.

Ideally stall recognition should comprise some prior warning from buffeting while any deterioration of the handling qualities should be progressive, followed by an inherent tendency to reduce angle of attack

at the stall; adequate stability and control, both longitudinal and lateral, must be present at all times prior to the stall. Unfortunately these ideals are becoming increasingly difficult to achieve: excessive buffeting, excessive build up of drag, pitch up, wing rock, excessive wing drop, loss of directional stability, lateral limit cycle oscillations are all phenomena said to have been observed in recent years.

In general it would be hoped that some 'a priori' knowledge on the stalling characteristics would be available from wind tunnel measurements before the flight tests are undertaken. But mainly because of difference in Reynolds number, wind tunnel results can be misleading in conditions where flow separations are occurring. This is one area where far more research is required to clarify the role of the wind tunnel measurements in providing reliable information concerning full scale stall behaviour.

Stall identification, per se, is not part of the requirements; these are more concerned with satisfaction of recovery procedures.

The British Civil Airworthiness Regulations (D2-11) refer the flight requirements to limiting speed conditions whose definitions may be paraphrased:

Stalling Speed - speed at which a large pitching or rolling motion, not immediately controllable, is encountered when the speed of an aeroplane, trimmed for a speed approximately 1.4 times the Stalling Speed, is reduced in straight flight at a rate not exceeding 1 knot per second; an uncontrollable pitching motion of small amplitude associated with pre-stall buffet shall not be taken as indicating that the Stalling Speed has been reached;

Minimum Steady Flight Speed - minimum steady speed obtained with the elevator control in the most rearward possible position following the same manoeuvre (as that described above in the definition of the Stalling Speed), this speed does not apply where the Stalling Speed occurs before the elevator control reaches its stops;

Minimum Speed in a Stall - minimum speed obtained when the (above) stalling manoeuvre is executed;

One-g Stalling Speed - minimum speed in flight at which the aeroplane can develop an aerodynamic force perpendicular to the flight path equal to the weight of the aeroplane.

These various speed conditions need to be established for the various conditions of loading, configuration and power which are necessary for compliance with the stall handling requirements.

The handling qualities are specified for the slow approach to the stall in steady flight with symmetric power, on and off:

> 'from a value sufficiently above the Stalling Speed (or Minimum Steady Flight Speed) to ensure a steady rate of decrease, the speed shall be reduced at a rate not exceeding 1 knot per second until the aeroplane commences a large amplitude pitching or rolling motion, or until the elevator control reaches its stops; in the recovery the engine power shall not be increased but normal use of the elevator may be made after the large amplitude pitching or rolling motion has unmistakeably developed.'

In straight flight the normal methods of (lateral) control should maintain the aeroplane substantially level and on a substantially constant heading until the large amplitude motions occur. After initiation of that large pitching motion and before completion of the recovery, .. disturbance in roll is acceptable provided that its magnitude does not exceed on the average approximately 20°. In turns with bank up to 30°, lateral control again needs to be adequate and the roll following the stall shall not be so violent or extreme as to make it difficult, with normal piloting skill, to make a prompt recovery and regain control of the aeroplane, without exceeding the maximum permissible speed appropriate to the configuration, or the allowable limit load factor, and in any case shall not be such that an angle of bank of 90° is exceeded!

These handling qualities need to be demonstrated for the most adverse c.g. position, range of wing flap positions, landing gear retracted and extended, cooling gills in 'appropriate' position and specified power levels. In addition recovery from stalls in steady straight flight with one power unit operative must be possible.

Several distinct aspects of these requirements deserve comment.

Anomalies have arisen in the past on conventional swept aircraft over the definition of the datum for the minimum speed condition. Using the minimum speed in the stall rather than the 1-g stalling speed, then with the same applied safety factors the margin of ability to manoeuvre can be considerably reduced. Safety factors and the establishment of the low speed operational limits affect the handling assessment indirectly in the sense that a pilot requires confidence in flying an aeroplane; if the factors are low or incorrectly based then too frequent excursions into the stall environment, even with an ideal inherent stall behaviour, must make a pilot uneasy especially when compounded with the total work load required in low speed phases of flight.

In respect to the handling requirements themselves it is seen that the classical concept of an inherent nose down motion if an aeroplane stalls is no longer implicitly stated in the regulations (pitch up has probably killed it), recovery is deemed satisfactory if obtained by the normal operation of the elevator <u>after</u> the large pitching or rolling motion has unmistakeably developed. Such a regulation cannot be said to be precise primarily because it is intended to provide the spirit rather than the letter of satisfactory airworthiness in its application to a range of configurations. Piloting skill and experience are important features in the demonstration of the stall manoeuvres, especially in the early stages as regards the timing of the recovery process itself, e.g. when to apply the down elevator action and the rate of application of the elevator. Small differences in the timing of the recovery action, and in the rate of

application of the elevator, can spell the difference between a satisfactory recovery and a major upset. It is not an easy task to ascertain what margins are present in a series of successful recoveries. Essentially there should be a comprehensive back up programme of analytical dynamic studies together with simulator studies although it is recognised that the aerodynamic input data may be somewhat unreliable; these points are discussed in more detail later.

For some conventional aeroplanes the stalling conditions cannot be investigated because the handling at low speeds degenerates to such an extent that there is a significant probability that the flight phase may not be completed successfully. It might be expected that auto stabilisation would be employed to alleviate this problem but vital questions are then raised regarding the relationship between the integrity of the system and the possible consequences of failure. From a handling point of view, in this case, the low speed datum should be in terms of a 'handling limit speed' but such a limiting condition may impose unacceptable performance penalties; possibly a situation which calls for a return to the drawing board.

One particular aspect of autostabilisation deserves special mention and which highlights other fundamental points. Some aeroplanes which operate close to, or below, the minimum drag speed, are being fitted with auto throttle to maintain speed stability. Since the low speed stall will also be below the minimum drag speed, then for consistency with operational flying, the auto throttle should be in operation. But the slow approach requirements as they stand are in terms of decrease in speed of not more than 1 knot per second which the auto throttle will presumably suppress. Fundamentally, and it has always been recognised as such, stall is a function of angle of attack, also rate of change of angle of attack, rather than speed. It would be more logical to express the safety margin in terms of angle of attack, especially from the point of view of accounting for atmospheric turbulence effects. However, the use of speed is more convenient and is by now well established; it is understood that the definition of the slow rate of decrease of speed is equivalent to a statement on the slow rate of increase in the angle of attack. Here the case of auto throttle must be regarded as a special case, although in the near future it may become commonplace, the requirements may need to refer to angle of attack; such requirements have yet to be declared.

Many commercial aeroplanes, although controllable to high angles of attack, do not experience distinctive stall characteristics; neither the large amplitude pitching nor rolling motion, asked for in the regulations, materialise. On the other hand large increases in angle of attack can build up sometimes resulting in large losses in height, both of these effects have led to catastrophes. Often these effects are not appreciated by the pilot. There is one recorded incident on a Lockheed C-141 on a stall manoeuvre in which the aircraft pitched down satisfactorily at the stall as far as attitude was concerned but the angle of attack trimmed out about 7° above the stall angle of attack; the pilot reported satisfactory stall behaviour! To ensure that high angle of attack situations do not build up, the identification of the stall is artificial, namely by the stick pusher. In general the stick pusher is actuated when the aircraft attains a predetermined angle of attack, which is monitored for flap position, rate of change of angle of attack, etc.; sometimes, as on the V.C.10, twin klaxon horns also sound to inform the crew what is happening. Once the aircraft returns to angles of attack some degrees lower than the predetermined settings the pusher is released.

Reliability of a stick pusher device, according to the B.C.A.R., must conform to the requirement:

'No single failure or likely combination of failures will result in failure of the device to actuate at any time when it is designed to be actuated unless the probability that it will fail in this way (from all causes) is less than one in a hundred.'

It is mandatory to provide warning when the system for actuating the device has failed.

Unwanted actuation of the stick pusher device, a point of major concern to airline pilots, is covered in the regulations in a gross sense; safety is not to be significantly prejudiced, structural limit loads are not to be exceeded, and no undue difficulty in control and operation of the aeroplane is to be caused; predicted rates of occurrence of unwanted actuation must be specified.

In the regulations it is stated

'a means for disarming the system should be provided and should be effective at all times; this means should be capable of being readily selected by the pilots; an unmistakeable indication should be given, and continue to be given, to the pilot that the system has been disarmed.'

It is intended that the device should be automatically armed, and stay armed, except

(a) at air speeds at and above which the risk of stalling as a result of an atmospheric disturbance is Remote (e.g. a 66 ft/sec gust) in which case the system should automatically re-arm when the air speed falls below these speeds;

(b) where it can be shown that the risk of stalling is Extremely Remote (e.g. when a high integrity automatic landing system with automatic speed control is in use).

It would appear that the complete stall identification system is complex, questions of integrity then come to the fore. But stall warning (shakes, knocks), stall identification accompanied by klaxon horns, warning for system failures, warnings for system disarming, must all contribute to the bewildering environment for the pilot.

All of the preceding discussion has been relevant to the more conventional aircraft with the standard flap systems.

One promising development especially for the control of large conventional aircraft along a specified flight path is the advent of Direct Lift Control. The suggested forms for D.L.C. at present depend on a fast-moving spoiler or flap; in its null position in steady flight the spoiler will be partly raised and the flap less than fully deflected, thus the stalling speed will be higher with the D.L.C. system operative

than that of the same aircraft with the D.L.C. inoperative. Whether or not the actual qualities at the stall would be modified is not known. The problem is now to ascertain what factors should be applied to the stalling speed of a D.L.C. aircraft bearing in mind its superior handling characteristics.

The introduction of the new configuration of the slender wing aircraft requires a complete revaluation of the low speed limits. Slender wing aircraft do not experience the stall of classical aircraft since flow separation at the wing leading edges is highly organised into discrete vortices, lift is not lost (until extreme incidence) but a large induced drag appears and the aircraft performance is impaired. It is necessary to define the zero rate of climb speed, V_{zRC}, as the minimum speed at which an aircraft, under a given set of conditions, can maintain level flight; this phenomenon has already been experienced in flight. Flight near this condition is potentially hazardous since a pilot may not be aware of approaching or passing below V_{zRC} and by the time the pilot has realised his position and recovered considerable height can be lost; such an event at low altitude could be catastrophic. One difficulty is that since V_{zRC} is not purely aerodynamic in origin it varies with many more factors than conventional stall, including altitude, lower setting, air temperature, aircraft configuration and weight. The airworthiness authorities propose to substitute V_{zRC} for the stalling speeds in the appropriate regulations and definitions for application to slender aircraft.

Because it is necessary to develop a clearer understanding of the factors involved in flight near V_{zRC}, research at the R.A.E. (U.K.) is focussed on

(i) the best technique for determining V_{zRC} during flight tests;

(ii) the best technique to minimise the height lost during recovery from speeds below V_{zRC}, and what height losses are incurred using this technique;

(iii) the training of pilots to follow the best techniques;

(iv) the speed margin required during normal flying operations to avoid the risk of speed accidentally falling below V_{zRC};

(v) whether a pilot during normal flying operations in a slender wing aircraft needs an instrument to warn him when the speed approaches V_{zRC}.

Finally some brief comments on V/STOL configurations. Because of the wide range of design options it has to be recognised that each configuration may need to be treated individually. But in general terms at low speeds in all types of V/STOL configurations, handling qualities differ substantially from conventional aircraft, due for example in the longitudinal motions to the coupling of phugoid and short period motions, and to lateral sensitivity to atmospheric turbulence; in those cases where the handling characteristics become deficient, the introduction of autostabilisation raises the problems of integrity mentioned earlier in relation to conventional aircraft.

In most V/STOL configurations it is expected that stall requirements will have to be met and that a stall condition will be used as the datum for operational limits; the stall condition would now be complicated by power effects and the stall would need to be defined in terms of operating procedures.

For configurations which achieve STOL capability either by combining moderate wing loading with high natural lift coefficients or by combining higher wing loadings with very high lift coefficients (induced artificially) the stall may be expected to be sudden with serious g loss; in this case because of low approach speeds atmospheric turbulence is relatively more effective so margins should be increased.

In the case of V/STOL aircraft that are only partly wing borne the severity and nature of stall behaviour depends on the ratio of wing lift to total lift but it is expected there will always exist some stage, most probably during the transition from wholly wing borne flight where stall is critical.

It would appear that in all of these cases of V/STOL configurations the concept of a unique stalling speed is not valid and the requirements and limitations upon margins will have to be related back to incidence.

3. DYNAMIC STALLS

In the preceding section, those problems associated with the identification of the stall characteristics in slow approaches have been discussed. In addition stall requirements also call for Dynamic Stalls; the philosophy of the Dynamic Stall manoeuvre is that it endeavours to represent a likely type of inadvertent stall as might be experienced in extreme turbulent conditions.

According to the B.C.A.R.,

'there shall be no violent wing-dropping and no tendency to spin when the aeroplane is stalled (and recovered), in turns with bank up to 30°, when the stall is approached at a natural rate - that is - a rate appropriate to the aeroplane and appreciably greater than 1 knot per second.'

The dangers of the dynamic stall manoeuvre are not so much due to the rate of approach, as such, although in some cases the characteristics of the stall are modified, but rather to the fact that the pilot has less comparative time to react to the recovery manoeuvre so that the stall incidence may be exceeded by a much greater margin possibly to a point where recovery is impossible. Compliance with the regulations depends on the interpretation of the phrase for the rate of approach being 'a rate appropriate to the aeroplane'.

Aircraft without automatic stall protection devices used to be required to demonstrate fairly gentle

dynamic stalls up to 0.25 or 0.3 g increments. But with the introduction of the stick pusher, to ensure integrity of the device and triggering system, much more severe dynamic stalls were called for, up to 0.62 g increment. The position with the stick pusher has now calmed down, and the regulations state:

> 'the actuation of the device (stick pusher) in turning flight and in dynamic stalls with total normal accelerations of up to 1.5 g should be such that the aeroplane, with the system operating normally, complies with all relevant stalling requirements'.

What is not clear in the current U.K. regulations is whether or not all aircraft are to be subjected to the same 0.5 g increment dynamic stall irrespective of whether the aircraft is fitted with automatic stall protection.

Dynamic stall tests can lead to excessive angles of attack, sometimes far beyond the stall incidence; large differences in overshoot behaviour can be obtained from small delay times by the pilot in initiation of the recovery. And it is not clear from flight tests what is the margin of safety between recovery, which sometimes involves large changes in altitude, and loss of control. It is therefore being questioned whether any aircraft should be allowed to get into situations where the angle of attack is far beyond the stall angle and recovery becomes uncertain. This is pertinent to the larger commercial aircraft where the inherent slower response times increase the time and height losses before trim is recovered, possibly imposing severe structural loads, and which at low altitude constitutes potential hazards. From both an economic and a humanitarian point of view such demonstrations are too great a risk. The U.S.S.R. has apparently responded to this problem for 'heavy aircraft are tested only for stall, and sometimes only to determine the control and stability characteristics up to high but unstalled angles of attack, exceeding by several degrees the angles of attack corresponding to (the onset of) buffeting but less than the stalling incidence'.

However it should be noted that it is not always the dynamic stall which leads to the highest overshoot conditions; in some cases apparently the slow approach has led to the most severe post stall gyrations.

If it is argued that the stall requirements should be relaxed, one possibility is that more analytic studies should be made of post stall gyrations together with simulator investigations of the post stall behaviour, then the full range of recovery procedures could be investigated in comparative safety. Continuing developments in digital computation facilities and techniques and in simulator facilities and experience suggests that such investigations are viable. It is realised that the major unknown in such ground based investigations concerns the aerodynamic input, for this is an area where wind tunnel results are often unreliable because they are obtained at too low Reynolds number; also dynamic (aerodynamic) effects are important which for investigation in a wind tunnel require specially developed oscillatory rigs. Serious consideration should be given to the type of wind tunnel tests which would lead to more reliable aerodynamic information in the stall and post stall conditions.

One might ask whether there is an analogy with flutter clearance procedures where extensive mandatory calculations are made in the design stage and then the calculations are up-dated progressively as data is confirmed, first from prototype ground resonance tests for the structural and inertial characteristics and then from structural response information in test flights from which the aerodynamic inputs can be checked, and if necessary modified. Gradual increase of test speeds then depends on successive clearances for flutter on the best available information.

Perhaps a similar approach could be applied for certification in respect to stall requirements in which the limit of flight stall demonstration is assessed from pre-stall behaviour, and buffet onset, based on both flight measurement and prediction, the excursions could be investigated theoretically, and by simulator with a pilot in a loop. Such an approach would require a more positive recognition of the stall aspect in the design stages and in wind tunnel investigations than given in the past.

4. STALL WARNING

Once the stall condition has been agreed upon it is mandatory that sufficient warning of the imminent possibility of stall be given. According to the B.C.A.R.

> 'In all stalls clear and distinctive stall warning shall be given to the pilot sufficiently in advance for the stall to be avoided by action after the stall warning first occurs. The warning may be furnished by the aerodynamic qualities of the aeroplane, by a suitable instrument, or by any means which will give unmistakeable warning under all normal conditions of operation. Prior to each of the slow approach stalls a warning shall occur at a speed which is not less than 5% above the stalling speed; a reduced figure may be acceptable if the physical difficulty of entering the stall, and/or the behaviour at the stall are considered to warrant it.'

Natural aerodynamic stall warning is usually interpreted as buffeting onset. Now buffet is the aerodynamic phenomenon associated with flow separation, usually from the wing; buffeting is the structural response to (aerodynamic) buffet; pilot assessment of the intensity of buffeting depends primarily on the location of the cockpit in relation to the structural modes excited by buffet. It is not unknown for pilots to be unaware that wings are buffeting due to the fact that the pilot is located close to the node of the structural mode of excitation. More information is required on how a pilot reacts to, and interprets, the buffet environment. In addition, prediction of onset of low speed buffet from wind tunnel tests requires some work, especially when flaps are down; predictions of buffet onset at high (subsonic) speeds for the deviation of the linearity of the C_L (α) are promising, the extension of these ideas to low speeds does not appear to have been made.

One aspect in operational flying concerns buffeting as a stall warning, namely the possibility that a pilot mistakes response to atmospheric turbulence as buffeting, for after all both sources of excitation affect the pilot through the structural modes although in the case of turbulence there is more aircraft response in its overall body modes. A corrective action could be dangerous. In any case there is the

possibility that structural response to atmospheric turbulence could mask the onset of buffeting which could then lead to an unexpected post stall gyration.

Artificial stall warning devices usually consist of stick shakers, or knockers, which are triggered by incidences sensing vanes on the fuselage of the aircraft.

Although stall warning is mandatory on all aircraft it is not clear what actions pilots take when the stall warning goes off. There has been at least one accident when the stall warning went off on take off, the pilot's subsequent nose down recovery put the aircraft back on the ground. It would be of interest to know what pilots do in the circumstances, both in test flying and in operational flying.

5. FLIGHT IN TURBULENCE

Upsets due to turbulence in operational flying in which loss of control occurs, usually temporarily, are still regarded as a continuing problem. Pilot briefing on this phenomenon has had a beneficial effect, but the understanding is far from complete. In some of those upsets where the aircraft has changes of + 1 g, pilots' impressions are found to be unreliable, in some instances the pilots thought that the aircraft was upside down. Such large g variations are qualitatively consistent with responses from computer simulation studies where aircraft have been shown to pass through positive to negative stall conditions.

It would appear that more theoretical work should be done to assess optimum control procedures in these situations.

It is not clear how the stick pusher device contributes to the dynamic behaviour in these turbulent situations. According to the regulations

> 'the system should be such that flight in turbulence, up to the most severe that is likely to be encountered, is unlikely to result in such actuation of the device as will significantly increase the difficulty of flying in such conditions';

exactly how this requirement is interpreted by the constructors is not clear.

Returning to the confused pilot, a recommendation has recently been made:

> 'it is difficult to avoid the conclusion that occasional re-familiarisation (of airline crews) with unusual positions and recoveries therefrom using small jet trainer aircraft would be a worthwhile measure in the interests of improved flight safety. Pilots involved in such upsets have in fact stated that prior military experience with instrument recoveries from unusual positions has been a factor in regaining control'.

6. CONCLUDING REMARKS

The main emphasis in this note has been on the interpretation of the handling requirements for commercial aircraft in the stall environment, together with a discussion of some of the factors which are currently under consideration.

No mention has been made of the most notorious post stall gyration, namely the spin. Commercial aircraft are not allowed to get into a spin situation whereas a military fighter type configuration must be recoverable from a spin. It is not intended here to discuss recent developments of the spin manoeuvre. But it is worthwhile noting that for aircraft which are to be flown into a spin and recover, there is an extensive programme of model testing in spin tunnels to identify the modes of spin and to determine the associated recovery procedures; in addition nowadays comprehensive model force and moment measurements are made at large angles and the spin dynamic motions are analysed numerically. Thus there is considerable background of knowledge before the aircraft is actually flown into a spin.

A similar wind tunnel effort at the design stage for a commercial aircraft would be highly beneficial for it would improve the predictive aspects of stall behaviour. These wind tunnel tests would necessarily have to be at sufficiently high Reynolds numbers for the stall characteristics to resemble full scale characteristics. Special dynamic rigs would need development for certain wind tunnel investigations. The combination of such aerodynamic results with extensive numerical analyses of recovery procedures in post stall gyrations, together with extensive simulation studies, would establish the stall and post stall environment with more confidence so the safety in test flying would be improved and certification simplified.

LEAD DISCUSSION

by
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INTRODUCTION

After a few readings of Dr. Hancock's paper, I realized that there was little I could take exception with and I suspect this applies to most of todays audience. The very few reservations I do have are duly noted in my discussion but the major portion of my comments emphasize and expand some of the points raised by Dr. Hancock. In so doing, I have leaned heavily on personal observations and experiences and the opinions expressed herein are, therefore, of a personal nature.

For convenience, I have listed my comments under the same section headings that Dr. Hancock used. Before beginning, I suggest that the word criteria in the title is misleading and should be replaced by requirements.

IDENTIFICATION OF THE STALL AND MINIMUM SPEED CONDITION

The author defined the stall characteristics which are considered to be ideal and then noted that they are becoming increasingly difficult to achieve. This is quite true, but I think it is also important to note that they are indeed achievable. To my knowledge, all of the civil aircraft manufactured in the U.S. to date have met these ideals and this, of course, also includes T tail aft mounted engine configurations. This success, especially in recent years, may be largely attributed to the fact that the BAC 111 deep stall accident alerted and motivated every airframe manufacturer to increase his efforts in this area. For instance, since the BAC 111 incident, aerodynamic data has been routinely obtained up to an angle of attack of 40 or 45 degrees at a Reynolds number of 6.0×10^6/ft. These data have been analyzed and also used to compute motions at high lift coefficients. In addition, simulators have been employed to conduct handling quality studies in the stall region. The design stage efforts recommended by Dr. Hancock, therefore, can indeed eliminate many of the difficulties that in the past have been discovered during the prototype flight program. Further improvements can be foreseen in this regard as well as the ability to design more optimum and safer vehicles as our experimental and analytical techniques are improved, especially those related to stall warning.

I would like to make a few comments relative to the type of simulators used during these stall studies. For over 18 years I pleaded the cause for a moving-base simulator when performing handling quality studies that involved precision control tasks such as landing, formation flying, tracking, inflight refueling, etc., and, as many of you know, I was always prepared to present a list of incorrect conclusions that had been established over the years using fixed-base facilities. It appears that this list will again be growing in the near future for the following reasons.

Precision control tasks such as landing or tracking are associated with flight at high lift and are the tasks assigned to a pilot during a simulator stall study. In the future we presumably will be determining the effect of buffet onset, buffet intensity and other stall characteristics on the pilot's ability to perform these tasks. At this point, one must recognize, however, that the pilot senses angular and normal accelerations with the cristae ampullaris and otoliths, respectively, of the inner ear and it is the angular acceleration that the pilot employs as an anticipatory cue in performing precision control tasks. Fixed-base simulators obviously do not supply this basic cue. If one extends the stall study into the spin/post stall gyration region, the limitations of a fixed-base simulator become even more serious. For instance, due to the inherent dynamic response characteristics and the threshold of perception that is associated with the vestibular organ, misleading cues are generated when a motion is suddenly terminated or its direction reversed. It is this physiological limitation of man that disorients him and degrades his ability to terminate a post-stall gyration, spin or upset. It is also the situation in which one wishes to train the pilot to respond strictly on the bases of information he receives from his instruments. I have been saddened to see some investigators, at this point in time, enthusiastically embrace a fixed-base simulator to evaluate and study the stall and spin and to advocate its spin training capability. Somehow one must get the point across that achieving an <u>illusion of realism</u>, through visual and aural cues and duplication of cockpit furnishings, is not the criterion for a valid simulation.

I would also caution investigators that the use of a moving-base simulator does not necessarily guarantee a valid precision control task evaluation. One must first verify that the dynamic response of the moving base matches the simulated vehicle to the extent that both the magnitude of the pitching angular acceleration and the transient relationship between argular and normal acceleration are faithfully duplicated.

The author points out that it has always been recognized that the stall is a function of angle of attack, also rate of change of angle of attack, and not of speed; and that it would be more logical to express the safety margin in terms of angle of attack. Whenever this point is raised during a conference, no objections are voiced. Certainly, the author has presented throughout his paper many reasons for making this change and I second his motion that civil regulating agencies include in their stall airworthiness regulations a reference to angle of attack and rate of change of angle of attack.

I would also like to take this opportunity to strongly recommend that angle-of-attack information be made available in the cockpit. The usefulness of this information has been demonstrated on V/STOL configurations during the transition flight phase, on carrier based aircraft which must operate close to their maximum potential, and on prototype test aircraft which demonstrate compliance with the Civil Airworthiness Stall Requirements. Its usefulness to the pilot during turbulence upsets should be obvious.

For over 70 years we have known that the stall angle of attack is invariant with weight, temperature

and altitude and yet we have convinced pilots that having this fundamental information would in no way influence their piloting proficiency or effect their safety. Instead, we have indoctrinated them with the belief that speed is the fundamental parameter effecting the stall and have then conscientiously supplied them with speed information. In spite of all this, the human pilot has been able to perform at an acceptable level probably because the airworthiness requirements reflected the absence of angle-of-attack information in the cockpit.

Fortunately, automatic devices such as stick pushers and automatic throttle systems could not be reasoned with nor mislead, and, therefore, would not fulfill their intended function without having recourse to angle-of-attack information. Consequently, accurate and reliable angle-of-attack sensors were developed and it is now possible to display this information to the pilot. The irony in all this is that in many instances the pilot may not be using this information for flying the aircraft but rather for monitoring the performance of some automatic device.

I also have a few observations relative to Direct Lift Control Systems. The author noted that direct lift controls (spoilers or flaps) must be placed in a null position during steady state flight and that the stalling speed will be consequently higher with the D.L.C. system operative than that of the same aircraft with the D.L.C. inoperative. I would like to point out that for the same reason (which is a loss of lift upon activation of the system) the angle-of-attack and correspondingly the pitch attitude angle must be increased for a given lg flight condition when the D.L.C. system is engaged. Consequently, the angle-of-attack margin between lg flight and stall is reduced as is the pilot's visibility of the landing site in conjunction with the aforementioned increase in the stalling speed. One would suspect that these inherent D.L.C. characteristics will not be judged as enhancing the handling characteristics.

Some years ago, while conducting a carrier landing study on a moving-base simulator I made the following observations relative to activating a D.L.C. system which I believe are appropo to this discussion.

1. Improvements in handling qualities were noted for airframes in which the variation of load factor with angle-of-attack, n_{z_α}, was small (i.e., where flight path control could not be achieved efficiently by adjusting the lift through aircraft rotation). The usefulness of the device appeared restricted to airframes which have both a low value of n_{z_α} and are deficient in precision controllability which is associated with a high moment of inertia or aft center of gravity location (i.e., an unacceptable low value for the control anticipation parameter, ω_n^2/n_{z_α}).

2. To realize the potential of a D.L.C. system, an effective approach power compensator (i.e., an automatic throttle) system must be available since almost all pilots felt that three altitude controls in the cockpit (i.e., stick, throttle and button) was confusing, and degradated their performance.

3. A D.L.C. system does not "cover up" basic airframe deficiencies since they are always evident during initial glide slope capture and gross-error correction maneuvers.

4. Activation of an automatic throttle system resulted in a greater improvement than was realized with D.L.C. activation and this improvement was experienced with all types of airframe characteristics. In other words, a very marked reduction in pilot work load was always noted when the automatic throttle system was engaged.

More recently, doubts have been noted relative to the need for and the improvement experienced with some aircraft that were equipped with a D.L.C. system. Also, a D.L.C. system, in common with all automatic systems, is quite complex. As for example, activation and consequent use of a D.L.C. system generates pitching moments which must be automatically compensated for.

It would appear, therefore, that some of us are not quite prepared to join Dr. Hancock in rendering the verdict that the handling qualities are superior with D.L.C. equipped aircraft.

DYNAMIC STALLS

In reference to dynamic stalls, the author indicated that it is not quite clear whether or not all aircraft are to be subjected to the same B.C.A.R. dynamic stall demonstration irrespective of whether the aircraft is fitted with automatic stall protection. I would think the answer is no but the fact that Dr. Hancock is not quite clear on this point stirs up the upsetting memory of a member of the British Air Registration Board intimating some years ago that this might very well be the case in the future.

I do not wish to belabor the point, but one should recognize that by specifying a severe dynamic stall demonstration one can in effect legislate the incorporation of a stall barrier device (i.e., stick pusher) on all aircraft - including those which possess all the ideal stall characteristics we have praised and struggled to achieve in the past.

If an aircraft has no primary stall warning, and has no inherent nose-down pitching moment at primary stall, but instead has a large nose-up moment which trims into a secondary stall around an angle-of-attack of 45 degrees (referred to as a deep stall, super stall, etc.) from which there is no escape because of insufficient control power then obviously I, as a passenger, have no quarrel with the need for installing an automatic stall barrier device. And just as obviously, one must select a stall demonstration maneuver which is not expected to be encountered in operational flight in order to insure that the device has been given the control authority and the required response characteristics to fulfill its function. But even in this situation one cannot arbitrarily specify an unrealistically severe stall demonstration since compliance can always be demonstrated by increasing the performance of the stall barrier device; that is, up to the point where it effectively removes the pilot from the control loop.

At any rate, my hope is that the dynamic stall to be demonstrated continues to be the one that is appropriate to the airplane.

CONCLUDING REMARKS

Dr. Hancock notes in his concluding remarks that for military aircraft which are to be flown into a spin, there is an extensive program of model testing in spin tunnels to identify the spin modes and to determine the associated recovery procedure, also that nowadays comprehensive model force and moment measurements are made at large angles and the spin dynamic motions are consequently analyzed numerically. All of this is quite true and I might add that these aerodynamic measurements are made up to an angle-of-attack of 90 degrees and over a 30 degree sideslip angle range at a relatively high Reynolds number of 6.0×10^{6}/ft. The author also noted that these efforts consequently form a considerable background of knowledge before the aircraft is actually flown into a spin. Fine, but I think it is reasonable to ask how predictive is this background information? The author intimates that the information is useful and, therefore, one must assure it to be accurate. However, is that really the case?

In this regard, it is interesting to observe that we can predict during the conceptual design phase that a fighter aircraft will have the inherent ability to enter different spin modes and/or post stall gyrations and that one of these modes will be probably characterized as a fast flat spin from which it will be difficult to recover. Furthermore, knowing the mass distribution of the aircraft, we can predict which controls and how they must be employed if recovery is to be realized. Understanding the physics of the spin pehnomenon permits us to make these gross predictions quite confidently before conducting any experimental or analytical studies. The only important and difficult task remaining, therefore, is to identify the flat spin mode and to predict if recovery can be affected from this spin without recourse to some major change in the configuration. This then is the function that spinn tunnel tests serve.

One familiar with spin tunnel efforts, however, realizes that the prediction of the full-scale spin modes and especially the acceptability of the associated recovery characteristics; requires a considerable amount of agonizing interpretation of the experimental results, hopefully made under devine guidance and with the application of various criteria which attempt to correlate past spin tunnel predictions with observed full-scale results. Also, one must recognize that free-spinning facilities have been sorely taxed for more than twenty years in serving this function because of their limited ability in simulating the full-scale spin environment, i.e., Reynolds and Mach numbers and the spin entry mechanism. (The latter limitation having been relieved to some extent through the use of radio-controlled free-flight drop models.) The serious challenge to the predictive powers of spin tunnel personnel can be traced to the point in time when highly swept, low aspect ratio, high wing loading configurations which had their mass heavily concentrated in the fuselage were introduced into the family of aircraft. It is my opinion that the level of confidence associated with recovery predictions leaves much to be desired.

Now although I'm not all that happy with the predictive powers of existing spin tunnels, let me hasten to add, that most of our knowledge relative to the spin is directly attributable to the astute observations and intuitive reasoning of past investigators conducting experimental free-spinning model programs.

It should also be noted that the continuing reliance on free-spinning model tests is indicative of a greater lack of confidence in the technique of analytically computing the spin motion. This situation will continue to persist until the incipient, developed and recovery phases of the spinning motion recorded in flight with the full-scale airplane are truly matched analytically on a computer. This "motion matching" demonstration would be even more impressive if the spins have been computed before the flight program. The inability to satisfactorily demonstrate this "motion matching" can be attributed largely to the use of an incomplete or a poor representation of the stalled aerodynamics that exist in a spin.

High performance aircraft have a spin mode which are characterized by a small or no spin radius (i.e., the aircraft rotate rapidly about a vertical axis which passes approximately through the center of gravity location). The technique presently employed to represent the aerodynamic forces and moments may very well be a pseudo-technique which must be abandoned when attempting to compute the spins of high performance vehicles. By installing a rotary balance rig (not to be confused with a rolling or oscillatory balance set-up) in a high Reynolds number facility one could obtain a set of aerodynamic data while the model is under the same local flow conditions that exist during the full-scale spin.

OPEN DISCUSSION

S.B. Anderson, NASA Ames, USA

Years ago we did studies of possible correlation of wind tunnel measurement of stalls to determine how well we could predict stall behavior. This showed that for swept wings if you had a roll moment coefficient of 0.6 it correlates with an unsatisfactory behavior in real flight. However, there were two important things to consider, that is (1) sideslip in both directions while testing in the tunnel because it is sensitive to sideslip and (2) you must take very small increments in angle of attack because the stall may occur only over a half degree angle of attack where you have a large asymmetry. If you take large increments you may miss the stall roll-off completely.

F.O'Hara, M.O.D. (PE), UK

Could I ask Dr. Hancock or maybe Mr. Davies about the use of angle of attack indication that Mr. Bihrle was proposing. I know it has some advantages, but I think it has some drawbacks too, particularly in the jet upset situation. Could I get some reaction to that, please?

W. Bihrle, Grumman, USA

Mainly the thing that bothers me is that when you take a prototype and you demonstrate the goodness of meeting the stall requirements, the first thing you do is put an angle of attack indicator in the cockpit. I think that is a little bit of an advantage to the test pilot. If he needs the indicator, why doesn't the day in and day out pilot?

D. Davies, ARB, UK

I agree with Frank O'Hara. I don't believe that incidence is half the advantage to airline pilots that some people think; simply because you are giving him too many parameters to integrate at the same time. At a given weight, he needs to be aware of vertical and forward airspeed. He should be able to deduce incidence. We have it on Concorde and rarely use it or look at it, apart from the high incidence exercise. One reason is that airline pilots are not educated in this fashion. There are a lot of traps. The main difficulty is that you are giving him one more parameter than he needs and he has difficulty in integrating it properly.

Dr. J. Roskam, University of Kansas, USA

The education problem, that is definitely tied in with the use of angle of attack indicators, can be solved. We have well over 180 Lear Jets with angle of attack indicators on both the pilot and co-pilot side and has been quite useful.

J. Teplitz, FAA, USA

As far as angle of attack is concerned, we haven't mentioned the widespread use of flight directors, which incorporate this information. A flight director organizes the information for the pilot and attempts to present the information without presenting too many parameters.

R.F. Siewert, U.S. Navy, USA

All Navy carrier airplanes have angle of attack indicators, but during the critical landing phase we present it in a little simpler form to the pilot, that as an indexer. This gives the pilot a more gross indication. This is the parameter correlated with airspeed that the pilots use.

F. O'Hara, M.O.D. (PE),UK

May I switch the discussion to Mr. Bihrle to ask his views in relation to Dr. Hancock's statement regarding the need for more thorough wind tunnel before flight, particularly in regard to the need for dynamic testing.

W. Bihrle, Grumman, USA

This is the biggest area where we are lacking both analytical and experimental techniques. As Mr. Anderson said what is lacking is the ability to accurately predict stall warning. This is a very difficult task of defining the stall.

J.H. Wykes, NAR, USA

Considerable success has been had in determining where the buffet occurs, from the nonlinearity, etc. It is not a hopeless task, it's just something you have to get down to work with.

W. Bihrle, Grumman, USA

It is true that since the BAC 111 that it is a routine that we go to a high Reynolds facility and test at 6.6 million per foot and up to 45° angle of attack. From this data, one is capable of predicting full scale characteristics, in terms of the directional, lateral, and longitudinal stability, etc. With this data it is also possible to design variable geometry devices like leading edge slats which can improve the stability. The prediction of acceptable buffet for stall warning is a difficult area to define at this time.

TURBULENCE MODELS FOR THE ASSESSMENT OF HANDLING QUALITIES DURING TAKE-OFF AND LANDING

by

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SUMMARY

Properties of atmospheric turbulence at low altitude are reviewed, with particular reference to those aspects relevant to an aircraft on a landing approach or during take-off. Recent measurements of power spectra are described and related to a simplified theoretical model. Looking beyond the power spectrum, an important property of turbulence is its intermittency, related to a tendency for aircraft response to show large peaks separated by regions of relative inactivity.

Pilots appear to be particularly sensitive to this intermittent structure, and their subjective comments can be related to measured turbulence characteristics.

It is shown how a discrete gust model for turbulence may be employed to predict the magnitude of large response peaks. As an example, the response to gusts of an aircraft constrained to fly at constant attitude is discussed, with particular reference to the effects of aircraft speed.

1. TURBULENCE AND HANDLING QUALITIES

Satisfactory handling and ride qualities of an aircraft depend upon good characteristics in both smooth and rough air. In some cases these can be conflicting requirements in that if aircraft stability, damping and control power are chosen to provide optimum manoeuvrability in still air, there may result an unsatisfactory degree of response to disturbances in rough air. We should thus aim to obtain an aircraft which has both good response to controls and minimum response to external disturbances. Recent trends in aircraft design have produced aircraft types for which the gust response is an important feature. In the case of the slender wing transport aircraft, response to gusts is increased both by high gust sensitivity associated with large ratio L_p/I_A and is further amplified by relatively low roll damping. In this case, and indeed for swept wing aircraft in general, control power requirements have been increasingly dictated by turbulence rather than manoeuvring. Another example is the STOL aircraft for which the reduced airspeed tends to make gust response a critical factor, particularly if the STOL capability is achieved by reduction in wing loading.

It is clear that an important ingredient of the assessment of handling qualities is the evaluation of the behaviour of the aircraft in rough air. For this purpose analytical methods and ground based simulation are required for predicting aircraft response to turbulence. The object of this paper is to outline some techniques which are now available, or are in the process of development, in this context. We have not attempted to give an unbiased overall picture - the emphasis is rather on techniques which have been only recently developed and with which the author has been directly concerned over the past few years.

The effect of turbulence upon an aircraft may be considered in terms of the 'systems' representation illustrated in Fig. 1. This shows three basic components: the gust input, the aircraft dynamics, and the aircraft response. In the most general interpretation of Fig. 1, the gust input $v(t)$ represents a vector field, including longitudinal, lateral and vertical components correlated with one another and varying over the surface of the aircraft, and the response $y(t)$ represents a complete definition of the aircraft state. In the present paper, however, we shall be mainly concerned with a much simpler interpretation of Fig. 1 in which $v(t)$ represents a single turbulence component, whose variation over the span of the aircraft is neglected, and $y(t)$ represents a single aircraft response variable. Whilst the limitations of this simplified representation should be remembered, it proves to be adequate for many purposes.

The definition of the gust input, in analytical terms, is the primary objective of this paper. To put it into perspective, however, it should be considered in conjunction with the aircraft dynamics, defined analytically by the equations of motion, and the resulting aircraft response. For the remainder of this section we will discuss features of the aircraft response, and will subsequently return to the specification of the gust input by means of turbulence models.

The response of an aeroplane to a given level of turbulence differs from one aircraft to another due to such factors as wing loading, lift slope and speed. A pilot flying an aeroplane with a high wing loading and low lift-curve slope may be relatively unaware of turbulence which could be causing considerable trouble to a colleague flying a light aeroplane nearby. In a given aircraft, a pilot is aware of turbulence in three main ways which are, in rough order of importance: vertical bumps, disturbances in roll, and instrument fluctuations - principally airspeed and rate of climb. At conventional landing approach speeds vertical bumps, i.e. fluctuations in normal acceleration, are due primarily to vertical turbulence acting to change angle of attack and therefore lift. At low flying speeds, horizontal gusts also make an important contribution to fluctuations in normal acceleration. These disturbances cause pilot discomfort and thus have an indirect effect on the control task.

After vertical bumpiness, the next most important effect is in roll, where the lateral component of turbulence produces deviations in bank angle. These roll disturbances are most important during the landing approach, when the pilot is trying to fly a defined heading. The rolling effect of turbulence

tests the aircraft's controllability and may well constitute a design case for roll control effectiveness. In the case of small aircraft, pitching response to turbulence can be a significant nuisance to a pilot attempting to follow a prescribed flight path, although this effect becomes much less important for large transport aircraft.

In general, a pilot is more worried by single peaks in response (normal acceleration, bank angle, etc.) than by continuous 'wobble' because, for a large disturbance, he has to take action to correct a divergence which might appear not to be correcting itself. In contrast to a linear automatic control system, which reacts always to an extent proportional to the magnitude of the disturbance, a human pilot tends to have a 'threshold', and only fluctuations in response which exceed this level lead to control action. Thus whilst the root mean square level of response may be an adequate measure of the input to an automatic control system, it is mainly the distribution of relatively large response peaks which influences the pilot. This concern of the pilot with large disturbances is important in relation to later statements (section 2.3) concerning the large and intermittent disturbances in atmospheric turbulence which stand out from the general 'noise' background.

A pilot's perception of, and concern with, turbulence varies with its severity. The primary cues to worsening turbulence are the variation in bumpiness and increase in lateral control activity. As turbulence becomes more severe, instrument fluctuations also become more pronounced. This is particularly true of airspeed fluctuations which become of more significance during landing approaches in heavy turbulence such as might be associated with a wind speed of 25-30 kt. Throttle adjustments become more frequent and it is common practice to add 5-10kt to the target approach speed to cope both with the increased intensity of random fluctuations and with the increased wind gradient.

Pilots' impressions of turbulence as altitude changes during an approach can be related to the gust models we shall describe. One pilot has commented that, in a 15-20 kt wind, he would not expect to find much turbulence at 1000 ft but as the aircraft descended he would first feel longer wavelength gusts and then, as the aircraft approached the ground, the higher frequencies would be accentuated, giving a generally 'choppier' response. At 500-600 ft there would be a wide distribution of gust wavelengths but nearer the ground the distribution of significant wavelengths would narrow, as the influence of long wavelength gusts decreases. A second pilot said that, for the height band below 1000 ft, bumpiness gets worse down to some height, then gets better. These comments can be correlated with the observed variation, with altitude, of the scale length of the power spectrum of vertical turbulence (section 2.2).

In the above remarks on aircraft response we have drawn heavily on Refs. 1 and 2, where the representation of low altitude turbulence in piloted ground-based simulators is discussed. This work is particularly relevant here in two senses. In the first place, an understanding of the significant properties of atmospheric turbulence is important for the creation, in simulators, of a representative environment and work load for the assessment of handling qualities. Secondly, the subjective impressions of pilots, by contrasting real flight with simulated flight using 'synthetic' turbulence, have provided useful cues as to the limitations of conventional turbulence models and assisted our understanding of gust structure. Frequent criticisms made in the Aero Flight simulator at the Royal Aircraft Establishment, Bedford, have been that the simulated, or synthetic, turbulence led to aircraft response that was too regular, that there were not enough 'big gusts'. The simulated turbulence tends to be too predictable, the number of large isolated gusts experienced in the simulator being low in comparison with flight. This criticism was voiced particularly strongly during simulation of a large slender-wing aeroplane. Pilots were mainly aware of this deficiency for side gusts and the associated bank-angle disturbances. These criticisms can be explained in terms of differences between the statistical properties of simulated and real turbulence (section 2.3). It appears that a conventional filtered Gaussian noise signal, which is common to standard noise generators and traditional turbulence models, is adequate in a simulation if the purpose is merely to force the pilot to exercise positive control over his aeroplane, but that simulations with the objective of assessing such factors as workload, or control-power requirements, require an input which reproduces the intermittent, large, and potentially more critical disturbances which occur in the real atmosphere. These characteristics of turbulence are of importance for a realistic assessment of the handling and ride qualities of an aircraft in rough air and are taken into account in the turbulence models that we shall now go on to describe.

2. POWER SPECTRA AND INTERMITTENCY

2.1 TURBULENCE IN THE EARTH'S BOUNDARY LAYER

Turbulence in the earth's boundary layer is derived from two principal sources, a mechanical source and a thermal source. The mechanical source is a combination of shear and surface roughness. The thermal source is the vertical motion of warm air.

In strong winds the stability is approximately neutral, the mechanical source dominates, and the air flow bears some similarity to the flow of a turbulent boundary layer around an aerodynamic surface. This is the most common source of large gusts. There is no clear upper height limit, but usually the turbulence below 1000 m is regarded as low altitude turbulence. For aircraft applications the main interest is up to some 300 m above the terrain with the bottom 30 m being of crucial importance for aircraft landing. Close to the ground the turbulence includes the eddies behind obstacles such as buildings, trees etc., (which define 'surface roughness'). Recent interest in the operation of STOL aircraft into urban sites has provoked investigation of this type of turbulence, although only preliminary results are at present available[3]. Higher up the wind shear is the main turbulence source, although downwind of an urban area the influence of terrain roughness might be expected to influence much of a landing approach.

Large and rapid fluctuations of wind are not, however, confined to situations where the mean wind preceding them is strong. Large gusts which occur when the wind had previously been relatively light are associated with thermal convection in and above the earth's boundary layer and the larger of them

(which have resulted in a number of accidents) are associated with thunderstorms[4,5] and are usually referred to as squalls. The average number of squalls per year at RAE Bedford, over the last five years, has been forty, and on one of these occasions an aircraft touched down with a large sideways velocity. Had the runway not been wet, allowing the aircraft to slide sideways, the result could have been serious. Standard meteorological records have a timescale such that the rapidity of wind fluctuations in squalls cannot be resolved to the accuracy needed to predict the effects they would have on aircraft. In an attempt to obtain further information, continuous records of windspeed at heights of 33 ft, 50 ft and 100 ft have been obtained on an expanded timescale using an instrumented tower at RAE Bedford. An example of such a squall is illustrated in Fig. 2. Although the recording speed is about twelve times that of the standard Meteorological Office instrument, it is still inadequate to resolve the more rapid fluctuations. A further recording system, involving an additional speeding up by a factor of 30 has therefore been introduced.

Taking together the cases of gusts associated with steady winds under approximately neutral conditions and gusts, or squalls, associated with convective conditions, we find turbulence records which have a predominantly irregular or random pattern together with cases where isolated 'discrete gusts' stand out in a clearly identifiable manner. Due to the randomness of turbulence it is necessary to introduce statistical analysis into its analytical definition. The ambivalent nature of turbulence has led in the past to widely differing ways of attempting to describe it: on the one hand its tendency to fluctuate in a chaotic random manner has suggested that the mathematical theory of continuous random processes be taken as a basis, on the other an impression that the larger, and for aircraft applications more significant, fluctuations could somehow be singled out as individual 'events' has led to various forms of discrete gust model.

The question of how to best describe atmospheric turbulence for aircraft applications has been the subject of a great deal of work in recent years, and in the present paper we contrast two proposed solutions: a Gaussian process model and a recently developed discrete gust model.

Two concepts that we shall emphasise in our descriptions of atmospheric turbulence are the power spectrum and intermittency. The power spectral density function is by now a well-understood concept[6] and has been used for some time as a basis for turbulence models. It describes the distribution of mean square gust velocity among the wavelengths of turbulence, for samples consisting of a sufficient number (of order ten to twenty) of the longest wavelengths of interest. Measured spectral densities of atmospheric turbulence show a high degree of consistency and agreement with theory, and provide our principal single source of co-ordinated information. Examples of measured spectra will be illustrated in the following section (Figs. 3,5). Two features common to all the measured spectra should be noticed. First, at higher frequencies (shorter wavelengths) the turbulence intensity decreases rapidly, approximately as frequency, or wavenumber, to power (-5/3). Second, at lower frequencies (longer wavelengths) the slope of the spectrum tends to decrease. Although the general shape is similar for many spectra, the form at the longer wavelength end tends to vary between the different velocity components of turbulence and to depend to a larger extent upon meteorological conditions. The wavelength marking the demarcation between the (-5/3) region and the longer wavelengths is related to the so-called turbulence scale, usually denoted by L. The turbulence scale is a very important parameter not only for the studies of turbulence itself but also in the study of aircraft response.

Whilst the power spectrum provides a great deal of useful information concerning the turbulence, it is not by itself sufficient to predict the magnitudes of the disturbances that turbulence produces in aircraft response, for example as measured by the magnitudes of response peaks. The point is that the spectrum only describes the 'average' energy, in any particular range of wavelengths over a relatively long sample. It does not specify the way in which this energy is distributed in space. Consequently, two random processes whose time histories differ considerably, one consisting of continuous random fluctuations and the other of intermittent 'bursts' of activity, may have identical spectra. They would, however, tend to produce very different effects on aircraft. In recent work[7-10] on the structure of atmospheric turbulence and its relation to aircraft response we have thus emphasised the importance of going beyond the power spectrum description, and of investigating the spatial distribution of turbulence energy in more detail. It has been found that, if measured turbulence is passed through a bandpass filter, with centre frequency on the (-5/3) part of the spectrum and bandwidth of about one octave between half amplitude points, significantly larger peaks occur, standing out from the average level of fluctuation, than in the filtered output of a standard Gaussian noise generator. This behaviour may be described as 'high intermittency', consisting of large fluctuations separated by regions of relative inactivity. This result applies both to the continuous turbulence fluctuations which occur under strong wind conditions, and, to an even greater extent, to the wind fluctuations in convective (squall) conditions. In the following sections we shall show how this intermittent structure of atmospheric turbulence can be quantified for applications to aircraft response, by means of a discrete gust model which is compatible with the measured power spectra.

Measurements of low altitude turbulence fluctuations can be made either by instrumented aircraft or by anemometers and wind vanes mounted on towers. For economic reasons most measurements have been made using tower based instruments, the fluctuations in time at a fixed point in space being converted to equivalent spatial fluctuations on the assumption that the turbulence is 'frozen' into the wind and convected past the measuring point at the mean wind speed (Taylor's hypothesis). Spatial frequency (or wavenumber) k, in cycles per metre, and frequency f in Hz are then related by

$$f = Vk$$

where V is the relative velocity, in metres per sec, of the mean wind and the measuring point. Whilst care has to be exercised using this technique, and cross checks using spatial measurements made wherever possible, the results obtained in this way appear generally to be adequate as a first approximation, and are the basis of the measured turbulence properties that we shall describe. An exception to the applicability of Taylor's hypothesis arises in the case of turbulence in the wakes of buildings, as significant time variations in wind velocity at a point can then arise due to lateral relative movement of wake and measuring point, particularly at the lower frequencies. Estimates of spatial gradients can then

only be made by spatial traverses, adding greatly to the complexity of measurement techniques.

2.2 POWER SPECTRA

As we have described in more detail elsewhere[10], both the concepts of power spectrum and intermittency can be interpreted in terms of the response to turbulence of a set of band pass filters.

Consider a turbulence sample v(t) of length T, from which the mean has been removed, expressed as a function of time t. Making use of Taylor's hypothesis, t can be related to distance s through the equation s = Vt, where V is the relative velocity of the recording point (aircraft or anemometer) and the mean wind. We suppose the sample v(t) to be passed through a set of band pass filters. These are illustrated (Fig. 7) as idealised filters with sharp cut-off, completely passing signals with frequency within the passband and completely rejecting signals with frequency outside it. In practice, of course, we are concerned with filters whose modulus decays smoothly to zero outside the passband (conveniently defined by the modulus half amplitude points). The ith filter (Fig. 7) has centre frequency f_i, bandwidth Δf_i, and output $v_i(t)$. This filter will be denoted by $(f_i, \Delta f_i)$.

The power spectrum of v(t) describes the distribution of AVERAGE ENERGY of the sample, with respect to the pass bands considered, as measured by the MEAN SQUARE filter outputs.

The theory leading to the definition of the power spectrum $S_v(f)$ involves simultaneously letting the bandwidths $\Delta f_i \longrightarrow 0$ and the sample length $T \longrightarrow \infty$. Then the mean square value of v(t) can be written in the form

$$\sigma^2 = \int_0^\infty S_v(f)\,df \qquad (1)$$

and $S_v(f)\,df$ corresponds in the limit to the mean square output of a filter of infinitesimal bandwidth df localised at frequency f. For the analysis of practical samples of length T, finite filter bandwidth has to be retained, and instead of a continuous function $S_v(f)$ we obtain a SPECTRAL ESTIMATE defined at a finite set of filter centre frequencies. Equivalent definitions of the power spectrum may be given by taking Fourier Transforms, either of the auto-correlation function of v(t) or of v(t) directly (Fast Fourier Transform). The measured spectra illustrated in this paper were in fact obtained via the auto-correlation function. We have outlined the approach in terms of filters as this method leads naturally to the quantification of the concept of intermittency (section 2.3).

A typical power spectrum of a measured[11] longitudinal, or along-wind, component of turbulence in a steady wind is illustrated in Fig. 3. Expressed in terms of wavenumber (spatial frequency) k in cycles per m, such spectra may be conveniently sub-divided into two separate regions; at the high wavenumber end the spectrum is proportional to $k^{-5/3}$, whereas at the low wavenumber end, down to the lowest wavenumber of interest in aeronautical applications, it takes the approximate form k^{-1}. The break point between these two asymptotic slopes defines the 'scale length' of the turbulence. In physical terms, the k^{-1} spectrum corresponds to a turbulence 'energy production' range of wavelengths containing the 'big eddies' of the turbulent atmospheric boundary layer, and the $k^{-5/3}$ spectrum is predominantly a range of energy transfer, consisting of eddies of all sizes between the energy production range and the small scale at which energy is dissipated by viscosity. Viscosity only begins to affect the spectrum at short wavelengths in the range 1 to 10 cm, which is not of practical aeronautical importance.

As an illustration of the practical significance of the above mentioned ranges of wavelengths, fluctuations in normal acceleration of a conventional aircraft in a landing approach are usually predominantly excited by the $k^{-5/3}$ region, in contrast to quantities such as rate of descent and airspeed fluctuations which are more likely to be excited by the k^{-1} region. In the case of STOL aircraft, however, flying at low airspeeds, the significant gusts tend to be much shorter (section 4), and these latter quantities also tend to lie in the $k^{-5/3}$ region.

Many workers in the past have fitted measured spectra to model spectra typified by the von Karman spectrum, given by

$$\Phi(k) = \sigma^2 L \frac{\{2 + 377 \cdot 5 (Lk)^2\}}{\{1 + 70 \cdot 78 (Lk)^2\}^{11/6}}, \qquad (2)$$

where σ^2 is the mean square intensity and L is a scale length. For large values of k, we have

$$\Phi(k) \sim k^{-5/3}$$

whereas for small k

$$\Phi(k) \sim \text{constant}.$$

A plot of equation (2) in log-log form is shown in Fig. 8.

The measured data (Fig. 3) fit the large wavenumber region of the von Karman spectrum model (equation (2)) very well, but there usually tends to be more energy at low wavenumbers than this model predicts[11]. Consequently we will model the measured spectra of the longitudinal component simply by means of the two asymptotes

$$\left.\begin{aligned}\Phi &\sim k^{-5/3}, \quad k > 1/2L \\ \Phi &\sim k^{-1}, \quad k < 1/2L\end{aligned}\right\} \qquad (3)$$

as illustrated in Figs. 3,4. This model spectrum (Fig. 8) has the advantage that it provides a better fit to the measured data and there is less ambiguity in the estimation of scale length L than with the von Karman spectrum.

More fundamentally, the scale length defined using equation (3) is a good measure of the largest 'organised eddies' in the turbulence as we shall discuss in the following section. Put simply, there is a detectable decrease in the intermittency of the turbulence as we pass from the $k^{-5/3}$ to the k^{-1} range, and the scale length defined by equation (3) thus has the advantage of corresponding to a change in the physical characteristics of turbulence.

For practical reasons, other forms of power spectrum model have been much used in the past. For example, by passing a white noise signal through a simple filter, spectra (the Dryden spectra) of roughly the same shape as the von Karman spectrum, but taking the form k^{-2} at short wavelengths, may be obtained. This type of model is therefore attractive for simulator applications[1,2,12], as 'synthetic' turbulence of this form is easy to generate electronically. However, a signal obtained in this way generally has the properties of a Gaussian random process and, as we shall describe (section 2.3) has important deficiencies for simulation purposes.

In the case of the vertical component of turbulence, the measured spectra indicate comparatively less energy at low frequencies (long wavelengths). A good description of the measured spectra may be obtained using an 'asymptote' model with three ranges: a $k^{-5/3}$ range at short wavelengths, a k^{-1} range at intermediate wavelengths and a range of constant spectral density at long wavelengths (Fig. 5). The first two ranges follow the same general pattern as for the longitudinal component, but now the measured k^{-1} range is more limited in extent. For many engineering purposes, as in the case of the longitudinal component, an adequate fit to the measured spectra may be obtained by appropriate choice of parameters in either the von Karman or Dryden spectrum forms.

The lateral (across wind) turbulence component has not been analysed so extensively as the other two. Existing data suggest that its power spectral properties are intermediate between the longitudinal and vertical cases. At short wavelengths the spectrum takes the usual $k^{-5/3}$ form. At the longer wavelengths there is more energy than in the vertical component, but not such an extensive energy production (k^{-1}) range as in the longitudinal component. Moreover, there is evidence that at these longer wavelengths the spectrum of the lateral turbulence component is particularly sensitive to meteorological conditions, varying from day to day. A further complication is that fluctuations in the lateral component measured at a fixed point in space by an anemometer may differ significantly from the corresponding fluctuations observed by an aircraft flying along the mean wind direction, owing to local effects of terrain on wind direction at the longer wavelengths. No direct comparisons of tower and aircraft data are available for this case.

Measured turbulence power spectra (e.g. Figs. 3,5) indicate a trend with altitude in which the scale length and long wavelength energy decrease as height is reduced (Fig. 4). Under certain conditions (particularly neutral tending to stable conditions) there is also an associated tendency in both longitudinal and vertical components for the short wavelength energy to increase as altitude is reduced (Figs. 4,6). Thus an aircraft descending through the earth's boundary layer, on a landing approach for instance, may experience a trend in which the disturbances at low frequencies, including airspeed and rate-of-descent fluctuations, decrease and those at higher frequencies, such as normal acceleration and rate of pitch, increase. In the latter case, there may be a subsequent decrease near to the ground as the change of scale length with altitude causes the turbulence wavelengths influencing the mode in question to pass from the $k^{-5/3}$ to the k^{-1} range. These inferences are compatible with the subjective pilot experience described in section 1.

The variation of scale length with altitude is illustrated in Fig. 9, the results for each component representing the mean of a series of about 16 one-hour measurements, under steady wind conditions. These RAE Bedford measurements have been compared[11] with data from other sources and, when put into directly comparable form, the agreement is good. The scale length L for the horizontal component was calculated by taking the break in the 'asymptote' model spectrum to occur at a wavelength of 2L as in Fig. 3. In the case of the vertical turbulence component, two scale lengths L, L_o are defined, L corresponding to the break between the $k^{-5/3}$ and k^{-1} spectrum ranges, and L_o to the break between the k^{-1} and constant spectral density ranges (Fig. 5).

2.3 INTERMITTENCY

Examination of filtered records of measured turbulence, using bandpass filters (of roughly octave width) with passband centre lying in the $k^{-5/3}$ spectrum region, shows that the spatial distribution of energy within such a passband is intermittent, in the sense that it contains localised concentrations of energy of considerably greater intensity than would occur in a sample taken from a Gaussian process with the same power spectrum. As discussed in Ref. 10, there is a reciprocal relationship between the bandwidth Δf_i of a filter and its decay time in response to a transient disturbance. For an octave width bandpass filter, with bandwidth Δf_i satisfying $\Delta f_i / f_i \doteq 1$, the decay time is sufficiently short for any large peak in filter response $v_i(t)$ (Fig. 7) at $t = t'$ to be associated with a limited region of the input v(t) in the neighbourhood of $t = t'$, covering an interval of approximately $1/(2f_i)$. Such an interval is a region of relatively high energy concentration in the sense that its contribution to the energy in the bandwidth Δf_i is abnormally high. For filters lying in the $k^{-5/3}$ spectrum region the probability distribution of peak amplitudes in the (octave width) filter response can be well represented

by an exponential distribution, showing that the energy concentrations are signficiantly greater than would be expected in a Gaussian process. This is illustrated in Fig. 10 where the probability densities of peaks in the output of such a bandpass filter, applied both to a measured sample of the longitudinal component of turbulence and to the corresponding signal from a matched Gaussian noise generator, are compared. In terms of the root mean square value σ of the filter output, it can be seen that a significantly greater number of large ($>2.5\sigma$) and small ($<\sigma$) peaks occur in the real turbulence, with a corresponding smaller number of peaks in the range between σ and 2.5σ.

Although intermittency has been illustrated for the case of octave bandwidth filters, it persists as bandwidth is reduced and appears as a property of the response to turbulence of many aircraft modes of interest. An important application of this property is to ground-based simulators[1,2]. There is a significant difference between the distribution of peaks in aircraft response to real turbulence and the distribution of peaks in simulator response using a conventional Gaussian noise generator, even though in the latter case the power spectrum is shaped correctly. Pilots appear to be particularly sensitive to the large, intermittent, response peaks and the increased number of peaks above the 2.5σ level (Fig.10), associated with real turbulence, may be correlated with their subjective criticisms of the 'predictability' of the disturbances produced by the standard noise generator. As a result of the good correlation between measurements and subjective pilot comments, work is in progress[1,2] at RAE Bedford on an improved gust generator for simulator applications, incorporating non-linear transformation of a Gaussian process, to reproduce the desired statistical features.

The measurement illustrated in Fig. 10 refers to wavelengths within the $k^{-5/3}$ spectrum range. At longer wavelengths the distinction between real turbulence and a Gaussian process with a matched spectrum becomes less marked. Recent measurements suggest that at the longer wavelengths, in particular the k^{-1} energy production range (Figs. 3 and 5), the intermittency becomes less significant and the current method of turbulence simulation using Gaussian noise is probably adequate.

3. TURBULENCE MODELS FOR PREDICTING LARGE RESPONSE EXCURSIONS

3.1 GENERAL REMARKS

It has been emphasised in section 1 that a pilot is mainly sensitive to the intensity of relatively large response peaks, rather than to the average level of fluctuating response as measured by the mean square intensity. Thus in order to be able to predict handling and ride qualities associated with turbulence, it is necessary to evaluate the probability of occurrence of relatively large response excursions. In this section we contrast two techniques that are at present available for this purpose: the Gaussian process model and a relatively new discrete gust model.

The problem may be formulated in terms of the 'systems' representation of aircraft response y to a turbulence input, Fig. 1. The transfer function, or frequency response function $T_y(f)$, relating input $v(t)$ to response $y(t)$, is determined by the aircraft dynamics. The question we now ask is: how can the average rate of occurrence of large excursions of y be expressed in terms of measurable properties of turbulence and the aircraft frequency response. This rate of occurrence (per mile, or per hour, etc.) may be expressed either in terms of the 'rate of crossing' or any arbitrary level or, equivalently, in terms of the rate of occurrence of peaks above such levels.

To determine the 'crossing rate' theoretically it is necessary to know the joint probability density $p(y,\dot{y})$, where $\dot{y} = \frac{dy}{dt}$ for the response quantity y being studied. If the number of crossings with positive slope (i.e. when the signal crosses the level y from below to above) is N_y, then

$$N_y = \int_0^\infty \dot{y}\, p(y,\dot{y})\, d\dot{y}, \qquad (4)$$

a result due to S.O. Rice. Thus if $p(y,\dot{y})$ is known, N_y can be evaluated. The principal difficulty is that in practice the form of the joint density $p(y,\dot{y})$ is NOT known. It is in general not a joint normal distribution, and it depends on the higher order joint probability distributions of turbulence velocity $v(t)$ in a complicated way, dependent on the system frequency response function $T_y(f)$. Thus this general method of approach to the problem has not proved particularly useful in practice, and no generally applicable results, based on measurements of atmospheric turbulence, concerning $p(y,\dot{y})$ are available.

In order to obtain practical results it is thus necessary to introduce a TURBULENCE MODEL at this stage, which simplifies the solution of the problem and yet retains sufficient of the characteristics of real atmospheric turbulence to provide realistic answers. We now briefly outline and contrast two models of turbulence structure that are currently available for this purpose: the 'Gaussian process model' and a relatively new discrete gust model.

3.2 GAUSSIAN PROCESS MODEL

The Gaussian process model[6.10] (often loosely referred to as a 'power spectrum model') makes use of the following relationship between turbulence input spectrum $S_v(f)$, output or response spectrum $S_y(f)$, and modulus of system frequency response function $T_y(f)$:

$$S_y(f) = |T_y(f)|^2 S_v(f). \qquad (5)$$

From $S_y(f)$ the mean square value σ_y^2 of the response $y(t)$ can be calculated by integrating over all frequencies. A knowledge of σ_y may be adequate for some purposes, for example the design of linear control systems, but in the present context we are interested in the rates of exceedance of relatively large levels of response. To this end the Gaussian process model is based on the following assumptions:

1. Atmospheric turbulence can be split into reasonably small patches, each with a constant value of root mean square turbulence velocity.

2. Turbulence in each patch can be regarded as a stationary Gaussian process.

3. The power spectrum for each patch is assumed known.

4. The patches are long enough for the aircraft response to be in a state of 'statistical equilibrium'.

From the above hypotheses it follows that the response $y(t)$ in each patch is also a stationary Gaussian process, allowing N_y, equation (4), to be calculated[6,10] simply on the basis of the power spectrum $S_y(f)$.

The weakness of the Gaussian process model is that measured peaks in the response of aircraft to patches of turbulence often closely follow an exponential distribution, containing more large peaks than in the response to a Gaussian process. This weakness derives from a failure to take account of the existence, in atmospheric turbulence, of the relatively intense concentrations of energy that have already been described in section 2.3. These remarks are particularly applicable in the case where the response mode is fairly well damped (damping ratio $>$ 0.1, which is usually satisfied by the modes relevant to aircraft handling) and where the response is predominantly at wavelengths less than the turbulence scale length.

3.3 DISCRETE GUST MODEL

The discrete gust model, in the form to be described, models the intense energy concentrations in atmospheric turbulence by means of a family of discrete ramp gusts (Fig. 11) covering a wide range of gradient distances and intensities. As described in section 2.3, localised regions of high turbulence energy concentration may be identified by means of the large peaks they produce in octave-width bandpass filters. Such an energy concentration takes the form of a large change in turbulence velocity over a distance related to the frequency of the filter and can be represented by a discrete ramp gust of appropriate gradient distance and intensity proportional to the magnitude of the peak in filter output. The ramp gust may be made up of straight line segments (Fig. 11a) or may contain half a cycle of a sine wave (Fig. 11b).

Starting from the concept of a self-similar random process it has been shown[8,9] that a suitable family of discrete gusts, appropriate in the range of wavelengths where the spectrum takes the form $k^{-5/3}$ is as follows:

$N_{H,w}dH$ is the number of discrete ramp gusts per mile (say), in the length range (H,H+dH) and having intensity greater than w (Fig. 11), where

$$N_{H,w} = \frac{k_1}{H^2} \exp\left\{-\frac{w}{k_3 H^{1/3}}\right\}. \qquad (6)$$

The parameters k_1 and k_3 which through equation (6) define the discrete gust model of a patch of turbulence, may be determined from the measured peaks in the outputs $v_i(t)$ of a set of bandpass filters (Fig. 7) as described in Ref. 10.

We now consider the evaluation of aircraft response on the basis of this discrete gust model. As for the Gaussian process model we consider the response $y(t)$ of an aircraft mode with frequency response function $T_y(f)$ to a turbulence velocity component $v(t)$ (Fig. 1).

Although the family of discrete gists, equation (6), consists of gusts of a wide range of lengths, it is a feature of the discrete gust theory[8,9] that for any particular aircraft mode the atmosphere appears effectively as a sequence of gusts with lengths in a limited range - centred on the 'tuned gust length' of the mode. The number of gusts per unit distance which produce significantly large peak values in the response depends both upon the statistical model of discrete gusts in the neighbourhood of this tuned gust length, and upon the 'gust length sensitivity' of the mode - a measure of the range of gust lengths contributing to the large response peaks. A peak response function $\gamma(H)$ is defined (Fig. 12) to be the magnitude of the peak response to a single discrete ramp gust of length H and intensity $w = H^{1/3}$. Denoting by n_y the average number, per unit distance, of response peaks greater than magnitude y, it is shown in Ref. 9 that $\lambda \bar{H} n_y$ is a universal function of $y/\gamma(\bar{H})$, where $\bar{H}$ is the TUNED GUST LENGTH at which $\gamma(H)$ attains its maximum, and λ is the GUST LENGTH SENSITIVITY, which is a measure of the breadth of the peak in $\gamma(H)$. λ may be evaluated using the equation

$$\lambda = \frac{1}{\log_e 2}\left\{\frac{2\gamma(\bar{H}) - \gamma(2\bar{H}) - \gamma(\bar{H}/2)}{2\pi\,\gamma(\bar{H})}\right\}^{1/2}. \qquad (7)$$

Integrating over gusts of all lengths in the discrete gust family defined by equation (6), n_y may then be evaluated as follows:

$$n_y = n_o \exp\left\{\frac{-1.15y}{k_3\gamma(\bar{H})}\right\}, \quad n_o = \frac{k_1}{\lambda\bar{H}}. \qquad (8)$$

Equation (8) and the associated equation (6) are equally applicable to an entire aircraft life history or to an approximately stationary patch of turbulence, although the appropriate values of k_1 and k_3 differ in these two situations.

The basic assumptions, and conditions for applicability, of the discrete gust and Gaussian process models have been reviewed in Ref. 10. It was concluded that these models are ideally applicable under differing limiting conditions. In particular, the discrete gust model is well suited to the treatment of most of the rigid body modes relevant to the assessment of aircraft control and handling qualities. The Gaussian process model is more appropriate for the treatment of modes whose primary response is at wavelengths longer than that defined by the turbulence scale length, and for calculating the response of very lightly damped modes.

4. EXAMPLE OF APPLICATION OF DISCRETE GUST MODEL

As an illustration of how the discrete gust model for turbulence may be employed to predict the magnitude of relatively large response peaks in aircraft response, we now consider the case of an aircraft constrained to fly at constant attitude, with particular reference to the effects of aircraft speed. Our basic interest is in the changes in gust sensitivity of aircraft as landing approach speeds are reduced to the values typical for projected STOL types.

We have considered two response parameters to cover what are believed to be the most relevant features of interest. Normal acceleration response has been calculated to represent ride quality - a measure of discomfort relevant to both the pilot and the passengers, but as a more meaningful criterion for control work load, fluctuations in airspeed have been evaluated.

A major assumption which has to be made before any response method can be applied is the choice of aircraft response mode. If one takes simply the aircraft transfer function with controls fixed, the results will not be representative of what actually happens to a controlled aircraft in turbulence. A great deal of work has been done in recent years on 'pilot transfer functions', where the pilot is represented by an average linear transfer function, similar to that which would represent a simple autostabiliser, possibly together with an additive noise source, or 'remnant'. Whilst this approach has led to useful results in control problems where a tracking task is clearly defined, its application to the case of a pilot controlling an aircraft would require careful validation in each particular situation, and it is not a simple technique to apply in practice. A more satisfactory process for present purposes is to assume an aircraft mode in which part of the response is suppressed by a suitable piloting constraint, as discussed in Ref. 16. We have here chosen a rather radical form of such constraint, namely the assumption that pitch attitude is held constant. Pitch attitude constraint is of course one basic aim of longitudinal control and hence is entirely plausible provided the short period dynamics of the aircraft are well enough behaved to allow this ideal to be approached[16]. Deficiencies in this area would demand correction, if necessary by artificial aids, and it is therefore not unreasonable to assume that this mode presents no inherent problems.

It can now be argued that an aircraft will be satisfactory if maintenance of pitch attitude - which requires a certain amount of pilot effort - results in a generally well controlled aircraft response. On the other hand if major excursions still occur, obliging the pilot to generate constraints in addition to that in pitch, he will register this as an undesirable increase in workload. The relative magnitude of such excursions can then be seen as a measure of control difficulty and can be expected to correlate in some way with pilot rating.

Rather than employ an explicit control law, which would be expressed as a postulated control movement in response to aircraft motion, we thus use a CONSTRAINT equation describing the EFFECT of control on the response. Since Neumark[13] drew attention to the practical importance of stability in flight under partial constraint, the idea of partially constrained flight has become accepted as a meaningful concept and has been successfully extended, for example, in Ref. 14. Moreover, the same technique can be used, not only to discuss stability, but to evaluate aircraft response to turbulence, as was demonstrated in Ref. 15.

Close control of pitch attitude is perhaps the most obvious piloting technique and is well achieved except in configurations prone to pilot induced oscillations. Pilots know from experience that by firm control of pitch the longitudinal motion of the aircraft as a whole is also well controlled. The most apparent result will be the effective suppression of the phugoid. It should be noted, moreover, that pitch attitude control is generally used as an inner loop in autoland systems. We will use the equations of pitch attitude constraint here to evaluate effects of changing aircraft speed. As speed is reduced to low values the attitude constrained motion develops an oscillatory mode which, as has been pointed out by Pinsker[16], could indicate a significant handling deficiency for STOL aircraft. Whilst the imposition of a constraint to represent pilot action is clearly an idealisation, and only represents a first approximation to the correct representation of the controlled aircraft, it is particularly useful as a technique for predicting trends in response associated with changing aircraft parameters, and it is in this sense that it will be employed here.

The equations for an aircraft constrained in pitch by means of elevator control have been given by Neumark[13]. We have used these equations in conjunction with the discrete gust model, section 3.3, in the case of an aircraft described by the following basic parameters

mass = 47000 lb	wing area = 960 ft^2
lift slope = 4.7	$C_D = 0.1 + 0.05\, C_L^2$

range of aircraft reference speeds is considered. A consequence of reducing speed is to increase the ...ed values of C_L and C_D. For each reference speed the gust response is evaluated by means of small ... matrix equations, using coefficients appropriate to that speed.

Results are illustrated in Figs. 13 and 14 for fluctuations in normal acceleration n due to both longitudinal u_g and vertical w_g components of turbulence and perturbations u_a in airspeed due to the longitudinal component. The results illustrated are only valid if the turbulence scale L is greater than $\bar{H}$.

Aircraft response at altitudes where L (Fig. 9) is less than the illustrated values of $\bar{H}$ will tend to contain fewer intermittent large peaks, tending towards Gaussian statistical properties. Because of the comparatively small values of the scale length L of vertical turbulence (Fig. 9), discrete vertical gusts have comparatively little influence on airspeed fluctuations during a landing approach, and consequently the discrete gust analysis has been omitted for this case.

The most important parameters in a discrete gust analysis are (equation (8)) $\bar{H}$, which through its effect on n_o largely determines the rate of occurrence of response peaks, and $\gamma(\bar{H})$, which may be taken as a measure of the amplitude of response peaks. The other aircraft dependent parameter, λ, appearing in equation (8) varies comparatively little, lying in the range 0.24 ± 0.04 for all cases evaluated.

Considering first the case of normal acceleration response n, it can be seen (Fig. 13) that at conventional approach speeds $\bar{H}$ is approximately speed independent and takes roughly the same value for the longitudinal u_g and vertical w_g components of turbulence. At very low speeds V however, below 30m/sec, $\bar{H}$ rapidly decreases implying, equation (8), that the rate of occurrence of response peaks, as measured by n_o, becomes large. At high speeds the amplitudes ($\gamma(\bar{H})$, Fig. 14) of the peaks in response to vertical turbulence are significantly larger than in response to longitudinal turbulence, but at low speeds of order 30m/sec the effects of vertical and longitudinal turbulence become of equal importance.

In the case of airspeed perturbations u_a, we have only considered the effects of longitudinal turbulence, as explained earlier. At conventional approach speeds the corresponding $\bar{H}$ is much larger (n_o much smaller) than that for normal acceleration response, but at approximately 30m/sec these $\bar{H}$ values become of equal order. As speed V decreases, the amplitude of airspeed response peaks, as measured by $\gamma(\bar{H})$ also rapidly decreases.

We have described here only a few results from a general study that is being made of the effects of gusts on aircraft flying at STOL speeds. It is hoped, however, that we have shown enough to illustrate the manner in which the discrete gust method may be applied in practice.

5. CONCLUDING REMARKS

We conclude by mentioning some areas of current work and problems for the future, related particularly to the discrete gust model we have described.

(a) Typical values of k_1 and k_3, describing the discrete gust content of turbulence samples through equation (6), are being measured for both horizontal and vertical components of turbulence under a wide range of conditions.

(b) The discrete gust method is being applied to assess turbulence characteristics of various types of STOL aircraft. The application to low wing loading aircraft with gust deviation (ride quality active control) is of particular interest.

(c) Related work using the discrete gust model is in progress on turbulence design loads, extending the design envelope and mission analysis criteria.

Finally we return to the basic formulation of the gust response problem, Fig. 1. The results of Figs. 13 and 14 indicate that for STOL aircraft the magnitudes of normal acceleration response to longitudinal and vertical turbulence are of about the same order, and the relevant gust lengths tend to be quite short. Thus the correlation between longitudinal and vertical gusts will influence the overall result and the effects of variation of gust intensity across the span of the wing may not be negligible. These are therefore important areas for future work. As the relevant experimental results are not as yet available, we have not so far attempted to take account of these effects in the discrete gust model.

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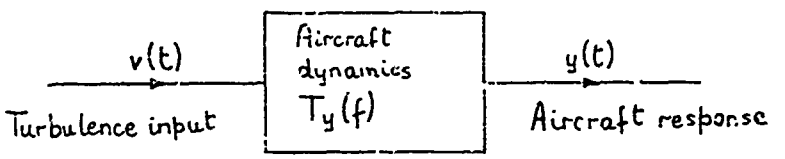


Fig.1 System representation for aircraft response.

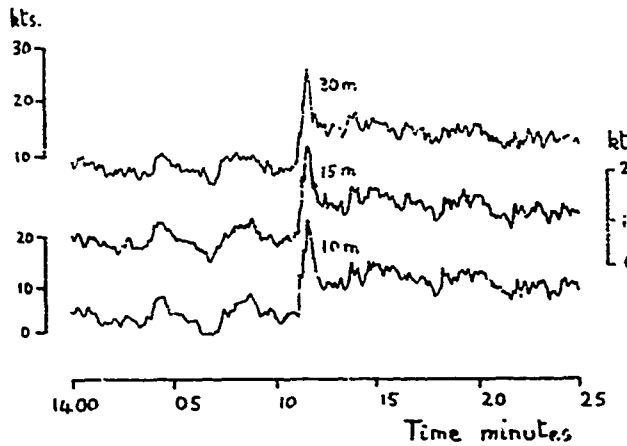


Fig.2 Time history including squall.

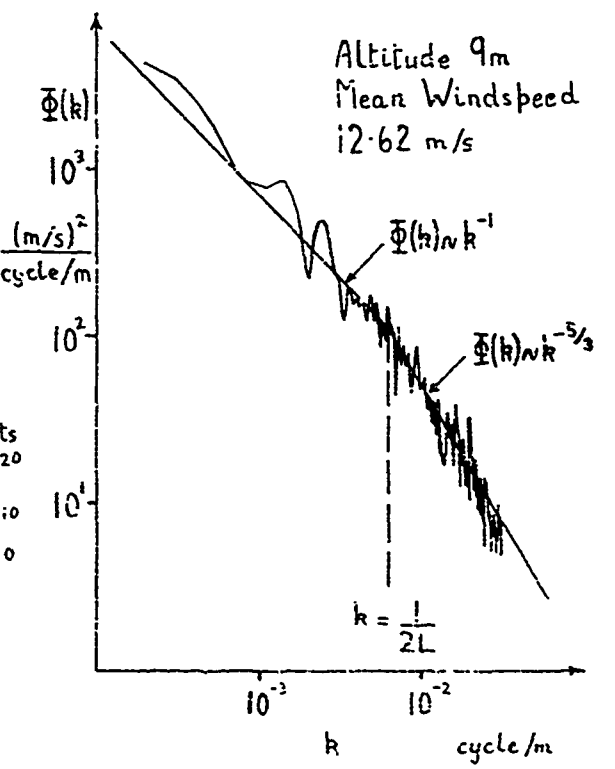


Fig.3 Measured spectrum of longitudinal component

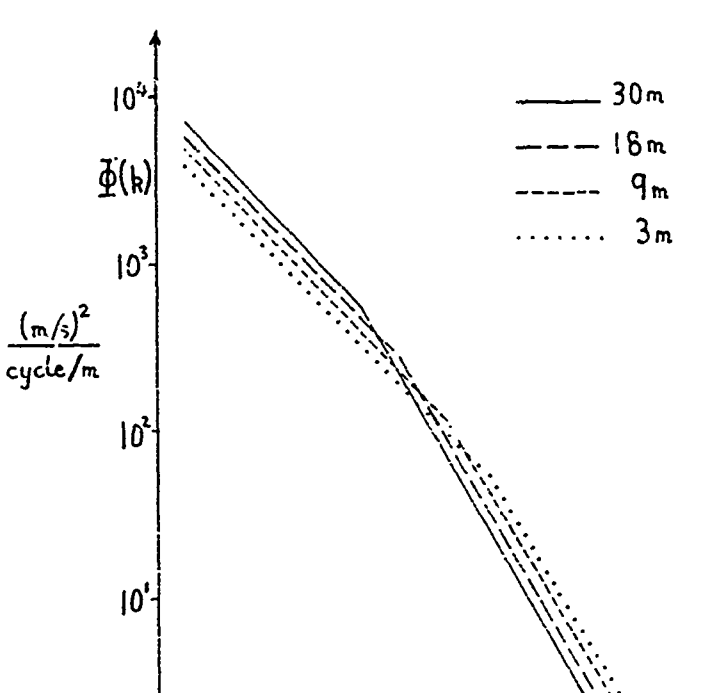


Fig.4 Effect of altitude on longitudinal spectrum.

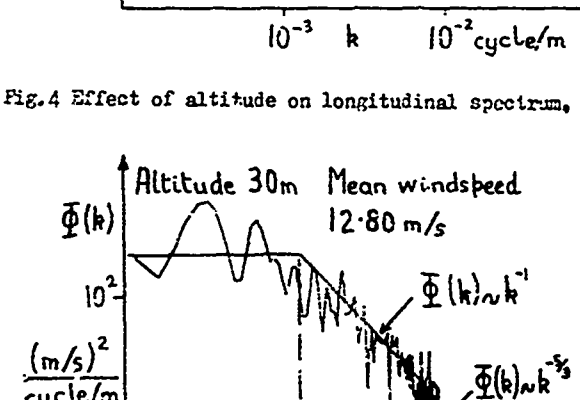


Fig.5 Measured spectrum of vertical component.

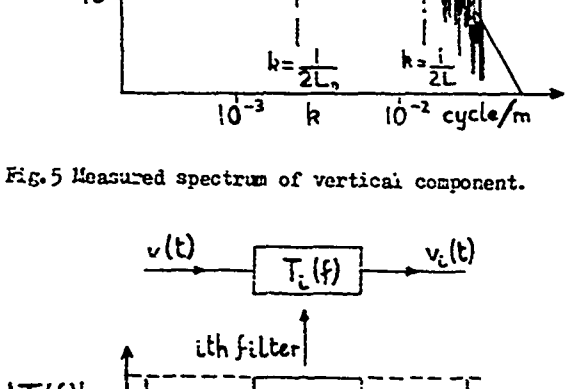


Fig.7 Set of bandpass filters.

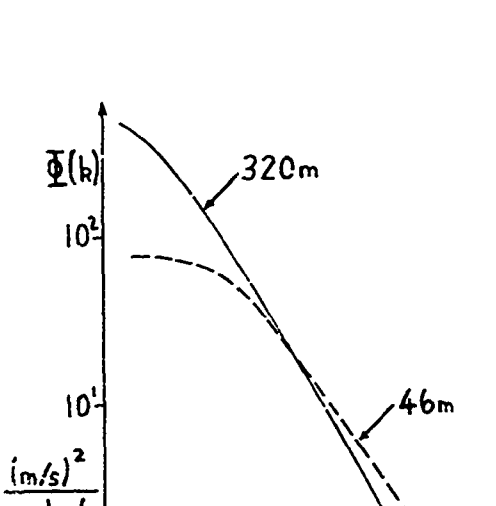


Fig.6 Effect of altitude on vertical spectrum.

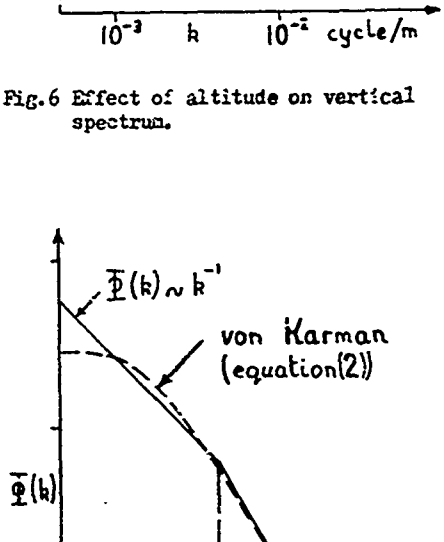


Fig.8 Model spectra.

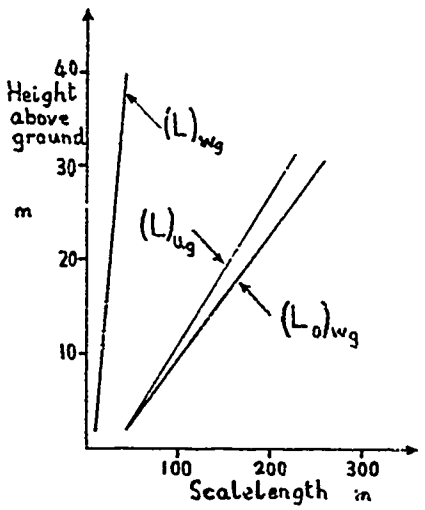


Fig.9 Variation of scale length with altitude.

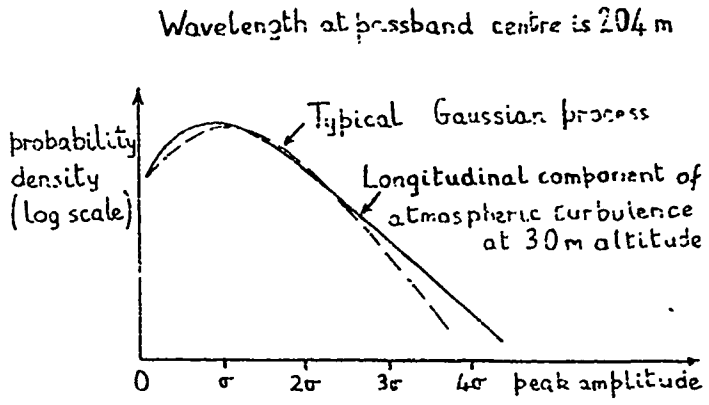


Fig.10 Measured probability densities of peaks in filter output.

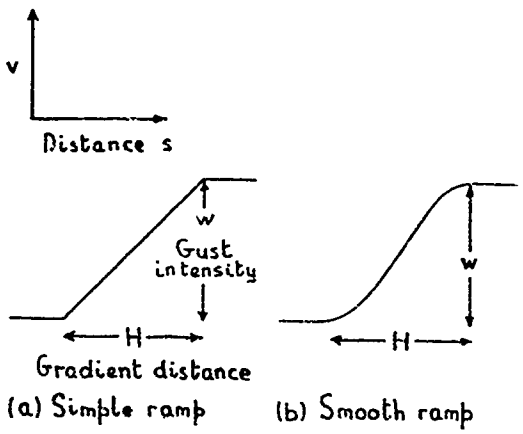


Fig.11 Discrete ramp gusts.

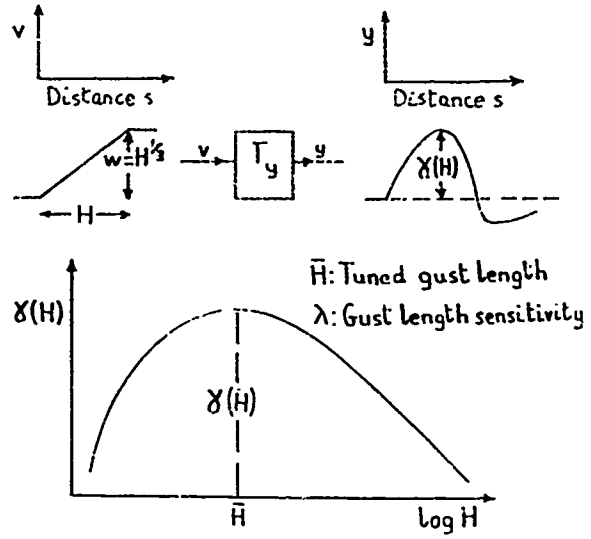


Fig.12 Peak response function.

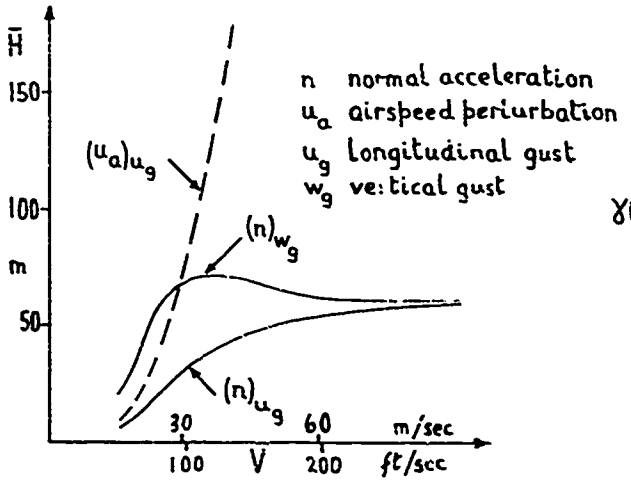


Fig.13 Effect of aircraft speed on tuned gust length.

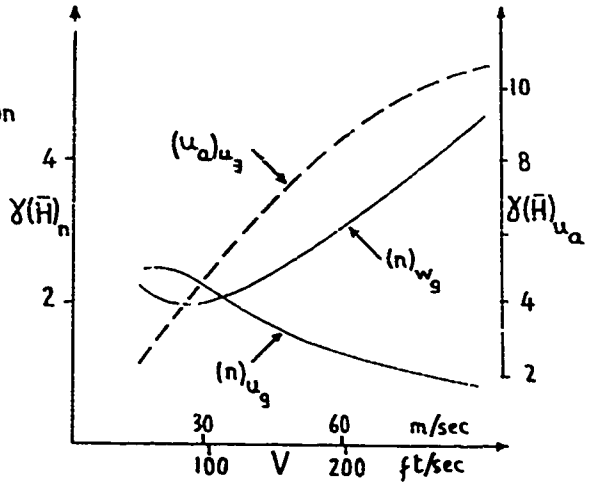


Fig.14 Effect of aircraft speed on tuned response.

LEAD DISCUSSION

by
Jean-Claude Wanner
Service Technique Aeronautique
Paris XV France

If I have understood correctly the philosophy of your paper, you have built a mathematical model of a single gust with three assumptions:

1. The turbulence can be reduced to the addition of discrete ramp gusts.

2. The resultant power spectrum is consistent with the Von Karman spectrum model with only some modifications for the low frequencies.

3. The level crossing law is nearer the experimental results than the Gaussian models generally used.

On the last point I would like to bring you new information. Mr. Coupry, whom I am replacing for this discussion today and who is the Chairman of the Working Group on Environmental Statistical Data of the AGARD Structures and Materials Panel, has analysed the results of the tests undertaken in various countries, and mainly in the United States, on the level crossing distributions. Mr. Coupry will give the details of his work next week in Bruxelles, but I can give you a partial result: the number of miles of crossings of a given level W is an exponential function of W. This result seems to be consistent with your last assumption. I have said "seems" only because I would like to check if I am right when I assume that your chosen law is actually an exponential one. It is certainly right for the level crossing law of the response of the aircraft - you have said this. But is it also right for the gust itself? This is my first question.

On another point, I would like to know the experimental basis for your first assumption reducing the turbulence to the addition of discrete ramp gusts. Have you made some experiments showing the compliance of your model with the true turbulence?

And last, a question on the way of using your turbulence model. I am afraid there is some confusion in the way the turbulence acts on the aircraft. We have to distinguish three ways of action:

1. A high intensity gust appearing among a mean level of turbulence (this is a remote but probable case) can force a parameter to trespass a limit, for instance the angle of attack crosses the maximum authorized value, producing then a stall and probably an accident, especially if in the approach flight phase.

2. A high level or turbulence, without special gusts producing risks of trespassing limits, can push the flight parameters near their limits, thus reducing the ability to manoeuver the aircraft. This is the effect of the state of the atmosphere on the manoeuverability of the aircraft.

3. The same level of turbulence as in case 2 can increase the pilot's workload and lead him to make mistakes, for instance to make an error in heading or to select the wrong channel for the ILS. This is the effect of the state of the atmosphere on the pilotability of the aircraft.

In my mind, the action of the pilot is negligible in the first case - suddenly there is a high level gust and the pilot cannot do anything (maybe this is not true for the jumbo jet aircraft for which the response is much slower than for most aircraft).

I think, consequently, that your model can be very useful to determine what I call the sensitivity to external perturbations. As a matter of fact, your model can give easily the probability of trespassing a limit as a result of the effect of a gust, assuming that the pilot does not do anything (fixed controls or autopilot on). In addition, your model can also be useful to determine:

1. The probability for a critical parameter to be at a mean value nearer the limit and consequently the probability of a reduction in the level of manoeuverability.

2. The probability of occurrence of an accident due to an increasing pilot workload, the type of accident I call pilotability accident.

For this double purpose it would be necessary to introduce in a simulator a synthetic turbulence based on your model; this turbulence should be perhaps more realistic than some samples measured randomly in real flight.

OPEN DISCUSSION

D.G. Gould, NRC, NAE, Canada

It is possible, by changing the intensity of a random signal of Gaussian distribution according to some probability of occurrence, to produce a distribution of levels of the exponential form rather than of Gaussian form. In practice this can be accomplished closely by using only two different levels of intensity, one a few times larger than the other, with the higher level occurring a small portion of the time (or distance) and the lower level occurring during the majority of the time. I think this procedure may have advantages over the discrete gust approach you have described in that it can more readily be implemented in both analysis and piloted simulation experiments.

I would also like to hear your opinion on a second point. During the last two days there has been some discussion on the deterioration of handling qualities that may result from combining a number of minimum control and stability requirements. I believe that similar inadequate handling qualities may be found when two or more adverse environmental effects occur simultaneously. I am thinking in particular of the possible cumulative adverse effects of vertical wind shear and turbulence which may occur together naturally. Shouldn't such effects be introduced into our flying qualities simulation experiments?

J.G. Jones, RAE, UK

I agree that you can generate non-Gaussian noise using Gaussian processes. But, I think it would be interesting to investigate the process that results and evaluate its properties as I have mentioned. I don't think there is any incompatibility.

In really intense turbulence cases, the gust will swamp the wind shear. This does not say that at the lower levels of intensity that wind shear is not a problem, indeed it may be.

F. O'Hara, M.O.D. (PE), UK

Would it be possible to get better representation by combining the discrete approach with the spectral one?

J.G. Jones, RAE, UK

Yes, you may well be able to come up with a realistic turbulence representation.

R.O. Anderson, AFFDL, USA

We have looked at a non-Gaussian turbulence model which was made by combining two Gaussian sources into the non-Gaussian. It has some of the properties discussed here. We tried this on a limited motion base simulation, and the pilot said that it's more like the thing you really encounter; that is smooth air, then bang-bang-bang. However, it did not have much of an effect on their opinion, one way or the other. It was more realistic, but as long as the rms intensities were about the same, their opinions didn't change.

A.D. Wood, NRC/NAE, Canada

It is generally agreed that (in using simulators for handling qualities studies) turbulence models ought to reproduce the sporadic peak responses which are not sufficiently prominent when a simple Gaussian disturbance distribution is used.

New modelling approaches, such as that described by Mr. Jones, suggest ways of introducing more representative peaks.

In his closing remarks, Mr. Jones touched upon the influence of combined vertical and longitudinal gust components for STOL aircraft. For V/STOL simulation at least, perhaps the real test is yet to come. The most valuable modelling approach is likely to be the one which lends itself to the treatment of more than one axis with intermittent large disturbances, even at the expense of some approximation in single-axis representation.

J.G. Jones, RAE, UK

I think that it would be quite difficult to try to reproduce the correct non-Gaussian properties, with correct correlations in three axes. So I think the engineering answer is to say we got a good representation of one axis and in cases where one axis is sufficient we should use it.

M.D. White, NASA Ames, USA

Studies have been conducted recently at Ames in which the University of Washington work described by Ron Anderson was extended, using larger motion simulators. The studies were conducted in two parts. In the first part, the turbulence models generated by combining frequencies to provide the "patchy" characteristics of actual turbulence was evaluated on a simulator providing only one degree of motion freedom. Among the data obtained was the pilot's rating of turbulence realism. The new model was not considered superior to the basic von Karman. Furthermore, pilots complained about the difficulty of evaluating with only one degree of motion freedom. The next phase was therefore conducted on the 6 degree-of-freedom motion simulator, with improvements in the model to account for correlation effects of flying with a given heading with respect to the wind. Still there was no real improvement in realism rating.

Taking these results in combination with the nature of pilots' comments in earlier related work, it appears to me that the basic problem of the power spectral representations is that the pilot can rideout the disturbances with some confidence that they will self-cancel, and that Mr. Jones' approach as described here is quite promising in meeting that consideration.

FLYING QUALITIES INTERACTION WITH ELASTIC AIRFRAMES

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SUMMARY

The trends in modern aircraft structural design and aerodynamics are such that vehicle flexibility increasingly impacts on vehicle flying (handling) qualities and the design processes necessary to provide satisfactory vehicles. In recent years, the flexibility effects on ride quality have impacted on handling qualities and, perhaps, should be added to handling qualities requirements or criteria. A presentation is given of some of the approaches currently being considered to reduce this interaction; these include such techniques as active seat isolation and active structural mode control. It is concluded that any ride quality solution method that includes inducing motion between the pilot and his controls and displays should be excluded by handling qualities criteria. The structural flexibility and flight controls interface is briefly examined, and a typical pilot-induced structural excitation is discussed. It is suggested that a pilot prefilter, a modern stability augmentation system, and a structural mode control system designed to meet ride quality criteria can solve the problem without additional criteria. This paper also discusses the handling qualities flexibility interaction and the vehicle design cycle. A problem is identified as developing between the requirements for large amounts of flexible vehicle analyses data and the shortening of vehicle development cycles. Despite some possible relief due to designer ingenuity, satisfactory handling qualities on future flexible aircraft may possibly be jeopardized by lack of design analysis time.

SYMBOLS

$\frac{b\omega_t}{a}\sqrt{\mu}$	Regier parameter evaluated at maximum dynamic pressure in vicinity of M = 1.0
b	1/2-Root chord of wing
ω_t	First wing torsion mode frequency determined from stiffness provided by strength design load uniformly distributed on wing
a	Speed of sound
μ	Mass ratio; weight of volume of air at design condition included in a trapezoid of revolution formed by wing planform divided by weight of wing
K	Arbitrary scaling parameter to put numbers in range of 1 to 10
α	Angle of attack
γ	Structural bending slope angle at horizontal tail
V_o	Velocity
C_{m_α}	Pitching moment slope against α, $\partial C_m/\partial\alpha$
Z_p	Displacement of pilot
Z_a	Displacement of cockpit floor
f	Frequency, Hz
ω	Frequency, rad/sec
Φ_{n_z}	Normal load factor power spectral density due to vertical gust
σ_{w_g}	Vertical gust intensity (root mean square velocity)
q	Pitch rate
n_z	Normal load factor
δ_e	Elevon deflection

INTRODUCTION

The trends in modern aircraft structural design and aerodynamics are such that vehicle flexibility increasingly impacts on vehicle flying (handling) qualities and the design processes necessary to provide satisfactory vehicles. These flexibility effects are found in both high-design-load-factor and low-design-load-factor aircraft; more so in the latter than the former, of course. Figure 1 displays an assessment of this trend, using a flexibility parameter developed at North American Rockwell for this purpose. The parameter is proportional to the inverse of the Regier parameter used in flutter work which is evaluated for wings defined by strength criteria only and an assumed uniform load distribution. Increasing magnitude of the parameter indicates increasing flexibility. The figure shows trends of this parameter for both high-load-factor designs and low-load-factor designs developed from the identified aircraft. On the right are comments which assess the primary structural design requirements set by the vehicle flexibility as reflected by North American Rockwell's experience.

Aircraft like the subsonic F-86 had structural design requirements which were set by strength and flutter, with little or no impact by stability and control. Fighter aircraft like the F-100 and F-107, together with subsonic transport-type aircraft like the DC-8 and C-5, had structural requirements set by strength, flutter, and stability and control (handling qualities). Aircraft with sustained supersonic

flight capability like the XB-70 and SST had these same requirements, but with increased emphasis on the flutter and stability and control requirements for stiffness.

This paper discusses some aspects of two broad categories of elastic airplane-handling qualities problems: (1) the flexible airplane in turbulence and (2) the aeroelastic impact on stability and control parameters. The first category, in recent years, has attracted increased attention; the second category has been the area of more traditional continuous concern. It is the intent of this paper to discuss these problems in light of the need for criteria, and the methods available for achieving compliance. The requirement for brevity of this paper precludes examination of the problems and proposed solutions in great detail, but it is hoped that the sufficient development of the principal factors will encourage discussion.

HANDLING QUALITIES-RIDE QUALITY INTERACTION WITH FLEXIBILITY

The manner in which a pilot is able to handle an aircraft in turbulence is greatly affected by the ride quality characteristics of the vehicle. Ride quality, in turn, is affected by the vehicle's flexible dynamics. The B-1 is one of the first aircraft designed to formally recognize the interrelation of handling qualities and ride quality with a specific requirement. The background of the criteria established is described in reference 1. Included in the criteria is consideration of the pilot's tracking task, pilot fatigue with time, and dynamics of the human body. There are presently under development two approaches to improving ride quality of flexible aircraft and, thus indirectly, handling qualities. One approach is the active control of structural modes, and the second is active seat isolation. It appears desirable in this discussion of handling qualities criteria to evaluate the appropriateness of each approach.

Figure 2 shows a sketch comparing the main features representative of each type of system. Typical of the structural mode control system is the external aerodynamic force generator activated by onboard sensors. When an input excites the structure, the motion is sensed and passed through electronic shaping networks which cause the aerodynamic surfaces to deflect and produce a motion controlling airload. The whole vehicle structural motion is damped by this method. In contrast, the active seat isolation scheme employs a seat separated from the vehicle structure by a hydraulic actuator. The hydraulic actuator is activated by a processed signal from motion sensors located on the seat and airframe.

For more detailed explanations of how these systems work, the reader is referred to reference 2, which discusses a typical structural mode control system, and to reference 3 for similar information on a typical seat isolation system.

It is revealing to look at the pilot normal load factor response due to turbulence in power spectral density form, with and without the typical structural mode control system operating in conjunction with a conventional stability augmentation system. As shown in figure 3, the stability augmentation system works well in reducing the short-period response, and the structural mode control system does well in reducing structural motion across a broadband of frequencies.

Before looking at what a seat isolation system would do in similar circumstances, consider the displacement transmissibility curve of a typical seat isolation system as displayed in figure 4. A key feature of the system is the notch (in the compensation) shown at about 4.5 Hz; this is a typical feature which can be tuned to any other frequency to eliminate the effect of a dominant mode. If, however, the notch is moved to a lower frequency, as required by the case of figure 3, then the motions at frequencies below the notch are amplified as indicated by figure 4. In figure 5, typical performance of a seat isolation system is displayed. The notch of the system is located to eliminate the effect of the large structural mode peak at 18 rad/sec (≈3 Hz). As expected, the formerly low peak at approximately 12 rad/sec is amplified greatly.

If the notch were to be moved lower to accommodate the 12 rad/sec m[illegible] double amplitude throw required by the system would begin to increase rapidly. This, then, leads to a key objection to the seat isolation system, and is particularly pertinent to handling qualities requirements.

The seat isolation system causes the pilot to oscillate in relation to his instrument panel and his controls. If conventional wheel or stick and rudder pedal controls are used, the pilot's arms and legs move in a potentially adverse manner, causing deterioration of handling qualities. Let us suppose, though, that the pilot really does not need to use the rudder pedals and can place his feet on a support on the moving seat, and further, that he can use a side arm controller. A serious problem still remains which affects the pilot's ability to handle his aircraft. The problem is in reading his instruments and operating switches, as figure 6 demonstrates.

The data shown are for the subject moving while the visual material remains stationary, which is the relative situation with the pilot in an isolated seat in a moving cockpit. The data indicate that, for a constant sinusoidal peak amplitude load factor of 0.25 g, there is a general degradation in ability to scan (read instruments) and to place (operate switches) as the frequency is reduced from 9.5 to 2.4 Hz, with a peaking of degradation at 3.4 Hz. The experimentor attributed this loss in performance to the relative motion between the subject and the near reading distance of the tasks.

The seat described in reference 3 had a linear capability of a range of ±1 inch and a maximum deflection of ±2 inches. The system was highly nonlinear over the range from 1 to 2 inches because of the

necessity to provide increasing stiffness to prevent hard bottoming of the system. At a forcing frequency of 3.4 Hz, then, this system would definitely have the problem demonstrated of scanning and placing, since the system would have a displacement of ±0.2 inch, well within the capability of the system.

Among other objections to the seat isolation scheme is a requirement to wash out inputs from constant maneuvering load factors. Also, the system is currently suited only to one-axis operation with the possibility of great mechanical complexity if extended to two-axis capability. (Future large low-load-factor aircraft may require this capability.) Each individual seat in the cockpit would require separate systems. Only limited simulator experience and no flight test to date exist for isolated seat systems.

While structural mode control systems have their own unique design problems, these do not impact as unfavorably on the handling-qualities aspects as the seat isolation system. The reader is referred to reference 2 for an overview of structural mode control system analytical and flight test experience. This experience shows that structural mode control systems can be made to operate without interfering with the basic stability augmentation system and, thus, a vehicle's handling qualities.

The U.S. Air Force handling qualities specifications do not presently include a quantitative ride quality requirement, but perhaps should. The author suggests that such a requirement should limit design solutions to those that do not induce objectionable relative motion between the pilot and his controls and displays.

STRUCTURAL FLEXIBILITY AND FLIGHT CONTROLS

The interactions between structural flexibility and flight control systems have grown in proportion to the trend of flexibility effects on stability and control indicated in figure 1. In addition, the demands on the control system performance have grown proportionately. A simplified way of viewing some of the flexibility interactions as they affect vehicle undamped natural frequencies and damping ratios is given in figure 7. The shaded area indicates where the parameters should be for generally favorable handling qualities.

Taking first the ride quality aspect, it is seen that increased structural damping is desirable. While it is indeed desirable to increase the structural frequencies to reduce the susceptibility to gust excitation, there is need to consider the fact that, in the 4 to 8 Hz range, the pilot will be more markedly affected by a given level of acceleration (reference 1).

If the short-period frequency and the first mode structural frequency are too close, it is possible to develop a structural mode instability (reference 5). In addition, if these two modes are close, it often complicates the stability augmentation system design. With increased control system component capability, however, some designers are attempting to have the control system do two jobs - the basic stability augmentation task plus control of several of the lower structural modes (reference 6).

As the figure shows, the undamped natural frequency and the damping ratio must be located within the ranges indicated to provide satisfactory handling qualities for general flight and terrain-following capability. It is of interest to note that improved ride quality due to large aircraft short-period characteristics represented by the lower right-hand corner of the plot require increased frequency and decreased damping (reference 7).

One of the significant aspects to be emphasized with this plot is that the control system designer must know where he is on this plot for the basic flexible vehicle before he can set the requirements for his system to solve these many conflicting requirements to provide satisfactory handling qualities and ride quality. To acquire and analyze the basic vehicle flexible structural and aerodynamic data in a timely fashion is probably one of the most difficult tasks the designer faces. Additional discussion of this problem is presented in the main section following this.

In figure 8, a specific flexible vehicle handling-ride quality interaction with flight controls is illustrated. It is to be emphasized that the interaction shown is not unique to the particular vehicle analyzed. Shown is the analytical time history of the response of the flexible XB-70 to a relatively sharp elevon pitch control pulse. The flight condition is M = 0.95 at 25,000 feet without stability and control augmentation. This calculation is more than 9 years old and reflects a much more flexible XB-70 than actually flew. At the time the calculation was made, the input was judged to be somewhat severe. In light of the research nature of the XB-70, though, it was felt that the pilot could maneuver the vehicle without using such sharp inputs, and thus a pilot prefilter was not warranted. Inclusion of such a system later was not precluded. Subsequent flight test data, however, showed that on many occasions the pilot did excite the structure with elevon maneuver inputs similar to those described here and then reported turbulence. The pilot of the accompanying B-58 would report no turbulence effects on his aircraft.

For aircraft with present levels of flexibility (figure 1), this type of problem can be solved through a balanced combination of the application of (1) a pilot prefilter, (2) a regular stability augmentation system with sensors placed and compensation designed to assist in structural mode control, and (3) a separate structural mode control as on the B-1. It appears that this design approach, together with a ride quality criteria requirement, could eliminate the objectional structural motion aspects of cockpit motion of the type illustrated in figure 8 without the need for more specific criteria than now exists.

HANDLING QUALITIES, FLEXIBILITY, AND THE DESIGN CYCLE

The fact that the U.S. Air Force specification on flying qualities of piloted airplanes gives such brief specific guidance on aeroelasticity and structural dynamic effects is, perhaps, an indication of the difficulty in determining how to successfully include such important effects in criteria form without unduly constraining the designer. The designer is increasingly challenged by the fact that these factors impact more and more on his preliminary design considerations, as has been illustrated by figure 1. Furthermore, the time that is allotted to adequate analyses of these important technical areas seems increasingly shortened by the pressure to get the hardware designed and flight tested.

This challenge has not gone completely unrecognized. The U.S. Government and industry have assembled complex structural and aerodynamic digital analysis programs (NASA's NASTRAN and North American Rockwell's ASKA are typical) to attempt to cope with the problem. The detail of data required is enormous, but rightly so, in order to produce meaningful answers. The design process is still iterative as illustrated in figure 9. The cycle illustrated can typically take 6 months or more. Recycling can add many additional months before satisfactory flexible vehicle characteristics are insured. The author believes that the increasing impact of flexibility on handling qualities, the increased scope of criteria to be met (illustrated by the U.S. Air Force handling qualities requirements), together with the increased effort and time required to obtain adequate data to demonstrate handling qualities requirements (illustrated in figure 9), has not been properly recognized in the development cycle scheduling of many modern aircraft.

In order to obtain some relief from this problem, the engineer can, and has, exercised some ingenuity. As an example of this, at the North American Rockwell Los Angeles Division, the loads engineers have developed a design criteria which involves the basic static longitudinal stability of the flexible vehicle. The present handling qualities criteria impact through specifying a minimum short-period frequency which can be interpreted as a static stability level or pitching moment variation with angle of attack (C_{m_α}). Given this vehicle level of static stability, the loads engineer establishes what he thinks is reasonable to allow as a flexible-to-rigid ratio for the aft fuselage-horizontal tail combination for the critical design case. It is assumed that he has already analyzed the flexible horizontal tail fixed at the root; thus he knows its flexible loading characteristics and sizes the tail accordingly.

With these items known, he then assumes the fuselage cantilevered at the center of gravity as shown in figure 10 and loaded with the flexible loading he knows will produce his required static stability. The slope at the horizontal tail root is given to the structural analysis group as a requirement. The structure is sized and iterated within this group and the weights group until the desired slope is obtained. A key point here is that the structure is sized with a correct coordinated flexible loading. The loads group, however, does not have to get involved in the iterative cycle, thereby saving valuable time.

It is obvious that this type of design criteria has no place in the handling qualities specification because it is not general enough in scope and is configuration-sensitive. More than that, similar criteria might arbitrarily restrict the designer's solution choices. Much imaginative work of this nature remains to be accomplished before the main problem discussed here can be solved.

CONCLUDING REMARKS

The author wishes to emphasize several important points in concluding this paper.

Ride quality is a legitimate aspect of handling qualities, and general criteria should be included under, or in conjunction with, existing handling qualities criteria. The ride quality criteria in current use appear adequate, except that solutions to meeting the criteria should exclude those that permit excessive motion between the pilot and his instruments and controls.

The time trends of flexibility impact on aircraft design show greater and greater effects on stability and control (and thus handling qualities). Yet development cycles are being squeezed. It is possible that future vehicles will have increasing difficulty in demonstrating satisfactory compliance with handling qualities criteria during flight test unless increased attention and time are permitted to be given to flexibility effects analyses during preliminary and early development phases.

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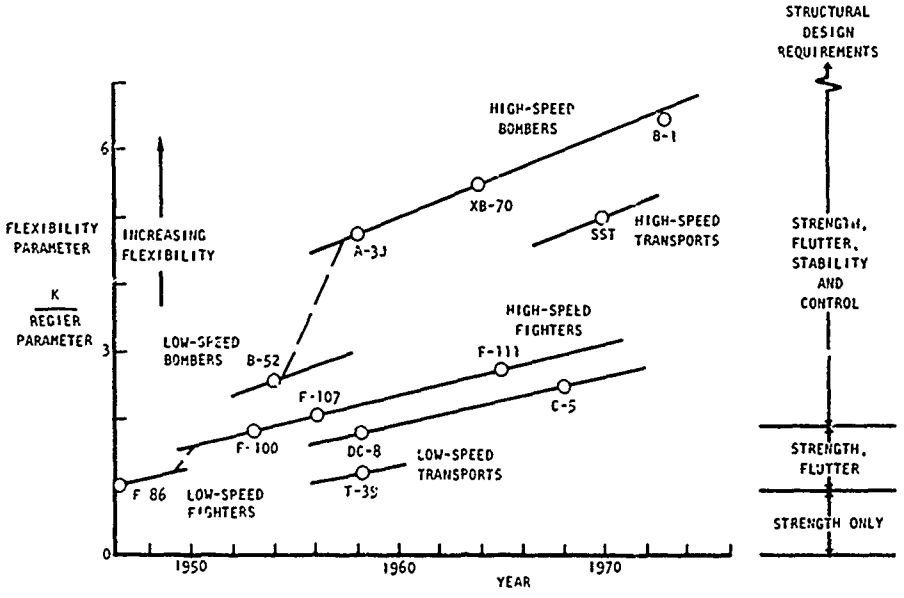


Figure 1. Impact of Flexibility on Aircraft Design

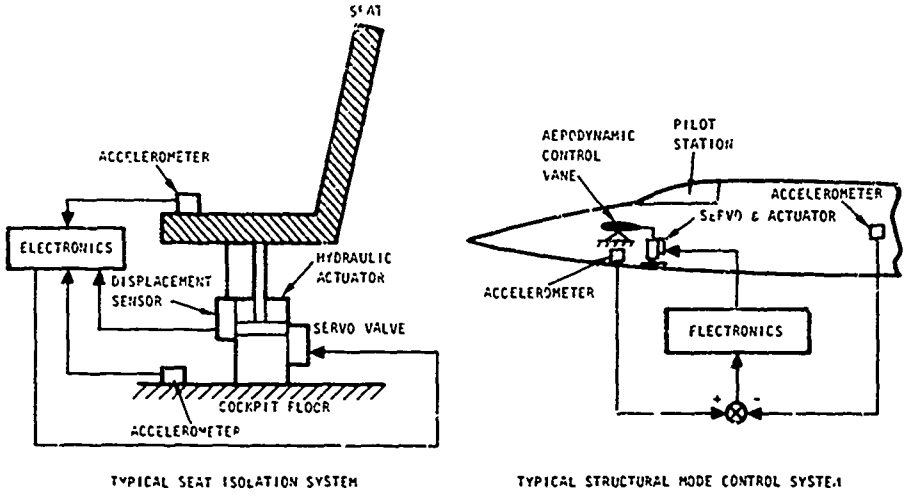


Figure 2. Two Solutions to Flexible Aircraft Ride Quality Requirements

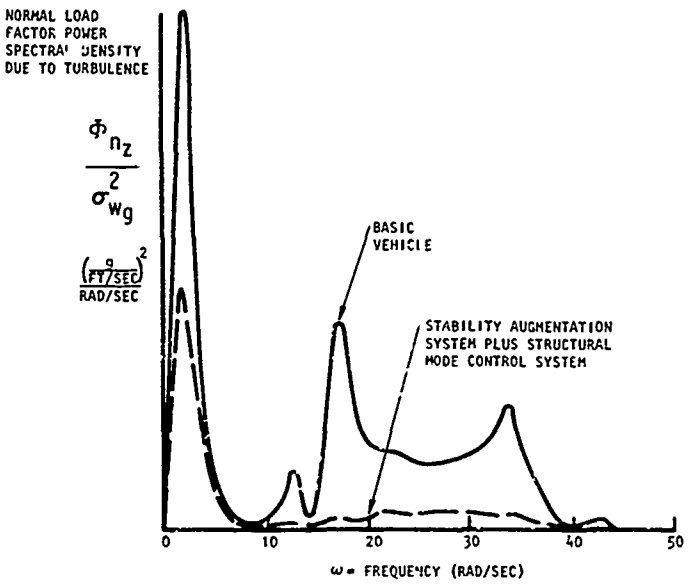


Figure 3. Effect of Structural Mode Control System on Pilot Load Factor Due to Turbulence, Low-Load-Factor Design Airplane, Calculated Data

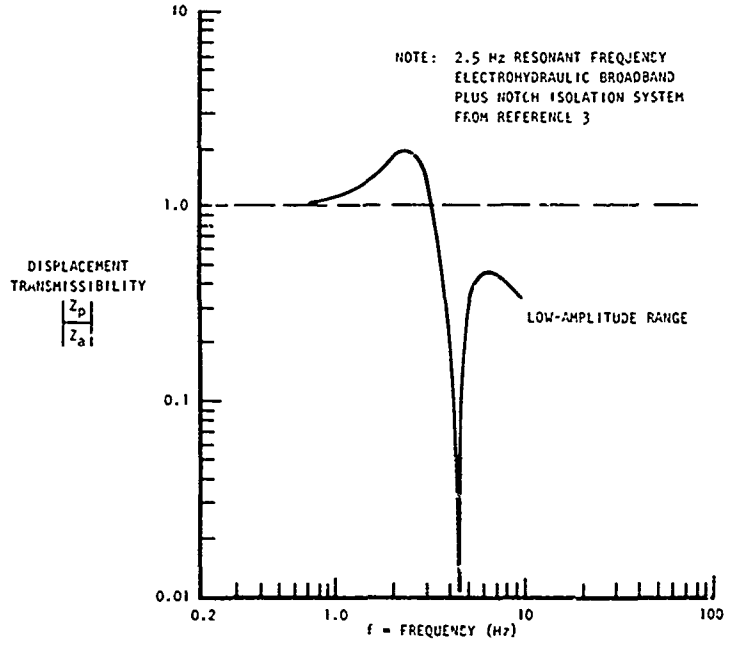


Figure 4. Absolute Displacement Transmissibility for a Seat Isolation System

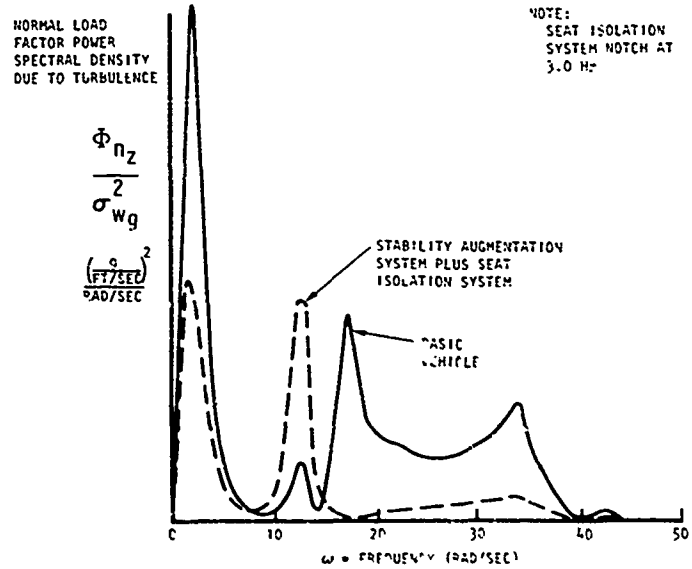


Figure 5. Effect of Seat Isolation System on Pilot Load Factor Due to Tubulence, Low-Load-Factor Design Airplane, Calculated Data

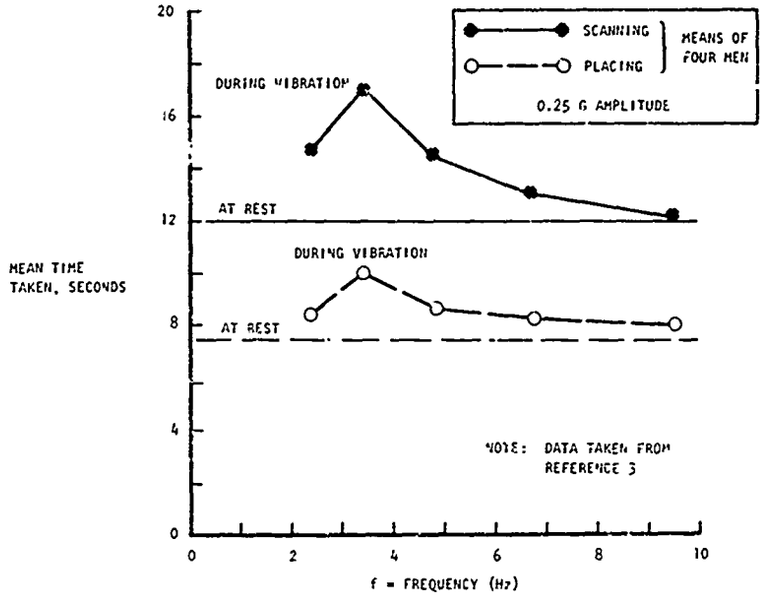


Figure 6. Effect of Relative Movement Between Pilot and Control - Instruments

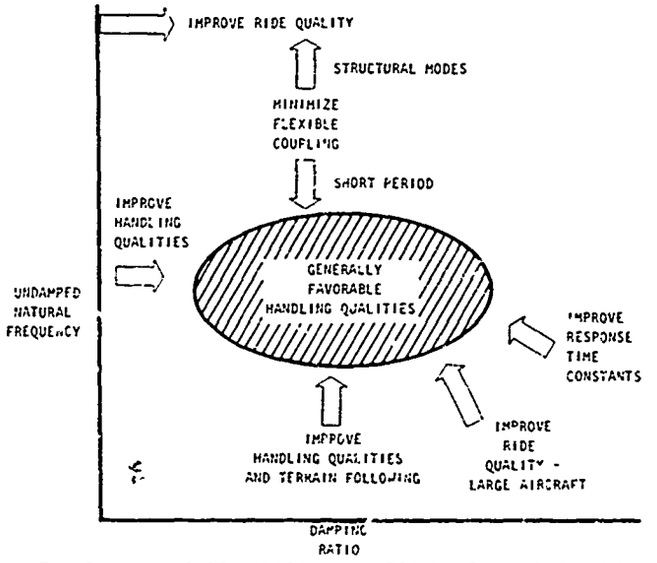


Figure 7. Structural Flexibility and Flight Control Considerations

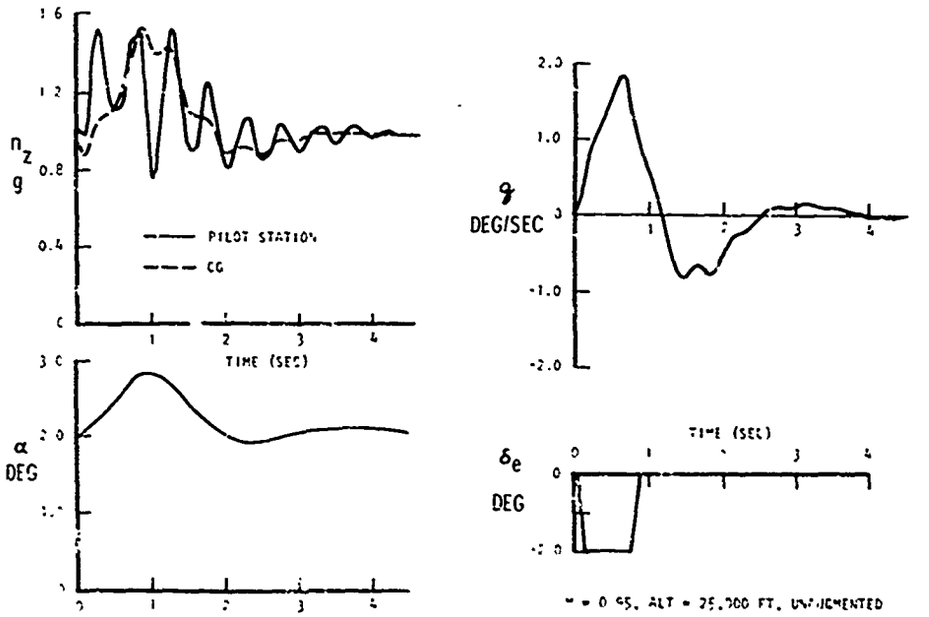


Figure 8. Typical Abrupt Pilot Input and Longitudinal Response, XB-70, Calculated Data

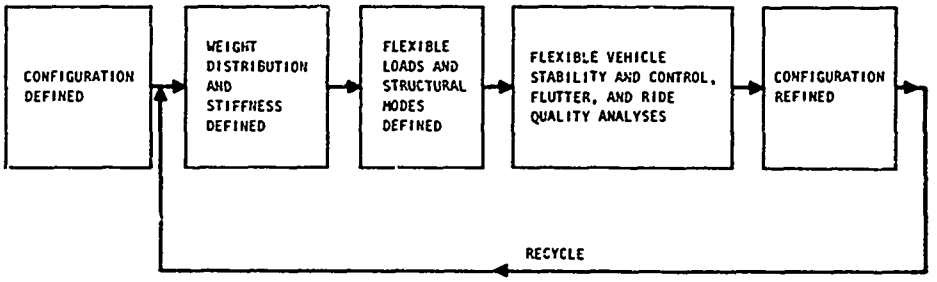


Figure 9. Typical Analysis Cycle for a Flexible Aircraft

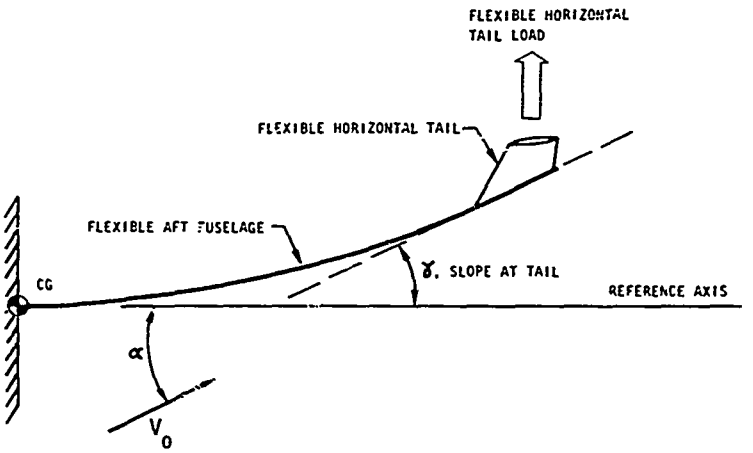


Figure 10. Slope Criteria to Define Aft Fuselage Stiffness to Meet Static Stability Criteria

LEAD DISCUSSION

by
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1 Introduction

This short paper must be regarded as just a few notes on important aspects of the impact airframe elasticity can have on flying and riding qualities. The author -regretfully- did not receive the lead-paper prepared by Mr. Wykes before the Meeting and thus no regular "discussion" could be prepared. He therefore tried to summarize the contents of a number of -in his opinion- important papers (literature 1-12) while adding his own point of view with the aim to give a survey of the problem areas in the field of interaction between flying qualities and riding qualities on the one hand and elastic deformations of the aircraft on the other hand.

2 Considerations

2.a General

The most important developments responsible for recently increased interest in the subject can be attributed to a number of changes in airframe construction evolving from the total technological advancement. To be able to penetrate domains of higher indicated airspeeds and higher Mach numbers, slender fuselages and relatively thin airfoils have come into use.
Introduction of materials with higher specific strength and relatively lower stiffness and more optimized construction technology have, together with the form of airframe just mentioned, led to more elasticity and associated lower structural frequencies.

It is further noticed here that in an appreciable number of aircraft (worth consideration with respect to the possible interactions between aircraft elasticity and flying/riding qualities), some sort of stability and/or control augmentation system forms an important part of the aircraft control system. Augmentation systems, having an important bearing on the total pilot-vehicle system, cannot be neglected in this discussion.

2.b Flying Qualities and Riding Qualities

Although other descriptions are possible, it seems appropriate to use the following descriptions:

Flying Qualities of an aircraft determine the suitability of the aircraft for control by a human pilot; to be a little bit more specific, the "suitability" can be interpreted as those qualities and characteristics of an aircraft which influence the precision, ease and safety with which a pilot is able to perform designated manoeuvres and tasks to fulfil a designated role.

Riding Qualities of aircraft is the property describing crew and passenger comfort in normal turbulence. Disturbances considered here are gust-induced rigid body and elastic mode dynamic response. The bandwidth of disturbances considered in this context is outside the band for effective pilot control (thus above some 1 c.p.s.).

2.c Characteristics of elastic airframes to be considered

It seems practical for the discussion here to distinguish between two characteristics of elastic airframes relating to the interaction with flying/riding qualities.

Aero-elasticity in the quasi-steady sense can be used to indicate the property of changing stability and control parameters under certain conditions; due to deformations of the aircraft structure as a result of high dynamic pressures, Mach effects and airframe stiffness during 1-g flight or long term manoeuvres, appreciable changes in stability and control parameters as compared to those in low speed flight can occur (e.g. Aileron-reversal problems).

Structural Dynamics is the other characteristic to be considered.
Structural dynamics here will be the name for additional degrees of freedom to be considered in the aircraft dynamical description, covering the frequency band up to the upper-limit considered important for Riding Qualities (10 to 15 c.p.s.). Only effects of structural dynamics will be discussed below.

2.d Type of interaction-effects

For discussion purposes it seems useful to distinguish between two categories of aircraft.
High performance, high load factor aircraft.[x]
"Influence of airframe elasticity on riding qualities".

High levels of pilot distraction and fatigue through a rough ride are possible. It is remarked here that the important effect of structural dynamics on the calculated power spectra for pilot station accelerations is often neglected for this category of aircraft; recent research has indicated that an increase up to a factor of two in root mean square accelerations of pilot station for certain configurations is possible when some fundamental structural modes are included. (e.g. symmetrical bending of fuselage, 1st wing bending and 1st wing torsion modes). In particular cases it is important to incorporate non-steady aerodynamics in calculations.

x) Although not described by the same characteristic properties, STOL aircraft should possibly be included in this category for the discussion of the influence of airframe elasticity.

Transport type, low load factor aircraft.
"Influence of airframe elasticity on flying qualities and on riding qualities".

The possible existence of very low frequency structural modes characterizes this category of aircraft.
As far as the effects on flying qualities are concerned, one can speak of "coupling of modes" in the sense that when the pilot wants to manoeuvre or stabilize the airplane he has to cope with higher order responses. For a pilot trying to control attitude of the airplane through the Short Period Mode and Roll Mode, the amount of nuisance dynamics -for the "rigid aircraft": Dutch Roll Mode and Spiral Mode- is now aggravated by Elastic Modes of the flexible aircraft. Pilots appreciation of transient dynamics will most probably be based on the total response motion.

Special problems may arise when frequencies of rigid body and elastic modes are in close proximity. Predictions are published (literature: Cleveland) indicating that for very large high subsonic transport aircraft (gross weights 5 to 10.10^6 lbs) the first wing symmetric bending frequency and Short Period Mode frequency approach each other. When such an aircraft encounters a gust the resulting wing bending induces motion of the pilot station. The pilot, in attempting to damp this motion -what to him appears as a Short Period oscillation- may intensify the wing bending, which was the original cause of the perceived motion.

As far as the effects on riding qualities are concerned, the same arguments as forwarded for the high performance, high load factor aircraft can be mentioned.
The probability that detrimental effects on riding qualities due to structural dynamics exist for transport type, low load factor aircraft, is higher than for high performance, high load factor aircraft, because most probably modes with 4-8 c.p.s. frequencies (most critical band) will occur.

3 The role of augmentation systems

3.a Augmentation Systems

As mentioned in the beginning of this paper, aircraft to be considered in a discussion about the interaction of flying/riding qualities and airframe elasticity will in most cases be equipped with some sort of augmentation system. In an effort to distinguish certain basic concepts, three basic groups can be discerned:

- Stability (and Control) Augmentation Systems (SAS)
Improvement of "rigid body" aircraft flying qualities

- Gust Alleviation Systems[x)]
Active reduction of "rigid body" gust sensitivity (artificial low lift-curve-slope) of the aircraft, aimed primarily at comfort improvement for crew and passengers.

- Elastic Mode Damping Systems
Improvement of structural mode response by dissipation of vibrational energy once present in elastic modes. The system is aimed at improvement of the riding qualities and fatigue damage rate reduction.

The author is perfectly aware that the scheme presented above is rather arbitrary, but it is one way to separate certain basic concepts in an area where in fact no clear separation is possible.
Due to relatively high power levels needed for the actuation of vertical force producing aerodynamic surfaces and the problems associated with the simultaneous excitation of elastic modes of the wing, the 2nd system holds the least promise for "real elastic" aircraft. Therefore a trend might be distinguished to prefer combinations of the 1st and the 3rd systems indicated above, thus SAS with Elastic Mode Damping capability. Thus, while contemporary systems are designed to provide stability and control augmentation for improved flying qualities, future augmentation systems will incorporate structural mode damping features as well.

3.b Advanced Concepts.

Due to the emergence of the concept of "hardened" SAS (being "as reliable as the structure") it seems that once these systems are fully developed, the addition of structural mode damping capability will, in general, not add "appreciably" to control systems complexity because all hardware elements are already available. Elastic mode damping will mainly be a matter of refined optimization for sensor location and filter design.
The concept of "hardened" SAS will be required for certain aircraft, because the basic rigid body airframe dynamics are such that no control is otherwise possible (e.g. very big CTOL: excessive rigid body response times to control inputs; STOL[xx)]: very precise control for approach and landing with preferably low static stability airframes).
Control augmentation in the form of Direct Lift Control (DLC), designed as an integral part of the overall system, might be needed to improve control for low lift curve slope aircraft (low normal acceleration sensitivity to gust inputs). Pilot opinion data have become available indicating pilots preference for low lift curve slope aircraft when equipped with adequate (DLC) capability.

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x) Systems to reduce vertical acceleration and pitch rotations are meant here. Lateral accelerations are basically only a small fraction of the vertical accelerations and are relatively unimportant compared to roll and yaw motions which can be taken care of by a SAS system.

xx) Unfavourable interactions between pitch attitude control and thrust control might exist as well as very adverse ground effects. A real requirement for rate-command/attitude-hold features of the flight control system could exist.

When aircraft are built such that a high-authority (hardened) SAS forms a basic part of the control loop, as might be expected in the near future as indicated above, one might say that the so called "Fly-By-Wire (FBW) principle" is realized.
A widely used definition is formulated as follows: "A FBW control system is an electrical primary flight control system employing feedback such that vehicle motion is the controlled parameter".
In this case one is fully dependent on the characteristics of the sensed state variables so that considerations of control system design and structural dynamics is of ultimate importance.
One beneficial effect of FBW control systems with respect to airframe elasticity forms the possibility to control the aircraft through a side-stick controller. Considerable reduction of pilot-mechanical-coupling between elastic modes and flight control system as compared to center stick or wheel type controllers could be realized.

3.c Criteria

Criteria indicating allowable degrees of interaction of elastic aircraft modes for pilot control are virtually non-existent.

The U.S. Military Specification on Flying Qualities of 1968 mentions the importance of the possible important interaction by stating: "the effect of aeroelasticity and structural dynamics should not be overlooked in calculations or analysis directed toward investigation of compliance with the requirements of the specification".

When important interactions exist in such a manner that dynamic responses to pilot inputs for aircraft attitude control cannot be longer adequately described by 2nd order (pitch attitude) or 1st order (roll attitude) responses, with additional constraints on 2nd order Dutch Roll characteristics and 1st order Spiral Mode (in)stability due to perceivable multiple frequency responses. generated by structural dynamics and stability augmentation dynamics, effort should be made to consider time history boundary criteria instead of rigid body dynamic stability parameter boundaries.

4 Concluding remarks.

By this very short and certainly not-complete discussion of the effects of airframe elasticity on flying qualities it is emphasized that this complex problem area will only increase for aircraft to be built in the future.

. Designs for low gust sensitivity to decrease the amount of energy transfer from the turbulent atmosphere to rigid and flexible aircraft modes must be considered the solution most probably selected by aircraft designers.
In most cases this will have the result that full reliance on stability and control augmentation systems incorporating elastic mode damping will be necessary.

. Because STOL aircraft are operating a high percentage of their flying time in a turbulent atmosphere, the importance of airframe elasticity for these aircraft will mainly be centered around the accurate predictions of riding qualities based on calculated rigid body and elastic mode responses to gust inputs.

. Favouring time history over dynamic stability parameter boundaries will possibly be the best way to cope with airframe elasticity in the field of criteria and specifications for flying qualities.

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OPEN DISCUSSION

A.L. Byrnes, Lockheed, USA

Mr. Mooij mentioned "fly by wire" control systems as a thing of the future. I'd like to mention that the U.S. Navy has had an airplane in the fleet since 1962 which has a "fly by wire" control system and the control system includes augmentation in which stick displacement commands load factor rather than control surface displacement. Perhaps Mr. Siewert might want to comment on the Navy experience with this airplane.

R.F. Siewert, U.S. Navy, USA

The airplane that Mr. Byrnes was referring to was originally called the A3J and subsequently the designation has been changed to the A-5. It is what we would call now a command augmentation system. It had no gust alleviation. The "fly-by-wire" operation is very reliable and has worked quite well. In the lateral mode the pilots prefer the "fly-by-wire" over the mechanical system.

Prof. K.H. Doetsch, DFVLR, Germany

Statement to Lead Discussor's remark on the usefulness of fly-by-wire with sidestick controller:

If this sidestick controller is fixed to structure it may not help in avoiding pilot's involuntary feedback into the control system in turbulent air, because of the reduction in force level, particularly centering force, on this type of controller. It should be fixed in the moving seat mentioned in Mr. Wykes's paper on the armrest.

After watching many attempts, during the last 30 years, at achieving gust alleviation, I put the question: Does anyone believe in its eventual success?

H.A. Mooij, NLR, Netherlands

I don't believe in using an active gust alleviation system in the more flexible aircraft of the future.

J.H. Wykes, NAR, USA

I don't think I would make as strong a statement, but again it has to be approached from individual applications. The flexible airplane application does present a problem, but it can be solved by coupling it with a mode control system and using these together.

J.T. Gallagher, Northrop, USA

If we do the job properly on the flying qualities specification in turbulence, then the flexible airplane problem will be taken care of. All that will be required is using a flexible mode description instead of the rigid body description. The ride qualities problem is a subregion of specifying flying qualities in turbulence, if you do it correctly.

C.R. Chalk, Cornell, USA

I would like to raise a point of warning regarding the design of these systems. You must be careful with all this compensation and using prefilters on the pilot input. You must be careful about using these techniques because they increase the order of the dynamic system. If your mission requires any precision tracking tasks (attitude tracking in particular) perhaps terrain tracking you may find yourself with a PIO problem.

W.T. Kemp, Jr, NASA Langley, USA

A comment regarding the lower frequency range. Some recent studies formulating a quasi-steady ae oelastic problem with inclusion of a speed degree of freedom, not just the two pitch and plunge degrees of freedom, have indicated the possible significance of aeroelasticity on the phugoid motion. This work has shown the possibility of a phugoid mode of considerably higher frequency then the equivalent rigid airplane would have and worse, a high phugoid damping.

INFLUENCE OF THE DESIGN AND FUNCTIONING CHARACTERISTICS OF THE FLYING CONTROL SYSTEM OF A TRANSPORT AIRCRAFT ON ITS FLIGHT QUALITIES

by

R. DEQUE
AEROSPATIALE
TOULOUSE, FRANCE

SUMMARY -

The flying control system, defined as consisting of all the devices which change pilot's action on cockpit controls into force and aerodynamic moments necessary to manoeuvre the aircraft, can be more or less complex and may, for instance, include various automatic compensators. In all cases, this system plays a prominent part in the behaviour of the manually operated aircraft system, the study of which enables the aircraft flying qualities to be determined. To illustrate this influence, reference is made to the problems encountered in the course of flying quality studies for both a supersonic and a subsonic transport aircraft. In a first part, a study is made of the influence of the static and dynamic characteristics of controls between cockpit controls and surfaces without automatic compensators. The second part the specific problems raised by automatic compensators are evoked. Finally, in the third part, a study is made of how flying qualities are affected by flying control failures and by the safety and reliability objectives which must as a consequence be achieved.

1. - INTRODUCTION -

The study of flying qualities consists mainly of evaluating in what performance and safety conditions the pilot can carry out a given task with his aircraft in a given state. By safety we mean not only the immediate risk, but also the long term risk caused by a control of the aircraft requiring too much attention and skill to enable the pilot to carry out his task.

The interface between the pilot and the aircraft defined by its aerodynamic propulsive and weight characteristics necessarily plays an important part in obtaining good flying qualities. This interface is essentially comprised of two parts : on one hand the instruments which supply the pilot with the information required to define his action and on the other hand the flying control systems which enable him to take action on the behaviour of the aircraft. We are going to study here the influence of the functionary characteristics of the flying control system on flight qualities. Since this subject is extremely vast and complex we shall not discuss it in general. We shall only quote a few examples to indicate the lessons which we have drawn from our experience in the design and development of civil transport aircraft and mainly of the CONCORDE S.S.T.

In the first part of our discussion we shall study the influence of the static and dynamic characteristics of the controls between pilot controls and surfaces. We shall then evoke the particular problems caused by automatic correctors, and finally we shall briefly examine the consequences of flying control system failures on flight qualities.

2. - INFLUENCE OF THE STATIC AND DYNAMIC CHARACTERISTICS OF THE FLYING CONTROL SYSTEM -

2.1 - Static linear characteristics -

These characteristics are defined by the relationships which exist between the displacement and force applied to the pilots' controls (control column, wheel, pedals) and the deflection of the corresponding control surfaces without considering non linearities (threshold, backlash, friction, hysteresis).

a) Kinematic relationships -

When several surfaces are controlled by the same pilots action, which is often the case in roll control it is possible to improve aircraft control by choosing the appropriate kinematics. On CONCORDE, for example, it has been possible to improve the ω_f / ω_p criterion which characterizes the roll-yaw coupling by playing on the relative roll deflection of the inboard elevons in relation to the outboard and central elevons (see Pl. 2). This optimization has enabled us to eliminate completely the tendency to pilot induced oscillations, in supersonic flight without stabilizers.

The choice between the pilot control displacement and the corresponding efficiency of the surfaces controlled by this displacement is difficult. In fact, control surface efficiency can vary considerably according to flight conditions (1 to 20 and even more on certain aircraft), and unless one adopts kinematics which are capable of varying according to flight conditions, which is rarely the case for complexity and safety reasons, one is obliged to accept a compromise. Large pitch or roll control displacements are considered to be uncomfortable mainly because they render coordinated pitch and roll manoeuvres difficult and inaccurate by the position which the pilot controls then occupy. It appears, on the other hand, that small control displacements can be accepted without difficulty provided one has appropriate force laws and very good control characteristics (very little non-linearity). On CONCORDE, we have a displacement of 10 mm in certain flight conditions to obtain a load factor variation of 1g, but we must remember that the accuracy of the electric flight control of this aircraft is excellent. At the worst, it is possible to control by application of forces without displacement of the control column and we have retained this as an emergency control mode in the event of pilot control jamming.

The relationships between pilot control displacement and angular aircraft speed are not perfectly linear for various reasons. In fact, in certain cases non-linearities are created voluntarily. Simulator testing sometimes tends to lead to excessive increases of efficiency for small control displacements particularly in roll control. This is due to the absence of correct simulation of angular accelerations.

b) Feel-force laws -

Different pilots have expressed varying opinions on force laws. Some of them would prefer to have small forces, particularly on the flight simulators because aircraft control is in this case in their opinion more accurate and less tiring. However control safety considerations soon lead to a compromise which on CONCORDE corresponds to 20 to 30 daN/g (See Pl. 3). Furthermore, it is also possible that in certain conditions of dynamic characteristics of the aircraft small forces lead to a tendency to pilot induced oscillations. We have encountered this situation in high supersonic flight with forces of 10 daN/g and by doubling the forces this problem disappeared.

2.2 - Dynamic linear characteristics -

On CONCORDE the maximum control surface displacement speeds are approximately 30°/second (total travel in 1.5 seconds). This has caused no problems. It seems, that these values can in the event of failure be divided by 5 without detriment to the safety of the flight.

The servo-control band pass (See Pl. 4) which corresponds to a maximum phase shift of 45° at 2 c.p.s is not a result of requirements for manual control but of automatic system stability considerations (damper and autopilot).

2.3 - Non linear characteristics -

The following non linearities are generally observed on a control : The kinematics between control displacement and surface displacement show backlash distributed elasticity and friction which causes hysteresis (See Pl. 5, 6).

If one examines the relationship between the force applied at the control and displacement of the surface, one can observe a hysteresis which is the result of the afore-mentioned backlash, elasticity and friction, and a force threshold which is voluntarily introduced to obtain a correct auto centering characteristic (See Pl. 7, 8). It is accepted that to obtain correct return to neutral position this threshold must have an amplitude of about 30 % more than the friction forces.

Flight qualities are generally affected by the position of the artificial feel device in the control or more exactly, in relation to the non linearities of the control. If there is backlash or hysteresis (friction, elasticity) between this device and the control surface, the position of the surface after control action will not be clearly defined. In roll control for example, this can lead to considerable apparent spiral instability or even pilot induced oscillations.

Pilots prefer small force thresholds (2 to 3 kg in pitch and 1 to 1.5 kg in roll) which is difficult to obtain with a control system comprising fairly long cables, taking friction into consideration, and one is then led to introducing boosters on the control. For this reason, we have introduced relay jacks on the CONCORDE mechanical standby controls. These jacks are also used as autopilot servoactuators.

Another type of non-linearity, consisting of a no-force displacement range, can be observed on certain controls. Such is the case on CONCORDE. Within this range (a few tenths of control surface displacement degrees) control column displacement does drive the surface but with very small force variations.

Such a characteristic noted by the pilots has not provoked any control difficulties, in spite of the considerable control surface efficiencies encountered in flight. But we now this is strongly influenced by damping and friction characteristics of the control around neutral position.

3. - PROBLEMS RAISED BY THE USE OF AUTOMATIC CORRECTORS -

The compromises made when designing an aircraft (weight, performance, etc...) can lead to deficiencies in its static and dynamic behaviour. Automatic devices are thus naturally called upon to remedy this. Our aim here is not to study what it is possible to do with correctors, since theoretically, almost any use can be made of them, but to mention a few practical limitations which we have encountered in their use on CONCORDE.

Dampers -

They elaborate control surface displacement orders in terms of the angular speeds detected in roll, yaw and pitch. The gain of these stabilizers is limited in certain parts of the flight envelope by the appearance of a new oscillatory mode (0.8 to 1 c.p.s) which is a result of the various delays introduced in the loop by the servocontrols and filters introduced to avoid de-stabilizing the structural modes of the aircraft. We are fortunate in that the gains thus obtained are adequate to ensure correct aircraft damping, as it would in fact be difficult and expensive to improve the present stability margins of the stabilization loop taking the various constraints into consideration.

For safety reasons, and in spite of the automatic monitoring devices adopted the authority of these stabilizers is voluntarily limited to relatively small values of control surface displacements (See Pl. 9). In pitch for example, we avoid going beyond an authority corresponding to a load factor variation of 0.5 to 1 g, and there are certain flight cases where this is far less this has never caused any control problems even in strong turbulence conditions when the maximum authority is frequently reached, but has on the other hand an unusual effect on force law characteristics (See Pl. 10) and has led us to find a compromise between gain and authority. It is possible to compensate the apparent loss of efficiency due to gyrometric terms by introducing a compensatory term elaborated from the detection of the surface displacement ordered. Such a solution has been developed on the simulator and tested in flight but has not been retained since the improvement in aircraft control has not been considered sufficiently significant to justify the added complexity.

Electrical pitch trim -

An electrical trim device not only enables the pilot to carry out the conventional trim adjustments but is also used as a static stability corrector. In transonic conditions, a trim displacement law, dependent on mach number and, at low speed, a law dependent on incidence, enables positive stick free static stability to be restored.

The safety of these devices is ensured not only by equipement self-monitoring, but also by a control surface displacement speed limitation controlled by the electrical trim system. This is designed such that the pilot is always able to take overriding action.

The control surface displacement speed controlled by the pilot is 0.5°/sec. The speed of the corrector devices is limited to 0.35°/sec. This means limiting the amplitude of the effectively obtainable static stability correction, to avoid anomalies in certain flight cases. In fact, in rapid but realistic variations of Mach and particularly of incidence (recovery from involuntarily exceeding the normal envelope limitations for example) aircraft control becomes extremely difficult if the trim system cannot carry out the planned displacement variations, as this can lead to a considerable increase or decrease of control forces Here, once again a satisfactroy compromise has been possible.

4. - CONSEQUENCES OF FLYING CONTROL SYSTEM FAILURES ON FLIGHT QUALITIES -

The Franco-British airworthiness regulations for supersonic aircraft link flight quality requirement levels with the probability of occurrence of the various states of the aircraft.

Application of these requirements leads in most cases to the rules of common sense applied to date for failures, but it enables the level of safety to be evaluated and controlled more accurately, particularly because of the increasing complexity of control systems.

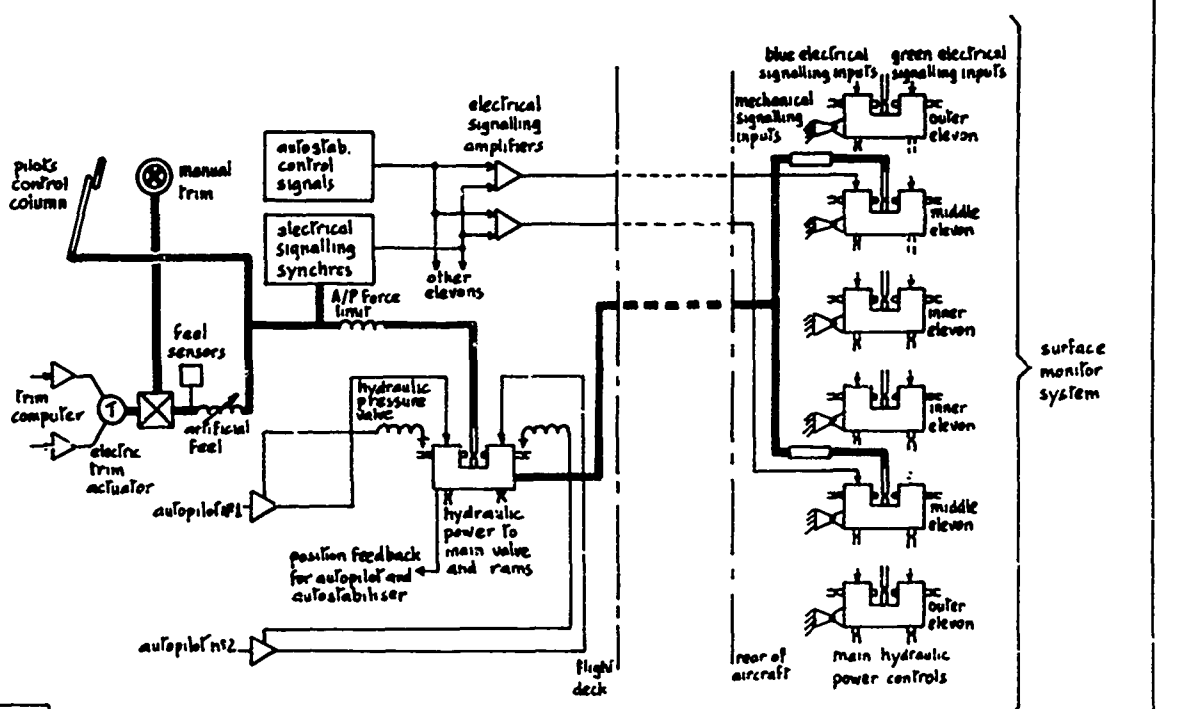
This evaluation (See Pl. 11) is based on automatic precessing of all the aircraft system safety and reliability analyses. A computer programme classifies all the states corresponding to the various failure conditions according to probability levels. The states to be evaluated on the simulator, and if required in flight are chosen after examining this classification.

As far as automatic correctors in particular are concerned our objective has been that in the absence of correctors, control of the aircraft is sufficiently safe to avoid jeopardizing the aircraft safety directly. This has indeed been acheived but leads for example to C.G. limitations which are nevertheless compatible with satisfactory commercial operation of the aircraft. It would probably be possible to improve the operational economy of an aircraft by not observing this rule, if there is a suficient redundancy of systems. All indications lead us to believe that this step will be taken in future generations of transport aircraft

5. - CONCLUSION -

Examination of a few concrete examples has enabled us to measure the close interdependency which exists between flight qualities and flying control systems. We are convinced that flight qualities and control systems should be studied in close association. CONCORDE is an example of this the flight qualities of this supersonic aircraft which the pilots consider to be at least equal to, if not better than those of the best subsonic transport aircraft, are in part the result of the optimization of its control systems.

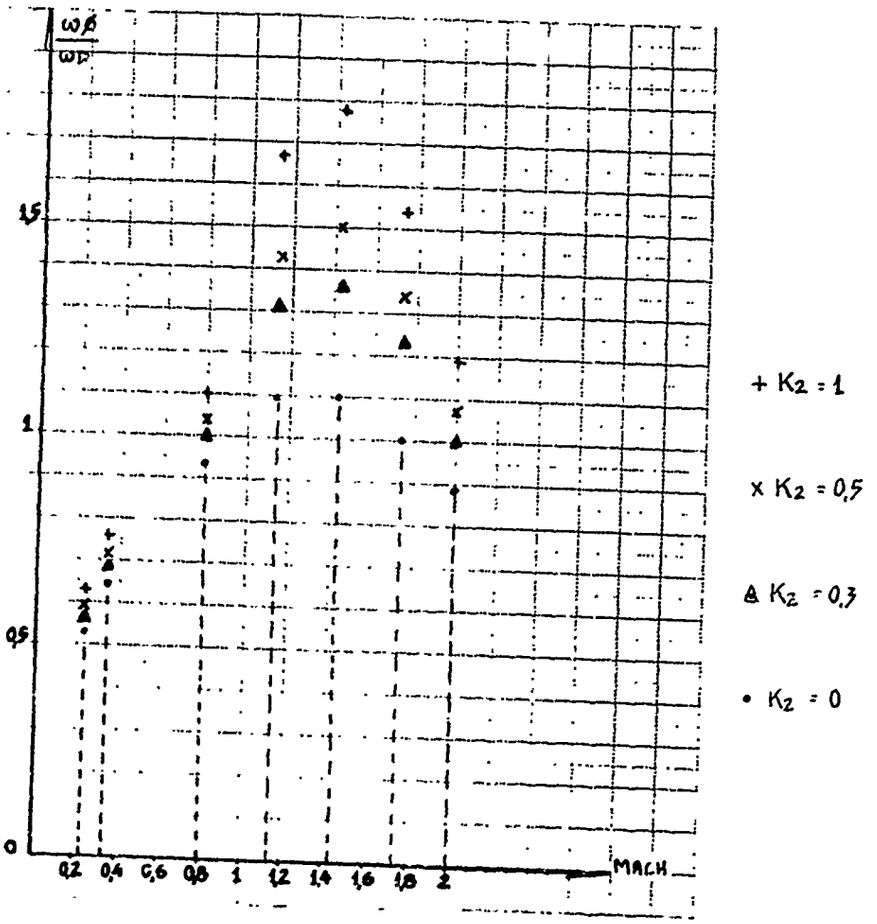
SCHEME SHOWING THE PRINCIPLES OF THE CONCORDE FLYING CONTROL SYSTEM



Pl. 1

AVION NATUREL

AIRCRAFT WITHOUT AUTOSTABILISATION

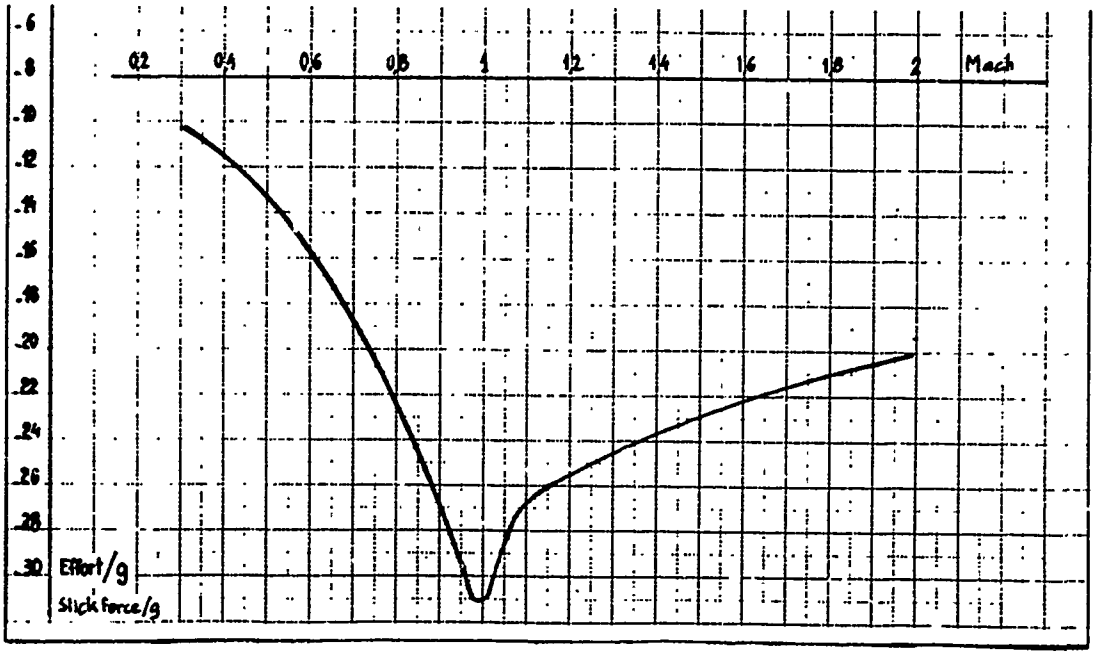


$K_2 = \dfrac{\text{braquage elevon interne}}{\text{braquage elevon externe/median}} = \dfrac{\text{deflection of inner elevon}}{\text{deflection of outer/middle elevon}}$

EVOLUTION DU RAPPORT $\frac{\omega\phi}{\omega D}$ EN FONCTION DE K_2

$\frac{\omega\phi}{\omega D}$ AS A FUNCTION OF K_2

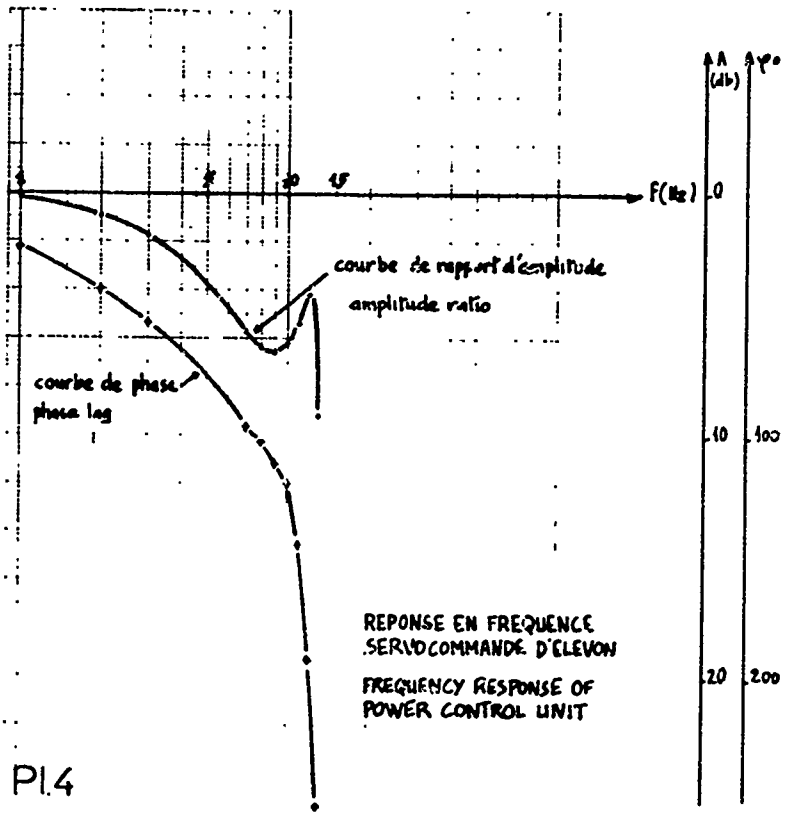
PI 2



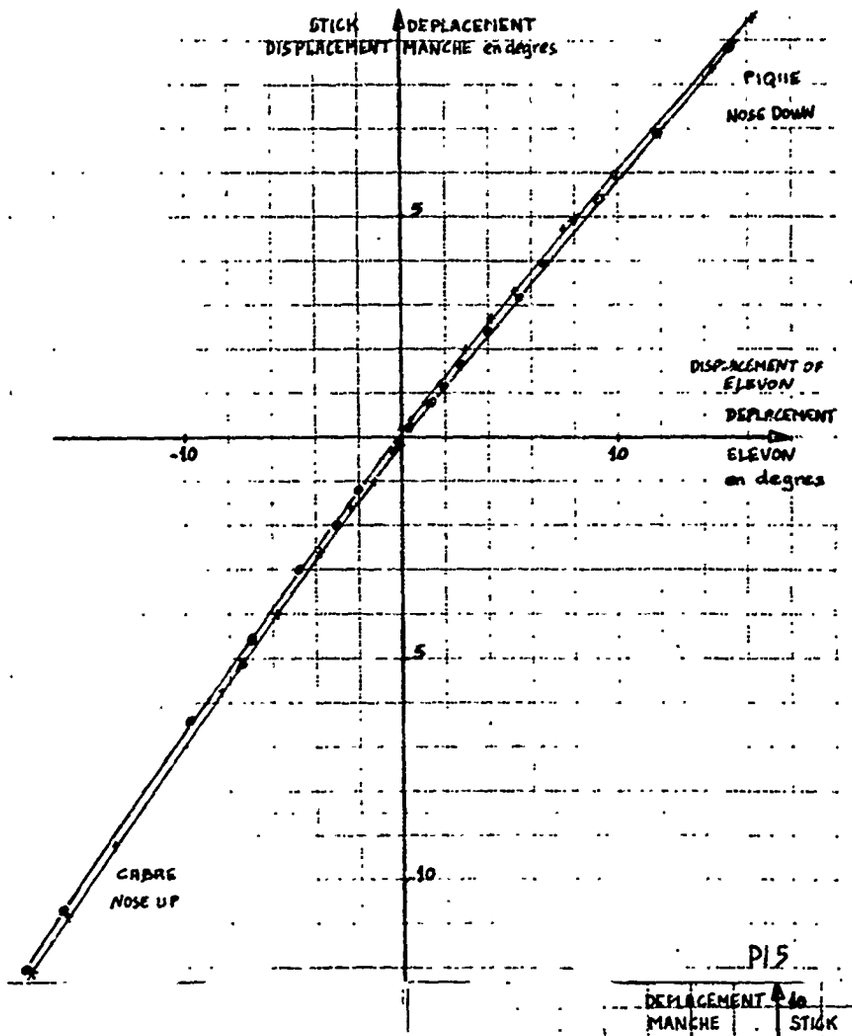
EFFORT PAR g LE LONG DE LA MISSION TYPE

STICK FORCE/g FOR A TYPICAL MISSION

Pl.3



Pl.4

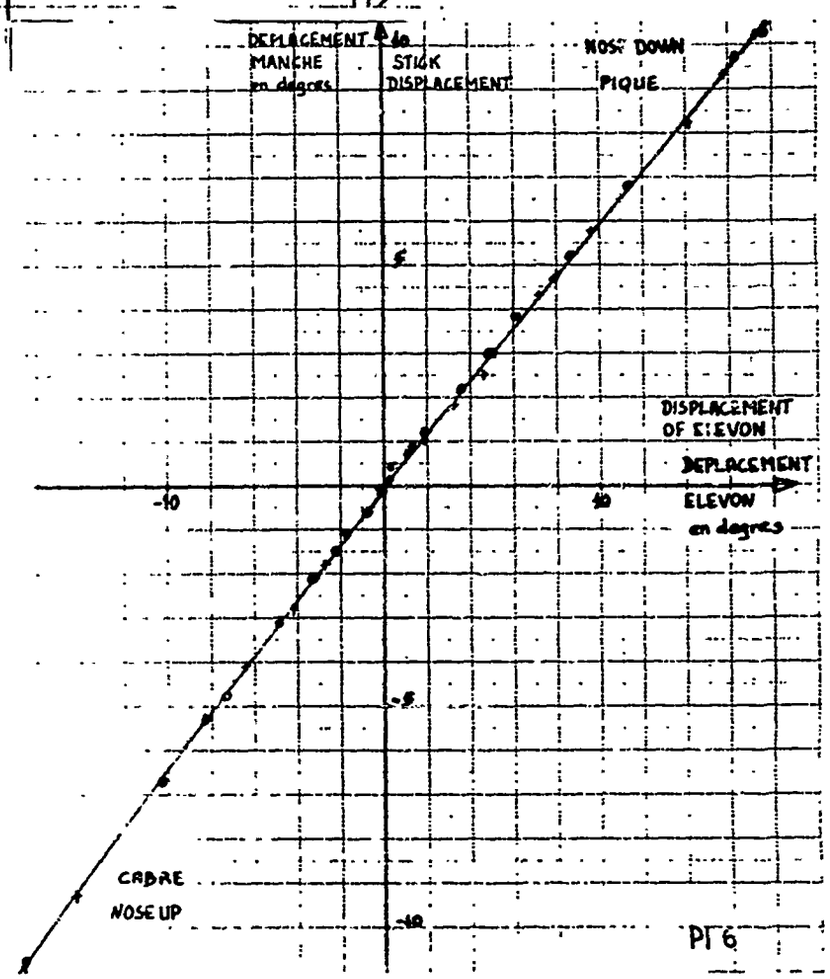


PROFONDEUR
DEPLACEMENT ELEVON
EN FONCTION
DEPLACEMENT MANCHE
COMMANDE MECANIQUE

ELEVATOR
ELEVON DISPLACEMENT
AS A FUNCTION OF
STICK GEARING
MECHANICAL

PI.5

PI.5

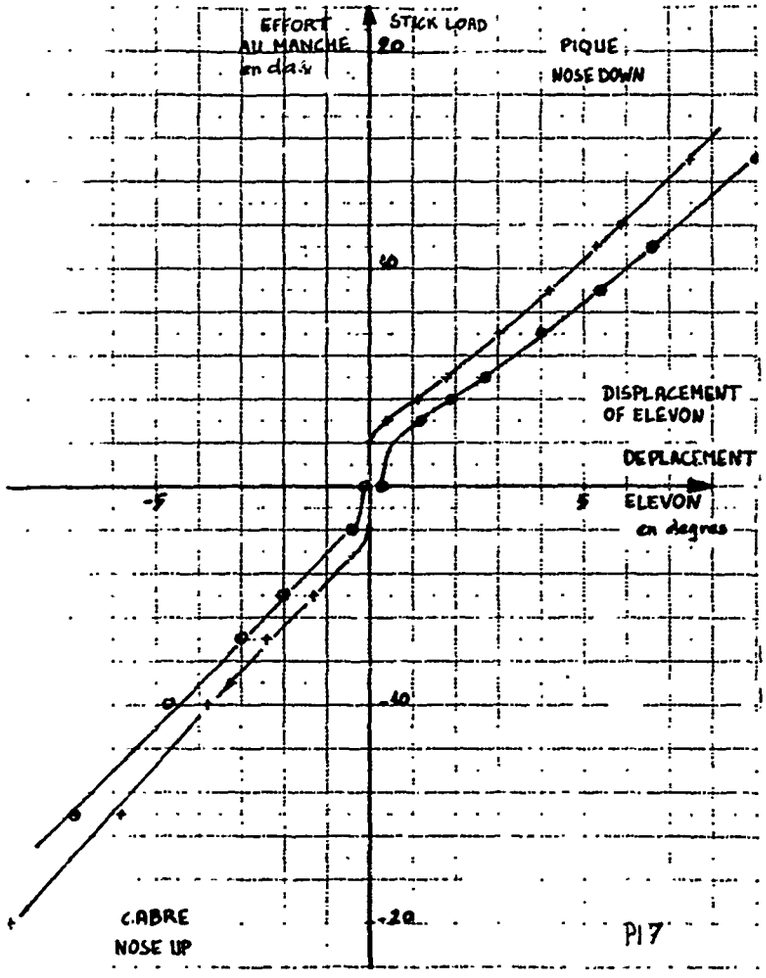


PROFONDEUR
DEPLACEMENT ELEVON
EN FONCTION
DEPLACEMENT MANCHE
COMMANDE ELECTRIQUE

ELEVATOR
ELEVON DISPLACEMENT
AS A FUNCTION OF
STICK GEARING
ELECTRICAL

PI. 6

PI 6



PI 7

- PROFONDEUR -

DEPLACEMENT ELEVON

EN FONCTION

EFFORT AU MANCHE

- COMMANDE MECANIQUE -

- ELEVATOR -

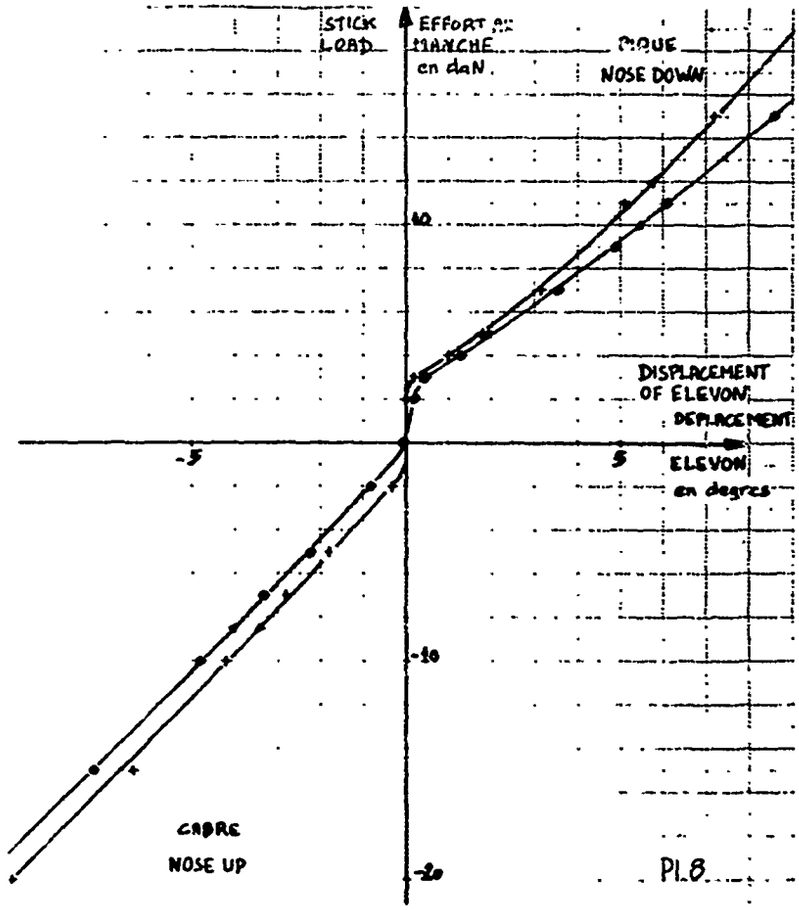
ELEVON DISPLACEMENT

AS A FUNCTION OF

STICK LOAD

- MECHANICAL -

PI. 7



- PROFONDEUR -

DEPLACEMENT ELEVON

EN FONCTION

EFFORT AU MANCHE

- COMMANDE ELECTRIQUE -

- ELEVATOR -

ELEVON DISPLACEMENT

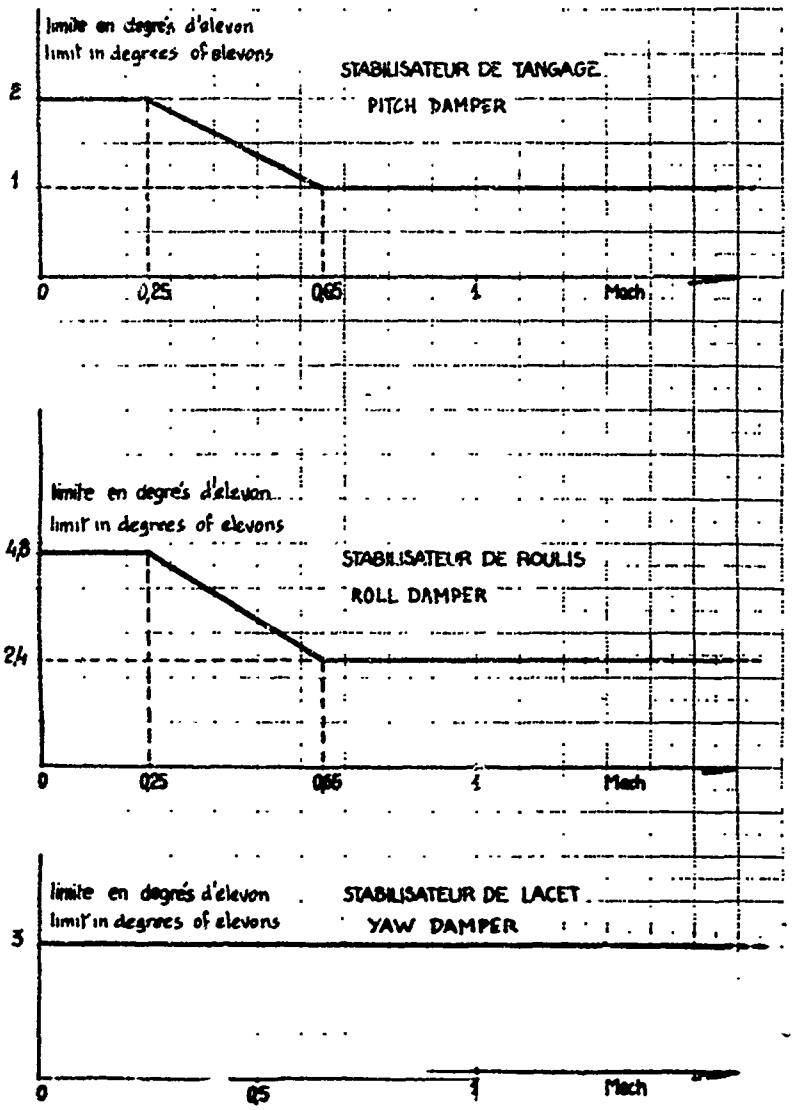
AS A FUNCTION OF

STICK LOAD

- ELECTRICAL -

PI. 8

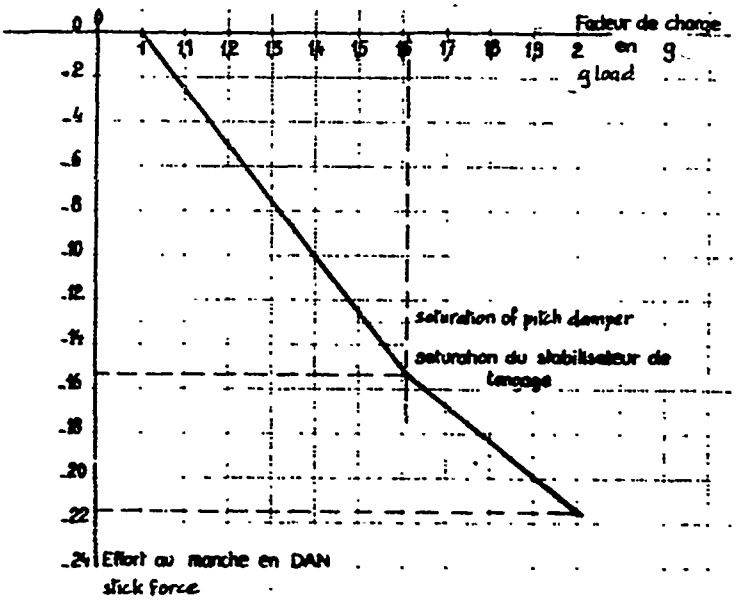
PI. 8



LIMITATION D'AUTORITE DES STABILISATEURS

AUTHORITIES OF AUTOSTABILISERS

Pl. 9



Pl. 10 Cas de vol : Mach 0,8 - Vc = 410Kt - Centrage 55,2%

STICK FORCE ~ g RELATIONSHIP

EVOLUTION DE L'EFFORT AU MANCHE EN FONCTION DU FACTEUR DE CHARGE

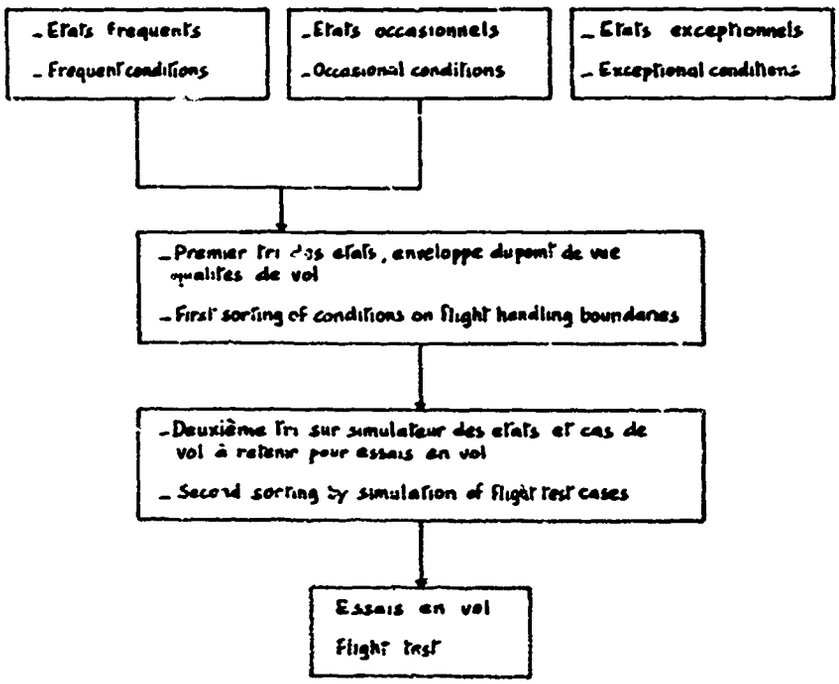
ESSAIS DE CERTIFICATION
Certification trials

BUT : Demontrer la conformite de l'avion aux reglements(T.S.S. standard)

OBJECT: To demonstrate compability of the aircraft with the TSS standards

CHOIX DES ESSAIS : Determination sur calculateur digital à partir des analyses de pannes :

CHOICE OF TESTS: After analysis of failures, determine by digital computer calculations :



PI 11

LEAD DISCUSSION

by
K. Sobotta
VFW-Fokker GmbH
Bremen, Germany

The first flight of the Concorde was not only an historical date in aviation because this airplane was the first civil SST, this date is also remarkable because with the Concorde the first true fly-by-wire system was flying in an operational civil transport aircraft. From my own experience I know how difficult it is to introduce fly-by-wire systems in aircraft projects. Therefore my congratulations go to the English and French control systems engineers for this success.

Now to the discussion of the paper by Mr. Deque. Unfortunately I have no experience with the handling qualities of large transport aircraft like the Concorde. Therefore, I was very surprised about the results. Mr. Sliff mentioned already in his paper earlier at this Meeting that for large and high-inertia airplanes the existing criteria are not in any case usable. He gave the example of the short period mode at small values of n_{z_α}, where the required tendencies are just reversed to the tendencies given in MIL-F-8785 over the Mach number range. Compared with the criterion in MIL-F-8785 the curve is well within the Level 1 region. But reducing the stick force per g gradient at high Mach numbers to 10 daN/g gave, in certain cases, PIO's. In MIL-F-8785 this point is located in the Level 3 region, but rather near to the Level 2 boundary, so that it can be assumed that other parameters like stick deflection gradient, short period oscillation characteristics, control wheel dynamics, distance between the pilot's station and the c.g., etc., would be the reason for these PIO's. All these parameters have to be taken into account in fixing the stick force per g by an optimisation process. Considering the optimisation process, it should be investigated whether the boundaries of the MIL-F-8785 criterion on stick force per g under certain circumstances can be changed, especially if simplifications of the control system can be attained.

A hopeful start to combining several parameters in an optimisation process was made in the last few years with the C^* criterion which combined the angular rate, angular acceleration and the load factor in one optimisation criterion. I am very surprised that nobody has mentioned this criterion at this Meeting. We found it very useful in the development of the AFCS for the VTOL aircraft VAK 191 B and the European project MRCA.

A very important problem with fly-by-wire systems having mechanical back-up is the change-over from the electrical to the mechanical system in case of a total failure in the electrical system. There are two effects following the change-over:

1. A transient which occurs due to the disparity between the electrical and the mechanical systems. The disparity consists of several components which are determined by the different relations between stick and surface deflections in the electrical and the mechanical systems, the portion of the SAS signal in case of a non-stationary flight condition, the run-away portion until the failed system is switched off, etc. The transient effect can be expressed either as a difference of load factor $\Delta n(g)$ or as an altitude change.

2. A change in the handling qualities due to changed stick dynamics and the loss of SAS operation.

In the length of Mr. Deque's paper it surely is not possible to present a quantitative analysis of these phenomena. But I want to express my feeling that it will be very helpful for the realisation of fly-by-wire systems in other aircraft to learn about what has been gained in flight tests with the Concorde in the near future. We look forward to your next paper, Mr. Deque.

OPEN DISCUSSION

W. Bihrle, Grumman, USA

The reference to the FAA comment that 8785B did not predict what was required during the landing task fo. an aircraft that had high inertia or low static margin - that is not quite so, and I would like to correct this statement. It isn't really the damping ratio, as mentioned, that is the problem. It just happens that as the c.g. goes aft, the airplane becomes very highly damped but this is not the problem. What the pilot is really complaining about is that when you have a neutrally stable airplane, you've got a low frequency and you don't get the required angular acceleration cue for performing precision control tasks. Specifying an $\omega_{nSP}/N_{Z_\alpha}$ value takes care of this problem as Don Berry will verify from NASA FRC experience. Those interested should read AFFDL-TR-65-198 and AIAA #69-894 preprint.

I would also like to emphasize the point that Mr. Chalk made after the previous paper regarding being careful in designing adaptive autopilot systems.

R.J. Woodcock, AFFDL, USA

I was hoping that the subject of c* would not come up. I have felt for some time the c* has no place being mentioned in a meeting dealing with handling qualities. We have found that c* does not always correlate too well. We don't think that 8785B is necessarily the best way to go, but I don't think c* is it. In two specific instances we have found that c* does not correlate with pilot rating or opinion: See AFFDL TR 67-120 by McCormick and Koepke of Northrop and AFFDL TR 70-74 (2 vols.) by Neal and Smith of Cornell Aero Lab.

Prof. R. Bernotat, Germany

Have you done any investigation concerning not only stick deflection but also stick rate and stick acceleration, respectively their weighting factors as a function of the changing aircraft dynamics over whole flight envelope?

R. Deque, Aerospatiale, France

We have not been doing this type of research on the Concorde.

D.T. Berry, NASA/FRC, USA

I would like to add to the comments on time history envelope criteria, such as pitch rate envelopes and c*. Results from the XB-70 program (and limited data from the YF-12) show poor correlation with time history envelope criteria, particularly for supersonic cruise flight. The parameter $\omega^2_{nSP}/N_{Z_\alpha}$, however, correlates very well with the data from these programs. We have also observed that pitch rate time histories from two different cases could be very similar, and yet receive different pilot ratings. These same cases, however, did have a significant difference in $\omega^2_{nSP}/N_{Z_\alpha}$ that did correlate with the pilot ratings. This implies that if time history criteria are to succeed, a response parameter must be chosen that is a stronger cue to the pilot. Perhaps pitch acceleration, as Mr. Bihrle suggests is implied in the $\omega^2 n_{SP}/N_{Z_\alpha}$ parameter, is what is needed.

H.A. Mooij, NLR, Netherlands

Could Mr. Chalk please comment on all questions raised here regarding time history criteria?

C.R. Chalk, Cornell, USA

I agree with Mr. Woodcock. The time history envelope in particular c* is not adequate to do the job. We have examples which refute the use of c* as a criteria. It can be overly restrictive as well as not screening out bad ones.

PARAMETERS AFFECTING LATERAL-DIRECTIONAL HANDLING QUALITIES AT LOW SPEEDS

by

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SUMMARY

A study is undertaken of the factors affecting the lateral-directional handling qualities of aircraft in typical VMC STOL flight manoeuvres as certain modal parameters are varied. It is found that for the low flight-speed and the low dutch roll frequencies investigated, the side force equation takes on added significance in establishing the oscillatory mode through the vector contribution of the weight component acting along the y-axis. When this contribution is large, secondary effects on handling qualities can arise if the relationship between the yaw rate and sideslip vectors in the oscillatory mode is established solely by varying the derivatives of the moment equations because, under these circumstances, unusual groups of derivatives may be necessary to satisfy the imposed constraints. Similar deviations from normal values for the moment derivatives may be required to force the zeros from the poles in the bank angle to aileron-control transfer function whilst simultaneously maintaining the correct vector relationships in the oscillatory mode. The secondary effects on handling qualities arising from these two sources of unconventional sets of derivatives may be of greater significance than the primary effects associated with changes in the modal parameters and, when this occurs, handling qualities criteria based on the modal parameters alone must be established with considerable caution.

SOMMAIRE

On commence à étudier les facteurs affectant les qualités de manoeuvre, en roulis, en lacet et en dérapage, d'avions ADAC pilotés à vue lors d'évolutions types de ces appareils et comportant des variations de certains paramètres modaux. On a trouvé qu'aux faibles vitesses et aux faibles fréquences du roulis hollandais, qui ont été étudiées, l'équation des forces de dérapage devient plus importante pour déterminer le mode oscillatoire par la contribution vectorielle de la composante du poids suivant l'axe y. Lorsque cette contribution est grande, des effets secondaires sur les qualités de manoeuvre peuvent apparaître si la relation, entre les vecteurs de dérapage et de vitesse de rotation en lacet dans le mode oscillatoire, est établie uniquement en faisant varier les dérivées des équations des moments car, dans ces circonstances, des groupes inhabituels de dérivées peuvent être nécessaires pour satisfaire les contraintes imposées. Des déviations semblables des valeurs normales pour les dérivées des moments peuvent être nécessaires pour chasser les zéros des pôles dans la fonction de transfert, permettant de contrôler l'angle de rotation en roulis à l'aide des ailerons, tout en gardant simultanément la relation vectorielle correcte dans le mode oscillant. Les effets secondaires, sur les qualités de manoeuvre, ayant leur origine dans ces deux sources de groupes inhabituels de dérivées peuvent être plus importants que les effets primaires liés aux changements des paramètres modaux et, lorsque c'est le cas, les critères des qualités de manoeuvre basés uniquement sur les paramètres modaux doivent être établis avec une attention toute particulière.

SYMBOLS

g	Acceleration due to gravity, ft/sec^2
L	Rolling acceleration per unit subscript, rad/sec^2/unit subscript
N	Yawing acceleration per unit subscript, rad/sec^2/unit subscript
p	Rate of roll, rad/sec. Positive starboard wing down
r	Rate of yaw, rad/sec. Positive nose to starboard
S	Laplace operator
U	Linear steady-state velocity along x-axis, ft/sec
v	Lateral component of velocity, ft/sec, positive to starboard
Y	Lateral acceleration per unit subscript, ft/sec^2/unit subscript
y	Distance in direction of lateral axis normalised by $\frac{1}{4}$ wavelength of oscillatory mode
$\beta = \frac{v}{U}$	Angle of sideslip, rad
δ_a	Pilot's roll control deflection, in., positive for positive rolling moment
δ_r	Pilot's yaw control deflection, in., positive for positive yawing moment
ζ	Damping ratio
λ_R	Roll subsidence root of the lateral-directional characteristic equation, rad/sec
λ_S	Spiral root of the lateral-directional characteristic equation, rad/sec
σ	Root mean square value
ϕ	Roll angle, rad
ψ	Heading angle perturbation, rad
ω	Undamped natural frequency of a second-order mode specified by a subscript

SUBSCRIPTS

c	Calculated (see Fig. 2)
cw	Crosswind
d	Dutch Roll
g	Gust
p	Roll rate
r	Yaw rate
S	Spiral
R	Roll subsidence
y	In direction of lateral axis
ϕ	Roll transfer function

1.0 INTRODUCTION

Owing to our lack of understanding of the exact form of the multiple loops involved in controlling aircraft in flight, a need for experimental data arises whenever attempts are made to establish criteria for handling qualities. It was to provide data of this nature that the Flight Research Section of the National Research Council of Canada, in conjunction with and under contract to Cornell Aeronautical Laboratory, Inc., USA and the United States Air Force, embarked on a programme to investigate the lateral-directional handling qualities of aircraft during typical STOL manoeuvres in visual meteorological conditions (VMC). (Ref. 1).

The simulator used in the investigation (Fig. 1) possesses four degrees of freedom that may be independently controlled, namely the rotational degrees of freedom about the principal axes and the translational degree of freedom along the z-axis. No means exists of independently varying the translational modes along the x or y-axes. The desired motion in the lateral-directional planes is obtained by appropriately controlling the rotational degrees of freedom whilst taking due account of the open-loop side force characteristics arising both from the generation of the moments and from the inertial and aerodynamic side force characteristics of the basic simulator.

A survey of the current literature at the outset of the investigation indicated that a logical framework for a programme would be one defined by specific modal parameters associated with the aircraft transfer functions. Previous work had shown that parameters of significance to the pilot in controlling aircraft at higher speeds than that to be investigated and with dutch roll natural frequencies in excess of 1 rad/sec were λ_R, λ_S, ω_d, ζ_d, ω_ϕ, ζ_ϕ, $|\frac{\phi}{\beta}|_d$, U and control characteristics.

Although it has long been recognised that the effects of these parameters are interdependent, certain primary characteristics are normally associated with each of them, namely:

λ_R - a measure of the damping in roll which gives an indication both of the piloting technique required to control bank angle with aileron and of the ease with which this control may be achieved.
High λ_R corresponds to a rate-type of aileron control whilst low λ_R corresponds to an acceleration-type of aileron control over bank angle.

λ_S - a measure of the spiral stability of the aircraft

ω_d, ζ_d - a measure of the open-loop oscillatory mode of the lateral-directional dynamics

ω_ϕ, ζ_ϕ - a measure of the extent of the excitation of the oscillatory mode when aileron is applied

$|\frac{\phi}{\beta}|_d$ - a measure of the relative magnitude of the moduli of ϕ and β in the undamped open-loop oscillatory mode.

Control characteristics - the control sensitivity and the maximum control power available are of importance to the pilot both for manoeuvring and for the suppression of external disturbances. The harmony of the effects of the controls over their respective degrees of freedom is also of significance to the pilot.

In the current work it was decided to place the major emphasis on an investigation into the effects of the oscillatory mode on flight characteristics. The roll subsidence mode was thus fixed at $\lambda_R = -4$ rad/sec, the spiral root at $\lambda_S = 0$ corresponding to neutral static stability, the maximum roll and yaw control powers at 1.2 and 2.25 rad/sec^2 respectively and the two corresponding control sensitivities at 0.4 and 0.75 rad/sec^2/in. The above are levels for these parameters likely to arise in V/STOL aircraft and it was hoped that they would not lead to secondary detrimental characteristics that would dominate the handling qualities of any configuration.

It subsequently transpired that the control sensitivities and maximum powers selected led, in general, to an aileron control with low to inadequate control power and to a rudder control that was too sensitive.

The evaluation task involved VMC flight at 50 knots and included for each configuration coordinated and uncoordinated turning manoeuvres, a constant speed, 6° glide-path approach with a simulated crosswind of 10 knots, and a sidestep manoeuvre into the crosswind initiated at 200 ft A.G.L. which was to result, before touchdown, in a lateral displacement from the approach path of 300 ft and in a final aircraft heading identical with the approach heading.

Moderate artificial turbulence ($\sigma_{\beta_g} = 3.4°$) excited the aircraft dynamics throughout the evaluations.

2.0 EQUATIONS OF MOTION

The lateral-directional equations of motion simulated made use of conventional derivatives and were:

Rolling Moment:

$$S(S-L_p)\phi - L_r r - L_\beta \beta = L_{\delta_a}\,\delta a + L_\beta\,\beta_g + L_\beta\,\beta_{cw} \quad (1)$$

Yawing Moment:

$$-N_p S\phi + (S-N_r)r - N_\beta \beta = N_{\delta_a}\,\delta a + N_{\delta_r}\,\delta r + N_\beta\,\beta_g + N_\beta\,\beta_{cw} \quad (2)$$

Side Force:

$$-(g+Y_p S)\phi + (U-Y_r)r + (US-Y_\beta)\beta = Y_{\delta_a}\,\delta a + Y_{\delta_r}\,\delta r + Y_{\beta_g}\,\beta_g + Y_{\beta_{cw}}\,\beta_{cw} \quad (3)$$

The rolling moment and yawing moment derivatives could be varied at will, whereas the side force derivatives were those inherent in the basic simulator and in the generation of the appropriate moments.

The derivatives changed to obtain the seven desired modal parameters were:

$$L_p\ ,\ L_r\ ,\ L_\beta\ ,\ N_p\ ,\ N_r\ ,\ N_\beta\ ,\ N_{\delta_a}$$

and the modal parameterr chosen to classify the configurations can be obtained from the bank angle to aileron control transfer function, namely,

$$\frac{\phi}{\delta a}(S) = \frac{K(S^2+2\zeta_\phi\omega_\phi S+\omega_\phi{}^2)}{(S-\lambda_S)(S-\lambda_R)(S^2+2\zeta_d\omega_d S+\omega_d{}^2)} \quad (4)$$

where, for this programme,

U = 84.5 ft/sec

λ_S = 0 rad/sec

λ_R = -4 rad/sec

$\left|\frac{\phi}{\beta}\right|_d$ = 0.2 , 0.75 , 1.5

ω_d = 1.0 , 0.5 , 0.25 rad/sec

ζ_d = 0.3 , 0.2 , 0.1 , 0 , -0.1 , -0.2 , -0.3 , -0.4

ω_ϕ and ζ_ϕ were assigned various values

In-flight responses of the aircraft to simultaneous aileron, rudder and gust inputs are compared in Fig. 2 with the desired responses subsequently calculated from the appropriate equations of motion for the same inputs. The close correspondence between the desired and actual responses is typical of that obtained throughout the investigation.

3.0 RESULTS

The pilots' comments on the lateral-directional handling characteristics encountered indicated that the prime causes of difficulty associated with the different configurations were varied, ranging from inadequate stiffness and/or damping associated with the lateral-directional oscillatory mode, excessive undesired response to control inputs, excessive response to turbulence and crosswind, apparent static instabilities, inadequate aileron control power and an over-sensitive rudder control.

The extent of some of these detrimental characteristics associated with secondary effects was greater than anticipated and the reason for this must be found in the groupings of the modal parameters chosen.

3.1.0 Influence of modal parameters in establishing the required derivatives

Conventional open-loop oscillatory modes are established primarily by the yaw rate and sideslip vectors, the latter providing stiffness to the mode through the coupling vector component $N_\beta \cdot \beta$ in the yawing moment equation, while the damping is provided by the vector component $N_r \cdot r$. The yaw rate and sideslip perturbations cause perturbations in roll but the latter normally only provide weak feedback to the oscillatory mode.

The roll subsidence mode is to a large extent established by the value of L_p and, in order to satisfy the oscillatory mode constraints in the rolling moment equation, a large vector component $L_\beta \cdot \beta$ is required virtually in antiphase to the $L_p \cdot p$ vector component. This relationship is insensitive to quite large variations in the yawing moment derivatives unless λ_R is reduced to the same order of magnitude as ω_d – a condition that did not prevail in the present investigation. (Refer to the Appendix for details.)

The spiral mode is established simply by whether

$$\frac{N_r}{N_\beta} \gtrless \frac{L_r}{L_\beta} \quad (5)$$

and, within the limits for λ_S normally considered as acceptable, this relationship places a strong restraint on the relative values of these derivatives. The actual value of the above ratios is established by the location of the zeros of the $\frac{\phi}{\delta a}(S)$ transfer function and the side force derivatives. $\left(\text{For } \lambda_S = 0,\ \frac{N_r}{N_\beta} = \frac{L_r}{L_\beta} = -\frac{2\zeta_\phi\omega_\phi + Y_v}{\omega_\phi^2}\right)$

3.1.1 Effect of $\frac{g}{U}\cdot\frac{1}{\omega_d}|\frac{\phi}{\beta}|_d$

The key equation in establishing the values of the yawing moment derivatives required to satisfy the modal constraints proves to be the side force equation. Conventionally, the sideslip generated in the oscillatory mode may be obtained to a good approximation by writing this equation as

$$\dot{\beta} = -r \ , \tag{6}$$

the implicit assumption being that both the aerodynamic side forces generated and the weight component acting along the y-axis have negligible influence on the mode in comparison with that of the yaw rate term. The assumption may be confirmed a posteriori if the displacements from the equilibrium flight path due to the oscillatory mode are negligible in comparison with the wavelength of the mode.

Some of the configurations evaluated in the current programme exhibited this characteristic and the resulting oscillatory motion was, in the directional plane, approximated well by $\psi = -\beta$. However, many other configurations were not adequately described by this simple approximation and, for these, the sideslip was better defined by the more complete side force equation in which the major external lateral forces are no longer neglected, namely,

$$\dot{\beta} = -r + \frac{g}{U}\phi + \frac{Y_\beta}{U} \tag{7}$$

For the modal constraints of the investigation, it is shown in the Appendix that the $\frac{g}{U}\phi$ term, representing the lateral force arising from the weight component acting along the y-axis, exerts an influence on the oscillatory sideslip that increases with the ratio $\frac{g}{U}\cdot\frac{1}{\omega_d}|\frac{\phi}{\beta}|_d : 1$. When this ratio is small, the characteristic oscillatory motion is established essentially by the yaw rate and sideslip vector components in the yawing moment equation and the usual approximation of $|\frac{\psi}{\beta}|_d = -1$ is valid. However, as the ratio is increased, the sideslip is affected ever more by the lateral forces, and the above approximation for the vector relationship between ψ and β in the oscillatory mode may become completely invalid. The changing nature of this vector relationship can result in the primary effects of many of the aerodynamic derivatives on the mode being altered. A further factor, which gains prominence when the characteristic frequency is low, arises from the relative magnitudes of accelerations, rates and displacements in the oscillatory mode, given by

$$\ddot{y} : \dot{y} : y = \omega_d^2 : \omega_d : 1 \tag{8}$$

Thus, when the characteristic frequency is decreased to values below 1 rad/sec, the increasing influence of the lateral forces is made apparent through large lateral displacements from the equilibrium flight path.

Examples of the shift in amplitude and phase of ψ relative to β, with increasing $\frac{g}{U}\cdot\frac{1}{\omega_d}|\frac{\phi}{\beta}|_d$, may be seen in Fig. 3a. A measure of the influence of this shift is given by the vector of the lateral displacement of the aircraft's centre of gravity normalised by a quarter wavelength of the oscillation.

The large changes required in the vector ratio $\frac{r}{\beta}|_d$ to satisfy the modal constraints are due to the fact that p and β, because of the relative magnitudes of λ_R and ω_d, remain essentially in antiphase for quite large variations in yawing moment derivatives. This means that the $\frac{g}{U}\phi$ term provides predominantly a stiffness term to the oscillatory mode in sideslip. If the vector component $(Y_p\cdot p + Y_\beta\cdot\beta)/U$ does not provide the correct damping for this mode there is a requirement that the remaining damping as well as the remaining stiffness be provided by the yaw rate term (Fig. 3b). Thus, particularly for those cases where $\frac{g}{U}\phi$ provides considerable stiffness, large changes in the vector r may be demanded. In order to achieve these changes it becomes necessary to adjust the values of N_p, N_r and N_β appropriately, and it is the secondary effects of these adjustments on the various transfer functions defining the aircraft motion that become of greater significance in the resulting handling qualities than the direct effect of altering the particular modal parameter under consideration. The influence of the magnitude of $\frac{g}{U}\frac{1}{\omega_d}|\frac{\phi}{\beta}|_d$ on the derivatives required to satisfy the oscillatory constraints may be seen from Figs. 3b, c and d. The shaded portion corresponds to the basic oscillatory mode in sideslip, yaw and roll respectively, and, whenever large vector components are required approximately in antiphase to close the vector polygon around this portion, secondary effects of significance to the handling qualities of the configuration result.

Such influences are well illustrated in Fig. 4. For $|\frac{\phi}{\beta}|_d = 0.2$, as $\frac{g}{U}\frac{1}{\omega_d}|\frac{\phi}{\beta}|_d$ is increased from 0.076 to 0.304 through changes in ω_d, one observes that increasing the damping ratio may in fact cause deterioration in handling qualities. The oscillatory motion following disturbances was quite apparent to the pilot for the group of configurations with $\omega_d = \omega_\phi = 1$ rad/sec, and the fact that increasing the damping ratio improved handling qualities was reflected in the pilots' ratings. In contrast, for those configurations with $\omega_d = \omega_\phi = 0.25$ rad/sec and $\zeta_\phi = \zeta_d$, the secondary effects of the yawing moment derivatives required to satisfy the modal parameters result in the generation of large sideslip angles proportional to the bank angles commanded by aileron control (e.g. $\frac{\beta}{\phi}|_{\delta a} = 0.625$ for $\zeta_d = 0.3$) as the damping ratio is increased and this effect more than

offsets the improvements afforded by the increased damping of the oscillatory mode.

For this latter group of configurations the optimum rating occurs when the r and ϕ (or $\dot{r}$ and p) vectors are in antiphase ($\zeta_d = 0.09$) and, simultaneously with this condition, one obtains both minimum sideslip generated by aileron and minimum sideslip due to β_g because of the small values of $N_{\delta a}$ and N_β required to satisfy the modal parameters. This configuration could be called the basic configuration for $\omega_\phi = \omega_d = 0.25$ rad/sec, $\zeta_\phi = \zeta_d$, $\left|\frac{\phi}{\beta}\right|_d = 0.2$ and for the values of λ_R, λ_S, $\frac{g}{U}$ and sideforce derivatives of the investigation. The open-loop oscillatory motion corresponds to a pendulous motion about the equilibrium flight path with aircraft heading changes that are smaller than sideslip-angle variations, whilst the bank angle and displacement from the equilibrium flight path remain in antiphase.

3.1.2 Effect of moving zeros of $\frac{\phi}{\delta a}(S)$ from complex poles

In the limit $\left|\frac{\phi}{\beta}\right|_d \to 0$, the zeros must coincide with the poles. Thus, for those cases where both $\frac{g}{U}\cdot\frac{1}{\omega_d}\left|\frac{\phi}{\beta}\right|_d$ and $\left|\frac{\phi}{\beta}\right|_d$ are small, movements of the zeros from the poles can only be achieved by large changes in the yawing moment derivatives from their normal values. Minimum oscillatory excitation with aileron occurs when N_p and $N_{\delta a}$ are related approximately by

$$\frac{N_{\delta a}}{L_{\delta a}} = \frac{1}{L_p}\left(N_p - \frac{g}{U}\right) \qquad (9)$$

and the secondary effects of large N_β, N_p and the corresponding $N_{\delta a}$ cause greater concern to the pilot than would be expected if these derivatives could have been kept at more normal levels.

As $\frac{g}{U}\cdot\frac{1}{\omega_d}\left|\frac{\phi}{\beta}\right|_d$ increases, however, it becomes possible to find configurations which are improved by moving the zeros from the poles because the changes in derivatives required by this movement counteract the requirements of increasing $\frac{g}{U}\cdot\frac{1}{\omega_d}\left|\frac{\phi}{\beta}\right|_d$. The improvement in the secondary characteristics can, in this case, more than compensate for the deterioration caused by the primary effect of exciting the oscillatory mode with aileron, particularly for the lower values of ω_d where the pilot has greater lead time available to control the oscillation.

3.1.3 Effect of increasing $\left|\frac{\phi}{\beta}\right|_d$

The effect of increasing $\left|\frac{\phi}{\beta}\right|_d$ was only investigated for those cases in which $\omega_\phi = \omega_d$, $\zeta_\phi = \zeta_d$ and, as a result, the $\frac{g}{U}\cdot\frac{1}{\omega_d}\left|\frac{\phi}{\beta}\right|_d$ effect on the yawing moment derivatives was such as to cause an even more rapid deterioration in handling qualities with increasing $\left|\frac{\phi}{\beta}\right|_d$ than was expected, particularly at the higher natural frequencies and damping ratios, where the pilot did not in general have sufficient aileron control power available to counter the large rolling moments generated by disturbances in yaw and sideslip.

It is possible that some improvement may be afforded to these configurations by moving the zeros from the poles in the $\frac{\phi}{\delta a}(S)$ transfer function, thereby reducing the magnitude of some of the derivatives associated with the generation of large sideslip and yaw disturbance, in particular, $N_{\delta a}$, N_p and N_β.

3.1.4 Effect of λ_R, λ_S constraints

(a) λ_R It may be felt that the open loop aperiodic constraints that were applied could have had a significant effect on the results. A study of approximations, valid for the present conditions, for the values of derivatives required to satisfy the various constraints indicates that the different transfer functions are not affected significantly by λ_R unless the latter is reduced to the same order of magnitude as ω_d. For the present conditions this would lead to an acceleration-type of aileron control which is to be avoided because of the resulting imprecise bank-angle control available to the pilot.

It is possible to shift the optimum configurations to those with slightly different parameters by decreasing λ_R, but the general pattern, although distorted, remains much the same. To be specific, those cases in which $\zeta_\phi = \zeta_d$ and $\omega_\phi = \omega_d$ may be improved by decreasing λ_R if the required $N_{\delta a}$ is negative, because the ensuing reduction in $\left(N_p - \frac{g}{U}\right)$ requires a smaller $N_{\delta a}$ which, in turn, results in less aileron induced sideslip for a given bank angle. The effect is most pronounced at high values of $\frac{g}{U}\cdot\frac{1}{\omega_d}\left|\frac{\phi}{\beta}\right|_d$.

(b) λ_S Movement of the spiral root within the limits normally considered acceptable does not in general have a significant effect, although once again it can cause a shift in the optimum configurations, particularly at the lowest frequency.

3.1.5 Effect of side force derivatives

The values of the side force derivatives can act as a constraint at the lower frequencies with large $\frac{g}{U}\cdot\frac{1}{\omega_d}\left|\frac{\phi}{\beta}\right|_d$ because of the large phase shifts in $\frac{r}{\beta}$ needed to satisfy the side force equation in the oscillatory mode as the $\frac{g}{U}\phi$ term increases in significance. If the side force derivatives could be varied to minimise this requirement, the secondary effects due to unnaturally large yawing moment derivatives would be reduced.

3.2.0 Primary effects of modal paramaters on handling qualities

Having discussed at some length the secondary effects on handling qualities caused by the above constraints the primary effects will now be summarised.

3.2.1 Effect of frequency and damping ratio

(a) Low $\left|\frac{\phi}{\beta}\right|_d$. At ω_d = 1.0 rad/sec, the oscillatory characteristics were apparent to the pilot as such and his ratings of the configurations improved with increases in damping ratio.

As the frequency was decreased, however, the period became so long that the only open loop characteristics of the oscillation observed by the pilot were the initial responses to various inputs. These responses would in general result in such large angular or lateral displacements that the pilot often felt that he was being required to control a static divergence. This factor was made worse by the fact that for the low stiffnesses associated with low frequencies, the rudder control, rather than being an angular displacement control for β became a rate control during the time scales of interest. This meant that the rudder had to be pulsed to correct sideslip excursions and any residual out-of-trim on rudder resulted in rapid increases in sideslip. The smaller the requirement for using rudder, the better the pilots liked the configuration and, for this reason, optimum ratings were obtained whenever $N_{\delta a}$, N_p and N_β were small. This secondary factor was of greater significance than whether the zeros of the $\frac{\phi}{\delta a}(S)$ transfer function coincided with the poles or whether the damping ratio was increased.

The general characteristic of these low frequency configurations was thus one of the low stiffness in φ, β, and ψ which required constant attention. The undesired responses to any corrective movements of the controls aggravated the problem.

As the zeros of the $\frac{\phi}{\delta a}(S)$ transfer function were moved from the poles the secondary effects due to the large changes required in yawing moment derivatives proved to have a greater influence on handling qualities than effects that can be attributed primarily to the relative location of the zeros to the poles. Indeed the crosscoupling derivatives could be so large that it was possible to initiate sustained PIO's when attempts were made to follow a track with aileron alone, even when dealing with these low characteristic frequencies (Fig. 5).

3.2.2 Effect of increasing $\left|\frac{\phi}{\beta}\right|_d$

One of the major effects of increasing $\left|\frac{\phi}{\beta}\right|_d$ was the primary one due to increases in L_β in the rolling moment equation. This caused problems associated with the maximum aileron control power and, in general, the large rolling disturbances caused by the crosscoupling inputs from the yawing moment and side force equations dominated handling qualities. The effects originating from high values of $\frac{g}{U}\frac{1}{\omega_d}\left|\frac{\phi}{\beta}\right|_d$ described earlier, aggravated the situation, mainly through the large changes in the $\left|\frac{r}{\beta}\right|_d$ relationship required to satisfy the oscillatory mode constraints. As frequency was reduced for the high $\left|\frac{\phi}{\beta}\right|_d$ ratios, the increasing time, associated with the longer periods, and the proportionally greater roll control power available to counter the strong L_β effects ($L_\beta = \lambda_R\left|\frac{\phi}{\beta}\right|_d\omega_d$) provided some relief to the situation.

4.0 CONCLUDING REMARKS

During the course of investigating the principal effects of low frequency dutch roll modes at a low speed it was found that the open loop characteristics changed from the conventional lateral directional oscillation in which it could be assumed that to a close approximation $\left|\frac{\psi}{\beta}\right|_d = -1$, to one in which the weight component along the y axis exerted considerable influence on the sideslip generated in this mode. This results in the necessity for the vector relationship between r and β to be changed and, if this is accomplished by changes in the moment derivatives, secondary effects are imposed on the handling qualities which are often of greater significance than the primary effect being investigated. When this occurs, the group of derivatives required to obtain the chosen modal parameters is unnatural when referred to the desired dutch roll mode and handling-qualities criteria based on the results obtained with these derivatives can be misleading.

It is found that vector polygons representing each of the degrees of freedom provide good indicators of when secondary effects can be expected to exert considerable influence on the handling qualities of the configurations because of their ability to provide suitable scaling for the various components of the characteristic mode. They do not, however, provide direct information about the time scales involved nor about the effects of numerators on the mode and these must ultimately be obtained from consideration of the appropriate transfer functions.

5.0 REFERENCE

1. K-H. Doetsch, Jr., D.G. Gould, D.M. McGregor, "A Flight Investigation of Lateral-Directional Handling Qualities for V/STOL Aircraft in Low Speed Manoeuvring Flight", NRC, NAE LTR-FR-12, 1969 (Also published as AFFDL-TR-69-41 and NRC, NAE Aero Report LR-549, 1971).

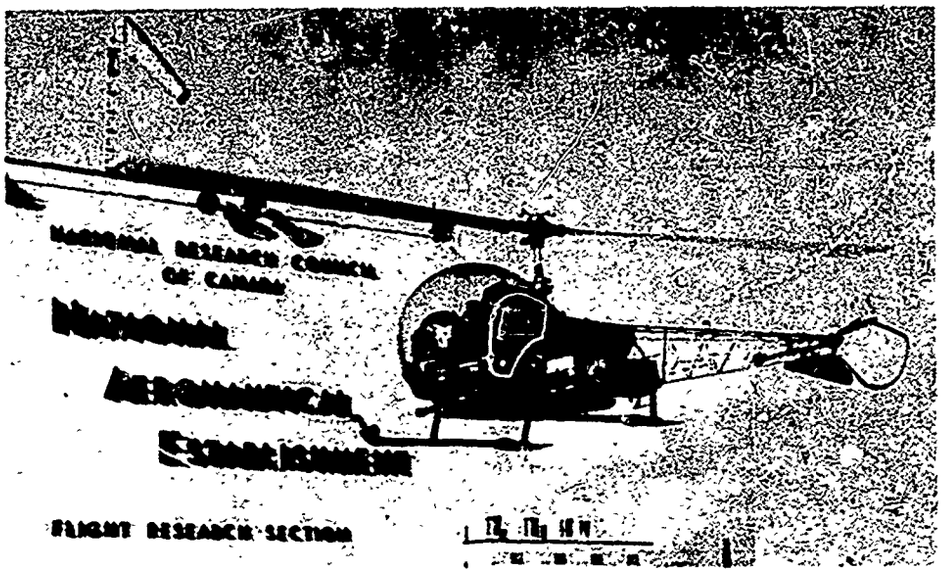


FIG 1 AIRBORNE V/STOL SIMULATOR

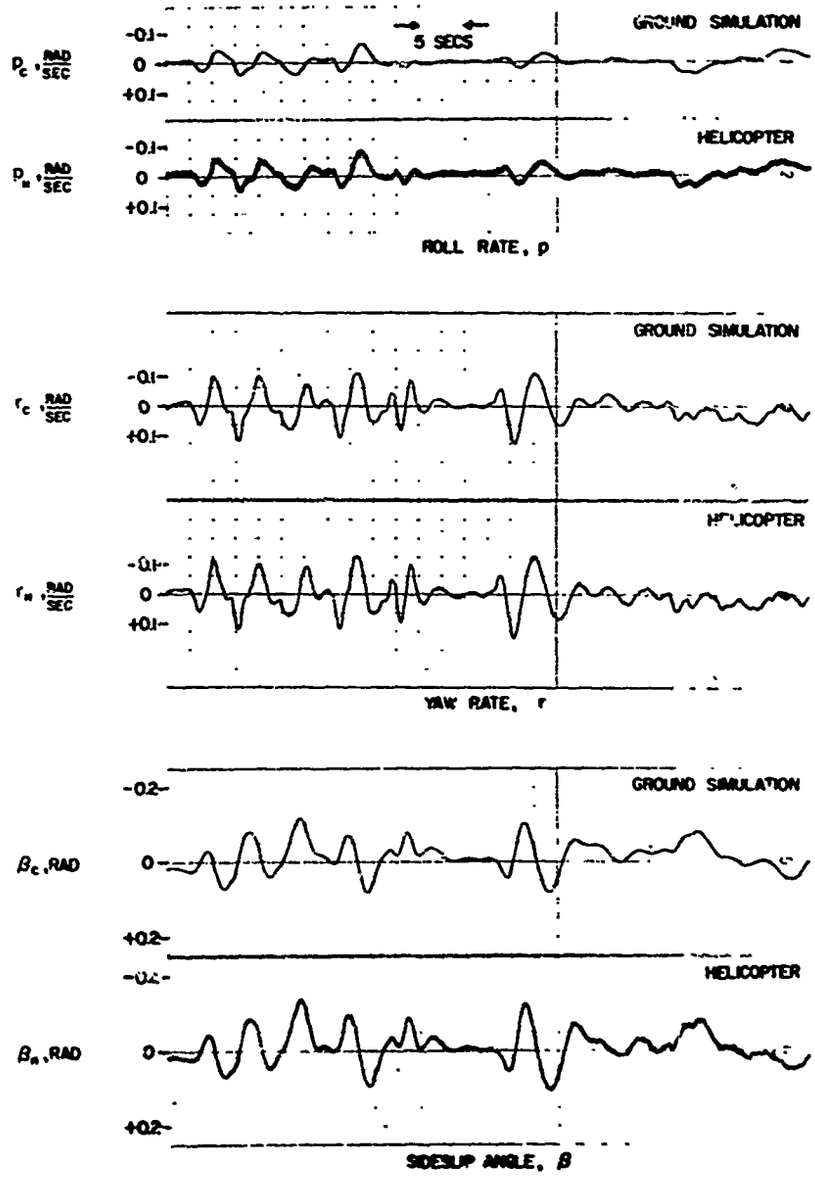


FIG 2 COMPARISON OF HELICOPTER RESPONSES TO CONTROL AND GUST INPUTS WITH THOSE EXPECTED FROM GROUND SIMULATION - MODEL No LH 129 + 20 + 50, REF 1

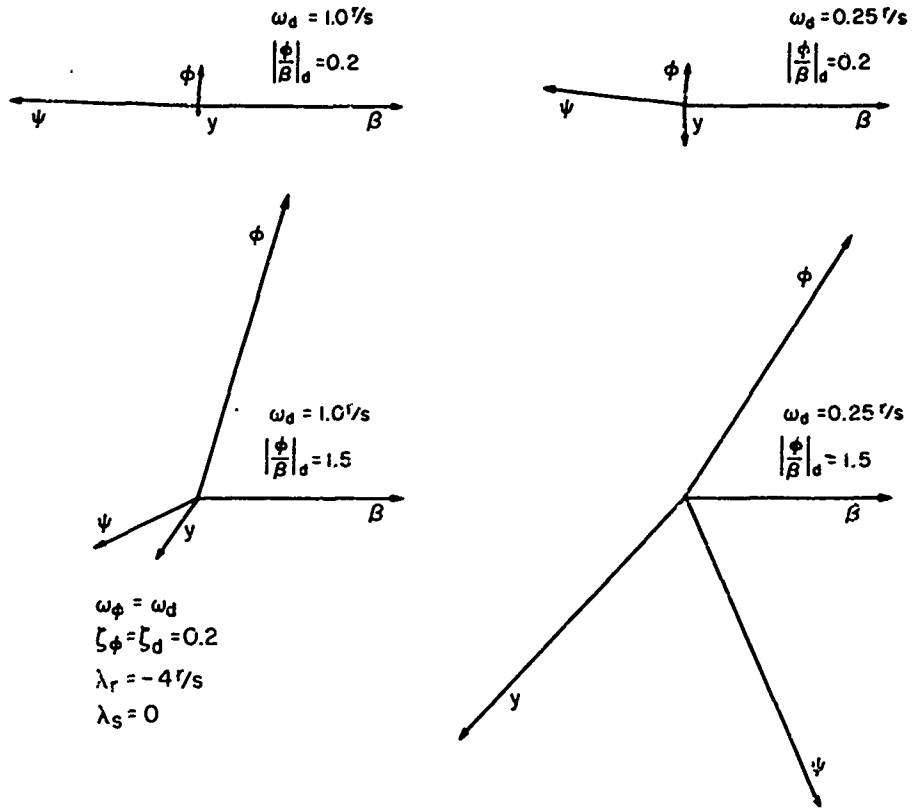


FIG 3a VECTOR RELATIONSHIP IN OPEN LOOP OSCILLATORY MODE - EFFECT OF ω_d & $\left|\frac{\phi}{\beta}\right|_d$

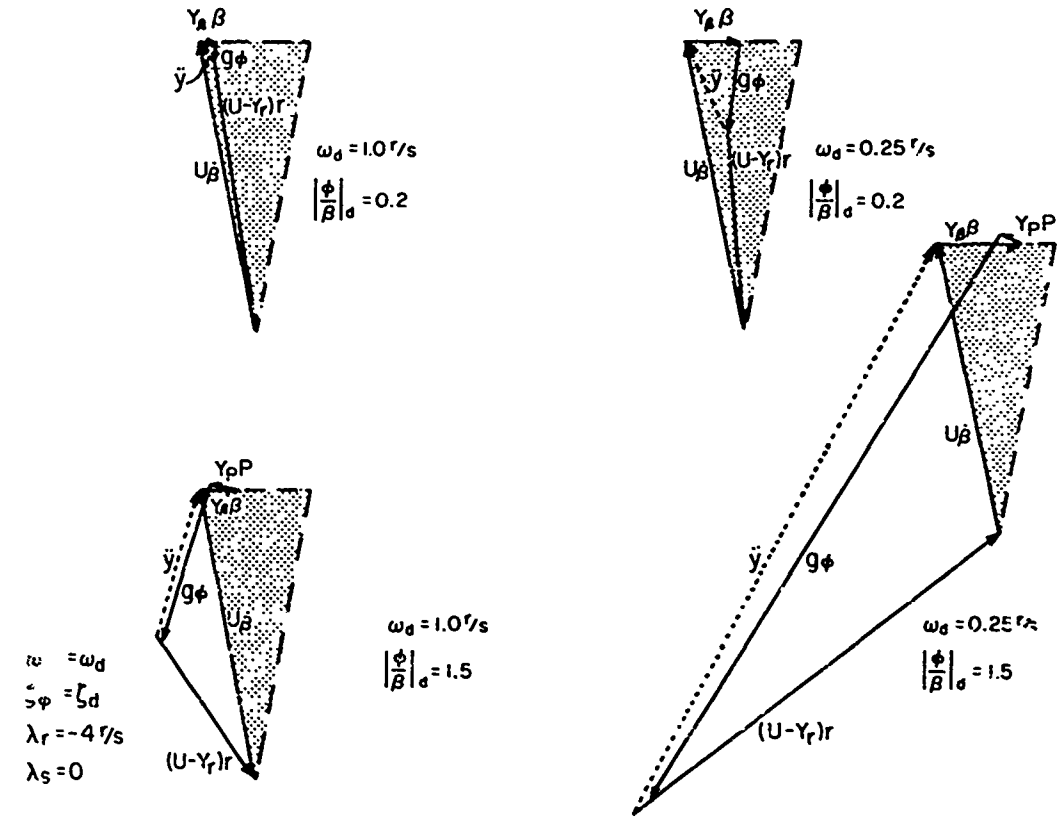


FIG 3b SIDEFORCE VECTOR COMPONENTS IN OPEN LOOP OSCILLATORY MODE - EFFECT OF ω_d & $\left|\frac{\phi}{\beta}\right|_d$

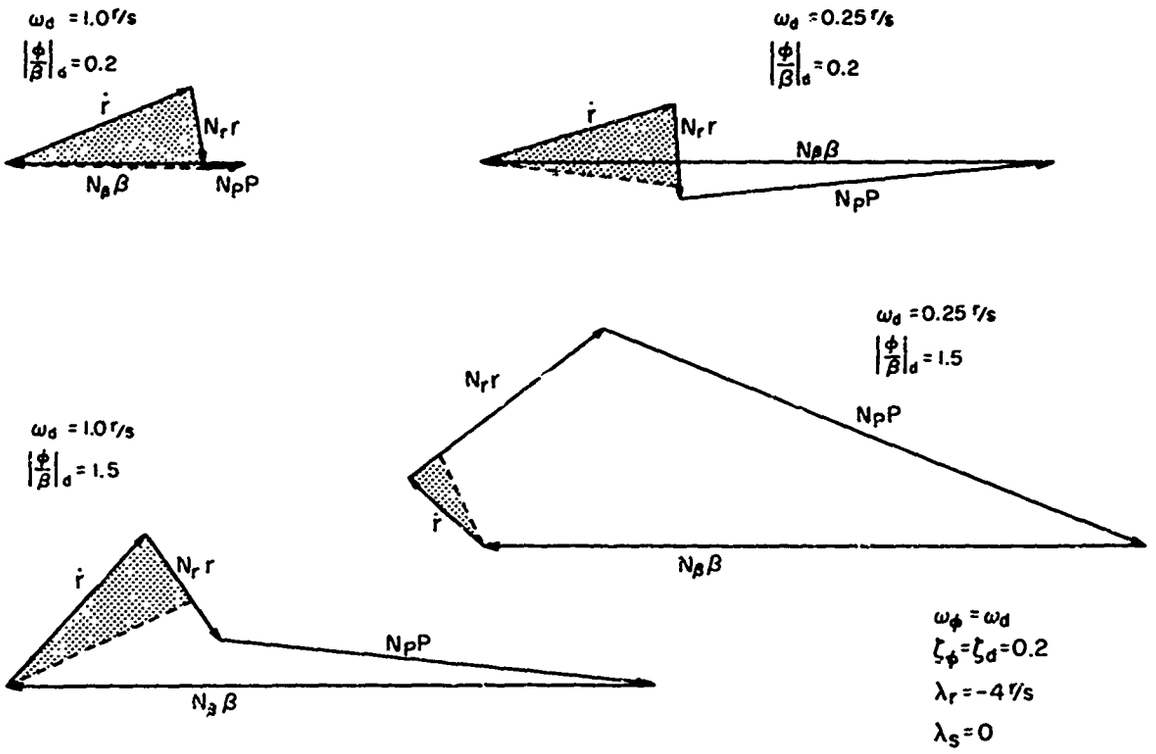


FIG 3c YAWING MOMENT VECTOR COMPONENTS IN OPEN LOOP OSCILLATORY MODE- EFFECT OF ω_d & $\left|\frac{\phi}{\beta}\right|_d$

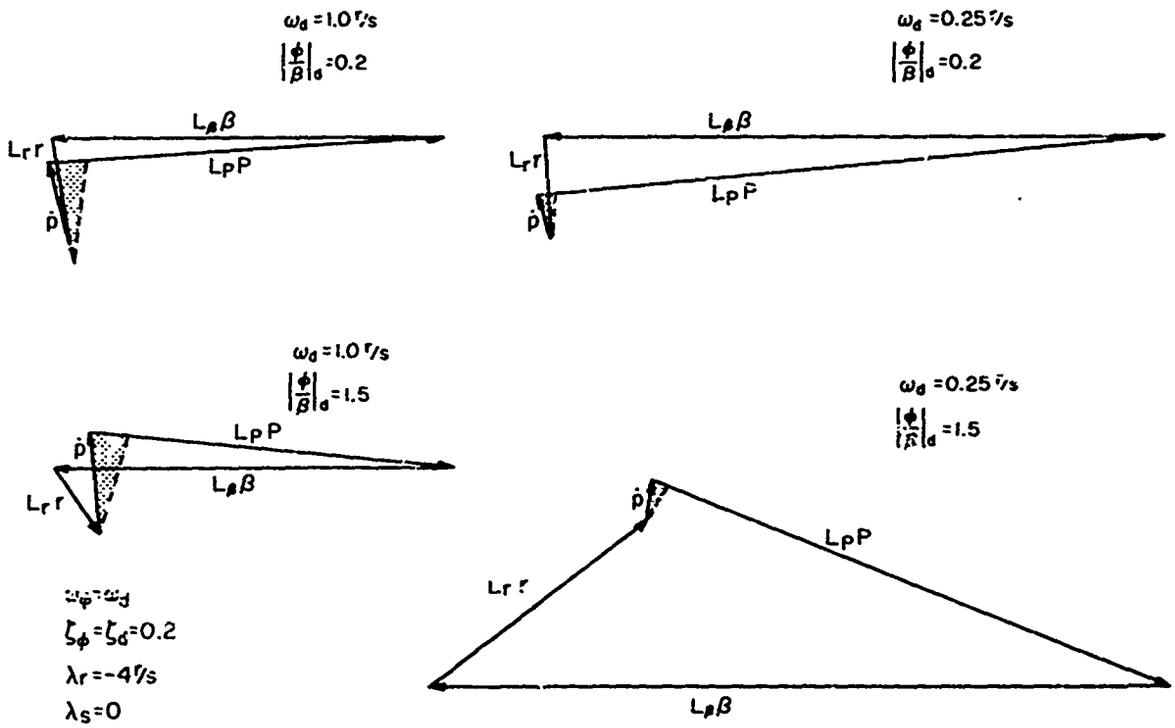


FIG 3d ROLLING MOMENT VECTOR COMPONENTS IN OPEN LOOP OSCILLATORY MODE- EFFECT OF ω_d & $\left|\frac{\phi}{\beta}\right|_d$

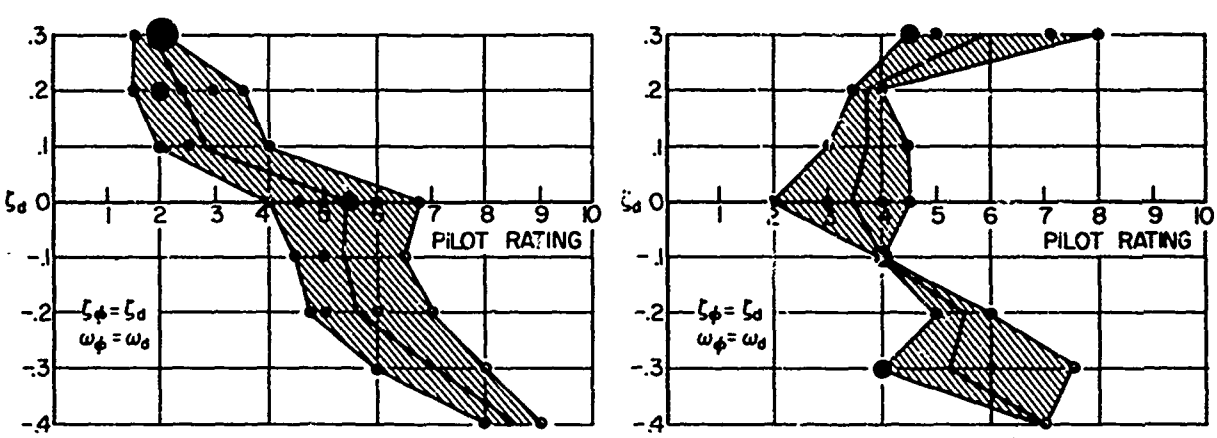


FIG 4 EFFECT OF DAMPING RATIO ON PILOTS' RATINGS FOR TWO DIFFERENT CHARACTERISTIC FREQUENCIES (REF 1)

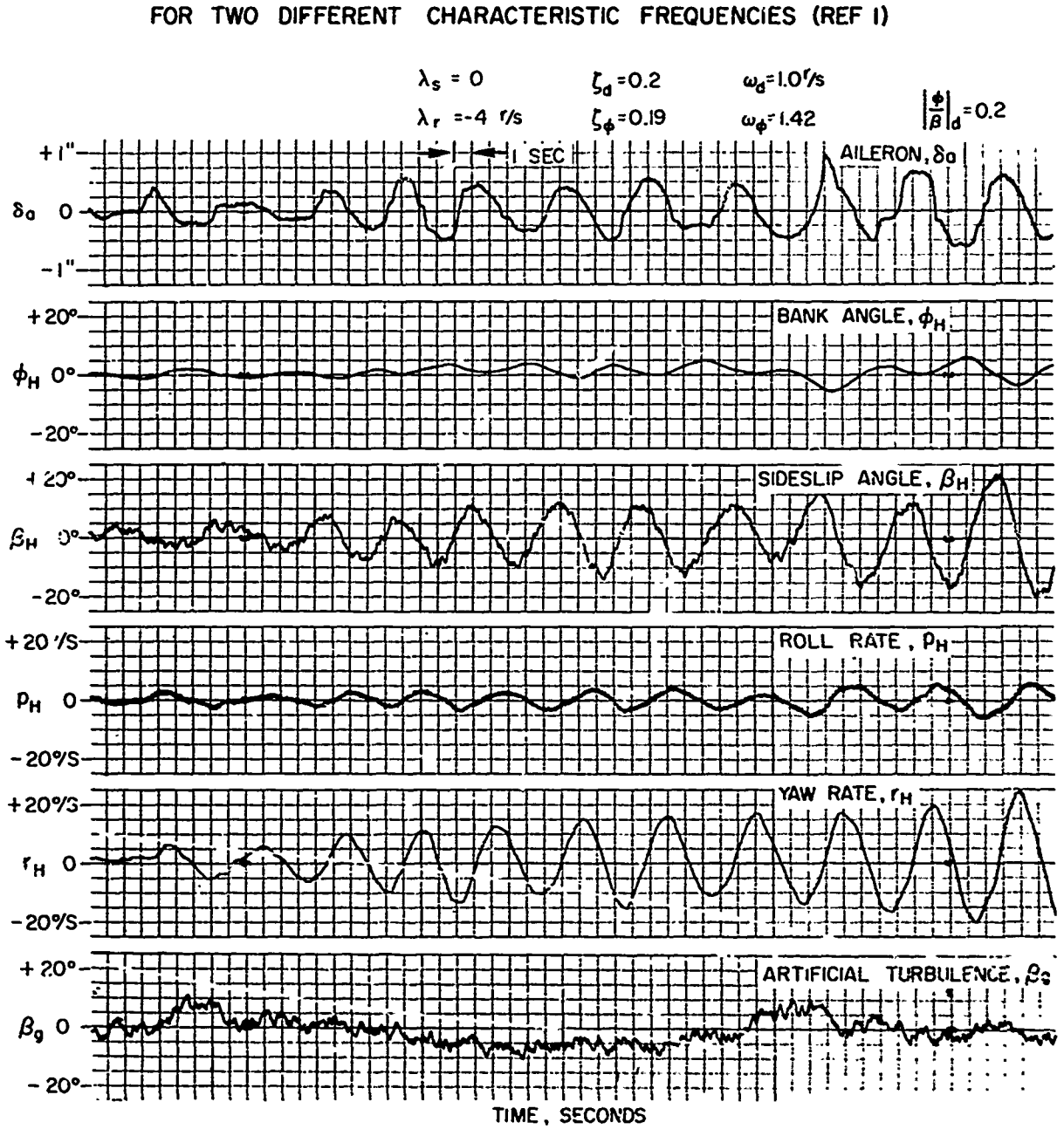


FIG 5 PILOT INDUCED OSCILLATION RESULTING FROM TRACKING ATTEMPTS USING ONLY AILERON CONTROL

Appendix

The relationship between the ϕ and β vectors and its effect on the oscillatory mode through the weight component acting along the y-axis

For configurations with conventional modal characteristics and with λ_S close to zero, the relationship between ϕ and β obtained from the equations of motion may be approximated as:

$$\frac{\phi}{\beta}(S) = \frac{L_\beta S}{-N_\beta S + \lambda_R \omega_d^2} \qquad A.1$$

The phase relationship between ϕ and β in the oscillatory mode is thus established to a large extent by the location of the complex roots relative to the root of Eq. A.1, i.e., by the magnitude of the ratio $\frac{\lambda_R \omega_d}{N_\beta} : 1$. Aircraft possessing high Dutch roll frequencies, high rolling inertias and/or low roll damping are characterised by $\frac{\lambda_R \omega_d}{N_\beta} < 1$. In the limit $\frac{\lambda_R \omega_d}{N_\beta} \to 0$ one may write Eq. A.1 as

$$\left.\frac{\phi}{\beta}\right|_d = -\frac{L_\beta}{N_\beta} \qquad A.2$$

It is seen that for this case, positive dihedral and weathercock stability cause ϕ and β to be in phase in the oscillatory mode. At the other extreme, namely that of $\frac{\lambda_R \omega_d}{N_\beta} >> 1$, one finds aircraft characterised by low natural frequencies, low rolling inertias and/or high roll damping. In the limiting case of $\frac{\lambda_R \omega_d}{N_\beta} \to \infty$ one may write:

$$\frac{\phi}{\beta}(S) = \frac{L_\beta S}{\lambda_R \omega_d^2}, \qquad A.3$$

and it is seen that at the characteristic frequency, ϕ leads β by $(90° + \varepsilon_d)$ where $\varepsilon_d = \tan^{-1}\zeta_d$.

The configurations of this investigation were of the type well approximated by Eq. A.3 and, as a result, the p and β vectors in the oscillatory mode remained essentially in antiphase for a wide range of derivatives.

The influence of the constraint imposed in Eq. A.3 on the overall oscillatory mode becomes apparent from a study of the side force equation which may be approximated as:

$$\dot{\beta} = -r + \frac{g}{U}\cdot\phi + \frac{Y_\beta}{U}\cdot\beta \qquad A.4$$

The relationship between the vectors ϕ, r, β and $\dot{\beta}$ does not change for a given open-loop oscillatory mode and when the terms in Eq. A.4 are rewritten relative to the $\dot{\beta}$ vector for this mode, one obtains:

$$\frac{\dot{\beta}}{\dot{\beta}} = -\frac{r}{\dot{\beta}} + \frac{g}{U}\frac{\phi}{\dot{\beta}} + \frac{Y_\beta}{U}\cdot\frac{\beta}{\dot{\beta}}$$

$$= -\left|\frac{r}{\dot{\beta}}\right|_d \cos\left(\angle\frac{r}{\dot{\beta}}\Big|_d\right) + \frac{g}{U}\cdot\frac{1}{\omega_d}\left|\frac{\phi}{\beta}\right|_d \cos\left(\angle\frac{\phi}{\beta}\Big|_d - (90+\varepsilon_d)\right) + \frac{Y_\beta}{U}\cdot\frac{1}{\omega_d}\left|\frac{\beta}{\beta}\right|_d \cos(-(90+\varepsilon_d)) \qquad A.5$$

The constraint imposed in Eq. A.3 is such that:

$$\cos\left(\angle\frac{\phi}{\beta}\Big|_d - (90+\varepsilon_d)\right) = 1 \qquad A.6$$

From Eqs. A.5 and A.6 it may be seen that the importance of the weight component acting along the y-axis in establishing the oscillatory mode in sideslip increases with the ratio, $\frac{g}{U}\cdot\frac{1}{\omega_d}\left|\frac{\phi}{\beta}\right|_d : 1$, and that the main contribution of this term is to the stiffness of the mode.

LEAD DISCUSSION

by
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It turns out that we sponsored the work upon which Doetsch based this paper, with Cornell Aeronautical Laboratory as intermediary. In this circumstance I could either maintain that we've already accepted the research so it must be good, or cry gee, now he tells us there's something the matter with it. These approaches are inappropriate, so I'll try to avoid both of them.

The flight program, reported in AFFDL TR-69-41 by Doetsch, Gould and McGregor, was quite helpful in drafting the MIL-F-8330C requirements for lateral-directional dynamics. In drafting these criteria CAL relied heavily upon the NRC data to fill in at low speed, tying in other results of investigations at higher speeds. We feel there is application to conventional airplanes too.

The NRC data were directly responsible for adding a requirement on $|\Delta\beta/\phi_1|\times|\phi/\beta|_d$ to supplement the roll-sideslip coupling requirements on p_{osc}/p_{av} and $|\Delta\beta_{max}/\phi_1|$. Sideslip oscillations had been thought to be critical only at low $|\phi/\beta|_d$, but they were found to be the determining factor also in some cases of higher $|\phi/\beta|_d$.

It's important to distinguish between modal parameters and input-dependent parameters. Especially with lateral-directional dynamics which have so many variables to be considered simultaneously, I sometimes tend to get confused. Parameters like ζ_d, ω_{nd}, $|\phi/\beta|_d$ and $\dot{p}/\beta|_d$ or ψ_β of the specification are characteristic of the mode, however it is excited. Others do depend very much on the input - its form and cross-coupling; these include ζ_ϕ, ω_ϕ, p_{osc}/p_{av} and $\Delta\beta_{max}$ for example to describe the amount of Dutch roll excited while attempting to roll. Confusion can come because large $|\phi/\beta|_d$ is conducive to large Dutch roll motion in response to rolling commands, but the relative amount still depends upon control cross-coupling, $N_{\delta a}/L_{\delta a}$. In root locus terms, the pole is modal and the zero input-dependent. Unless the pole and zero are separated they will cancel each other.

NRC used a digital computer program to determine how to vary their helicopter's stability derivatives in order to get specified combinations of $|\phi/\beta|_d$, ζ_d, ω_d, ζ_ϕ and ω_ϕ while keeping the roll and spiral time constants invariant. As it turned out, to vary $|\phi/\beta|_d$ they altered the derivatives L_β, L_r, N_β and N_r. There are two possible problems with this approach. First, by varying so many derivatives at one time one has no insight on the effects of individual derivatives. Then, with so many lateral-directional parameters that need to be considered together, holding this one group tightly may cause a bulge in some other response parameter. The time-vector method is a good tool with which to investigate these matters. It might be quite helpful in trying to decipher pilot's comments.

The argument about the increased influence of the gravity vector as $|\phi/\beta|_d/\omega_d$ increases is so convincing, though, that Doetsch seems to describe what it takes to achieve these combinations of parameters - then any unrealism may be because of the impracticality of achieving certain parameter combinations as indicated by the oddity of the derivatives necessary. But then the V/STOL flight regime abounds with vehicles of unusual appearance.

It is interesting to see what others have made of the data of AFFDL TR-69-41. The requirements of MIL-F-83300 have already been mentioned. The Background Information and User Guide for MIL-F-83300, AFFDL TR-70-88 shown by Westbrook yesterday, discusses at some length to the effect that Dutch roll excitation is a minimum when $N_{\delta a}/L_{\delta a} = (N_p - g/V_o)L_p$. In an August 1971 report by STI for Naval Air Systems Command Stapleford, McRuer, et al set out to show how to outsmart MIL-F-8785B - to find unacceptable airplanes the specification would allow and also to find acceptable but unallowable configurations. Examining the same basic NRC data, they suggest that rather than sideslip, the requirements should be related to heading change. This, they feel, would relate more directly to the pilot's task and thus tend to correlate the data better. N_p can be an important contributor to the relationship between the heading and sideslip vectors. Thus it seems that both the CAL and STI analyses fit in with Doetsch's observation about the importance of changes in the heading vector.

The present complicated requirements reflect the complicated picture we have of roll-sideslip coupling. Any attempt either to refine the requirements or to apply them to a specific case needs insight from all possible sources. I thank Dr. Doetsch for providing some of this.

OPEN DISCUSSION

I.L. Ashkenas, Systems Technology, Inc., USA

As Mr. Woodcock mentioned, we at STI have continued to look at heading control per se rather than at possible secondary responses. Our presently-favored concept is to identify the rudder activity required to coordinate the turn. We do this with two parameters, one characterizing the rudder dynamic sequencing to a step aileron input; the other the rudder magnitude. The actual parameters used involve: for sequencing, the ratio of the domain first-order numerator and denominator time constants in the aileron to rudder cross-feed dynamics (e.g., lag/lead) required to make sideslip identically zero; for rudder magnitude, the ratio $N_{\delta_a}/L_{\delta_a}\omega d^2$. Using these coordinates, we have been able to obtain consistent iso-opinion contours for selected data from Princeton, CAL, NRC and our own recent moving simulator tests at NASA Ames. I should point out that the data used are in all cases those where gust sensitivity and response (e.g., due to high $L_{\beta\beta g}$) was not an issue, consistent with the desire to characterize only the heading control problem.

Sqn Ldr D.C. Scouller, RAF/ETPS, UK

Referring to the trace of the unstable snaking oscillation, were the rudders fixed or free?

Free.

In that case, I feel that the experiment should also consider the control free case, since control float can be significant at low speeds and could be designed to be favorable.

K.H. Doetsch, NRC/NAE, Canada

The rudders were fixed. I would agree with you on the designing of float characteristics but it would depend on the particular task.

J. Buhrman, NLR, Netherlands

Have the vector diagrams (as shown in fig. 3) been derived from the tests with the variable stability aircraft in flight?

K.H. Doetsch, NRC/NAE, Canada

No, they have been calculated for illustrative purposes.

PILOT VEHICLE ANALYSIS

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Delft - The Netherlands

SUMMARY

In this paper an experiment is described in which measurements were performed on human operators in single axis tracking tasks.

The controlled element used was a simulated transport aircraft, the angle of pitch was controlled by the human operator. The forcing function was a gust signal acting on the simulated aircraft. The aircraft was simulated at three centre of gravity positions at which it was stable, neutral and unstable respectively. During the test runs the human operators had to perform simultaneously an auditory additional task.

On the basis of the results obtained from this experiment a new sampled data pilot model will be briefly discussed.

1. Introduction.

For several years the Department of Aeronautical Engineering of the Delft University of Technology has been investigating the behaviour of the human pilot in aircraft control tasks. The purpose of the programme is to contribute to the research aimed at finding criteria for desirable handling qualities of aircraft.

The research programme can be divided into two main parts :

1. Measuring the pilot's behaviour in representative control tasks to extend the quantitative knowledge of the pilot's behaviour.
2. Development of a sampling mathematical pilot model having some novel features.

This paper describes in the first place a series of measurements which were performed on a single axis tracking task. Special attention was given to the problem of making this task similar to the control task of the pilot in an aircraft.

Some results of these tests are presented. Thereafter some details of the pilot model are discussed.

In order to describe the test the pilot's task can be divided very roughly into two main parts :

1. Control, by which is meant in this connection the task of manipulating the cockpit controls.
2. Flight management, which is meant to comprise the various remaining tasks the pilot has to perform for a safe conduct of flight.

The first of these two parts presents to the pilot both a mental and a physical load, while the second part presents to the pilot mainly a mental load. Both parts have to be performed simultaneously.

The mental load of the pilot can be described in terms of information processing as has been done e.g. in Refs. 1 and 2. A highly simplified schematic indication of the information processing performed by the pilot is given in Fig. 1. The pilot model described in Section 5 of this paper is partly based on this concept.

A central question in this context is whether the human nervous system can deal with more than one source of information at the same time. In Refs. 3 and 4 reviews have been given of research results on this matter. From these reviews it can be concluded that the human nervous system acts mainly as a single channel processor. This holds particularly for the decision element indicated in Fig. 1.

Accepting this fact leads to the conclusion that the pilot, when controlling an aircraft, has to devote his attention sequentially to the different parts of his task. In order to study the effect of this attention sharing in the experiments described in this paper an additional task presenting as nearly as possible a pure mental load was given to the subjects when performing the single axis tracking task.

The controlled element in the tests was a simulated transport aircraft. The aircraft's angle of pitch Θ was presented to the subject through an artificial horizon indicator. Θ was controlled by changing the stick position s_e of a side-arm controller. To study the behaviour of the human operator the angles Θ and s_e were recorded.

To obtain data about the human operator's behaviour in tracking tasks with different mental load levels, the characteristics of the controlled element as well as those of the additional task were varied during the experiments.

The mental load imposed on the pilot when controlling the aircraft in the tracking task strongly depends on the stability characteristics of the aircraft. Therefore, the aircraft was simulated at three different centre of gravity positions. The aircraft at these three c.g. positions was stable, neutral and unstable respectively.

The additional mental task was an auditory binary choice task.
Details of this task will be given in Section 2.

In Section 2 of this paper the experiments are described. The data analysis is discussed in Section 3. In Section 4 the results obtained so far will be given. Finally, in Section 5, a discussion of the new pilot model will be given and some conclusions will be drawn.

2. Experimental setup.

A diagram of the closed loop in which the subjects performed the tracking task is presented in Fig. 2. The simulated aircraft used as the controlled element was a piston engined transport aircraft in the cruise configuration. Data of the aircraft at the three c.g. positions are given in Table 1.

The forcing function used consisted of two simultaneously acting gust signals. These gust signals were obtained by filtering white noise from a digital noise generator with two separate filters : one for the horizontal component of the gust velocity u_g and one for the vertical component w_g. In Table 2 the transfer functions of the gust filters are given.

The two gust signals, derived from a single noise generator, were correlated. Since, however, Θ was the only variable presented to the subject the correlation should not influence the test results. Because a digital noise generator was used, the identical gust signal was obtained during every test run. The test run each lasted 254 seconds. The test subjects stated that they were not able to memorize any part or sequence of the forcing function even after many practice runs.

The gust signals as a forcing function differ somewhat from the widely used S.T.I. forcing function as described e.g. in Ref. 5. The latter forcing function consists of the sum of ten sine waves with fixed amplitudes and random phases. The spectrum of the angle of pitch due to the gust signals Θ, shown in Fig.3, is continuous rather than descrete like the spectrum of the S.T.I. forcing function. The gust spectra do not have the high frequency shelf which is a feature of the S.T.I. forcing function.

The angle of pitch Θ was presented to the subjects by a servo-driven artificial horizon indicator. A change in Θ of one degree gave a displacement of the horizon datumline relative to the fixed image of 0.9 mm. The measured transferfunction of this instrument has been given in Fig.4.

The manipulator used for the experiments was a side-arm controller mounted on the righthand armrest of the subject's chair, see Fig.5. Some characteristics of the controller are given in Fig.6. A side-arm controller was used instead of a conventional control-wheel to obtain results which were comparable in this respect with the results of other tracking experiments e.g. described in Refs.5 and 6. In addition, by using the side-arm controller the subject's left hand was completely available for answering the additional task.

The position of the subject relative to the artificial horizon and side-arm controller is given in Fig.7.

The additional task used in the tests was an auditory binary choice task. In this task high and low tones are presented in random order to the subject via his headset. The subject has to answer the tones by correctly pushing either of two buttons. The latter were mounted on the lefthand armrest of the subject's chair. Since the subjects used their right hand to control the angle of pitch Θ and their left hand to answer the additional task, interaction between the two tasks was eleminated as much as possible.

The number of tones per minute presented to the subjects was adjustable. The number was chosen as a percentage of the maximum which the subject was individually able to answer making not more than one error per minute. Maxima between 75 and 100 tones per minute were obtained depending on the subject. During the experiments 0%, 40% and 80% of the maximum number were presented to the subjects.

The auditory binary choice task and the use of this task as an additional task in experiments was derived from Ref. 4. In Ref. 2 an experiment is described in which the same binary choice task was used.

Three subjects were available for the experiments. They were pilots with experience in general aviation aircraft varying between 700 and 800 hours. Training in the tracking control task was performed over a rather long period and was continued till the performance in the different tasks had stabilized at constant levels. The subjects were instructed to divide their attention between the tracking- and the additional task in such a way that the total number of errors in the additional task made during one test run was less than the rather arbitrary chosen number of eight.

The experimental variables investigated were the centre of gravity position, i.e. the stability of the aircraft, and the level of the additional task. There were three c.g. positions, three levels of the additional task and three subjects. This yielded a three way (3x3x3) factorial design. Five data runs were recorded of each combination, resulting in a total number of 135 data runs.

As described in the following Section, when estimating the human operator describing function, problems are encountered concerning the accuracy of the estimation process. Therefore, some additional measurements were performed on analog pilot models in open- and closed loop situations. Three different analog pilots were used. They were based on preliminary results obtained from data runs of subjects controlling the aircraft at the three c.g. positions. The open- and closed loops used are shown in Fig. 8 . The remnant signals added to the model output in the closed loop case had the same spectra as the measured remnant in the data runs from which the analog models were obtained. The aim of the measurements on the analog models was to study the accuracy of the estimated describing functions.

A digital recording system was available for the tests. The angle of pitch Θ and the stick position s_e were each measured twenty times per second. The recording of Θ and s_e started 30 seconds after the beginning of the test run and lasted for 210 seconds.

3. Analysis.

The results obtained from each data run were :

1. The variances σ_θ^2 and $\sigma_{\delta_e}^2$
2. The power spectra $\Phi_{\theta\theta}(\omega)$, $\Phi_{\delta_e\delta_e}(\omega)$ and $\Phi_{\theta\delta_e}(\omega)$
3. The correlation functions $C_{\theta\theta}(\tau)$, $C_{\delta\delta}(\tau)$ and $C_{\theta\delta_e}(\tau)$
4. The estimate of the pilot describing function

$$\hat{H}_p(\omega) = \frac{\Phi_{\theta\delta_e}(\omega)}{\Phi_{\theta\theta}(\omega)} \quad , \qquad (1)$$

the pilot remnant power spectrum $\Phi_{nn}(\omega)$,

the coherence factor

$$\rho^2(\omega) = \frac{\left|\Phi_{\theta\delta_e}(\omega)\right|^2}{\Phi_{\theta\theta}(\omega) \cdot \Phi_{\delta_e\delta_e}(\omega)} \qquad (2)$$

5. The coefficients K, τ_1, τ_2 and τ_3 of a fitted pilot model

$$H_p(\omega) = K \cdot \frac{1-\tau_3 j\omega}{1+\tau_3 j\omega} \cdot \frac{1+\tau_1 j\omega}{1+\tau_2 j\omega} \qquad (3)$$

This model is based on Ref.5. A first order Pade approximation was used instead of the factor $e^{-j\omega 2\tau_3}$ representing a pure time delay in the original model due to the reaction time of the pilot. The model was fitted by means of a least squares method. To determine the power spectra and the correlation functions use was made of the Fast Fourier Transform as described in Ref.7.

When estimating the describing function $\hat{H}_p$ of the pilot the following problem was met. At low frequencies ($\omega < 0.5$ rad/sec) large phase lags were obtained from the test data. It was not quite clear whether the subjects were the only source of these phase lags. Similar phase lags have been observed by Elkind and McRuer as described in Ref.5. In Ref.8, however, Taylor mentioned that unfavourable forcing function to remnant ratio's can influence the estimate of the human operator describing function. It was shown in Ref.8 that :

$$\hat{H}_p(j\omega) = \frac{H_p(j\omega) + \frac{F_n(j\omega)}{F_i(j\omega)}}{1 - H_a(j\omega) \cdot \frac{F_n(j\omega)}{F_i(j\omega)}} \qquad (4)$$

for the tracking experiment described in that Reference. In this expression $F_n(j\omega)$ and $F_i(j\omega)$ are the Fourier transforms of the remnant and the forcing function respectively.
If $F_n(j\omega) \gg F_i(j\omega)$ this relation changes to :

$$\hat{H}_p(j\omega) = -\frac{1}{H_a(j\omega)} \qquad (5)$$

When fitting the model to the estimated describing function $\hat{H}_p(\omega)$, the uncertainty in $\hat{H}_p(\omega)$ due to the effect just mentioned has to be taken into account. This can be done by using a weighting function the magnitude of which depends on the remnant power spectrum. The choice of the weighting function is discussed in the next Section.

The expression for the coherence factor $\rho^2(\omega)$ as given in Eq.(2) can also be written as

$$\rho^2(\omega) = 1 - \frac{\Phi_{nn}(\omega)}{\Phi_{\delta_e \delta_e}(\omega)} \qquad (6)$$

and the coherence factor can be interpreted as a measure of the linearity of the pilot's behaviour at the particular frequency concerned.

4. Results.

Although the measurements were not completely analyzed when preparing this paper, it is well possible to present significant results obtained so far. As previously indicated, the experiments differed somewhat from similar experiments in single axis tracking tasks as described e.g. in Refs. 5 and 6. Differences can be noted in the forcing function, the controlled element and in the application of an additional mental task.

Due to the use of the equations of motion of a transport aircraft and of an actual servo driven horizon instrument the bandwidth of the error signal presented to the subjects was limited to about 2 rad/sec. The standard deviations of Θ_a varied between 0.45 and 0.85 degrees. This corresponds to displacements of the horizon datumline of 0.41 and 0.77 mm.

In the experiments described in Refs. 5 and 6 standard deviations of the error signal between 8 and 10 mm were used. It is considered that the standard deviations of Θ_a in the present experiments are of the same order as occur in transport aircraft flying in moderate turbulence.

4.1. Tests with analog pilots.

As mentioned in Section 2 measurements were performed on analog pilot models in open- and closed loop situations.

The estimated describing functions of the analog model controlling the aircraft at the stable c.g. position are given in Fig.9. In Fig.9a the describing function determined from measurements in the open loop is given. The fitted pilot's model had very nearly the same coefficients as the simulated model. In Fig. 9b the estimate of the describing function determined from measurements in the closed loop is given. As shown in Fig. 8 remnant was added in this case to the analog pilot's output during the test runs.

The differences between Fig. 9a and 9b indicate that both the phase angle φ and the absolute value of $\hat{H}_p$ are influenced at the low frequencies by closing the loop and adding a remnant signal to the analog model output.
In Fig. 9c the coherence factor $\rho^2(\omega)$ of the open- and closed loop cases are given. In the closed loop case the deviations of the estimated describing function $\hat{H}_p(\omega)$ from the describing function of the simulated analog pilot are strongly correlated with the deviations of the coherence factor $\rho^2(\omega)$ from the values obtained with the purely linear analog pilot in the open loop case. Therefore the coherence factor $\rho^2(\omega)$ was used as a weighting function when fitting the mathematical model to the estimated describing function $\hat{H}_p(\omega)$. The fitted model shown in Fig. 9b was obtained in that way. At the other two c.g. positions the same procedure was followed.

4.2. Tests with human pilots.

4.2.1. Performance.

The variance of θ_m has been used to express the pilot's performance in the experiments. In Fig.10 the mean variance of θ_m of all the replicates and the subjects is shown as a function of the c.g. position and the additional task level. In Table 3 the mean values of the replicates are given as functions of the c.g. position, the additional task and the subjects. The variances for the first c.g. position are hardly influenced at all by the additional task. Since the aircraft is stable at this c.g. position, this is not surprising. As a matter of fact the variance of θ_m, the elevator angle being zero, is only slightly larger than the average value given in Table 3 : $\sigma_{\theta_m}^2(\delta_e=0) = 0.230$.

The performance as expressed by the variance of θ_m is, however, influenced by the additional task for the neutral and unstable aircraft. The differences between the subjects are relatively small.

In Table 3 the variance of δ_e is also given.

4.2.2. Describing functions.

From the data analyzed so far the mean values of K, τ_1, τ_2 and τ_3 of the fitted human operator model, Eq.(3), were determined. The coefficients are given in Table 4 as functions of the c.g. position and the additional task level. The time lag constant, τ_3, appears to generally increase with increase of the load due to the additional task. The differences between the subjects were not systematic. The best way to look at the other coefficients in the mathematical model seems to be by considering the crossover frequency ω_c and phase margin φ_m.

4.2.3. Crossover frequency and phase margin.

Using the provisional results of the fitted model, the known describing functions of the aircraft and the artificial horizon indicator, the crossover frequency ω_c as well as the phase margin φ_m were computed. They are given in Table 5 as functions of c.g. position, additional task level and test subject. The crossover frequency ω_c increases and the phase margin φ_m decreases with decreasing stability of the aircraft.

The crossover frequencies without the additional task, averaged over the three subjects are 0.19, 0.38 and 1.2 rad/sec for the stable, neutral and unstable aircraft respectively and the phase margin φ_m are 95, 89, and 36 degrees.

From Table 5 a decrease of ω_c with increasing additional task level is found. It is considered that this decrease is caused by the fact that the pilot was forced to give less attention to the control task when the level of the binary choice task was increased.

The values of the crossover frequencies just mentioned are lower then those found in the tracking experiments described in Ref.5 which were between 3 and 6 rad/sec.

The phase margins corresponding to the stable and neutral aircraft are larger than the values of approximately 40° given in Ref.5. The origin of these differences have to be found in the rather different setup of the two experiments.

4.2.4. Perception of the first derivative $\dot{\theta}$ of the angle of pitch θ.

In Fig.11 the elevator angle δ_e is plotted as a function of time as recorded in two data runs of one subject controlling either the stable or the unstable aircraft. It can be seen that the behaviour of the subject in these two cases is rather different. The stable aircraft is controlled more or less by step inputs while the unstable aircraft is controlled by the sum of step- and pulse inputs.

In Fig.12 describing functions of one subject controlling the aircraft at the three c.g. positions are given. From these Figures it can be seen that in the case of the unstable aircraft the pilot is forced to act as a differentiator, i.e. the pilot uses the first derivative $\dot{\theta}_m$ of the angle of pitch θ_m to determine his output, the elevator angle δ_e.

In Ref.9 the same behaviour of human operators was observed when controlling controlled elements having describing functions of the type $H_a = K/(j\omega)^2$ and $H_a = K/(j\omega)^3$.

From the above data the assumption seems to be justified that the human operator is able to perceive the first derivative $\dot{\theta}_m$ of θ_m as well as to use this information to improve the control. Subject's comments on the control tasks were in agreement with this assumption.

4.2.5. The coherence factor.

In Fig. 13 the coherence factors $\rho^2(\omega)$ corresponding to the three describing functions $H_p(\omega)$ of Fig.12 are shown. It appears from this Figure that the coherence factor corresponding to the stable aircraft has the lowest values, while $\rho^2(\omega)$ corresponding to the unstable aircraft is highest.

From these data it seems that the stable aircraft leaves the pilot the widest choice in his control actions, resulting in the least linear behaviour.

5. Discussions.

As stated in the Introduction the aim of the present investigation on the behaviour of the human pilot is to find criteria for desirable handling qualities. A possible aid in obtaining such criteria may be a pilot model somewhat more refined than the well known describing function of Eq.(3). It is considered that some or all of the following characteristics of the human operator could possibly be implemented in a model.

1. The pilot has to sample the instruments.
2. The pilot behaves as a single channel information processor and yet has to perform different tasks simultaneously.
3. The observations of the instruments and the perception of the output signal have a limited accuracy.

It is proposed that a mathematical model simulating the above characteristics be a sampled data model quantifying the input and/or the output variables. The processes of sampling and quantification can be

shown to produce a remnant signal in the control loop, thereby obviating the extraneous remnant signal required in the usual describing function model. Details on the quantification process will be given later in this paper. In the following such a model will be applied to the control of the aircraft's angle of pitch θ.

The results of the experiments previously described indicated that the pilot can be assumed to be able to observe both θ and its first derivative $\dot{\theta}$. Accordingly, the sampling pilot's model has the same capability. A block diagram of the model is shown in Fig.14.

In addition to θ and $\dot{\theta}$ the elevator angle δ_e is fed back, because the pilot senses this variable, either through the control force he exerts or through the control position he notes through his proprioceptive sensors. The gain of the three feedback variables will depend on the characteristics of the controlled element.

The output signal of the model is assumed to consist of the sum of step- and impulse functions. In Ref.10 a somewhat similar model is described which uses triangular pulse functions as the output signal. In the present model the magnitudes of the steps A(i) and impulses B(i) are assumed to be linear functions of the sampled and quantified variables $\theta(i)$, $\dot{\theta}(i)$ and $\delta_e(i)$ at time t_i. Between the instant of sampling the variables and the start of response to the observations, a time delay τ is added. This time delay is thought to be equivalent to a part of the total reaction time delay $2\tau_3$ in Eq.(3).
Therefore :

$$A(t_i + \tau) = c_1\theta(i) + c_2\dot{\theta}(i) + c_3\delta_e(i) \qquad (7)$$

$$B(t_i + \tau) = c_4\theta(i) + c_5\dot{\theta}(i) + c_6\delta_e(i) \qquad (8)$$

The steps and impulses are fed to a second order system which simulates the pilot's neuromuscular system. The sum of the step and impulse responses of the second order system represents the change in elevator angle due to the observations θ, $\dot{\theta}$ and δ_e at time t_i, the most recent sampling instant.
The second order system causes an other part of the total time delay $2\tau_3$ which is due to the characteristics of the neuromulscular system.

According to Ref.5 the open loop characteristics can be described by the crossover model in the crossover frequency region.

$$H_p H_a(\omega) = \frac{\omega_c e^{-j\omega\tau_e}}{j\omega} \qquad (9)$$

This implies that the closed loop behaves approximately as a first order system in the crossover region. In accordance with these observations it is assumed that the human operator tries to return the perceived error θ to zero according to the time function $e^{-\omega_c t}$.
When the human operator tries to return the error to zero according to the exponential function $e^{-\omega_c t}$ he has to verify this return by sampling the error signal at regular intervals in time. The sampling frequency may well be expected to be closely related to the crossover frequency ω_c.

Returning now to the sampled data pilot's model, the coefficients $c_1 \ldots c_6$ used to calculate the step and impulse magnitudes, see Eqs. (7) and (8), have to be determined such that the error $\theta(t)$ - in the absense of further disturbances - actually follows the time functions $e^{-\omega_c t}$ as well as possible.

The quantification process will now be further discussed. It is proposed that the relevant variables are quantified as follows. Assuming that the variables have a Gaussian distribution, it is possible to divide the range of each of these variables in n intervals of equal probability. An example is shown in Fig.15. Each interval has a mean value which is returned to the model if the sampled variable is within the boundaries of that interval. In Fig.16 the standard deviation of the relative error, introduced by quantification of a variable as a function of the number of intervals n, is given. It can be shown that the power spectrum of this error is approximately white and the power increases with decreasing number of intervals.

The importance of the sampling and quantification processess in the model may be evident from the following. In the Introduction of this paper it has been stated that the pilot has a limited capacity to process the information derived from different sources when controlling the aircraft. The suggestion is made here that the mental load of the pilot due to information processing might be related to the sampling frequency and the number of quantification intervals in the sampling pilot's model, needed to duplicate in some general sense the pilot's behaviour. Since the minimum sample frequency and the minimum number of quantification intervals, necessary to obtain adequate control of the aircraft by the model, are determined by the characteristics of the aircraft, it might be possible to study the mental load of the pilot in terms of information processing with the above described sampling model.

The above reflections on a mathematical pilot's model may be related very briefly to the experiments described in this paper. If the assumption that the crossover frequency ω_c is related to the required sampling frequency is correct, than the expected low mental load of the pilot controlling the stable aircraft in the experiments is in accordance with the low value of the crossover frequency shown in Section 4.2.3.
The lower coherence factor exhibited with the stable aircraft, see Fig.13, indicating less linear behaviour of the subjects as previously discussed, can now be interpreted as the result of a coarser quantification and hence a lower flow of information than is required with the neutral or unstable aircraft. From these data obtained from the experiments, an increase of mental load with decreasing stability of the aircraft can be made plausible.

It will be clear that more experiments and much more analysis of these experiments are required to verify and further elaborate upon the various assumptions made in setting up the sampling pilot's model. The preliminary results briefly discussed in the foregoing seem to justify continued efforts in this direction.

6. Conclusions.

From the results of the experiments described in this paper the following conclusions can be drawn.

1. The variance of the error signal Θ_m in a single-axis tracking task generally increases when an additional mental task is given to the human operator in the tracking task. The influence of the additional task on the variance of Θ_m depends on the characteristics of the controlled element.
2. A decrease of the crossover frequency ω_c is found as a result of the additional mental task.
3. A sampled data model described in this paper may eventually provide the possibility to study the mental load of the pilot in terms of information processing.

7. References.

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8. Tables.

Table 1. Data of the simulated aircraft.

$W = 59000$ kg

$S = 153$ m^2

$V = 145$ m/sec

$C_L = 0.6$

1. $x_{c.g.} = 0.29\ \bar{c}$

$$\frac{\theta(j\omega)}{\delta_e(j\omega)} = -4.19\ \frac{(1 + 1.49\ j\omega)(1 + 54.9\ j\omega)}{D}$$

$$\frac{\theta(j\omega)}{u_g(j\omega)} = -14.8\ \frac{j\omega(1 - 0.15\ j\omega)}{D}$$

$$\frac{\theta(j\omega)}{\alpha_g(j\omega)} = -0.946\ \frac{j\omega(1 - 0.705\ j\omega)(1 - 80.1\ j\omega)}{D}$$

$$D = \left\{1 + 2.\ \frac{0.0475}{0.0743}\ j\omega + \left(\frac{j\omega}{0.0743}\right)^2\right\}\left\{1 + 2.\ \frac{0.687}{1.85}\ j\omega + \left(\frac{j\omega}{1.85}\right)^2\right\}$$

$P = 84.6$ sec $\qquad P = 4.7$ sec

$T_{\frac{1}{2}} = 196$ sec $\qquad T_{\frac{1}{2}} = 0.35$ sec

2. $x_{c.g.} = 0.415\ \bar{c}$

$$\frac{\theta(j\omega)}{\delta_e(j\omega)} = -5.27\ \frac{(1 + 1.45\ j\omega)(1 + 55.4\ j\omega)}{D}$$

$$\frac{\theta(j\omega)}{u_g(j\omega)} = +2.90\ \frac{(j\omega)^2}{D}$$

$$\frac{\theta(j\omega)}{\alpha_g(j\omega)} = -1.13\ \frac{j\omega(1 + 25.6\ j\omega)(1 + 2.22\ j\omega)}{D}$$

$$D = j\omega(1 + 96.4\ j\omega)(1 + 1.04\ j\omega)(1 + 0.665\ j\omega)$$

$T_{\frac{1}{2}}$=66.7 sec $T_{\frac{1}{2}}$=0.7 sec $T_{\frac{1}{2}}$=0.46 sec

3. $x_{c.g.} = 0.505\ \bar{c}$

$$\frac{\theta(j\omega)}{\delta_e(j\omega)} = -5.97\ \frac{(1 + 1.43\ j\omega)(1 + 55.8\ j\omega)}{D}$$

$$\frac{\theta(j\omega)}{u_g(j\omega)} = -14.8\ \frac{j\omega(1 + 0.227\ j\omega)}{D}$$

$$\frac{\theta(j\omega)}{\alpha_g(j\omega)} = 1.261\ \frac{j\omega(1 + 108.9\ j\omega)(1 + 0.523\ j\omega)}{D}$$

$$D = (1 + 0.414\ j\omega)(1 - 6.17\ j\omega)\left\{1 + 2.\frac{0.542}{0.185}\ j\omega + \left(\frac{j\omega}{0.185}\right)^2\right\}$$

$T_{\frac{1}{2}}$=0.29 sec T_2=4.3 sec P = 40.4 sec $T_{\frac{1}{2}}$ = 6.9 sec

Table 2. Gust filters.

$$\frac{u_g(j\omega)}{i(j\omega)} = K_1 \cdot \frac{1}{1 + \frac{L_g}{V}\ j\omega}$$

$$\frac{\alpha_g(j\omega)}{i(j\omega)} = K_2 \cdot \frac{1 + 3\ \frac{L_g}{V}\ j\omega}{\left(1 + \frac{L_g}{V}\ j\omega\right)^2}$$

$i(j\omega)$ = white noise signal

L_g = 300 m

V = 145 m/sec

The gains K_1 and K_2 depend on the scale factors in the analog computer.

$$\frac{u_g(j\omega)}{i(j\omega)} = K_1 \cdot \frac{1}{1 + 2.07\ j\omega}$$

$$\frac{\alpha_g(j\omega)}{i(j\omega)} = K_2 \cdot \frac{1 + 3.58\ j\omega}{(1 + 2.07\ j\omega)^2}$$

Table 3. The average value of the variance of the angle of pitch θ_m of the replicates, in degrees squared.

Additional task level	Subj.	1st.c.g. stable aircraft	2nd.c.g. neutral aircraft	3rd.c.g. unstable aircraft
0°/o	A	0.200	0.209	0.706
	B	0.162	0.201	0.601
	C	0.210	0.222	0.776
40°/o	A	0.264	0.230	1.190
	B	0.180	0.180	0.775
	C	0.273	0.276	1.048
80°/o	A	0.206	0.308	1.459
	B	0.180	0.216	0.979
	C	0.285	0.311	1.285

The average values of the variance of the elevator angle δ_e of the replicates, in degrees squared.

Additional task level	Subj.	1st.c.g. stable aircraft	2nd.c.g. neutral aircraft	3rd.c.g. unstable aircraft
0°/o	A	0.00602	0.0134	0.355
	B	0.0131	0.0194	0.218
	C	0.0140	0.0202	0.140
40°/o	A	0.00882	0.0103	0.256
	B	0.0112	0.0189	0.179
	C	0.0176	0.0337	0.147
80°/o	A	0.00666	0.0141	0.282
	B	0.0070	0.0153	0.197
	C	0.0845	0.0212	0.093

Table 4. The coefficients K, τ_1, τ_2 and τ_3 of the pilot model.

$$H(j\omega) = K \cdot \frac{1 - \tau_3 j\omega}{1 + \tau_3 j\omega} \cdot \frac{1 + \tau_1 j\omega}{1 + \tau_2 j\omega}$$

Additional task level	Coeff.	1st.c.g. stable aircraft	2nd.c.g. neutral aircraft	3rd.c.g. unstable aircraft
0°/o	K	0.113	0.099	0.200
	τ_1(sec)	1.32	1.94	1.82
	τ_2(sec)	0.41	0.34	0.23
	τ_3(sec)	0.26	0.28	0.15
40°/o	K	0.103	0.085	0.171
	τ_1(sec)	1.67	2.34	2.07
	τ_2(sec)	0.41	0.33	0.35
	τ_3(sec)	0.28	0.28	0.15
80°/o	K	0.088	0.070	0.176
	τ_1(sec)	1.42	2.30	1.81
	τ_2(sec)	0.37	0.37	0.26
	τ_3(sec)	0.31	0.34	0.18

Table 5. The crossover frequency ω_c and the phase margin φ_m.

Additional task level	Subj.	1st.c.g. stable aircraft		2nd.c.g. neutral aircraft		3rd.c.g. unstable aircraft	
		ω_c rad/sec	φ_m	ω_c rad/sec	φ_m	ω_c rad/sec	φ_m
0°/o	A	0.149	92°	0.404	81°	1.424	29°
	B	0.182	98°	0.387	90°	1.262	37°
	C	0.229	95°	0.336	96°	1.032	43°
40°/o	A	0.146	94°	0.239	89°	1.027	34°
	B	0.166	98°	0.349	93°	1.086	42°
	C	0.220	95°	0.246	92°	0.962	41°
80°/o	A	0.135	93°	0.211	90°	0.987	30°
	B	0.158	93°	0.232	97°	1.034	39°
	C	0.171	93°	0.255	94°	0.826	39°



Fig. 1. A simplified scheme of the information processing by the nervous system, derived from Ref. 4.

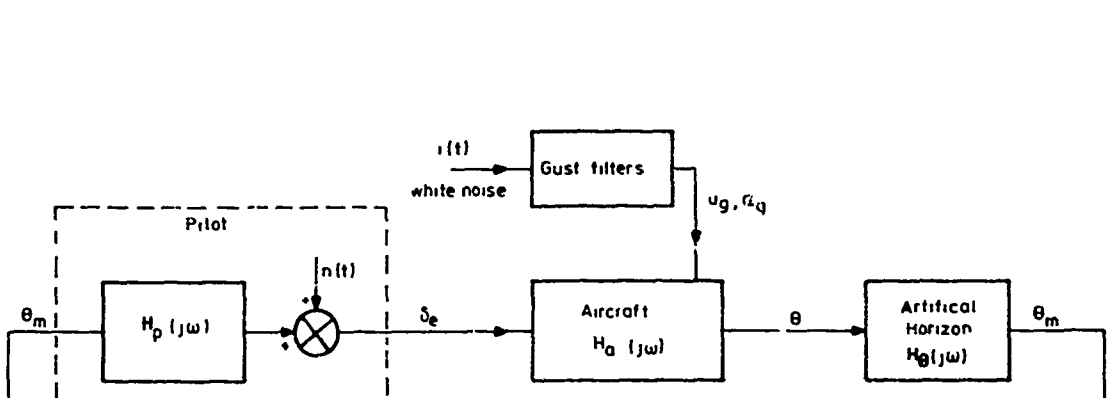


Fig. 2. Block diagram for the single axis tracking task.

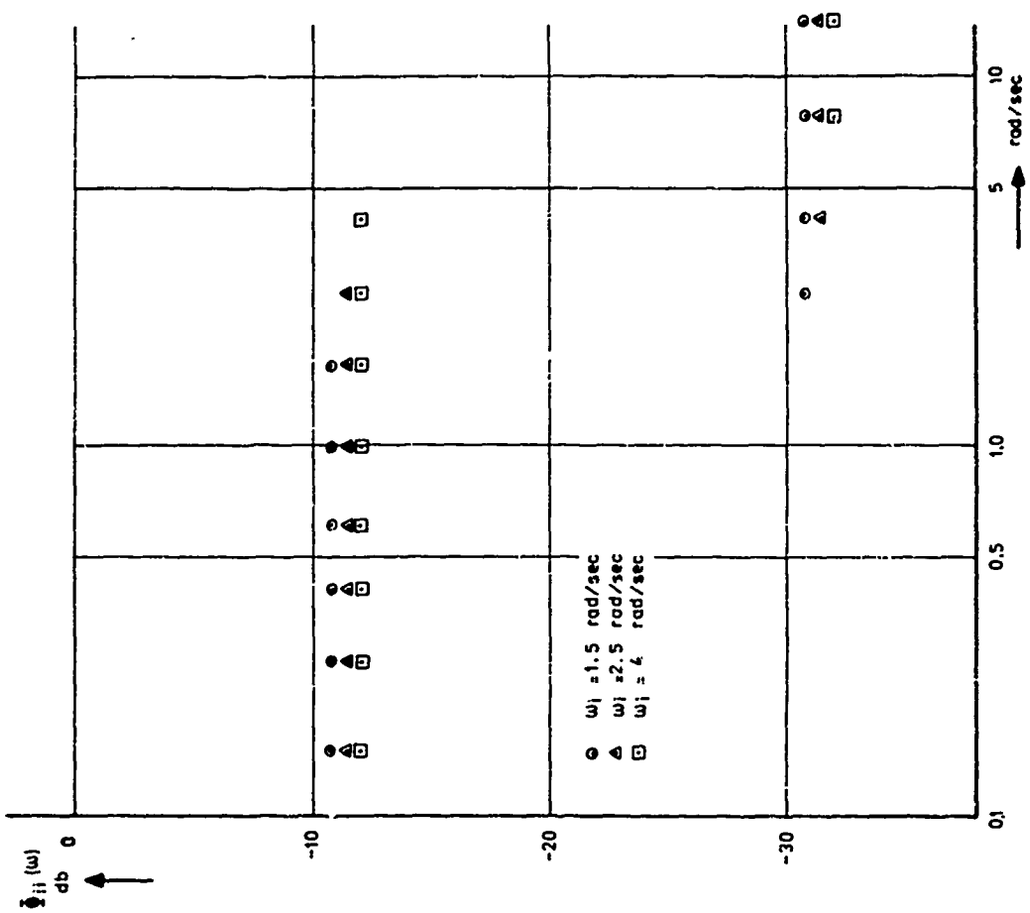


Fig. 3b. Powerspectra of the S.T.I. forcing function, derived from Ref. 5.

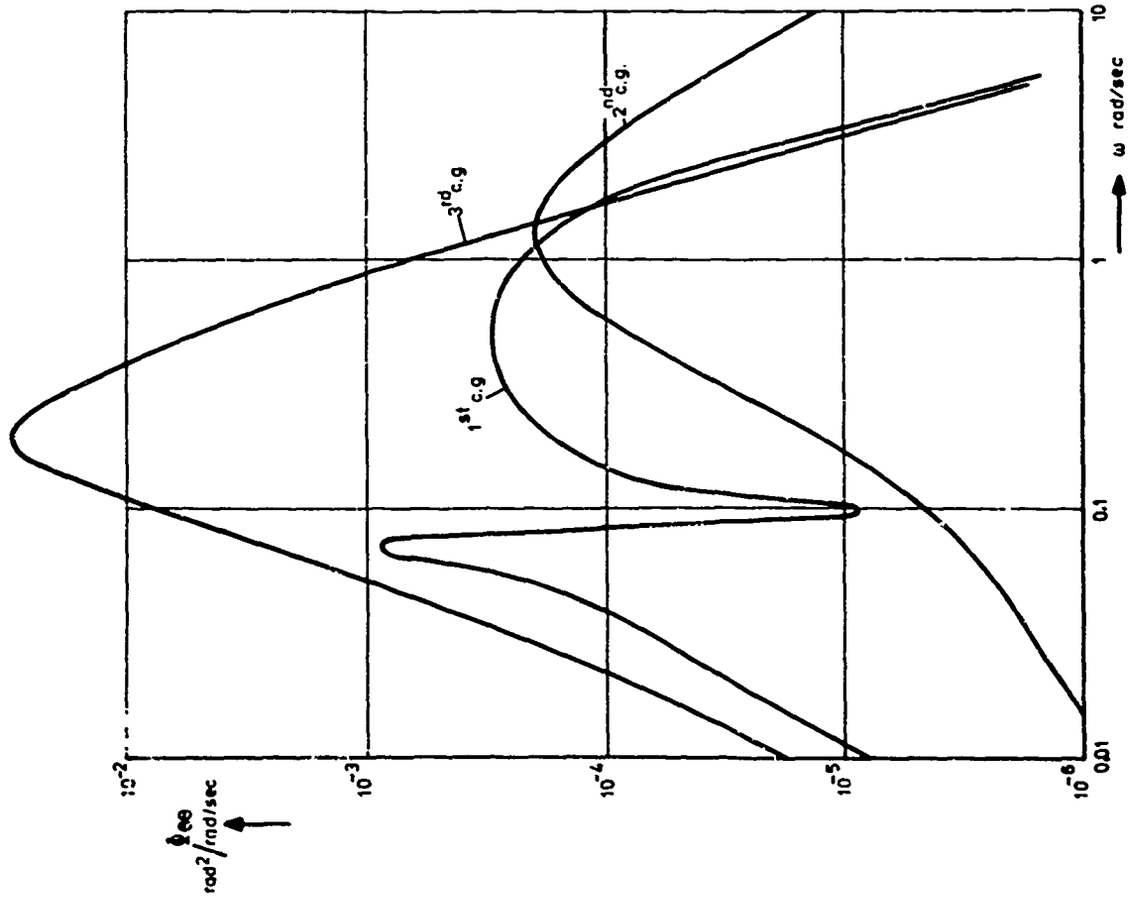


Fig. 3a. The powerspectra of θ due to gust signals.

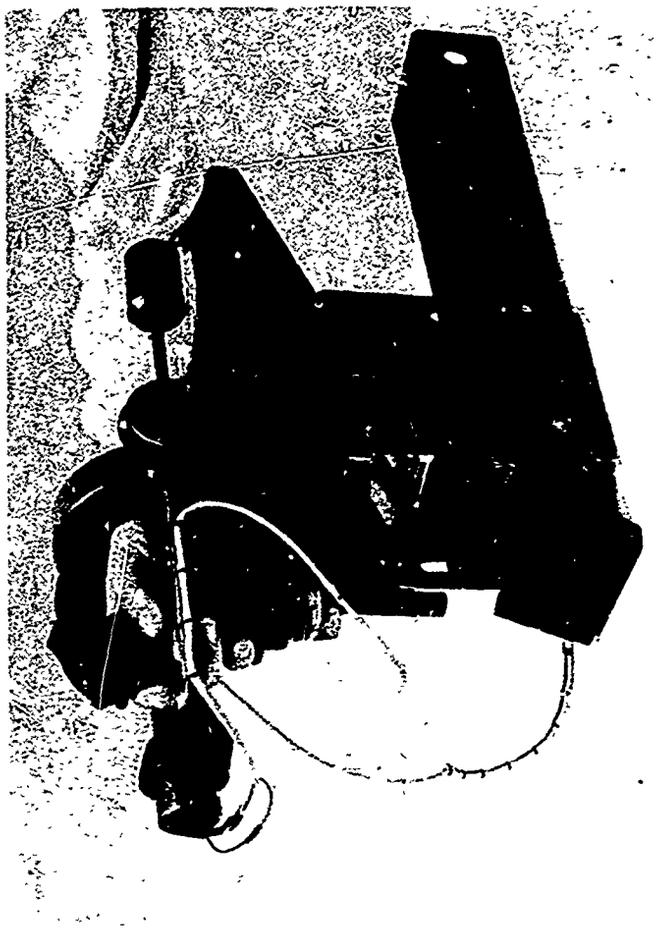


Fig. 5. The side-arm controller.

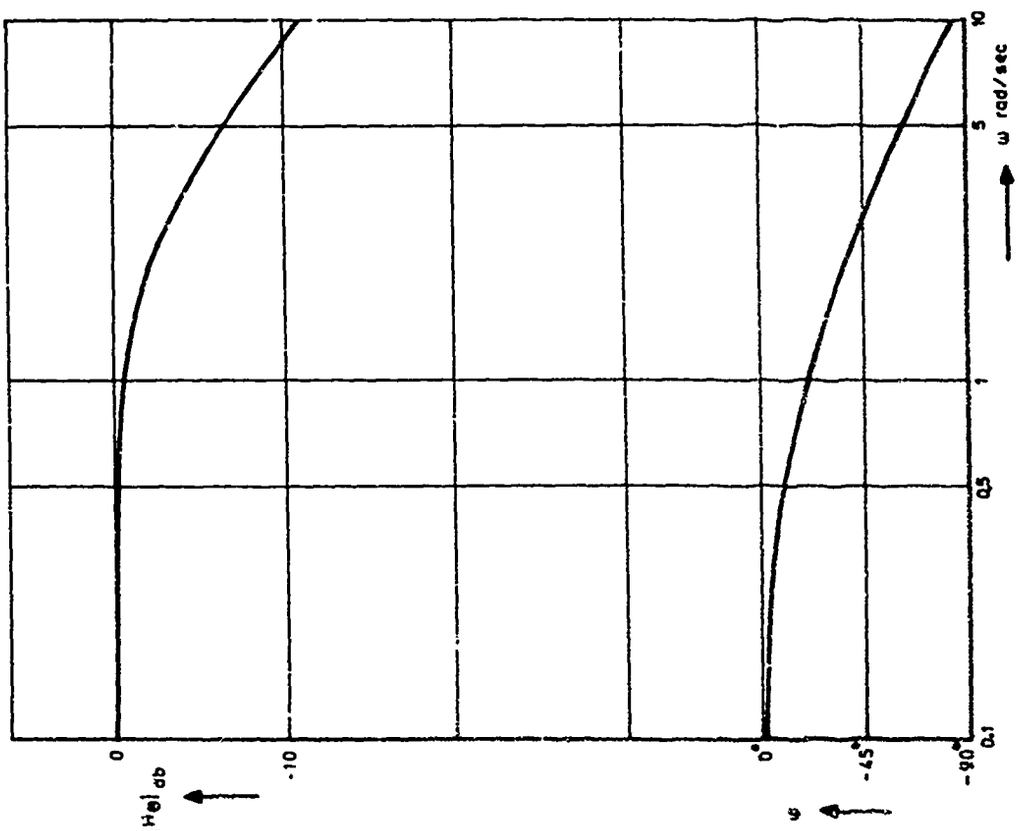


Fig. 4. Describing function of the artificial horizon.

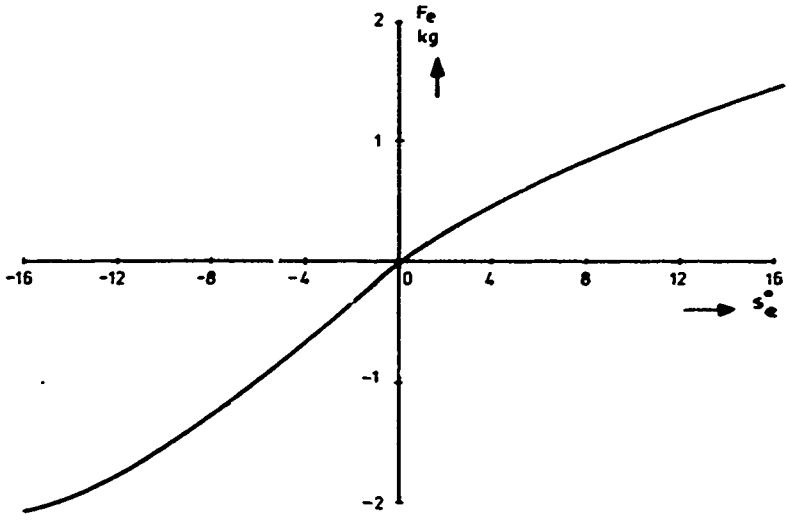


Fig. 6a. Stickforce F_e as a function of side-arm controller deflection, s_e.

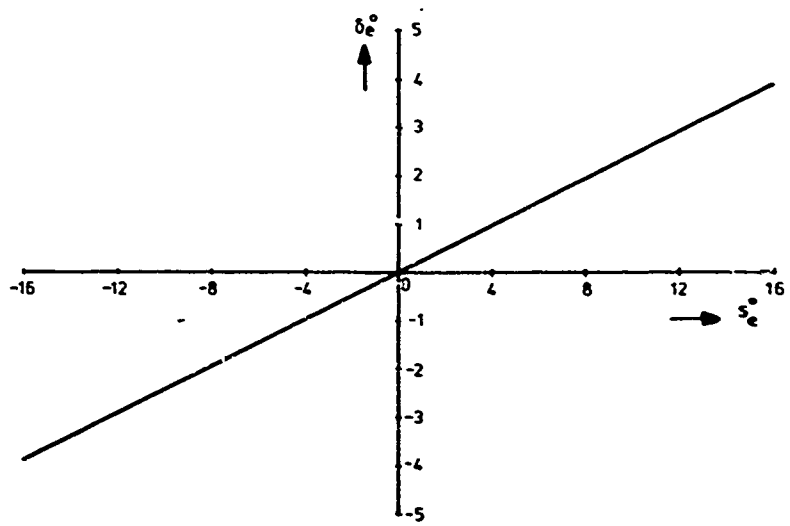
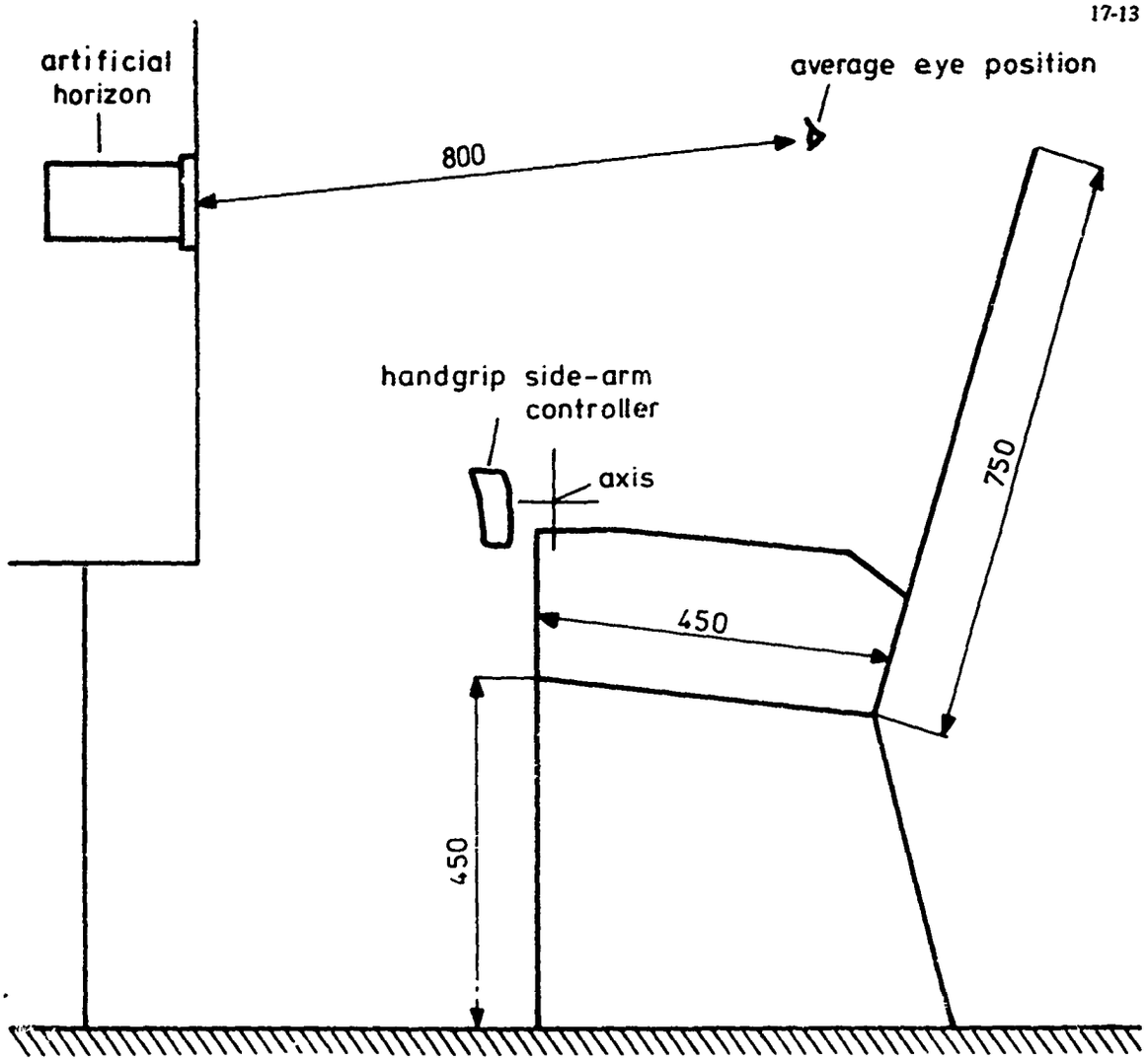


Fig. 6b. Elevator angle, δ_e, as a function of side-arm controller deflection s_e.



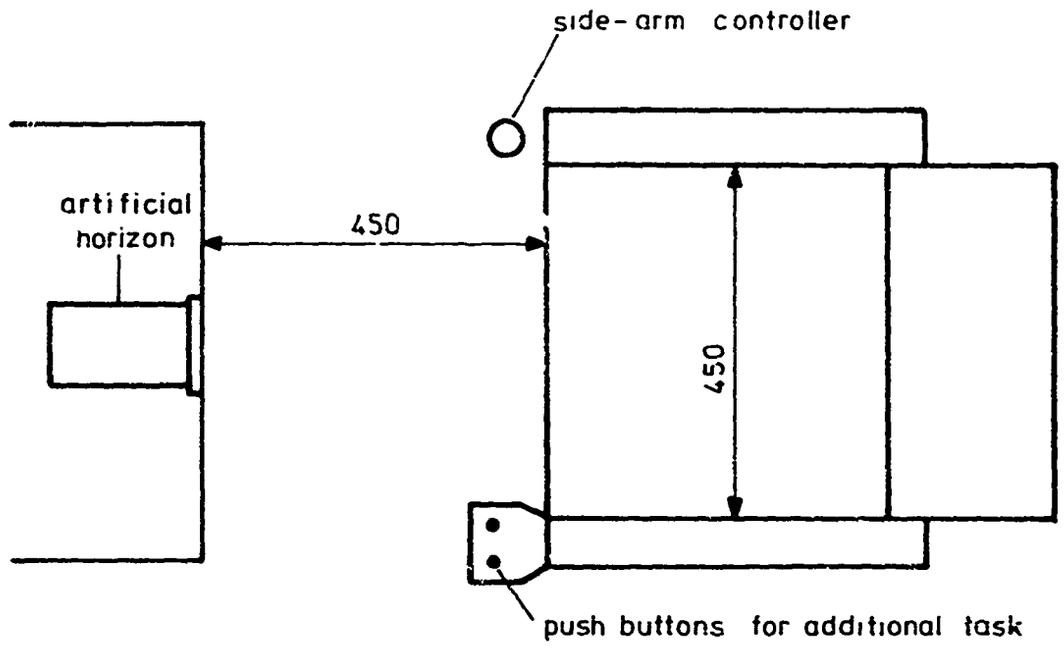


Fig. 7. Position of the subject relative to the horizon. Dimensions in mm.

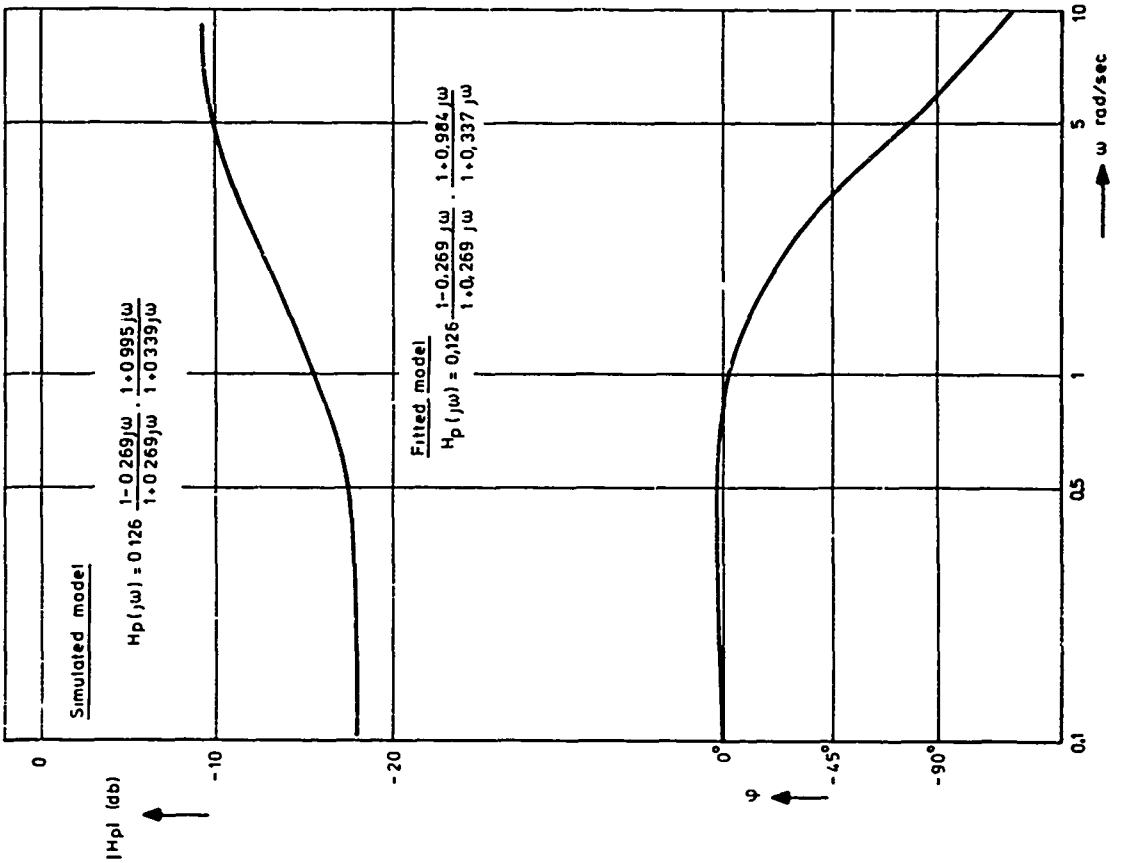


Fig. 9a. Describing function of the analog pilot measured in the open loop, 1st. c.g., stable aircraft.

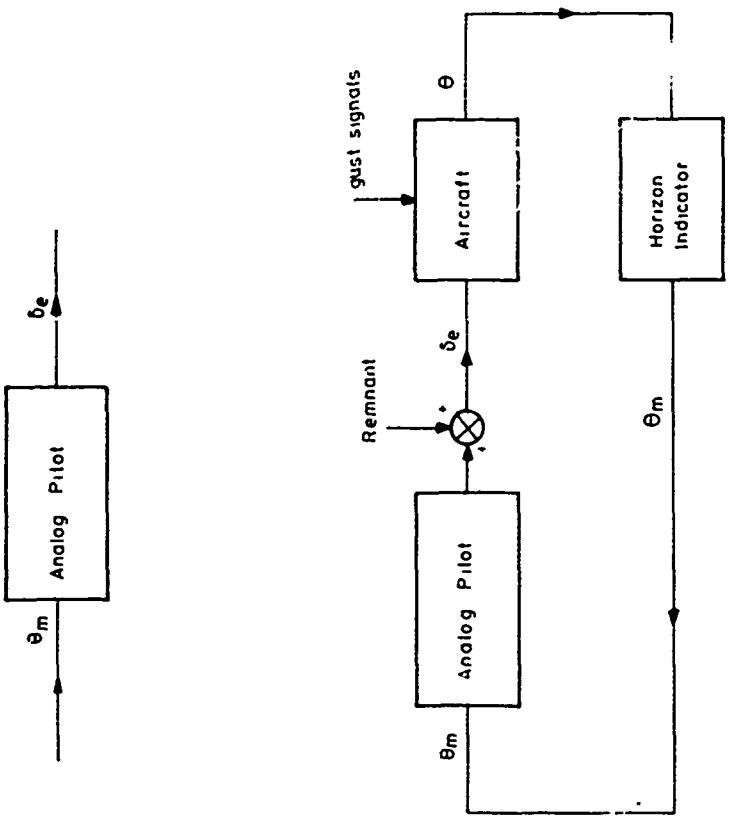


Fig. 8. Closed loop, powerspectrum of added remnant is similar to remnant powerspectra determined from measurements on test subjects.

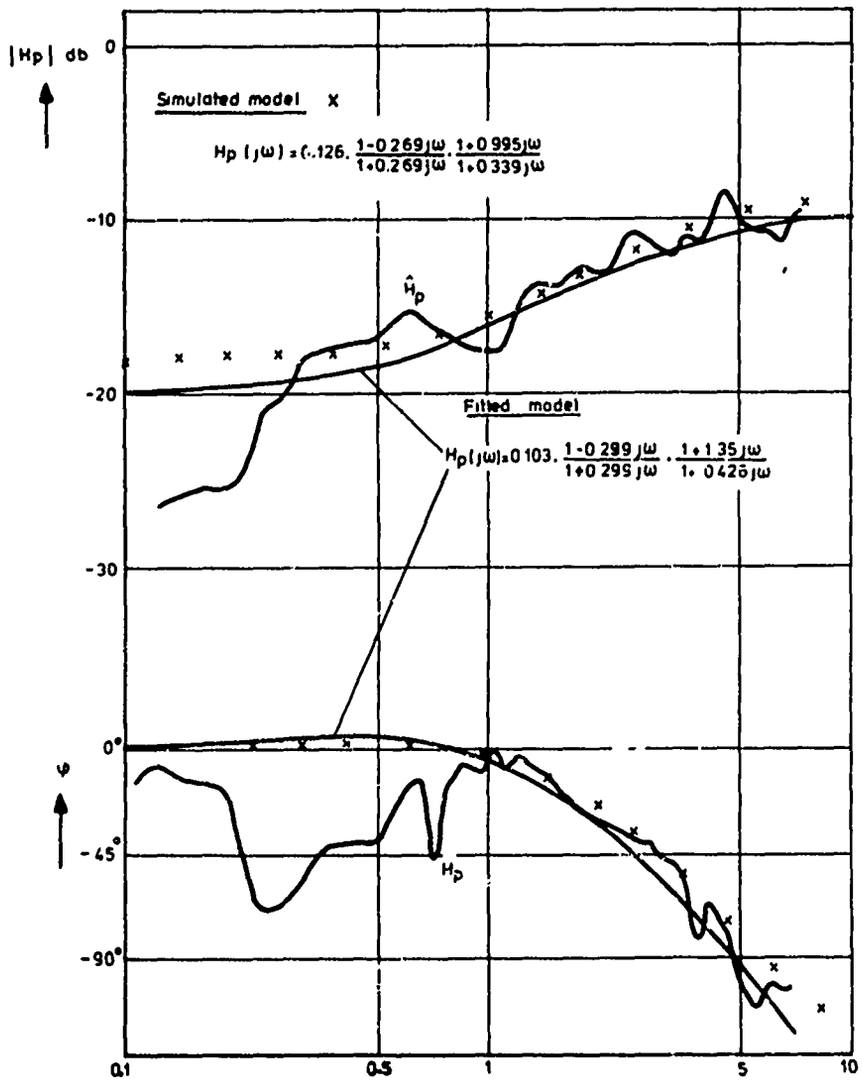


Fig. 9b. Describing function of the analog pilot with remnant measured in the closed loop, 1st. c.g., stable aircraft

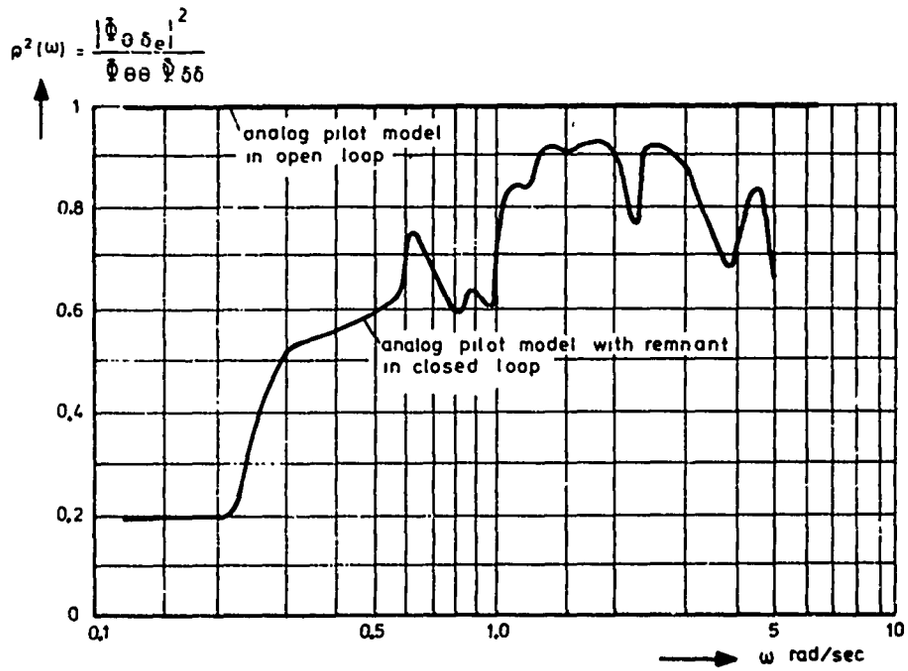


Fig. 9c. Influence of remnant and loop closure on the coherence factor $\rho^2(\omega)$, 1st. c.g., stable aircraft.

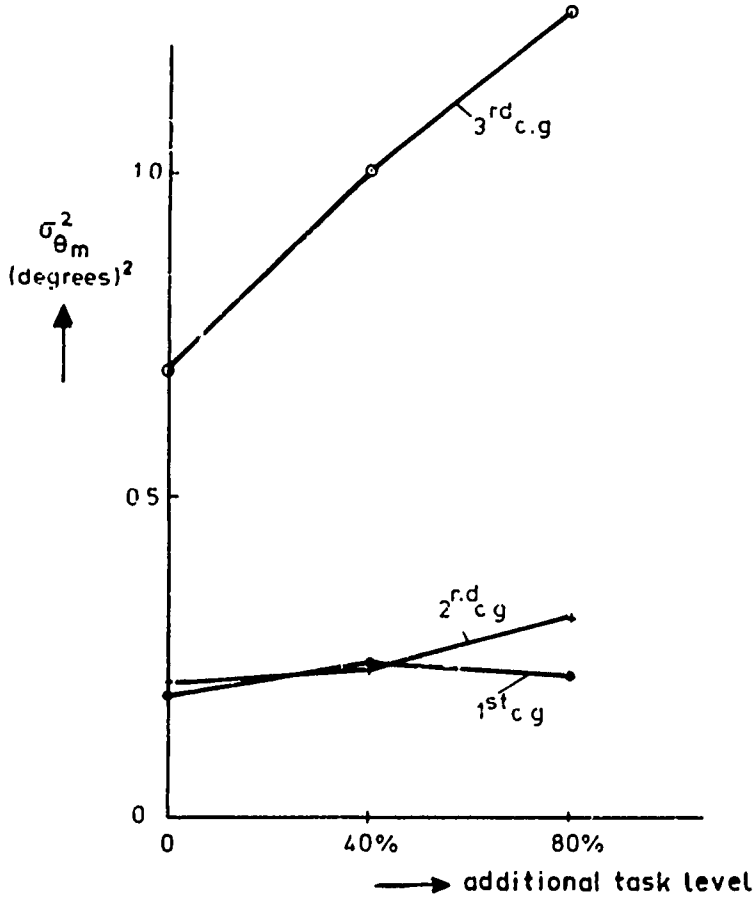


Fig. 10. Variance of σ_m as a function of c.g. position and additional task level.

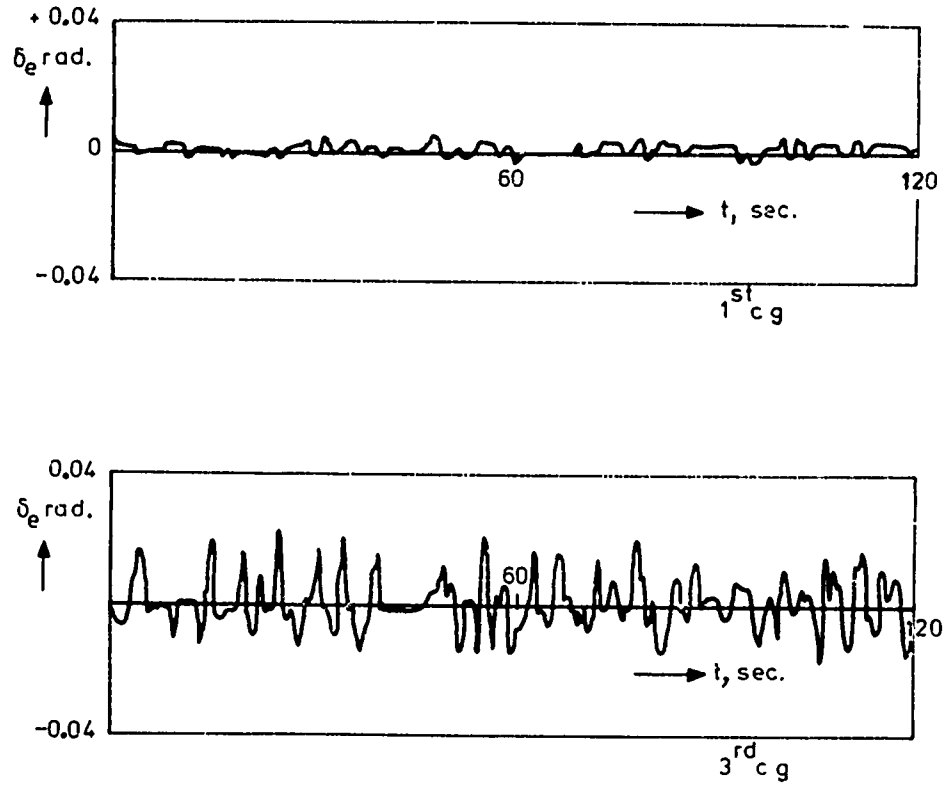
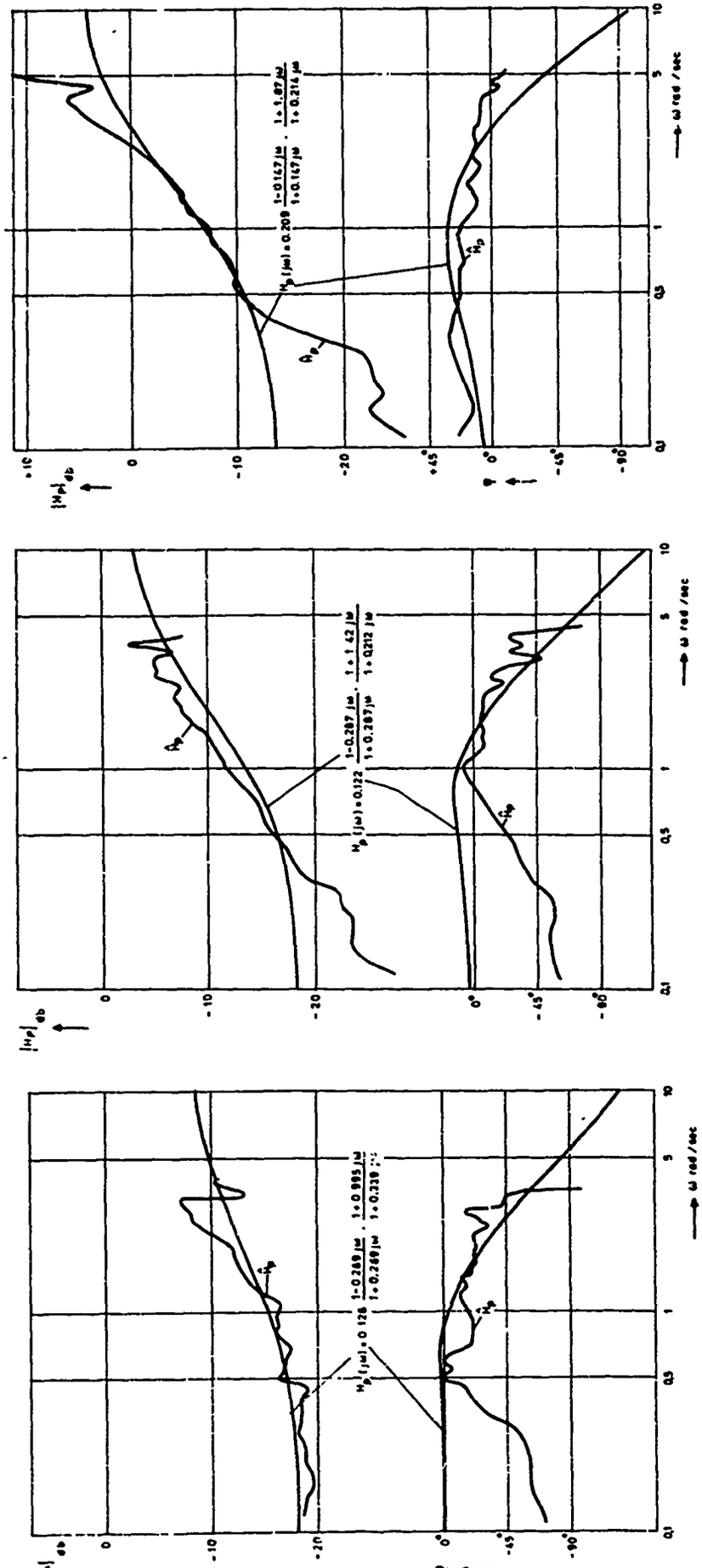


Fig. 11. Examples of time histories of δ_e.



a. 1st. c.g., stable aircraft

b. 2nd. c.g., neutral aircraft

c. 3rd. c.g., unstable aircraft

Fig. 12 Examples of human operator describing functions.

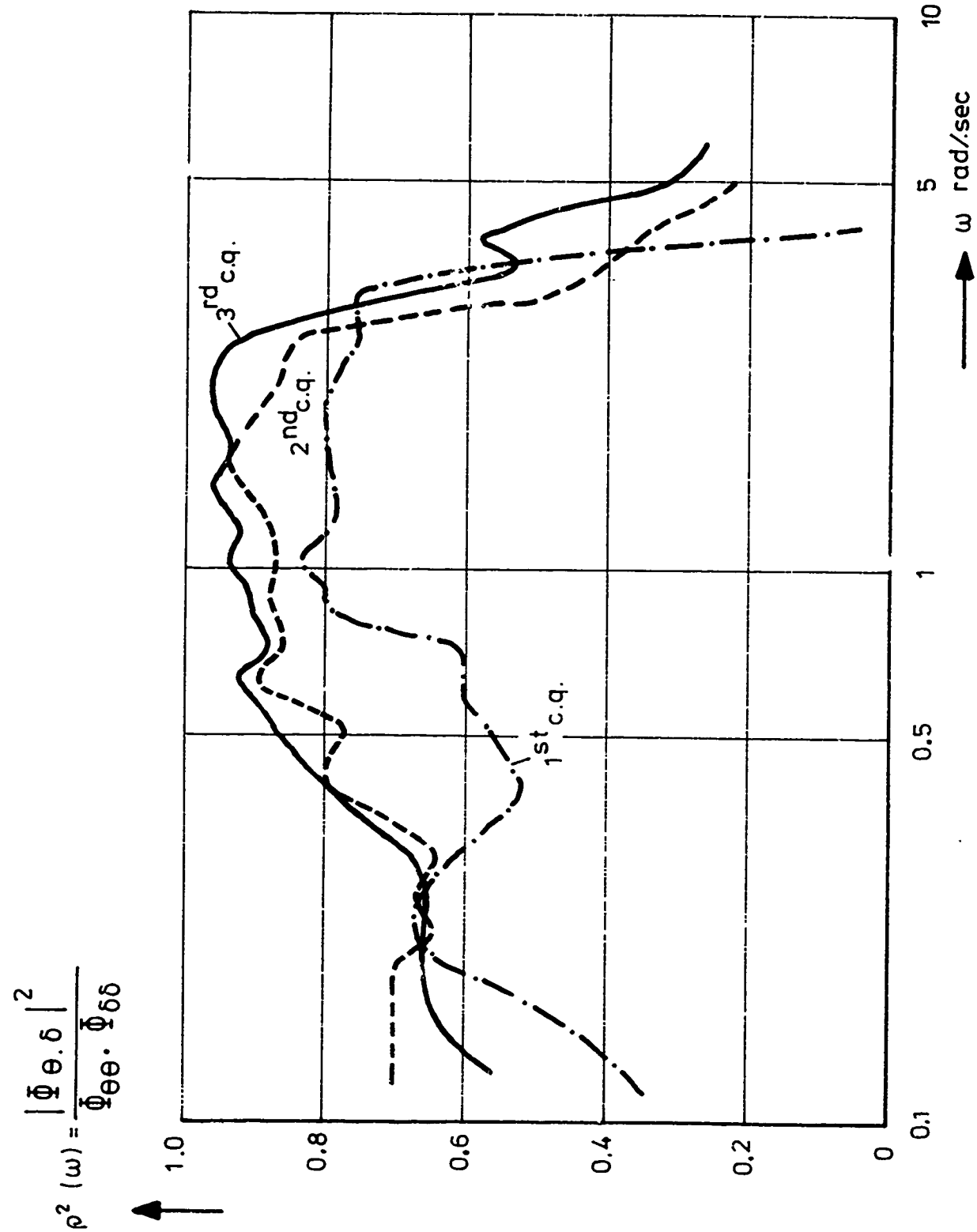


Fig. 13. Examples of the coherence factor for three c.g. positions without additional task.

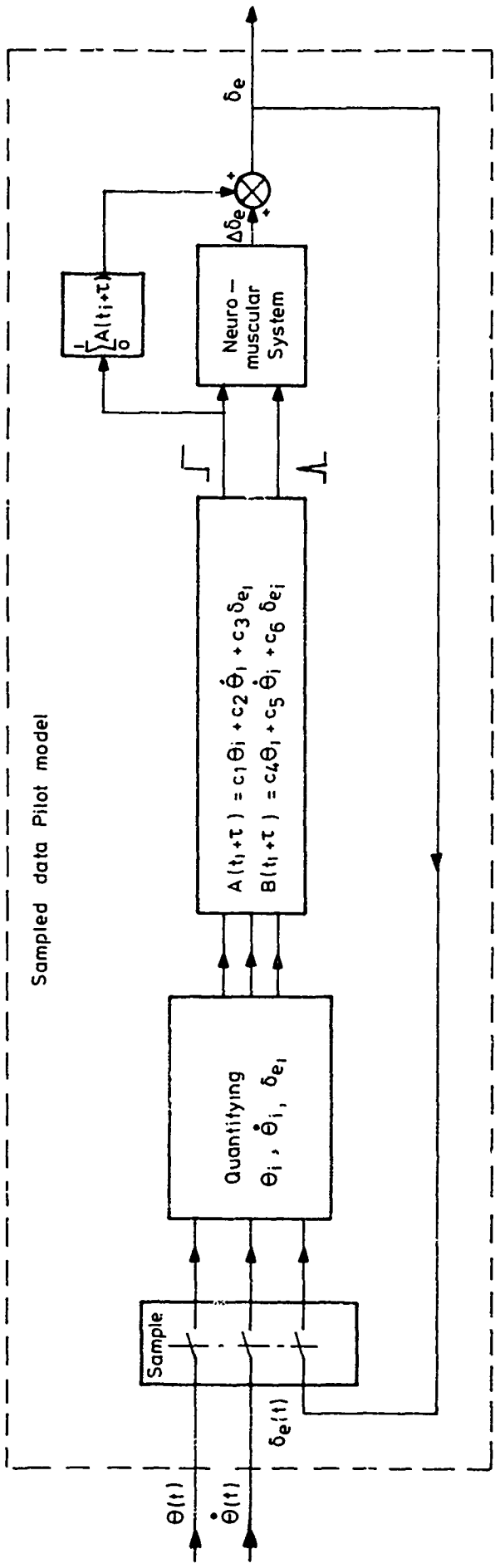


Fig. 14. Block diagram of the Sampled data Pilot model.

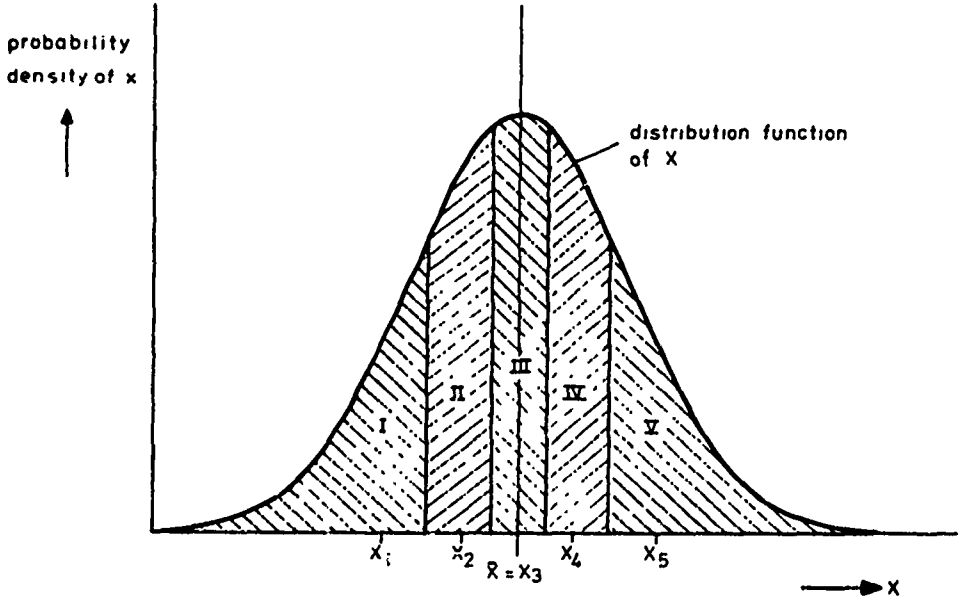


Fig. 15. Example of quantification of the variable x.
Number of intervals is 5.
x_1, x_2, x_3, x_4 and x_5 are the mean values of the intervals.

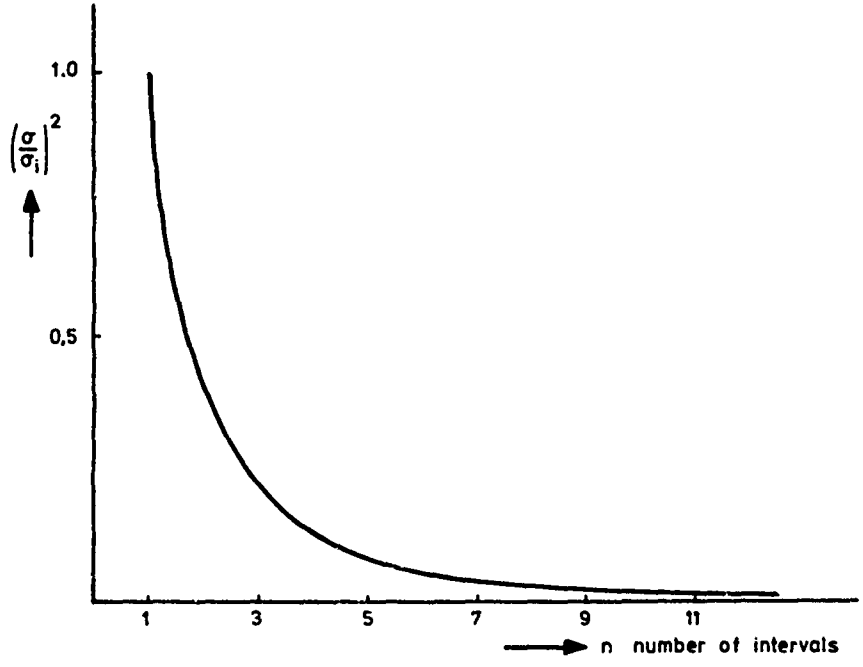


Fig. 16. Relative error due to quantification as a function of the number of intervals n.

LEAD DISCUSSION

by

I. L. Ashkenas
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Mr. Hosman's experiments and analyses have presented us with a number of interesting observations and conjectures deserving of comment and comparison with other results. Of course, with the advantage of total hindsight such comments can be quite a bit more perceptive now than at the outset of the experiments. Also, the fact that I speak from the vantage point of the relevant collective experience of our group at STI gives me an additional advantage. Under these circumstances, it may be difficult to avoid what some of you may consider a pedantic tone. Please realize, in any event, that my purpose is to convey, to those of you interested in the field, more of the present state of art relative to Mr. Hosman's subject.

In reviewing Mr. Hosman's paper we found that the areas deserving comment broke down into four major categories, as listed below:

1. Pilot measurement "problems."
2. Interpreting pilot/vehicle results.
3. Secondary task implications.
4. Sampled data models.

I'll discuss these various categories in the order listed.

PILOT MEASUREMENT PROBLEMS

Mr. Hosman's Figure 9b is a typical example, and a graphical demonstration, of an old problem in pilot behavioral measurements. It shows the considerable scatter and low frequency anomalies in the describing function measurements due to a remnant-like injected noise; and it also illustrates the effectiveness of the weighting procedure used by Mr. Hosman to obtain somewhat better fits to the data in the presence of this noise. Although it is not clearly described in the text, we understand that the model-data matching errors are weighted by the first-estimate of the local ρ^2. In essence, this forces the model to fit near the crossover region. Of course the real impact of Fig. 9b is that it "explains," by virtue of injected remnant effects, the considerable extra phase lag in the low frequency region. However, in certain of our experiments we have often found such low frequency lag effects to be real, rather than noise-induced.

On the other hand, as I have previously indicated, we have had similar problems with low frequency scatter and poor signal to noise; and, in fact, such problems led us to adopt a sum-of-sine-waves input, as mentioned by Mr. Hosman. We have, however, made some fairly recent changes to the spectral form which now differs from that shown in Fig. 3b in that the cut-off corner of the spectrum is attenuated in a manner similar to Mr. Hosman's random input, except that our high frequency "shelf" is still retained (Ref. 9). The "rounded" corner is considered by the pilots to be a more reasonable kind of a command input, than the abrupt cut-off, for use in real airplane simulations. This may have been a point that bothered Mr. Hosman, and I mention it because in our experience we have found such rounding to satisfy pilot requirements.

The use of a finite sum of specific sine waves to approximate the general spectral shape described above permits one to use the ratio of Fourier transforms for the cross-spectra in Eq. 1 without getting into low signal-to-noise problems (see Ref. 10). That is, referring to Mr. Hosman's Eq. 4, we make certain that the remnant power relative to the signal power is quite small at each input frequency. On the other hand, Mr. Hosman's input spectrum, which at low frequencies corresponds to white noise acting through the airplane as a filter, actually has a reduced signal at low frequencies according to Fig. 3a; and additionally has spectral properties which make it difficult to distinguish signal from noise. Early experiences with spectral inputs led us and others to conclude that we were better off, with such inputs, to express the desired quasi-linear describing function in terms of $H_p = \Phi_{u_g e_m}/\Phi_{u_g \delta}$. If the remnant is considered to be an injected noise and the signals correspond to a stationary random process, then this form always yields a better estimate for H_p than Eq. 1. However, as noted earlier, if a sum of sine waves is used, Eq. 1 or even simpler relationships can be utilized with little error.

Another advantage of sum-of-sinusoid inputs is that, with special techniques, one can obtain the desired describing function on-line using the error signal alone! This is done by using the input's cosines and derived sines as the Fourier-integral multipliers of the selected signal (error has the best properties) (Ref. 10). It is even possible to obtain an estimate of the signal coherence at <u>each</u> input frequency using this approach (Ref. 11). With 5-7 sinusoids the effective local ρ^2 at each frequency remains above 0.80-0.90, even though the average correlated power is only 0.20-0.50!

As a final comment in this area, it would be interesting to examine the remnant spectral form (not shown in the paper) to see how it compares with other researches in the field.

INTERPRETATION OF PILOT/VEHICLE RESULTS

The system performance results tabulated in Table 3 show, as also noted by Mr. Hosman, that for the stable aircraft the closed-loop values of σ_e^2 are not much different from those for the airplane alone. This comment also applies to the neutral aircraft because the airplane-only value of σ_e^2, obtained by roughly integrating the spectrum shown in Fig. 3a, is only slightly higher — about 0.33 deg^2, as opposed to 0.23 for the stable airplane. Furthermore, as also noted (and shown in Table 5), the closed-loop crossover frequencies for the stable and neutral aircraft are quite low, being respectively of the order of 0.2 and 0.4 rad/sec. On the basis of this evidence it seems that the pilots were not doing a lot of active tracking for these two configurations. A possible explanation may be that the signal levels were within

the pilot's indifference or visual threshold. For example, the σ_θ of about 0.48 for the stable airplane converts to approximately a subtended visual angle at the pilot's eye of roughly 0.54 milliradians; the corresponding value for the neutral aircraft is about 0.65 milliradians. From data given in Ref. 1 it appears that visual threshold values are of the order of about 1 milliradian. For the unstable aircraft the value of σ_θ^2 deduced from Fig. 3a was about 23.5 deg^2, which raises the value of σ_θ by roughly an order of magnitude over that for the stable airplane. For such a large input there is now no question of threshold effects; and, in fact, this is the only one of the three configurations for which the crossover frequencies are in a range consistent with reasonable tracking efforts, as discussed below, i.e., $\omega_c = 1\text{-}1.4$ rad/sec. Recent work on display scaling by STI and others has also shown crossover frequency regression for near-threshold display signals (Refs. 8, 12).

Whether or not the low crossover frequencies noted above were due to threshold, the effects of increasing input excitation noted above are consistent with other findings, i.e., that increasing the input above a certain low level sometimes increases the pilot's gain and corresponding crossover frequency. We have observed similar effects in some of our own multiple-loop test situations where the disturbances were deliberately kept small to prevent other instruments in the pilot's view from fluctuating too wildly. In a recent series of tests we simulated a DC-8 airplane approaching at 135 kt (Ref. 2) with airline pilots told to fly in their "natural" way. We found that, even though the σ_θ input was approximately 1.2 deg at roughly the same display scaling used by Mr. Hosman, one pilot's crossover frequency was only about 0.4 rad/sec with a corresponding phase margin of 85 deg; whereas a second pilot had about a 0.9 rad/sec crossover frequency and roughly 74 deg of phase margin. The first pilot had about the same low crossover frequency for the outer loop indicating, in effect, that he did not really use an attitude inner loop in his normal flying. When these same two pilots were given a flight director in which the display scaling increased the apparent disturbance input by about a factor of 3, both pilots had roughly similar crossover frequencies now ranging between 0.8 rad/sec for the previously low pilot to 1.4 rad/sec for the second pilot, with respective phase margins of 55 and 30 deg. These latter data compare quite favorably with those shown for the unstable aircraft in Table 5. We should note in connection with these results that, because the pilot had a full instrument display panel and was flying a whole landing approach task, the reduced crossovers relative to those obtained in pure single-loop tasks are due, at least in part, to the effects of scanning.

In addition to the above differences in crossover frequencies and performance, Mr. Hosman notes in connection with Fig. 12 that, as the airplane becomes progressively less stable, the pilot adapts more lead. However, Table 4 shows less systematic variations of lead time constant (τ_1) with changes in the airplane's stability than Fig. 12. Table 4 also shows a marked decrease in the effective time delay ($\doteq 2\tau_3$) for the unstable aircraft. This result is quite consistent with our findings that, for unstable aircraft where the value of τ_3 is especially critical to closed-loop performance and stability, the pilot tenses up and effectively reduces his neuromuscular lag. In fact, we quite often use instability as a device to increase the pilot's tension; we also use increased input bandwidth and, in some cases, electromyographic feedback to the pilot so that he can see his own tension level.

SECONDARY TASK IMPLICATIONS

Figure 1, which Mr. Hosman uses as the basis for setting up the philosophical point of view relative to secondary tasks and modeling, we find somewhat confusing and misleading, or at best only partially true. For example, we would say that there are feedback paths other than conscious perception which the pilot can close; for instance, through unconscious sensation, as in joint receptors. Also, the block labeled "Decision" in Fig. 1 is not generally a factor in the closed loop itself, but rather is a parallel function which can operate to affect switching, lead generation, or other pilot activities in the loop under control. We prefer an hierarchical structure, with the decision-making "metacontroller" governing the often-parallel multiple control loops.

Also, the notion that the human cannot deal with more than one source of information at a time, we feel, is not truly a well-accepted dogma; although it does reflect a simplistic view held by many in the psychological fraternity. For example, in multiple input/output operations (e.g., using elevator, aileron and rudder) the pilot can handle more than a single continuous task. In this connection, the data and results of Ref. 3, concerned with a series of tests where a variety of configurations were flown using aileron-only, and rudder as required to stabilize a divergent dutch roll mode, are of direct interest. The dutch roll damping ratios were varied from 0.75 to -0.075 to -0.35. The roll axis, which was the command axis, was easily controlled with only aileron for the stable dutch roll, but both levels of dutch roll instability required simultaneous control of a rudder inner loop to improve the airplane, or make it flyable. The observed crossover frequencies for the outer bank angle command loop were 3.2 rad/sec with a phase margin of 20 deg for all configurations regardless of the secondary task requirements. It is important to note in this connection that the pilot was apparently not pushed to capacity despite the increasing load. That is, he was able to continue doing the same command/control job despite an increasing secondary "load." In view of such results (and we have obtained others of a similar nature), it seems obvious to us that the pilot is really much more than simply a sequential processor.

Whether "mental load" describes such increased demands on the pilot is questionable. However, we quite agree that decreasing airplane stability will force the pilot to work harder by tensing to reduce τ_3, by adopting high frequency lead, and by requiring him to operate above some minimum gain. Such descriptions of what the pilot has to do to control the vehicle in the assigned task are much more concrete than a phrase like "mental load." In any event, both descriptions indicate a certain reduction in the pilot's excess capacity for additional tasks.

Of course, the addition of another task further reduces the pilot's excess capacity; and if we can arrange both tasks — that is, the primary and the added or secondary task — to be such that his total excess capacity is zero, then there are a variety of ways in which we can quantify his excess capacity when only performing the primary task. For instance, if the primary task performance is held constant, the performance achievable in the secondary task is then a direct measure of the excess capacity with only the primary task (Ref. 4). Conversely, if the secondary task is held constant, then the performance degradation in the primary task is also a measure, although not quite so directly, of excess capacity,

provided that the combined task is really saturating the pilot.

In Hosman's experiments the auditory, binary choice, secondary task was set at various levels corresponding to percentages of the pilot's total capacity in that task. Accordingly, the reduction in primary task performance is expected to be indicative of some change in the pilot's available capacity. However, there was no provision for the sum of the combined tasks to totally saturate the pilot, which might have been a better strategy. Also, the fact that the scores on the additional (secondary) task were not kept (or at least were not given) indicates that the pilot had some leeway in trading off secondary versus primary tasks in priority. Accordingly, there is at least some philosophical basis for questioning whether or not the resulting reduced performance in the primary task is necessarily indicative of a reduction in the pilot's capacity when also performing the additional auditory task.

If with this background, we look at Fig. 10, it is clear that the additional task has no real effect on the closed-loop performance of the stable aircraft. This isn't too surprising when we remember that the pilot really wasn't doing very much toward controlling this particular configuration. For the neutral aircraft we see some increase in tracking error, but the pilot still, we suspect, is not really trying (or can't accurately perceive the error) as evidenced by the low crossover frequencies. These are 0.2 to 0.25 rad/sec (Table 5) for the 80 percent auditory task, decreased from 0.34 to 0.4 rad/sec without the auditory task; but far below the pilot's true capability as shown by crossovers of 1 to 1.4 rad/sec for the unstable aircraft. It seems fairly clear that for the unstable aircraft the pilot was forced by the additional task to pay less attention to the control task and that he was truly quite nearly saturated. However, for the other cases, it appears that the pilot may not have been operating near full capacity, especially in view of the multiple-loop data cited previously (which showed no changes in command task performance with an additional control task). Nevertheless, we can't deny the data, so we wonder whether there were changes in the actual scores on the additional task which perhaps could account for the slight differences shown in the performance trends for the stable and neutral aircraft.

In our own work we considered a variety of secondary task loadings and ended up with a preference for what we call a cross-coupled secondary task (Ref. 4), which always stresses the pilot to his limit capacity while maintaining some specified performance in the primary control loop. Accordingly, we use the secondary task score as a direct quantitative measure of excess capacity for the primary task. Incidently, the secondary task scores thus obtained correlate quite well with pilot ratings of the primary task alone which indicate that, among other things, the pilot rating is a pretty good measure of his capacity to take on additional work.

SAMPLED-DATA PILOT MODELS

In connection with the advanced pilot model proposed by Mr. Hosman, we agree that the process of sampling and quantification can produce remnant. In fact, we've been through about four generations of development on such models in our own work on display scanning and sampling. (Hosman's Ref. 9 gives one third-generation example.) Some of the things we've tried, and some of the results we've obtained are of direct pertinence to Mr. Hosman's proposed modeling effort.

In this work we have developed explanations and models for the quasi-linear describing functions and remnants experimentally observed. Two "mental processes" have been hypothesized for the models (Refs. 5 and 6) called "switched gain" and "reconstruction-hold" models. For the switched gain process, the quasi-linear describing functions in the several loops incur no time delay because of the scanning and sampling processes, although the gain switching (multiplexing) from loop to loop reduces the effective gain in each. In the reconstruction-hold model a sampling delay is incurred that may be largely offset by lead equalization as part of the signal reconstruction process.

The principal cost of the scanning, sampling, and reconstruction (or switching) behavior is an increased "remnant." This depends on the sampling frequency, fixation dwell time, and sampling frequency variations, as well as the signal variance. It acts like a multiplicative (proportional) injected noise, and is the real cause of saturation in multi-instrument displays (e.g., Ref. 8).

We recognize six possible sources of remnant:

Observation Remnant due to poor coupling between the displayed signal and the eye. Resolution, retinal rate thresholds and saturation levels, and refractory delay are of key relevance to instrument design.

Scanning Remnant due to scanning and sampling of multiple instrument displays. To the extent that parafoveal information can be used for nonfixated instruments in an array or for symbols within a display, the parafoveal display perception is of interest because it can reduce scanning remnant.

Equalization Remnant due to asynchronous, discrete mental data processing to derive rate (lead equalization), time and amplitude variations in gain, and intentional dither. Except in properly designed flight directors, these are dominant remnant sources, and can affect the remnant resulting from use of a given instrument design (e.g., if low frequency lead generation is required, the instrument must provide smooth data in the low frequency range).

Motion-Cue Remnant due to vestibular feedback noise.

Crosstalk Remnant due to neuromuscular commands for other axes in a given control action (e.g., some aileron control showing up in elevator control inputs).

Neuromuscular Remnant due to neural and muscular nonlinearities and tension (gain) variations. An important remnant source is residual neural noise and tremor which remain even when no command is being followed.

It can be shown (Ref. 7) that the types of quasi-randomly sampled and processed signals of concern here can be modeled by (1) replacing the sampling or switching process by a continuous transmission path with a describing function model, and (2) adding an uncorrelated wideband noise process whose power spectral density is proportional to the variance of the signal before sampling, which in our case is the displayed signal. For the switched gain model, the quasi-random sampling process has a finite foveal dwell interval, and the wideband noise process exhibits a low-pass power spectrum with a first-order break frequency which is inversely proportional to the average foveal dwell interval (Ref. 6). The measurements of this switched-gain remnant (Ref. 6) have shown that it so predominates over the other sources of remnant that the other sources cannot even be identified.

CONCLUSION

I sincerely hope that this recitation of some of our work and results vis-a-vis the experiments and data obtained by Mr. Hosman is not construed in any negative way. I hope instead that my comments, criticisms, and references to some of our pertinent parallel work may be helpful to those of you planning similar experiments; and that is the spirit in which this discussion has been rendered. The work described in detail by Mr. Hosman is valuable regardless of the questions and issues raised in my discussion. Certain of his data, as reduced, appear to have more validity than others; however, as with all such data, it may be possible or feasible for some of the questions raised in today's discussion to be resolved by additional manipulations of the fairly solid data bank he has collected with his carefully conducted experiment.

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OPEN DISCUSSION

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We know ground base simulator limitations. Have pilot transfer functions been also measured from real flight?

I.L. Ashkenas, STI, USA

Yes, we have used some variable stability aircraft, the Princeton Navion and USAF T-33. My recollection is that we got good agreement between the flight test and the ground based results. The important differences were the crossover frequencies and gains.

R.O. Anderson, AFFDL, USA

There has been other more recent work. NASA did some work using the variable stability Lockheed Jet Star, GPAS. But an even more dramacic effort was the work done by Mr. Wingrove at NASA Ames, where he made actual measurements of the Gemini manually controlled retro-rocket firing for reentry. He found very good agreement with general theory, except for the differences that Mr. Ashkenas mentioned.

PILOT WORKLOAD

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The following paper is not a carefully prepared conference paper but was made ready by the two authors on request of the chairman on very short notice during the meeting to serve as a basis for discussions concerning this very special topic.

1. Schematic of pilot in the loop

Figure 1 is a schematic of the possible functions of the human operator within the whole guidance and control system[2]. We notice the three hierarchical control loops. The "captain" gives his commands, as for example, point of destination, to the navigation loop which computes the appropriate flight programme.

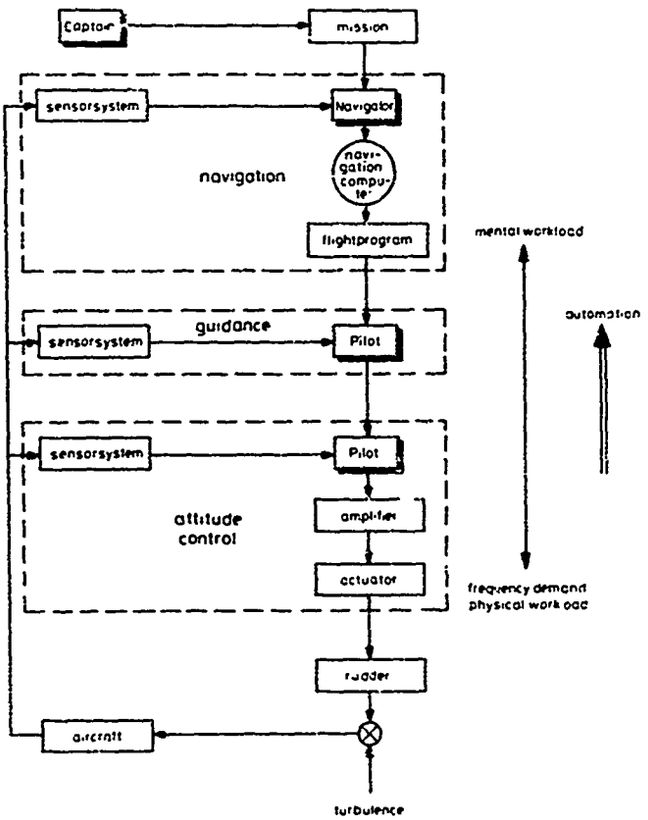


Figure 1 : Functions of the human operator in the guidance and control loops

During flight the "navigator" checks, whether there are large deviations from the programme. If this is the case he will start the computation of a new programme.

The forcing function given by the programme is followed by the "guidance" loop. Smaller deviations from the programme are corrected by the "pilot" acting as a computer.

The output of this loop is the forcing function of the inner loop, responsible for attitude and speed of the aircraft. Within this loop too the pilot mainly has the function of a very flexible and adaptable computer.

From the viewpoint of pilot workload it can be stated that

a) because of the increasing frequency demand within the control loop the physical workload increases from the higher to the lower loop.

b) because of the increasing level of information processing, the mental load increases the other way from bottom to top.

c) following from a) and b) the automation started in the attitude loop (stabilizer, simple attitude hold autopilots), continues into the guidance loop (more complex autopilots with flight path coupler) and moves toward the navigation loop (space flights).

Let us try now to structure these different considerations by giving some definition [5, 6] .

The total mission of an aircraft can be divided in a certain number of parts we call "Phases", like for instance, Take Off, Climb, Cruise, Descent, Approach, Landing and so on; but the objective of a Flight Phase is too general, so we divide each phase into a number of elementary parts we call Sub-phases. The objective of each sub-phase is specified within a given set of tolerances which take into account the likelyhood of performing the succeeding sub-phase.

During a given sub-phase the pilot has to adhere to airplane limitations, for instance, limitations on angle of attack. He has also to adhere to operational limitations, for instance, height above the ground, flight level prescribed by the air traffic control; this first objective to be met by the pilot is called Immediate Safety (figure 2).

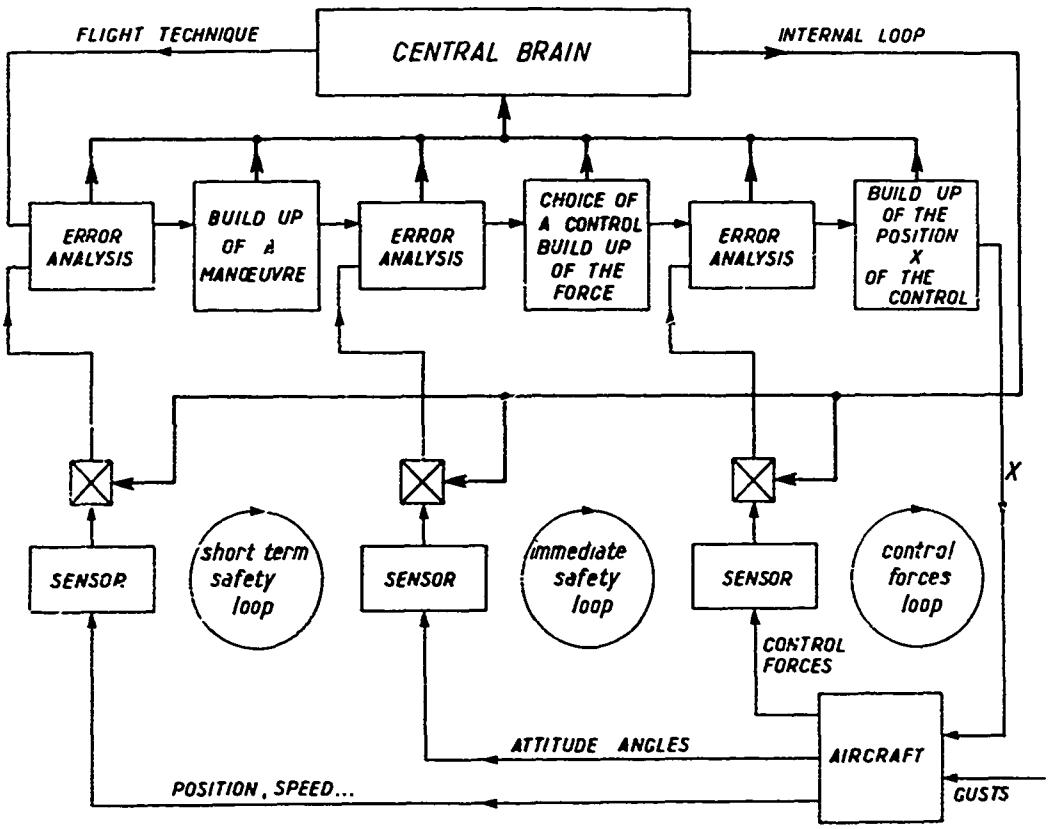


Figure 2 : The pilot in 3 loops

On the other hand, the pilot must not jeopardize the achievement of the following sub-phase; in other words, he has to reach the elementary objective of the sub-phase within the tolerances (position, height, speed, heading and so on). This second objective is called Short Term Safety, the Long Term Safety being the observation of the objective of the phase (navigation and guidance).

In order to observe this double objective, short term and immediate safeties, the pilot uses a flight technique as a guide, this flight technique depends on the state of the aircraft (mass, C. G. location, failures, and so on) and on the state of the atmosphere (visibility, turbulance, wind, and so on). The flight technique is generally given in the flight manual by rules for combining the different flight parameters used by the pilot (speed, altitude, attitude angles, position in space provided by I. L. S. or other guidance systems, and so on).

The data concerning the short term and the immediate safeties are provided to the crew in different ways:

- some data are directly or indirectly measured and provided on the instrument panel in analog or sometimes in digital form
- some data are not measured because they are directly accessible to the pilot; for instance position of the airplane with regard to the runway in visual landing, linear and angular accelerations

- and last some data concerning the state of the aircraft are provided on the instrument display (position of the landing gear, of the flaps, engines R.P.M., systems failures and so on)

Cues relevant to the short term and immediate safeties are collected by the different human sensors, which are eyes, ears, hands and legs, and the whole body.

We have to notice that eyes are double sensors: central vision, collecting few but precise data, and peripheral vision, collecting numerous but not precise cues. The ears are also multiple sensors: the external ear collects sounds, and the internal ear collects linear, angular accelerations and direction of the apparent vertical.

It is very important to note that data are collected by a sensor and transmitted to the brain and are used by the brain only when the brain gives the corresponding order, in other words, "calls" the data.

This remark is very important because it means that the collection of different data cannot be made in a simultaneous way: the brain asks the eyes to look at this instrument then at another instrument and later asks the ears to listen to this or that signal; the way of scanning, generally learned by training, may be modified by an alarm signal coming from peripheral vision or from the internal ear.

The data, collected by the various sensors are transmitted to the brain, which, by direct comparison with well-known situations or by computations according to programmes stored in the memory, gives two kinds of orders:

- order for action by hands and feet on the controls
- call for new data to be collected by a given human sensor

The first type of orders generate the external loops and the second ones generate the internal loops (see figure 3).

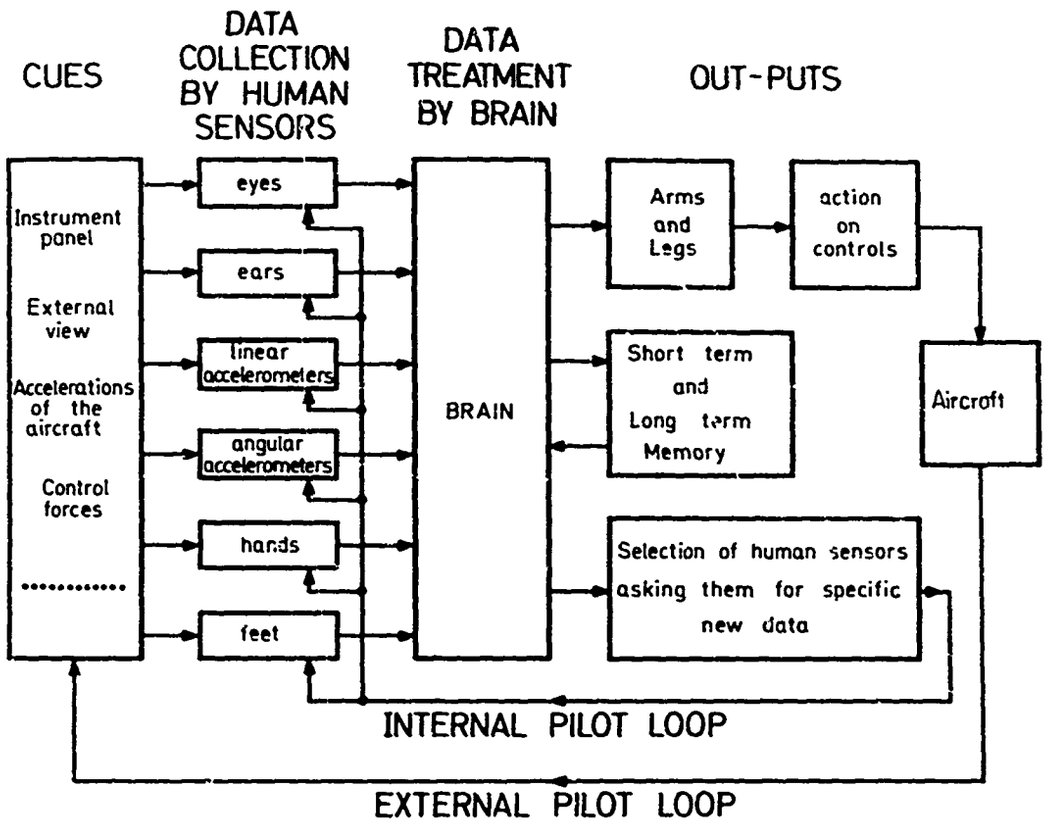


Figure 3 : Internal and external pilot loop

Let us examine now these two outputs of the brain by considering a specific example. We assume that the pilot has to perform the "Final Descent" Sub-phase of the "I.L.S. Approach" Phase under zero visibility conditions. He has at his disposal the I.L.S. cross pointers and the conventional instrument panel which includes the altimeter, the horizon, the rate of climb indicator, the air speed indicator, the direction holder and the turn and bank indicator. The chosen flight technique is:

- speed maintained constant at a given value
- wings maintained horizontal

- the two I.L.S. cross pointers at the center of the indicator

At a given moment the pilot has received the following information:

- the speed is equal to the desired approach speed
- the heading is the localizer heading
- the wings are horizontal
- the pitch attitude is at the correct value, taking into account the slope and the recommended value of the angle of attack
- the I.L.S. indicator shows that the aircraft is above and to the right of the I.L.S. path

In reality the pilot's brain has not assimilated directly all of this information. By scanning the instrument panel, he has noticed the position of the airspeed pointer, the position of the pointer of the direction holder, the position of the artifical horizon bar, the position of the two I.L.S. pointers.

Thus we see that a fairly complex mental exercise, which includes comparison with data stored in the memory, is performed before the pilot can analyse the situation.

We shall note that several values are sometimes memorized in terms of the required needle positions. For example it is known that in approach, the pointer of the airspeed indicator is horizontal to the left or vertical above. Such memorization depends on the type of display used.

Now the pilot performs a second mental operation to plan his strategy for achieving the short term safety, that is, to guide the aircraft through the three hundred feet window.

The flight technique helps him to find the proper procedure.

Then, the pilot decides to incline the aircraft to the left and reduce the pitch attitude. Knowing from experience that a reduction in pitch attitude goes with an increase in speed, he decides to reduce the thrust as well or to increase the drag by using the airbrakes. Depending on his training, that is, depending on how much information he has memorized, the pilot decides with more or less precision what magnitude the elementary manœuvres will have. The pilot knows that to correct a two point deflection of the I.L.S. indicator along the lateral axis at the beginning of descent, he must bank the aircraft twenty degrees to the left for five seconds and then bank it twenty degrees to the right after which he returns to the wing horizontal position.

Of course the pilot does not know exactly how long the manœuvre takes, and he has no chronometer available. Indeed he uses the usual banking rate, and he knows that a twenty degree left bank followed by a twenty degrees right bank and a return to horizontal gives the desired correction. Likewise, a trained pilot will know that reducing the pitch attitude by two degrees for ten seconds followed by a return to the initial attitude will correct the altitude deviation. Finally, he knows that a reduction of one hundred r.p.m. is required in order to prevent an unacceptable increase in speed during this manœuvre; if the speed is not below the minimum drag speed, the pilot can decide that a thrust variation is not needed for such a short manœuvre.

Up to this point, the pilot has not acted; he has only performed mental operations to analyse the situation and decide what strategy to use. There remains one more mental operation to be performed: determining how to actuate the controls in order to perform the desired elementary manœuvres. These controls are the stick for pitch and bank attitude, the rudder pedals and the throttle. If he is trained thoroughly enough, he will know how much force to apply to the control and how long in order to bank the aircraft twenty degrees to the left at the normal rate. He will also know how much forces should be applied on the stick to control the pitch attitude and how far the throttle should be moved.

Once these decisions have been made, the pilot can act, that is, move the controls. Then come the checking operations; the various sensors have to collect new data.

The forces applied to the controls are modified according to the results, that is, as a function of the data collected. Thus, there is a set of control-action-loops between each force applied to the control and its resultant action, until the desired result is reached.

To acquire the information needed to evaluate the results of actions taken, the brain must call for it; there is a signal to the appropriate sensor to switch it into a state of readiness for transmission. The command to "enter into service" is transmitted to the sensors by what we will call an internal loop of the brain, distinguishing it from the external control loop described above.

The first internal loop actuated is the brain-hand loop, which alerts the hand or foot serving as a force sensor.

Thus the brain will request that the control stick be moved to the left and that a force sensor transmits an indication of the amount of force applied. The brain keeps on requesting that the control be moved until the desired force has been applied. The work can be chopped up as follows:

- order to move the stick
- request for information on force

- transmission of information
- comparison between the measured force and the desired force
- corrective action
- request for new information, and so on

In this way the elementary action is done, a given force is applied to the stick and a second external loop begins to check the elementary manœuvre.

The pilot knows that the rate of roll should be closed to the desired rate, but he must check this, and stop the roll when the twenty degrees of bank are reached. Then he calls by a second internal loop, the brain-eye loop, for information needed for external loop operations.

Just as above, the work can be chopped into several parts:

- order to apply the scheduled force which assumes that the force is checked as above
- request for information about the bank angle
- transmission of that information
- comparison with the desired bank angle
- correction of the control force
- request for new information about the bank angle

If the pilot wants to make sure of the bank rate, the work will be complicated because the bank angle ϕ will have to be checked twice over a given time interval in order to estimate $\frac{\Delta \phi}{\Delta t}$.

Once the pilot has changed the bank angle, he should look at the effect of that manœuvre on the flight path. In order to do this he must call upon a new internal brain-eye loop to transmit new information by looking at the right instrument.

This time an external loop is not established since it is carried out immediately by an action of the pilot. First, position and direction information must be obtained from the I.L.S. indicator. Then, the situation is analysed, and a similar but simpler method is used to modify the original procedure.

What we have described here is the process by which the airpath is checked in the I.L.S. system. If this is done with the G.C.A. system, the information is obtained orally, and it is the internal brain-ear loop which is used.

It should be noted that in the latter case, part of the situation is analysed by the G.C.A. ground controller who "prepares" the procedure to be followed and gives not only positions, but also instructions setting the airpath to be followed and the variation in rate of descent.

Now that this has been shown, we can return to our analysis of the work performed by the pilot: it can be divided as follows:

- acquisition of general data on the position of the aircraft compared with the intended path, and the attitude of the airplane relative to the ground, that is, information on the parameters essential to short term and immediate safety; (of course not only position parameters but also their time derivatives are of interest)
- analysis of the situation and selection of a procedure to be followed based on the flight technique
- splitting of the procedure into elementary manœuvres and choice of their amplitudes
  for each elementary manœuvre, choice of the amplitude of the elementary operation on the controls
- action on a control and checking the effort by use of the internal loop brain-hand
- checking the manœuvre and modification of the elementary action, that is the effort, by use of the internal loop brain-eye which collects information on parameters concerned with immediate safety
- checking the procedure by analysing the parameters concerned with short term safety by use of the internal loops brain-eye or brain-ear

So far we have only described the first part of the pilot's general activities in trying to maintain the flight technique. Fortunately it takes much longer to describe the manœuvre than it does to perform it.

As soon as the pilot completes his first elementary manœuvre, that is, twenty degrees bank angle, the internal brain-eye loop is activated to collect the necessary data for analysing the situation.

The situation is not necessarely as expected. For instance, a gust may have produced a decrease in velocity; the pilot may have consequently to change his strategy to deal promptly with the new situation which is perhaps dangerous.

Generally speaking, the pilot analyses the parameters concerning immediate safety first and then those for short term safety. In other words, the first aim is to observe immediate safety in choosing elementary manœuvres; once immediate safety is insured, the pilot is busy with the short term safety.

This means, that once an elementary manœuvre has been executed (and sometimes during the manœuvre), the pilot should watch not only the parameters concerned with that manœuvre, but also all the others.

This operation is controlled by the brain which focuses the internal brain-eye loop from one instrument to another. The order in which they are scanned is controlled by a programme which has been memorized and ingrained in the pilot's mind by experience; or it could be the result of a logical deduction from reading the instruments or analysing the situation. For instance, the pilot can skip reading the altimeter if the rate of climb indicator is still at zero, or he could skip reading the heading if the bank angle is zero.

Note that the "non noble sensors" play a small part in this check over operation; they only interfere to warn the pilot of an abnormal condition.

We have described in detail the development of a manœuvre for which an external monitoring loop requires the use of an internal loop, generally the brain-eye loop. In some cases, the pilot can perform a manœuvre partially in an open loop. It enables him to use his internal brain-eye loop to check other parameters and thereby quickly review his analysis of the situation. In this way delays in the external loop during the check can be curtailed. This brings to mind a very important fact:

All the mental processes involved in analysing the situation, selecting a strategy, evaluating the elementary manœuvres and control forces, as well as the collection of information after an internal loop instruction, all these are performed one after the other except in very rare cases.

So the concept of the pilot functions can be summed up in the following way (figure 2).
There are three types of loops: the biggest one which is the shor term safety loop, the second one which is the immediate safety loop and the smallest one which is the control forces loop.

It is very important to note that the entire diagram must be made much more complex. As a matter of fact it is possible to picture every output parameter coming from the airplane and every human sensor so as to obtain a great number of loops of the three kinds given on the diagram. Let us notice also that at each moment there is only one loop in service, and this is one of the fundamental differences between pilot and autopilot. The selection of the loop in service is made by the central part of the brain, as represented at the top of the diagram, by means of order to the chosen sensor to transmit the necessary data.

2. Definition

The mental workload may be defined as the processing of information by the human being; the information is coming from the aircraft and the environment to the brain through the human sensors, eyes, ears, skin, internal ear and equilibrum system, is treated in the brain for analysis of the situation, decision for action on controls, decision for asking for new information and transmission of information to the environment (A.T.C.). Additionally the physical effort of the human being on the controls in order to transmit the result of the mental processing to the machine may be defined as physical workload.

3. Objective of the measurements of workload

Our objective should be to get the highest performance of the man-machine system, that is to say, the highest probability of fulfilment of the mission. The probability of fulfilment of the mission is related to some extend to the pilot workload. This means we have to make sure that the human pilot is not too near the lower and upper limitations of his information handling capacities. For instance, lower limit may correspond to monotony and upper limit to stress and the danger of no safety margin.

4. Measuring methods

Human engineering, or Anthropotechnics as it is called in Germany, as such has the task of optimizing a man-machine system in regard to performance, reliability and economy [2]. Within the frame of this paper, only the technical performance is to be considered.
Normally the control effort of the human operator and/or the result, i.e. the control quality are used for evaluation. The evaluation methods differentiate in the approach of measuring these quantities (figure 4) [2].

As regards these approaches the following can be stated in detail:

4.1 Control effort

Let's begin with the measurement of the effort of control, i.e. the physical effort of the human operator when operating the signal-output. For reasons of measuring techniques, normally a scoring is arrived at, only for continuous control and not for operation of switching elements (main control and selectors). Example: stick activity of a pilot controlling an aircraft. Decisions have to be made individually whether an amplitude or a rate scoring is the better describing method.

It must be pointed out, that one can frequently assume defined positions in the error effort plane by varying the system parameters. Example: prediction display; here the position in the error effort plane is defined by the type of control dynamics and the choice of prediction time (figure 5) [4].

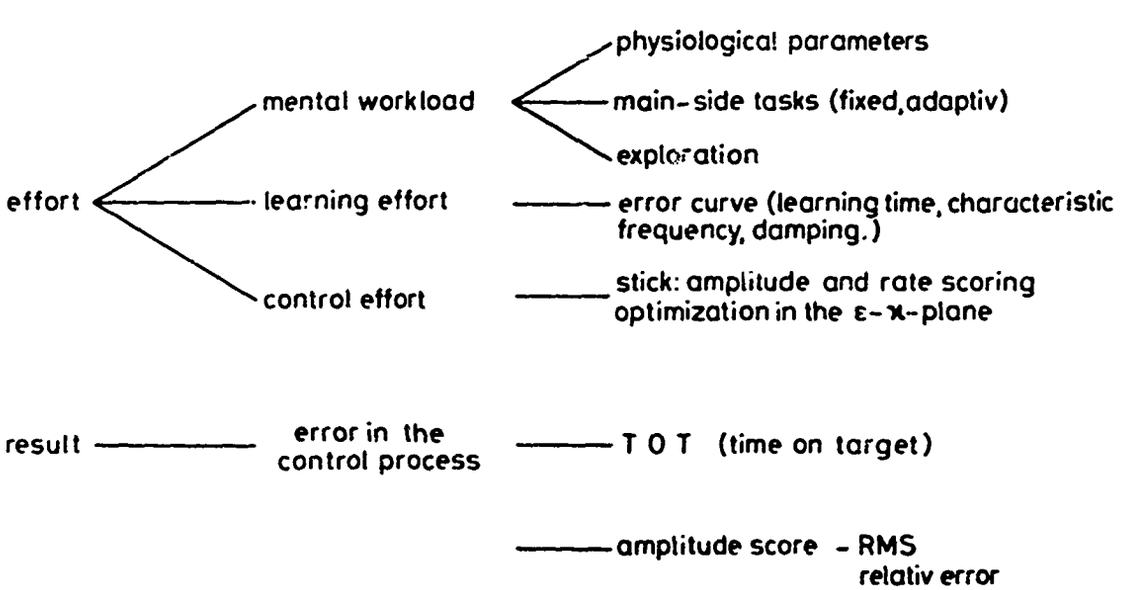


Figure 4 : Evaluation of anthropotechnical optimization

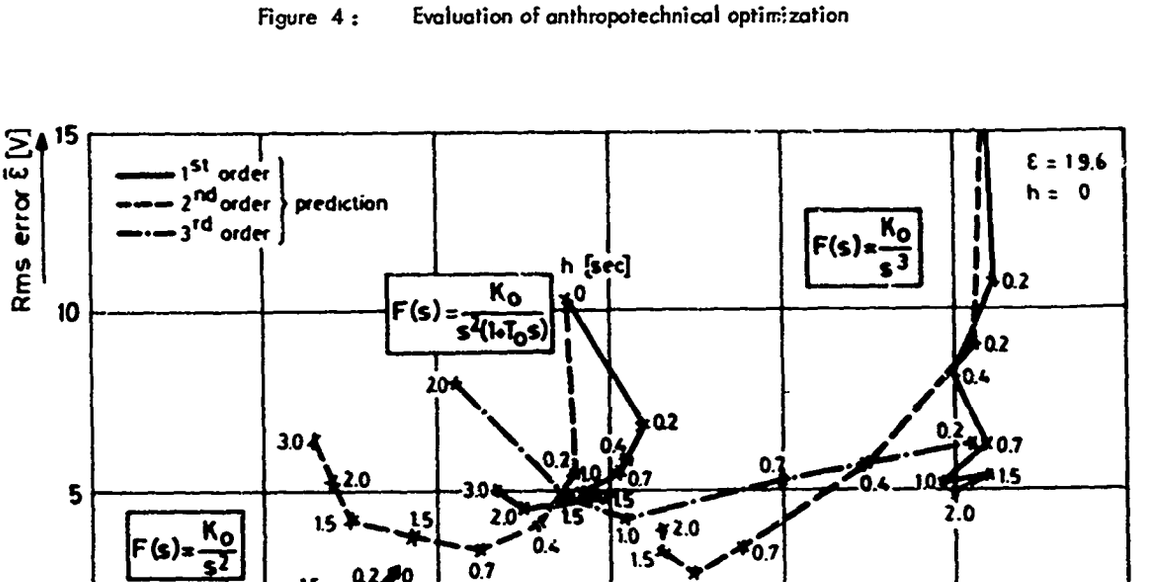


Figure 5 : Position in the error effort plane as a function of prediction

4.2 Mental workload

As could be seen from figure 1 the effect of mental load on the human operator becomes more and more important in future guidance and control systems. All over the world there is a lot of research work going on to measure mental workload. Some of these apporaches are listed below.

4.2.1 Measurement of information transfer

We can try to define the amount of information going into the human pilot. However, we often can say what amount of information is presented to him, but we do not know, what he is perceiving ! Only under some very specific conditions can we measure the direction of his attention. Eye movement recording is one example for this approach.

4.2.2 Measurement of physiological parameters

A mental workload affects the physiological condition of the human operator. The question arises: is one able to draw clear enough conclusions from the physiological data concerning mental workload level ? The answer to this has not yet been given. The great problem still exists of the physiological results also depending on other quantities such as physical labour, environmental conditions like temperature, air humidity etc., and on the state of health of the subject concerned [1] .

Besides these intraindividual variations there is a strong interindividual variability. This means, the investigator has to be very careful in the mathematical processing of his experimental data of different subjects (averaging etc.).

On the other hand it has to be pointed out at this time, that many methods which seemed to be useful, such as adrenalin-measurement (which gives an integrated measure of the effect of human effort over a certain period of work) or brain wave recording, are only applicable in defined laboratory conditions but not in flight.

4.2.3 Measuring the performance capacity by subsidiary tasks

The less the human operator is taken up with his main task, the more capacity he has available for secondary tasks. With a certain amount of restriction (coupling main-side task) the performance for the secondary task can be made to serve as a measuring element. Secondary tasks can be as follows:

Mathematical test (such as Düker test)

Simple time-reaction tests

Choice-reaction tests

Tapping tests

Additional control tasks

.....

While the first four types are being investigated at different places in Europe, the Americans have used an adaptive tracking task with much success during the last years. If the main task is carried out successfully then the degree of difficulty of the secondary task is increased until the performance for the main task decreases. Vice versa: the degree of difficulty for the secondary task decreases again, when the errors for the main task increase too much. In accordance with American results this type is much more sensitive regarding the changes in the main task as compared with those of the above mentioned fixed tasks. The high degree of motivation of the subjects is worth mentioning; it is maintained also for longer test series. The reason for this being, that although the demands of the system vary, the human operator never becomes over- or underdemanded for longer periods. Tests carried out here have confirmed the useability of this method.

4.2.4 Exploration of subjective data

The most used method and the one requiring the least effort is questioning the subjects, i.e. obtcining a subjective answer regarding the degree of demand. This method, in particular, requires a lot of care, in order to obtain the verbal data from the subjects and to arrange them in a uniform, i.e. in a comparative manner, without the influence of the questioner entering into the answers given.
Apart from that, it is impossible to obtain a continuous measuring value, as the answers comprise medium values for certain periods of time.

A special problem is the "linearisation" of such rating scales and the standardization of the demand reaction level of the individual subject.

Examples are the Cooper-Harper scale and bipolar scales (0 = zero workload, 100 = highest possible workload).

4.2.5 Learning effort

The effort of learning has not been much observed up to now, it seems, i.e. the time taken for the human operator, in acquiring the dynamics of a system in such a way, so that he is able to react by a control signal appropriately adjusted in its direction and size. Apart from long-term learning, motivation, tiring effects etc., this state becomes apparent when the error time curve becomes parallel to the time-axis. Another measuring method may possibly be, amongst other things, a change in frequency and damping value of the time variable error curve. However, this is not proved up to now.

When adopting this method the considerable effort is in respect of the subjects, as one cannot, for instance, use a few experienced test pilots (1 - 2). One has to make use of so called "virgins", who have no experience with the control of such dynamics (e.g. learner-pilots).

The choice of one or the other method should be made depending on how many aircraft of this type will be put into service.

4.2.6 Effectiveness

The measurement of effectiveness of a control unit and also of the human controller is the degree of achievement of the task. This seems quite obvious, but as will be seen, is a very difficult state to realize in actual life. It depends strongly on what has been defined to be the fulfilment of the task or in the contrary the error dimension.

As regards experimental psychology, on the findings of which Human Engineering or Anthropotechnics is also based, one often uses time as a measuring element.

After 1945 the emphasis was on target designation using "time on target" (ToT) as the performance measure. Here, the error is often made to directly sum up the value that were measured at irregular intervals, in order to formulate medium values and thus arriving at learning curves etc. According to Kelley mostly a conversion to equidistant intervals is required before a comparision with other measurements is possible 3 . Accordingly about 50 % more measuring data is generally necessary for a comparison with amplitude measurements.

Measurements are nowadays preferred that describe the error amplitude and its distribution. A successful measurement is the medium squared error, i.e. the difference between the actual and the nominal values, and established for short time intervals.

Presentation of these values, within a time frame, also supplies the sequence of learning, if the time intervals are selected sufficiently short.

If the in ervals are chosen equal to test time, then one obtains the one measuring data frequently desired for comparisons.

It often proves essential to already differentiate for a 1-dimensional control task between the acceptable deviations; this becomes clear with the example of a vertical control of an approaching aircraft and its upward and downward deviations. In these instances a measuring factor proves efficient that registers distribution of relative errors, i.e. the absolute value to the pre-selected acceptable maximum error. Here, one can especially take into account the locally dependent changes of the tolerable maximum value.

5. Conclusions

This very short introduction does not cover all the aspects of pilot workload measurements, but we feel it may be used as a basis for discussions.

In spite of all the research effort which has been spent on this subject, it has to be clearly said that there is up to now no inflight-method for continuous precise measurement of mental load, which could help us to adapt the machine to the human pilot.

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THEORETICAL PILOT RATING PREDICTIONS

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SUMMARY

The present method of specifying flying qualities leaves much to be desired when the designer is (a) coping with relatively new flight regions (e.g., lifting reentry), (b) evaluating new and promising control concepts (e.g., load alleviation and mode stabilization), and (c) using the specifications directly as design information for the synthesis of flight control augmentation systems. These shortcomings might be overcome by one or more new methods that have recently been suggested. These range from the expansion of the classical approach to new dimensions (i.e., catalog past experience including new parameters such as "effective" control system time constant) to somewhat radical approaches that rely completely on theoretical predictions of pilot ratings. Each new approach has its own limitations, but the results of some very recent work indicated that the prediction of pilot ratings can be done fairly accurately; in fact, within the normal range of pilot-to-pilot variability. It would seem, then, that this prediction capability could be used to specify flying qualities. That is, with a well defined "prediction procedure" (similar to "accepted methods" of predicting aircraft loads) the aircraft can be designed to meet a level of predicted pilot acceptance (rating) instead of designing to limits of static stability, short-period frequency and damping, etc. True, one cannot directly rely on flight testing to show compliance, but one can use a flight-test-proven dynamic model of the aircraft, with the same rating prediction procedure, to demonstrate compliance. Of course, the latter approach is only as good as the prediction method. The admittedly biased author feels, however, that the advantages of this approach greatly outweigh the residual inaccuracies, and the time for acceptance is near. At least a few United States aircraft companies feel this way also. The final answer to the question "are theoretical pilot ratings ready for application?" is left to the reader for due consideration. But even better, try it for yourself. "Paper Pilot" computer programs are available upon request.

IS A NEW APPROACH NEEDED?

The accepted method of establishing handling qualities criteria through the correlation of pilot acceptance with open-loop vehicle dynamic characteristics of existing aircraft has certainly served the test of time. Nonetheless, most workers in this field are well aware of the inherent limitations in this approach. As a point of departure, a few of these deficiencies are listed below:

(a) extrapolating past experience into entirely new flight regions is difficult at best. For example, the new V/STOL specification (Reference 1) and the very new reentry vehicle specification (Reference 2) were difficult to generate simply because of a lack of past experience in these flight regions. The new specifications are finished, but everyone involved in their preparation is probably quite willing to admit that further refinement based on additional data will be necessary.

(b) whenever the vehicle doesn't "fly like an aircraft" the present criteria are of little value. For example, when the pitch response is not predominantly that of a second-order system, short-period frequency and damping ratio requirements cannot be applied. This has not been a large problem in the past, but current trends are towards more reliance on augmentation system, the necessity to consider high-order dynamics such as flexibility effects, and the possible employment of unconventional types of control as with control configured vehicles (Reference 3). In each case, the pilot may experience effective dynamics that are quite "un-aircraft-like". This problem is, of course, closely related to the previous item.

(c) the form of the current specifications is not necessarily conducive to direct flight control synthesis. Control system designers have argued that they must design a system first and then, if possible, evaluate the augmented aircraft dynamics in terms of the handling qualities specifications. Although strides have been made to remedy this problem (Reference 4), a universal answer is not yet available.

(d) the origin and/or reason behind a specific requirement is often not clear. Despite the fact that background information of the form presented in Reference 1 is available, the physical reasons why pilots do or do not want a certain dynamic response are often unknown. Certainly everyone wishes to expand our understanding in this area.

(e) the present specifications do not adequately address the atmospheric disturbance question. It is known, for example, that the same vehicle can be rated very differently in mild versus heavy turbulence. However, the specified linear analysis parameters, such as natural frequency and damping ratio, do not change with the magnitude of the gust disturbance (unless nonlinear control system effects are present). Yet pilot acceptance with linear systems does vary with disturbance level. Improvements in this respect are obviously in order. The above facts at least suggest that some new approach may be in order. The need became even more apparent, however, in connection with the hover dynamic requirements presented in Reference 1. This problem is covered in Paper No. 6 (Refererce 6) in more detail, but in short the specification appeared to be a function of the type of augmentation system being used. This, in turn, opened the door to the consideration of all possible augmentation systems, with separate flying quality requirements for each. Such an approach is, of course, quite unacceptable.

WHAT ALTERNATIVES ARE AVAILABLE?

Accepting the need for some alternate approaches to specifying handling qualities, there are at least

a few candidates that are being, or have been, considered. The simplest method is to expand the catalog of data, using simulators or variable stability aircraft, to include variations of pilot acceptance with commonly used aircraft dynamic characteristics plus an "effective system" representation of other non-aircraft-like dynamics. "Effective" means a generalized, yet simple, representation that will, hopefully, fit many future designs. Such an effort is reported in Reference 5. This concept is straightforward, but to include all types of possible vehicle/control-system concepts requires an endless series of data collections.

Another approach currently gaining favor is some form of time history matching. Again, Paper No. 6 (Reference 6) discusses such an approach to the specification of hover dynamic requirements. This approach also relies on an "effective" representation of a high order dynamic system with a low order equivalent. However, its simplicity is appealing.

Another whole class of new approaches centers on the use of pilot models in one form or another. No attempt will be made here to review pilot modeling and human response theory per se. Instead, only the more recent references that relate pilot models and handling qualities will be discussed. For a condensed summary of this field see Reference 15.

Reference 7 contains a good summary of pilot modeling as related to pilot acceptance ratings in particular, and handling qualities in general, as of 1968. The ideas and data presented show a good quantitative correlation of pilot ratings with closed-loop performance and pilot model parameters. Similar trends have been used before to qualitatively evaluate handling qualities. Later, Reference 8-10, and Reference 6 to a certain degree, used these observations to perform some type of theoretical flying qualities predictions or analyses.

In particular, Adams (Reference 8) showed a somewhat quantitative correlation of pilot rating and predicted closed-loop time constants using relatively simple pilot models. The effect of turbulence was not considered, however, and no attempt was made to formalize the procedure into a specification form. His approach does, however, provide a rough estimate of pilot acceptance.

Neal and Smith (Reference 5) also used pilot models to explain the data obtained during a fairly recent in-flight simulation program. Furthermore, they showed good correlation between pilot rating, performance (in this case "closed-loop resonance"), and pilot model parameters (pilot lead or lag). For the pitch control case, they indicate how certain frequency-domain open-loop parameters (these include the effects of control system dynamics) can be used to evaluate closed-loop characteristics and pilot acceptance. Both their open and closed-loop parameters could be used as the basis for specifications, but the authors do not specifically propose this. Perhaps this omission is due to the fact that the closed-loop parameters must be obtained with a somewhat "arty" application of pilot-vehicle analysis theory. That is, one person may arrive at one conclusion, while another person using the same inputs produces a different result. Their open-loop parameter criterion, in turn, is proposed only as a "quicky" evaluation method; it is a somewhat oversimplified procedure. In any event, turbulence effects are not accounted for in these evaluation procedures. This work is, however, being extended, and some of the above problems may be resolved.

While turbulence effects are not accounted for in any of the above approaches, Onstott and Salmon (Reference 10) show that performance (in terms of root-mean-square-tracking errors) in turbulence can be predicted using pilot models. Their correlation of these predictions with ratings is, unfortunately, limited. This work is also continuing.

Finally, Franklin (Reference 16) shows good correlations between pilot ratings and closed-loop performance and workload (in this case root-mean-square control inputs) in turbulence. Pilot-vehicle analyses are also included to explain the results obtained, but no actual rating predictions are given.

Each of the above programs shows some degree of success in the theoretical prediction of pilot opinion ratings. There remains a gap, however, between these efforts and an actual specification format. Reference 9 attempts to fill this gap, and a discussion of the approach used in this reference, and quantitative results to date, forms the remaining portion of this discussion. Before going into this method, however, it should be pointed out that all of the above pilot model applications attempt to predict pilot opinion ratings. This is primarily because these ratings are currently the very basis of the existing U.S. Specifications (e.g., References 1 and 2). Therefore, it seems that any alternate approaches must of necessity deal directly with pilot ratings. This may or may not be true, but it is assumed to be the case for this discussion.

THE "PAPER PILOT" APPROACH

Reference 9 describes another alternate approach based on pilot models. Specifically, the longitudinal dynamics of an aircraft in hover, with longitudinal random gust disturbances, are considered. A procedure is described whereby a theoretical rating prediction is based on the following expression (Cooper Rating):

$$R=R_1+R_2+R_3+1.0$$

R_1 is a function of closed-loop performance in keeping displacement and attitude to a threshold level:

$$R_1 = \frac{\sigma-.8}{.8} \; ; \quad \sigma=\sigma_x + 10\sigma_q; \quad 0\leq R_1 \leq 2.5$$

and: σ_x = standard deviation of longitudinal displacement (x) in feet.

σ_q = standard deviation of pitch rate (q) in rad/sec.

R_2 is a function of the lead the pilot furnishes in pitch to get that performance:

$R_2 = 2.5 T_{L_\theta}$ $\quad T_{L_\theta}$ = Pilot lead time constant in pitch (sec)

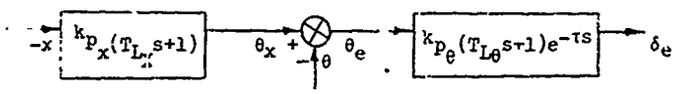
$R_2 \leq 3.25$ $\quad 0 \leq T_{L_\theta} \leq 5.0$

R_3 is a function of pilot lead in longitudinal displacement:

$R_3 = T_{L_X} \leq 1.20$ $\quad T_{L_X}$ = Pilot lead time constant in longitudinal displacement (sec)

$0 \leq T_{L_X} \leq 5.0$

The pilot model is specified to have the following form:



where the time delay τ is 0.44 seconds, and $e^{-\tau s}$ may be approximated by

$$\frac{-(s-2/\tau)}{(2+2/\tau)} \text{ ; with}$$

θ = pitch attitude

s = Laplace variable

δ_e = Longitudinal control input to the vehicle

k_{p_x} and k_{p_θ} are pilot model gains in displacement and pitch.

Using the above "pilot" and a linear simulation of the vehicle dynamics while hovering in turbulence, the pilot model parameters are adjusted (within the given bounds) until the predicted rating is minimized within a boundary on closed-loop stability. Other details (*e.g.*, gust spectral density, minimization procedures, etc.) are contained in Appendix B of Reference 9.

This may seem like quite a complicated procedure, but it is supposed to cure all of the problems associated with the conventional approach listed previously (at least for the hover task). The claim is great; does it really work?

First of all, this procedure does an amazing job of predicting ratings and closed-loop performance compared to a series of fixed-base simulations performed by Vinje and Miller. The following summarizes the prediction "errors" for some 76 different aircraft/gust configurations (Reference 11, Table V):

Parameter	Mean "Error"*	"Error" Standard Deviation
R	.14	.63
σ_θ (deg)	-.70	.48
σ_q (deg/sec)	-1.12	.91
σ_x (ft)	.28	.44
σ_u (ft/sec)	-.14	.24

* = average difference between predicted and real pilot values.

The above predictions were made with a digital computer program dubbed the "Paper Pilot" (Reference 11) by simply inserting vehicle dynamics and gust level into the computer. The remainder is automatic! The results speak for themselves, and at least for this data source the results are excellent. Other data sources are considered in Reference 9, with fairly good results in general.

"CURES" TO PRESENT SPECIFICATION "ILLS"

The following comments apply to each item listed previously:

New flight regions: Once the task is defined, a similar procedure may lead to valid rating predictions. This, however, remains to be proven. Only one other (non-hover) task has been considered to date (Reference 12). In that case, the Paper Pilot concept was applied to pitch attitude control of conventional aircraft. The same pilot lead term, R_2, was used as in the hover inner (pitch) loop, but the performance term, R_1, was changed to:

$$R_1 = \frac{0.1}{0.974-c}$$

where:

$$c = \sigma_e/\sigma_i, \qquad R \leq 10$$

and σ_e is the standard deviation in pitch tracking error ($e=i-\theta$) and σ_i is the standard deviation in the random command input (i). The performance term had to be changed from the hover task expression to reflect the "command input" versus "atmospheric disturbance" tasks, as well as to represent the proper control parameter. The constants in the performance term were selected to match a set of fixed-base

simulator data obtained by Hall (Reference 13) in 1958. These "old" data were used because actual pilot model parameters, and performance measures, are recorded; this is not the case with more recent data. The Pitch Paper Pilot, therefore, does provide predictions of rating, closed-loop performance, and pilot parameters as does the Hover Paper Pilot. In both cases pilot parameters are selected by the computer to minimize pilot rating. In this case, $K_{p\theta}$ and T_{L_θ} are found using a time delay, τ, of 0.42 seconds.

The prediction results in pitch are not as good as the hover correlations, primarily (we believe) because of the limited data base; only 13 configurations with performance and pilot parameter values are available to generate the rating expression. In particular, predictions are very poor when the open-loop short-period damping ratio is small (below about 0.40). The Hall data correlations follow.

The low damping ratio cases clearly stand out. Recent, unpublished, results indicate that a better correlation is found if the remnant normally associated with pilot describing functions is included in the computation of σ. However, more data are required to resolve this deficiency.

Case	Short Period Damping Ratio	"Paper Pilot"	Two Other Pilots	
a	.35	10	10	10
b	.75	10	10	9.5
c	.20	5.08	10	10
d	.35	5.09	7	8
e	.75	4.69	3	2
f	1.0	4.65	6	3
g	.20	3.76	10	10
h	.50	3.13	2	6
i	1.0	3.20	3	1
j	.20	2.97	5.5	8
k	.75	2.47	3	2
l	.75	2.04	4	2
m	.35	2.13	7	7

Using this same computer program, more recent data from in-flight simulations were used to compare actual and predicted ratings.

These results are presented in Reference 12. The correlations with the most recent data from NT-33 flights (Reference 5) are shown below: (Cooper-Harper ratings)

Case	Short Period Damping Ratio	"Paper Pilot"	Two Other Pilots	
1D	.69	3.14	4.5-5	3-4
6C	.67	2.91	4	2.5-5
2D	.70	2.11	2.5-3	2.5
4A	.28	2.36	5.5	5
5A	.18	2.74	7	5-6
7C	.73	1.92	3-3	1.5-4
3A	.63	1.91	4-5	4-4
8A	.69	1.88	2.5	4

(4-5 indicates repeat ratings of same configuration)

With the exception of the low damping ratio cases, 4A and 5A, the results are fairly good. However, recalling that the original performance term was obtained using fixed-base data obtained twelve years before the NT-33 in-flight data, and the fact that the early results were for command tracking while the latter represented "overall flight ratings", we believe the correlations are really quite good.

In summary, it appears that the approach can be applied to other tasks and, therefore, perhaps to new flight regions where the task remains the same as that for the original data base.

Vehicle Doesn't "Fly Like an Aircraft": In the hover case, the basic prediction procedure was used to determine the effects of the addition of a first-order lag representation of actuator (or "effective" control system) dynamics. Early results, as shown in reference 9, follow:

Case	Actuator Time Constant	"Paper Pilot"	Other Pilot
PH3	0.10 sec.	4.14	4.0
FH3	0.50 sec.	5.93	6.0

More recent results in Reference 11 show an additional 48 different cases with simulated actuator lags, stability augmentation system lags, or both. Actual pilot ratings ranged from 2.5 to 6.0 in Cooper units, yet in only 6 out of the 48 cases did the "paper pilot" rating differ from the real pilot by more than one rating unit! The largest rating error was 1.69 units!

For pitch control, the same computer program that was used with the Hall data was applied directly

to predict similar "effective" control system dynamics, as presented in Reference 5, based upon NT-33 flight tests. The results for damping ratios greater than 0.3 are shown below (the cases are those presented earlier, only with the simulated actuator added):

Case	Actuator Time Constant	"Paper Pilot"	Two Other Pilots	
1D	.20 sec.	5.12	6	-
	.50	6.85	8	8
	2.0	9.44	8.5	8.5
6C	.125	3.76	5.5	-
	.303	5.30	5.5-8.5	7
	.80	6.63	6-8	8.5-10
2D	.083	2.43	4	-
	.20	2.79	3	-
	.50	3.50	5-6	5.5
	2.0	6.08	6	6
7C	.053	2.28	5.5	-
	.125	2.54	6	5
	.303	3.07	3-4-4	7-7-7
	.50	3.65	5	6
	.80	4.76	-	5
3A	.083	2.10	4.5	-
	.20	2.25	4	3
	.50	2.82	4	4
	2.0	5.72	4	4
8A	.053	1.91	3.5	-
	.125	2.55	3.5	3
	.303	3.18	2	4
	.80	3.22	2.5-3	5

With the exception of the 3A block of data (where the real pilots apparently were "unconcerned" about a two second time constant actuator!) these results are considered very good. Note that over all of the cases the predicted ratings span from 1.9 to 9.44 (Cooper-Harper Units), while the "other" (real) pilots' ratings vary from 2 to 10; clearly this approach <u>can</u> handle a large rating range with quite reasonable accuracy.

A final example of non-aircraft-like dynamics comes from Reference 11. In this hover task, the effects of artificial rate damping saturation were investigated. In turn, Paper Pilot was used with the nonlinear element replaced by its random process describing function. The results follow:

Case	"Paper Pilot"	Other Pilot
PN1	4.6	4
PN2	5.7	5.5
PN3	5.8	6

Based on this admittedly limited sample, the ability of the approach to handle nonlinear effects is rather dramatic at best, and worthy of further study at worst.

In summary, attempts to date to predict non-aircraft-like configurations with a procedure based <u>solely</u> on aircraft-like data have been successful.

<u>Control System Synthesis</u>: Having the capability to predict pilot acceptance for a specific flight task immediately suggests using the same procedure to design flight control systems. Reference 14 presents just such a procedure using the Pitch Paper Pilot. Briefly, a performance measure of the form:

$$J=R+k\sigma_s^2$$

is selected, where R is pilot rating (as predicted by Paper Pilot), k is a constant, and σ_s is the standard deviation of elevator deflection rate caused by the stability augmentation system (not the pilot). A digital computer program is used to find control system feedback gains (in this case for pitch rate and normal acceleration) that minimize J for a given value of k. Then as k is varied, a configuration is found that satisfies $\sigma_s \leq \sigma_a$ where σ_a is the allowed authority of the stability augmentation system. The result is an augmentation system providing the "best" flying qualities (minimum R) for the allowable authority.

The whole procedure has been programmed for the digital computer to provide an "automatic" system design. The system so designed gave the augmented-airframe characteristics shown in the following table (Reference 14):

Pitch Rate and Normal Acceleration Augmentation				
Flight Condition	"Paper Pilot" Design		MIL-F-8785B(ASG)	
(T-33)	(ω_n)	(ζ)	(ω_n)	(ζ)
1	6.71	.787	3.5-11	.35-1.3
2	4.69	.799	2.5-9.25	.35-1.3
3*	2.87	.748	1.5-5.6	"
4	9.93	.788	5.1-10.8	"
5	6.78	.812	4.0-10.3	"
6	4.03	.826	2.5-9.0	"
* = based on a 3 sigma elevator displacement limit of 6 deg. All the other cases lie on the 3 elevator rate boundary of 26 deg/sec.				

The resulting natural frequencies (rad/sec) and damping ratios for the six flight conditions of a T-33 aircraft fall in the mid range of allowable values.

The procedure can also be used (see Reference 14) to select augmentation authorities to meet a specified pilot rating value. Using this approach, design trade-offs become apparent.

In summary, the above results are very encouraging, suggesting that this method or some derivative of it can easily be used to synthesize flight control systems.

Atmospheric disturbances: As noted earlier, pilot models can be used to predict closed-loop performance under varying intensities of random turbulence (Reference 10). Since Paper Pilot also predicts this performance and ratings as well, the approach should be very useful in this respect. Only a few examples are available to date. One is shown below for hover (Reference 11):

Case	σ_g(ft/sec)	"Paper Pilot"	Other Pilots
PH13	2.6	2.08	2.5-2.5
PH16	7.7	3.90	4.75-4.75

where everything was the same except for the gust standard deviation, σ_g. The turbulence-induced rating degradation is predicted quite well.

Once the follow-on results to Reference 10 are available (this newer work includes longitudinal data) further examples can be prepared.

Reasons for the Requirement: Using the Paper Pilot approach, the reason for the requirement is quite apparent. That is, the pilot must be able to obtain good task performance (in the sense of root-mean-square tracking errors) with a minimum workload (in terms of pilot lead generation) before the flying qualities are considered acceptable. As atmospheric turbulence intensity increases, performance and rating degrade. If higher-order aircraft dynamics (e.g., actuator dynamics) necessitate increased pilot workload (lead), ratings will be degraded. The designer can examine the contribution of performance and pilot parameter to the rating. Thus, the reasons for the rating become very easy to understand for a given task requirement.

"PAPER PILOT" PROBLEMS

Certainly there is another side to the story. It can be told in three parts, namely: (a) technical problems associated with the accuracy of the method (prediction accuracy), (b) technical problems associated with implementation, and (c) basic concept acceptance.

The technical problem of prediction accuracy cannot be overlooked. In the case of hover, the method has never really "failed", in that it always produced a "rather accurate" estimation of actual pilot ratings. Pitch control applications have not been as successful. In particular, cases of low damping ratio and high natural frequency, as mentioned earlier, have posed a problem. More work is needed in this respect. Also, applications to more than one task at a time may not be possible. This is not really a problem for this method alone, however, since the current specification method is likewise limited. Secondly, perhaps applications to other tasks will not be as successful. This remains to be seen. Finally, Paper Pilot must have an accurately-defined control task. This is not always easy to establish.

Technical problems of application are, perhaps, more serious. In particular, just how one shows compliance with a "theoretical" requirement may be the biggest problem. The approach cannot be flight tested in the usual sense. That is, while a hardware-type pilot model might be mechanized, it would also take a "standard gust" day to verify a design directly. However, flight tests could be conducted to arrive at the best possible dynamic representation of the vehicle, and these data used as inputs to the computer program for a rating verification. Another approach would be to simulate gust inputs during

flight test, measure actual closed-loop performance with real pilots, and reduce time history data to obtain measured pilot parameters. Then the specified rating expression could be evaluated using these parameters to demonstrate compliance.

The final problem, concept acceptance, has been interesting. Comments on the alternate hover requirements discussed in Reference 9 ranged all the way from "great" to "ludicrous".

Paper Number 6 (Reference 6) discusses the general trend of replies to this alternate. In short, most constructive comments were of the type "... too new, not enough proof..." and "... cannot flight test to show compliance."

Nonetheless, it is known from private communications that several organizations in the United States are using the Paper Pilot programs, or very closely related pilot-vehicle analysis methods. In particular:

> Two aircraft companies have used the hover computer program. One checked the results against V/STOL aircraft flight data with "excellent" results. The other is using the program for company funded design studies.
>
> Another aircraft company is using similar procedures for all of its current systems designs.
>
> An autopilot manufacturer has developed his own version of the hover computer program, extending the method to include pilot remnant.

Specific company names have not been used above since formal reports documenting these programs are not presently available and some of the work itself is considered company proprietary.

Perhaps the best way, however, for individuals to weigh the overall concept is to use it. Paper Pilot computer programs are available for hover and for pitch attitude control. For copies of these write:

Paper Pilot
AFFDL/FGC
Air Force Flight Dynamics Laboratory
Wright-Patterson AFB, Ohio 45433
U.S.A.

Try it!

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LEAD DISCUSSION

by
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Introduction

The information contained in Mr. Anderson's presentation on "Theoretical Pilot Rating Predictors" is reviewed and some of the data analyzed and presented in a form different from that of the paper.

It is agreed that "the present method of specifying flying qualities leaves much to be desired" and some sort of analytical approach to the determination of what pilots like and dislike is sorely needed. I am sure that any pilot who has been through several handling qualities programmes during which the same task is repeated as closely as possible for each of a large number of characteristics will concur. Attempts in the past to correlate pilot ratings with performance indices or the placing of limits on a variety of closed loop parameters, having assumed a pilot transfer function, have met with only moderate success. The concept of combining both these approaches to predict pilot ratings directly, as is advocated by Mr. Anderson, is appealing and, intuitively, has merit. Unfortunately, the data presented in the tables do not appear to support the claims of success contained in the text.

A detailed analysis of one set of data was undertaken to test the claims made and is contained in this critique. Individual comments on the material are presented in the order of the original. Only the draft of the paper was available to this reviewer; hence, some of the comments may not be applicable to the final version. The reference numbers and table numbers are those of the original text while the lettered reference applies to this critique.

Maximum Pilot Ratings

Each component of the Paper Pilot Rating (PPR) in the first-mentioned experiment (hovering) was assigned a maximum value by Mr. Anderson as follows:

$$R_{1_{max}} = 2.5$$

$$R_{2_{max}} = 3.25$$

$$R_{3_{max}} = 1.20$$

When these were combined with the unity factor of the composite rating it was found that $R_{max} = 7.95$. However, the data shown subsequently contain ratings as high as 10! This discrepancy could not be resolved from the text.

Comparison of Actual and Paper Pilot Ratings

One of the criticisms of numerical pilot rating scales as opposed to adjectival scales is that statistical games will be played with numbers that are not statistically meaningful. If statistical indices are used they must be adequately enough defined to enable the reader to assess their validity and sufficient data presented to allow a check to be made of the results.

Table 1

The results presented in Table 1 (Ref 11, Table V) appear to fall into both these traps since neither the basic data were readily available nor were the terms defined. This reviewer interpreted the parameters "Mean Error" and "Error Standard Deviation" to be

$$\text{Mean Error} = \frac{\Sigma(\text{PPR} - \text{Actual Pilot Rating})}{\text{Number of Ratings}}$$

$$\text{Error Standard Deviation} = \sqrt{\frac{\Sigma(\text{PPR} - \text{Actual Pilot Rating})^2}{\text{Number of Ratings}}}$$

The first of these would always seem to be capable of erring on the low side, since any positive and negative errors would tend to compensate one another. A more meaningful index would be

$$\text{Mean Error}^* = \frac{\Sigma|\text{PPR} - \text{Actual Pilot Rating}|}{\text{Number of Ratings}}$$

but even this is of doubtful value. Having derived statistical evaluations of pilot ratings let us indulge in some to make a comparison with Mr. Anderson's claims.

Table 2

Figure 1 is a plot of the data presented in Table 2 of Mr. Anderson's paper. It is seen that the "Paper Pilot" is a very insensitive individual over the region of real interest in the rating scale - from 2 to 8 - and he would be well advised to take up another line of work. The distribution of the results appears to be merely scatter about a constant rating line of approximately 4 until agreement is finally reached (four times) in the upper right hand corner of the figure (Pilot Rating = 10). At that extreme the results are, in general, of academic interest only since the pilot and aircraft have long since parted company. However, the data were analyzed with all the points included and yielded the results summarized in the figure.

That is, the quantities defined were found to be:

Mean Error = 1.5

Mean Error* = 2.3

Error Standard Deviation = 3

If the Paper Pilot is assumed constant at the average of 4.64 the error standard deviation increases only 0.45 to 3.45.

In addition to these parameters, a least-squares linear fit was calculated for the data. It can be seen to be quite different from the line of perfect agreement and, indeed, has a slope of only 0.44 as compared with 1.0 for the perfect fit.

The standard deviation of the paper pilot ratings from the least-squares line (which apparently is a significant parameter) is defined as:

$$\sigma_{LS} = \sqrt{\frac{\Sigma(\text{PPR} - \text{Least Squares PPR})^2}{\text{Number of Ratings}}}$$

For these data

$$\sigma_{LS} = 2.04$$

To obtain a measure of how well correlated the PPR and the actual pilots' ratings were, a so-called Index of Correlation was computed (Ref A). This quantity is defined as:

$$r = \sqrt{\left[1 - \frac{\sigma_{LS}}{\delta}\right]^2}$$

where δ = standard deviation relative to a line parallel to the actual pilot rating axis through the average of the paper pilot ratings

$$\delta = \sqrt{\frac{\Sigma(\text{PPR} - \overline{\text{PPR}})^2}{\text{No. of Ratings}}}$$

$$\overline{\text{PPR}} = \frac{\Sigma(\text{PPR})}{\text{No. of Ratings}}$$

For the data of Table 2,

$$\delta = 2.56$$

Consequently, the index of correlation for the data was a very poor

$$r = 0.61.$$

To ensure that these indications of a poor statistical significance were not entirely due to differences between the two participating pilots, their ratings were compared as shown in Figure 2. Although this comparison was not conclusive, it can be seen that the least-squares line through the data comes very close to the line of perfect agreement but the scatter keeps the index of correlation fairly low at 0.85 which is still much better than the paper pilot's performance.

It would appear from observing the array of points in Figure 1 that one could almost match the performance of the paper pilot by merely assuming a constant pilot rating. When this was done at a rating of 4.64, the arithmetic average of the PPR's, the error standard deviation rose only 0.45 rating point to 3.45.

Considering these points leads one to the conclusion that the paper pilot does not do a good job with the data of Table 2.

Table 3

The data presented in Table 3 from an in-flight experiment reported in Reference 5 has been plotted in a similar fashion to that described above. Figure 3 compares the paper pilot with the real pilots while Figure 4 compares the pilots with each other. A statistical analysis of these data was not performed, but it can be seen readily that as a pilot the paper variety falls well outside the normal range of pilot-to-pilot variability. Once again he is insensitive to changes of the handling qualities and it would appear that a constant rating of approximately 2.5 would replace him nicely. Actually the least-squares linear fit does show a slight slope of 0.16.

No such criticisms can be made of the real pilots, since, although there is scatter in their ratings, each has the same trend. Mr. Anderson states that "with the exception of the low damping cases, 4A and 5A, (see Fig. 3) the results are fairly good." However, it is in the region of cases such as 4A and 5A - with pilot ratings of 5 to 7 - where pilots experience the most difficulty in arriving at a conclusion and a device such as the paper pilot would be most advantageous. When the characteristics are good the pilot can usually tell with a minimum of difficulty and when they get very poor there is no doubt of the numerical value to be assigned. This latter point is adequately illustrated by Figure 2 where the two pilots converge rapidly as a rating of 10 is approached. If the paper pilot fails in the difficult rating area it would seem to be of questionable value.

Results from Reference 11

Unfortunately, the data referred to in Reference 11 were not available to this reviewer, but the claims made concerning them in Mr. Anderson's paper are not surprising. The range of pilot ratings cited was from 2.5 to 6.0. If the paper pilot merely predicted the mid-point of this range, 4.25, the maximum error would never exceed 1.75. Hence, the statement that the largest error was only 1.69 does not indicate very startling results. The fact that only six out of forty-eight cases were in error by more than one unit is encouraging, however.

Table 5

The data presented in Table 5 are plotted in Figure 5 and are seen to indicate that the paper pilot is starting to learn a little more about conformity. No detailed statistical analysis was performed on these data due to a lack of time. Only a least-squares linear fit, which yielded a slope of 0.68, was calculated. It can be seen, however, that the paper pilot fairly consistently assigns values lower than those assigned by the real pilots and two fairly distinct levels, of approximately 3 and 6, seem to dominate the graph.

From the results of Table 3, it would appear that the performance of the paper pilot would be degraded significantly if the low damping cases (cases 4A and 5A) had been considered in Table 5. The exclusion of them from the analysis appears to be avoiding an area in which the paper pilot has difficulties.

Non-Linear Effects

The three cases presented in Table 6 indicate that the paper pilot holds some promise for the prediction of the influence of non-linear effects on handling qualities, but it may be premature to come to this conclusion from such limited data. Some types of non-linearities would, no doubt, cause at least as much difficulty for the paper pilot as they cause real pilots. An example of this is the problem encountered in several jet-VTOL aircraft where handling qualities appear to be satisfactory as long as the sideslip is held below a certain level. Exceeding this critical level, however, causes a rolling moment larger than that available from the roll control system and the pilot loses control. If the limit is not exceeded, acceptable or even satisfactory ratings can result, but pushing the manoeuvre just past the limit due to a more aggressive performance of the task or turbulence, for example, can produce an entirely unacceptable pilot assessment. Warning devices such as rudder pedal shakers and stick pushers are used to alleviate such problems and how the paper pilot could account for the very non-linear problem and the almost mathematically indescribable fixes is not appreciated.

Table 7

It would appear that a constant damping ratio of 0.8 would be as useful as those selected by the paper pilot. This value happens to land almost exactly in the centre of the MIL-F-8785B(ASG) results shown in Table 7.

Paper Pilot Problems

Mr. Anderson has pointed out several of the difficulties with the paper pilot approach which seem to this reviewer to almost invalidate its usefulness at its present stage of development.

Limited Task

Like all analytical approaches to handling qualities criteria, certain pilot inputs and outputs must be assumed. The real pilot responds to so many different parameters, the weights of which are a function of the phase of the task (and are, in any case, unknown), that it is not surprising that the paper pilot must be limited to a single task to achieve any semblance of success. An accurately defined control task, as required by this system, represents a very small percentage of the flight regime of any aircraft.

Verification of Paper Pilot

It is submitted that the paper pilot rating system can be put to the test by exactly the procedures outlined above to verify its usefulness. That is, meaningful comparisons with actual pilot ratings obtained from flight testing with such devices as variable stability and actual aircraft.

Acceptance

This reviewer is convinced that all that is necessary for a reliable analytical method of predicting pilot ratings to gain acceptance is to be able to show that it works. Certainly, the pilots involved would be more than happy if they could avoid the repetitive operation of data acquisition presently used and such a tool would bring even the least imaginative handling qualities research engineers and aircraft designers a flurry of excitement.

The basic difficulty of any analytical approach in trying to replace the extremely complex sensing instrument called the pilot is that the latter is able, with varying degrees of success, to assess the importance of a myriad of parameters. These, for example, range from how the aircraft responds to control inputs and external disturbances to the difficulties encountered in reaching a particular switch at a particular time during the exercise.

Nevertheless, a paper pilot predictor producing positive postulations presents possibilities and should be pursued.

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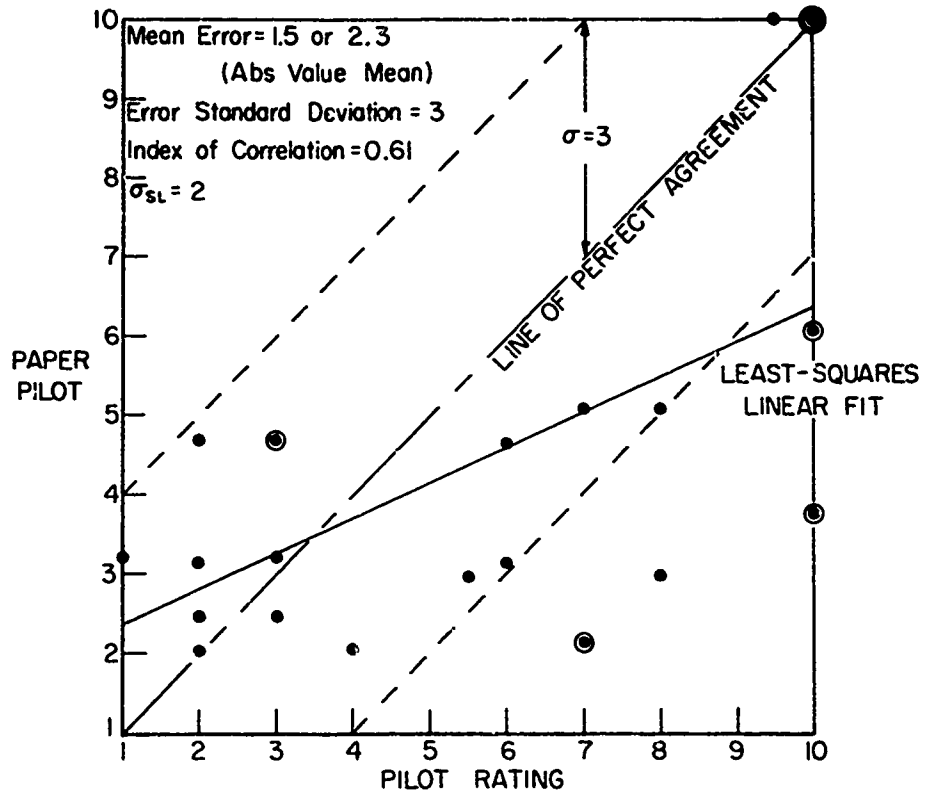


FIG 1 COMPARISON OF "PAPER PILOT" WITH REAL PILOT RATINGS - TABLE 2

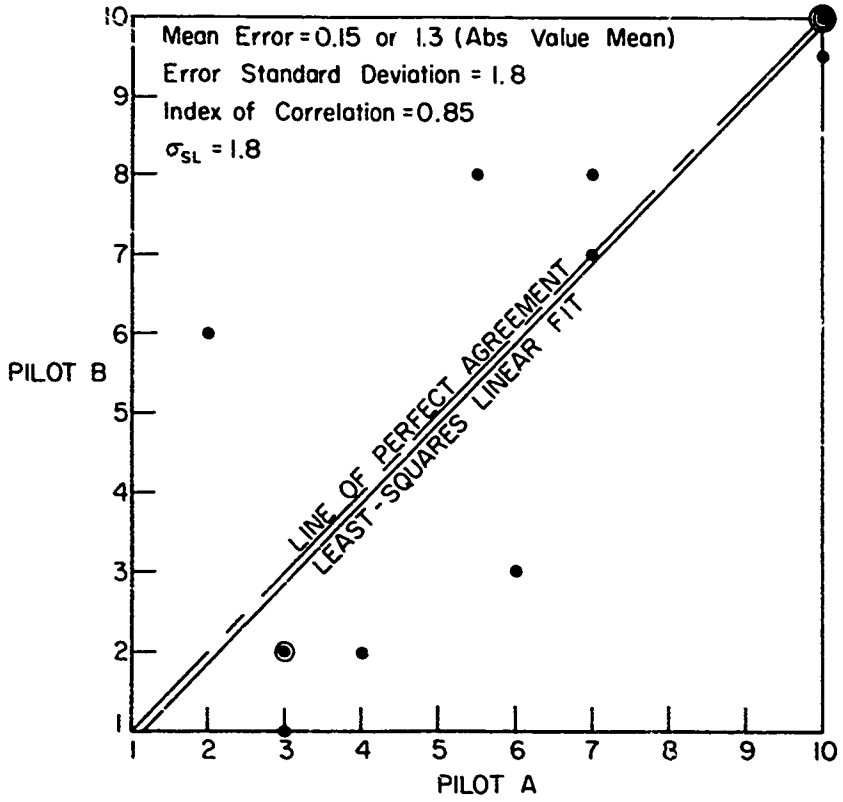


FIG 2 COMPARISON OF TWO REAL PILOTS - TABLE 2

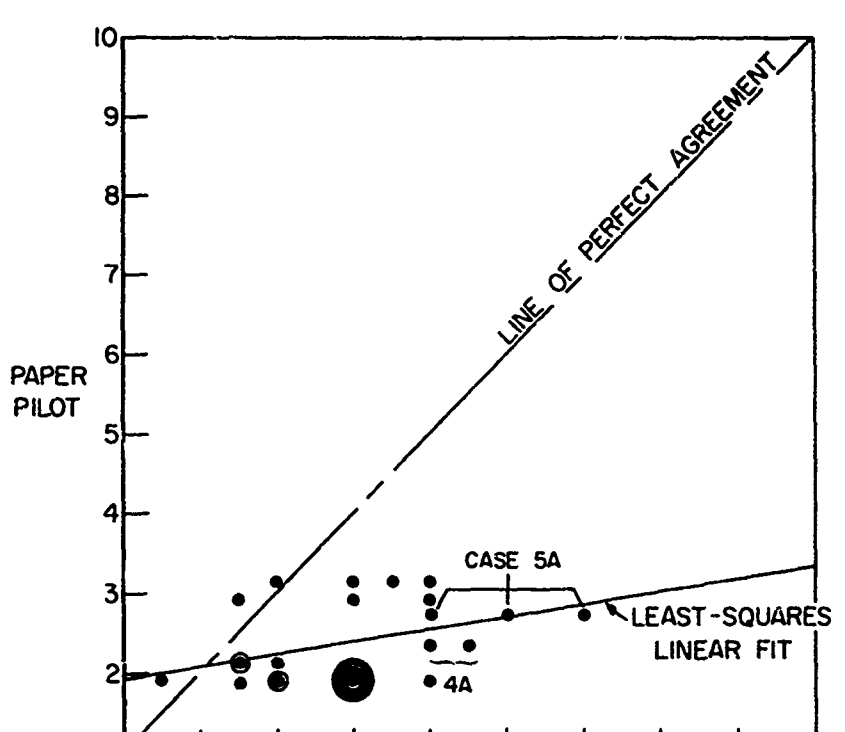


FIG 3 COMPARISON OF "PAPER PILOT" WITH REAL PILOT RATINGS - TABLE 3

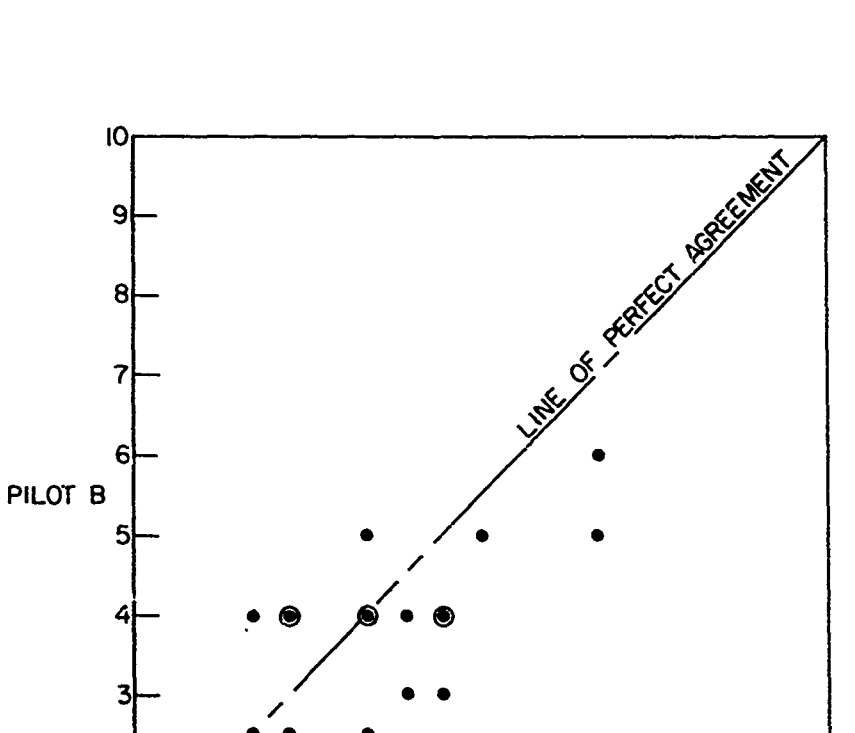


FIG 4 COMPARISON OF TWO REAL PILOTS - TABLE 3

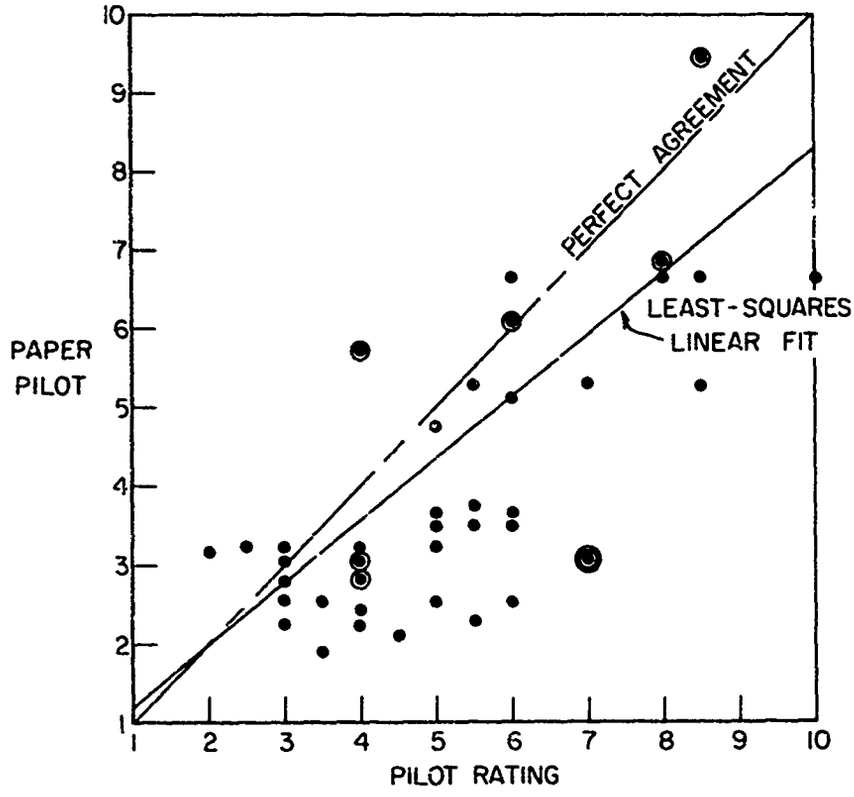


FIG 5 COMPARISON OF "PAPER PILOT"
WITH REAL PILOT RATINGS - TABLE 5

RECENT U.S. NAVY FLYING QUALITIES RESEARCH

by

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SUMMARY

This paper presents the results of U.S. Navy sponsored flying qualities research conducted over the past five years. Inflight variable stability airplane investigations were conducted in simulated carrier approaches to determine the effect of the principle Flying Qualities Parameters on approach performance. Limits have been established on the values of the major longitudinal and lateral-directional parameters, to insure good carrier approach characteristics. In addition to the carrier approach studies, moving base simulator investigations were conducted to further develop PIO criteria, and extend the aircraft maneuvering potential at high angles-of-attack. The inclusion of maneuvering force gradient and/or stick sensitivity has been determined as a requirement for a meaningful PIO criterion.

LIST OF SYMBOLS

g - Gravitational Acceleration Constant - 32.2 feet/sec/sec.

F_s - Longitudinal Stick Force - Pounds.

L_β - Dihedral Effect - Rad/sec/sec/Rad.

L_{δ_e} - Incremental Lift Due to Elevator Deflection - feet/sec/sec.

L_{δ_a} - Incremental Roll Due to Lateral Control Deflection - Rad/sec/sec/in.

M_{δ_e} - Incremental Pitching Moment Due to Elevator Deflection - Rad/sec/sec/in.

N_{δ_a} - Incremental Yawing Moment Due to Lateral Control Deflection - Rad/sec/sec/in.

n_z - Aircraft Normal Load Factor - g units

$n_{z/\alpha}$ - Normal Load Factor Per Unit Angle-of-Attack - g per rad.

V - Flight Velocity - feet per second

$1/T_{h_1}$ - Altitude Reversal Parameter - 1/sec.

α - Angle-of-attack - Deg or rad.

τ_{r_m} - Roll Mode Time Constant - sec.

τ_{SP} - Spiral Mode Time Constant - sec.

τ_t - Thrust Response Time Lay - sec.

ω_{SP} - Short Period Frequency - rad/sec.

ω_d - Lateral Directional Frequency - rad/sec.

ω_{ST} - V/STOL Longitudinal Short Term Mode Frequency - Rad/sec.

ζ_{SP} - Short Period Damping Ratio.

ζ_d - Dutch Roll Damping Ratio.

ζ_{ST} - V/STOL Longitudinal Short Term Mode Damping Ratio.

γ - Flight Path Angle - Deg.

INTRODUCTION

U.S. Navy flying qualities research has traditionally proceeded along two broad lines. First, emphasis is put on seeking answers to those flying qualities problems peculiar to Naval aircraft and secondly to contribute to the solution of flying qualities problems of general interest, particularly when a unique Navy capability or facility exists.

The operation of an aircraft from a ship at sea is probably the most unique and well known of Navy peculiar problems. The landing of a high performance aircraft aboard a carrier has often been described as the most demanding and dangerous of all routine aircraft operations. It therefore follows that a considerable amount of Navy flying qualities research is directed toward improving the safety and operational capability of future carrier based aircraft.

Utilization of the human centrifuge at the Naval Air Development Center (NADC) as a flying qualities simulator to investigate spins, high angle of attack maneuvering and PIO criteria is representative of research efforts undertaken to exploit a unique Navy facility. These programs are again aimed at improving the safety and operational capability of tactical aircraft, a goal which has always motivated the establishment of Navy flying qualities research objectives.

This paper summarizes the results of Navy sponsored flying qualities research over the past five years. Due to space limitations, only the highlights of the various programs can be presented. Those interested in more detailed results and analyses are invited to consult the references from which the material presented herein was derived.

DISCUSSION

Carrier Approach:

During the past several years, the carrier approach problem has been under intensive attack both analytically through the use of pilot models, and experimentally in ground based simulators and variable stability aircraft. The impetus behind this continued research effort has been to reduce the carrier landing accident rate, which has historically exceeded the land based accident rate by a factor of ten or greater. The present paper discusses the results obtained utilizing the Princeton Variable Stability Navion in simulated carrier approaches.

Experimental Procedure:

The variable stability airplane used in these tests was a single engine, propeller driven, two place North American Navion. A complete description of the airplane and its variable stability and turbulence simulation system is given in reference (1). Basically, the system provides independently variable forces and moments about five axes; only the side force characteristics of the airplane are not alterable. However, the lateral directional simulation was not compromised since the sideforce characteristics in slideslip of the test airplane were comparable to those of current jet fighters, the class of airplane which was being simulated. The airplane's dynamic, control, and turbulence response characteristics may therefore be modified over a wide range. The basic evaluation task was a simulated landing approach to an aircraft carrier. The simulated approaches were made to the Princeton runway having a width of 70 feet, corresponding to the painted area of a carrier deck. Glide slope information was provided by an optical landing aid which simulated the Fresnel Lens Optical Landing System used on all Navy carriers. A diagram of the flight procedure appears in Figure 1. With the exception of the variable approach speed tests to be discussed later, all approaches were flown at an approach speed of 105 knots airspeed approaching a carrier with 30 knots of wind over deck. The entire simulation, including the artificial turbulence, has been rated by Navy carrier qualified pilots to be quite representative of the task.

Longitudinal

The longitudinal control task in carrier approach requires extremely tight control of altitude and airspeed while tracking an optical glide path display which increases in sensitivity as the aircraft nears the landing spot. This in turn involves the interaction of all of the aircraft longitudinal response and control modes. These have been studied singularly and in combination with the following results:

Short Period Frequency and Normal Acceleration Response:

It has now become accepted that the basic parameters governing the longitudinal response characteristics are the short-period frequency and the normal acceleration per unit angle of attack. In order to establish limits on these parameters, several flight investigations were conducted and reported in references (2), (3), and (4) with the results as shown in Figure 2. Also included to demonstrate the consistancy of the data are selected points from an U.S. Air Force study utilizing the Cornell Variable Stability T-33. The flight data are compared with the results of a recent U.S. Navy sponsored moving base simulator study of reference (5). It can be seen that while the flight data are all consistent and agree well with the simulator data for the lower frequency values, the higher frequency boundary of the simulator tends to be extremely conservative. This difference may be due to two methods used to fix the control system characteristics in the simulator and the aircraft. In the aircraft the control displacement gradient was held constant, thus as the frequency increased, the maneuvering gradient (Fs/g) increased, while at the same time the pilots were allowed to choose the optimum control sensitivity. In the simulator, the gradient was held constant at 12 pounds per g, thus as the frequency increased, so did the control sensitivity. This resulted in a tendency for "nose bobbling" at the higher frequencies, even with the high value of airframe damping ($\zeta = .7$) that was used.

The results of the simulated carrier approach tests are also compared with the current U.S. Military Specification, reference (6), in Figure 3. These data substantiate the specification requirements, within the limits of the variable stability Navion ($n_{z/\alpha}$ less than 3.3 cannot be obtained due to limited flap travel).

Tail Lift

The adverse effect of tail lift on tight altitude control, was suspected to contribute to the piloting difficulties, particularly in close-in situation, where the sensitivity of the optical landing aid was increased. In order to verify this thesis, a brief flight investigation was conducted. The basic short period characteristics were selected to meet the Level 1 requirements of reference (6), as shown in Figure 4 and the value of the tail lift parameter ($L_{\delta_e}/V/M_{\delta_e}$) was evaluated at zero and -.1. The results indicated that the Pilot Rating varied markedly as a function on the pilot technique and background. In those cases where the pilots noted tail lift problems, they described the effect as floating or lofting on push-over and settling on pull control. The maximum value of the tail lift parameter of -.1 resulted in an average Pilot Rating degradation of one rating unit.

Flight Path Stability and Thrust Response

The longitudinal short period characteristics and tail lift investigations established limits on the parameters governing the short term altitude response of the aircraft. The reference (7) investigation also undertook to determine limits on the long term altitude response characteristics, namely flight path stability and thrust response. The values of the flight path stability parameter $1/T_{h_1}$ and engine thrust lag were varied over a broad range, while maintaining the short period characteristics as shown in Figure 4. The results of this investigation are compared with the requirements of reference (6) in Figure 5. The data indicate that for reasonable values of engine thrust lag, the specification requirements are adequate, but as engine lag increases, pilot altitude control problems increase, and the aircraft is barely acceptable, even though the flight path stability meets the Level 1 requirements. While acceptable characteristics can still be obtained with the present generation turbofan engines, future engine developments will have to be closely watched to insure that allowable thrust response lags are not exceeded.

Approach Speed (Closure Rate)

There is a continuing tendency to correlate increased carrier landing accidents with increased approach speed. One such correlation, taken from reference (8) is shown in Figure 6. In an attempt to isolate the effects of approach speed on carrier landing performance a study was undertaken where the closure rate was varied from 95 knots to 125 knots, while maintaining constant values of the aircraft dynamic characteristics. A comparison of height at the ramp (a key carrier landing parameter) between the results obtained with the variable stability airplane and those obtained in actual carrier operations is shown in Figure 7. It can readily be seen that within the accuracy of the data the approach performance of the test airplane agrees with that obtained in operational use. It was concluded in reference (9), that based on 80 recorded landing approaches, that no significant correlation, positive or negative, of carrier landing accident rate with approach speed could be formulated from the results of these tests. Thus the effect of approach speed is still open to question.

Lateral - Directional

While glide path control is of paramount importance in the carrier approach, the lateral-directional characteristics are not to be neglected, particularly with respect to heading control. An arrested landing off center by more than 15 feet can cause severe damage to an aircraft. In order to establish limits on the basic lateral - directional characteristics, the investigations of references (1) and (10) were undertaken. Although these experiments included investigations of lateral control sensitivity, a lateral control power, yaw due to lateral control, only the effects of basic dynamic response characteristics will be discussed here; however, a thorough treatment of these topics can be found in the references.

Figure 8 presents the effect on Pilot Rating for variations in rolling time constant, τ_{rm} and dihedral effect, L_β at near optimum control sensitivity, with zero yaw due to lateral control. The resulting iso-opinion lines indicate that it is desireable to have a little stable dihedral effect, but not too much. The higher values of L_β are undesireable due to the increase turbulence response of the aircraft, while the low effective dihedral results in large yawing motions, which could result in a landing accident. The higher values of roll time constant cause precise control of bank angle to become difficult. Having established limits on L_β and τ_{rm}, the effect of dutch roll frequency, ω_d, on Pilot Rating was investigated. As shown in Figure 9, there exists a maximum and minimum value of this parameter. Again the maximum value is associated with excessive turbulence response; however, in this case the minimum value of ω_d is associated with the inability to maintain heading. Of particular note is the steep gradient of Pilot Rating as the frequency is decreased below one radian per second. Experience with several carrier aircraft exhibiting low dutch roll frequencies has born out these results.

LOW ALTITUDE HIGH SPEED FLIGHT (LAHS)

The results of a Navy sponsored moving base simulator study in the LAHS flight regime presented in reference (11), caused considerable discussion among the experts at the time. These results indicated that there was no upper frequency limit, with regard to the short period dynamics, a conclusion that was in direct conflict with existing variable stability airplane data. In order to clarify this apparent discrepancy, an F-8D aircraft was fitted with a specially modified Lear-Siegler Autopilot which provided a variable frequency damping capability and short period frequencies comparable to those investigated in the reference (11) simulator study. During the time between the inception of the F-8D program and its readiness for flight, other investigators had shown that the upper frequency boundary does exist and that it is a function of the load factor to angle of attack response (n_z/α). Reference (11), never attained frequency values high enough for the large value of n_z/α that was used in the tests. However, it was decided to pursue the F-8D flight tests in order to help fill the void in the amount of flight data in the LAHS region. The results as obtained in reference (12) are compared with the reference (11)

simulator data in Figure 10. The flight data show reasonable agreement with the simulator data at the higher frequencies, but poor correlation at the lower frequency values. However, a word of caution concerning the applicability of the flight results is in order. The characteristics of the autopilot introduced a "real root" in the frequency range interest, thus the classic second order system now becomes third order, with effectively attenuated response characteristics. This in turn accounts for the sluggish pilot rating at the lower frequencies. It is not known how much the "real root" influenced the pilot assessment at the higher frequencies. The presence of the "real root" should not invalidate the flight data, as the pilot rating and pilot commentary are still valid for a system with these characteristics. What remains to be done is to compare the results of reference (12), with those obtained on a "pure" second order system so that one may better determine how to establish handling qualities requirements for higher order systems.

In order to make the PIO criterion of reference (11) more readily useable, a refinement of the basic boundaries was proposed in reference (13). This refinement put forth a PIO criterion which was a function of the time to damp to one-tenth amplitude and maneuvering force gradient and longitudinal stick sensitivity. While considerable substantiating data were presented in reference (13), the soundness of the criteria is still in dispute. In order to shed additional light on the PIO problem, the moving base simulator sutyd of reference (14) was conducted.

This investigation utilized the Naval Air Development Center (NADC) human centrifuge as a moving base simulator. The centrifuge was constrained to the gimbals only mode, that is only pitch and roll rotational degrees of freedom were present; however, this should not have affected the validation of the results. As pointed out in reference (14) simulator correlations with actual flight data were excellent for non-PIO flight conditions. The results of the reference (14) study are shown in Figure 11, where excellent agreement with the reference (13) criterion is indicated. One of the principal conclusions of reference (14) is that the inclusion of maneuvering force gradient and/or stick sensitivity as used in reference (13), is necessary in a meaningful PIO criterion.

SPIN SIMULATOR

The continuing loss of high performance aircraft to stall/spin accidents led to the conclusion that if a realistic ground based spin simulator could be developed, intensive pilot training and proficiency could be maintained, which should result in reduced aircraft losses. With this goal in mind, a program was undertaken utilizing the human centrifuge at NADC, to answer two basic questions. First, is spin simulation feasible? Second, if it is feasible, then what degree of fidelity must the simulator have, to be an effective trainer?

The answer to the first question was affirmative, as indicated in reference (15). To illustrate the characteristics of the simulator, a typical spin time history is shown in Figure 12. Shown in Figure 12 are the pilot control actions during an actual spin encountered in an F-4 aircraft, and a similar spin in the simulator. The agreement is quite good, even with regard to timing of the control applications. Several experienced pilots agreed the simulator characteristics were very close to those encountered in flight.

In order to get an answer to the second question, that of degree of fidelity, the simulator was run in the following three modes:

1) Static - no motion.
2) Gimbals only - rotational motion.
3) Fully dynamic - dynamic force field.

As can be seen in Figure 13, which was obtained from reference (16), the majority of the pilots rated the fully dynamic mode excellent. However, the gimbals only mode may be realistic enough to be used as an effective spin trainer, thereby reducing the cost of such a device considerably.

CURRENT FLYING QUALITIES PROGRAMS

A program has recently been initiated to develop V/STOL flying qualities criteria, utilizing the variable stability X-22A V/STOL aircraft shown in Figure 14. This program is being conducted by Cornell Aeronautical Laboratory under joint NASA, U.S. Air Force and Navy sponsorship, with the Navy as the lead agency. The initial program will be a STOL landing investigation, both visual and instrument, to determine the effects of approach angle and closure rate on aircraft dynamics requirements. The test matrix for this investigation is shown in Figure 15. Future programs will include lateral - directional STOL investigations, as well as transition and hover.

Another current program of interest is the determination of flying qualities criteria to insure adequate tracking accuracy during high angle of attack maneuvering. This investigation will be performed on the human centrifuge simulator at NADC. The results will stress pilot tracking performance, as well as pilot rating, with the objective of developing meaningful criteria in this flight regime.

CONCLUSIONS

1. Through systematic investigations in the Princeton Variable Stability Navion, the effect of the principle Flying Qualities Parameters on carrier approach performance have been determined, and limits established on the values of these parameters to insure good carrier approach characteristics.

2. Additional moving base simulator data further substantiate a previously proposed PIO criterion and that such a criterion should include maneuvering force gradient and/or stick sensitivity as a parameter.

3. A realistic high fidelity spin simulator has been developed. This simulator should be an excellent tool for further investigations of post stall and incipient spin criteria to fully utilize the aircraft

maneuvering potential in flight at high angle of attack.

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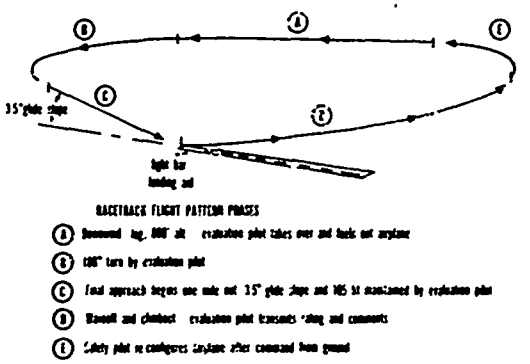


FIGURE 1 PRINCETON NAVION FLIGHT PATTERN
(FROM REFERENCE 1)

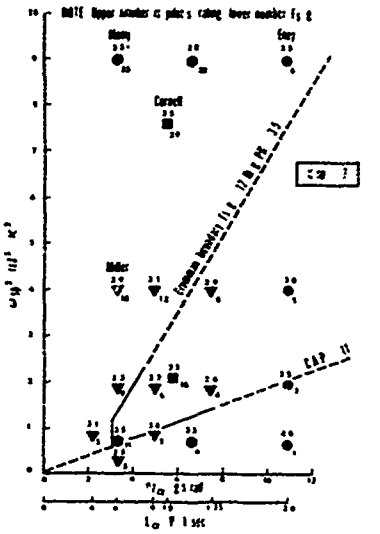


FIGURE 2 PILOT RATING AND STICK FORCE PER "g" COMPARISON
(FROM REFERENCE 4)

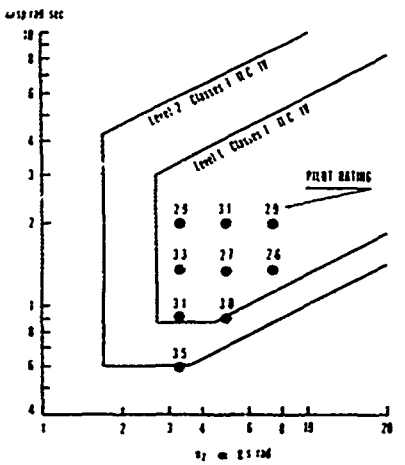


FIGURE 3 COMPLIANCE OF CONFIGURATIONS
WITH REFERENCE (6)
(FROM REFERENCE 4)

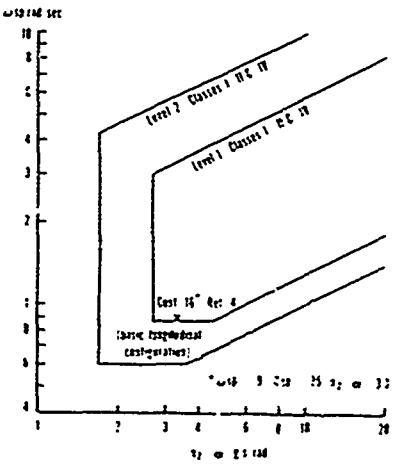


FIGURE 4 COMPLIANCE OF TAIL LIFT
CONFIGURATION WITH REFERENCE
6 REQUIREMENTS
(FROM REFERENCE 7)

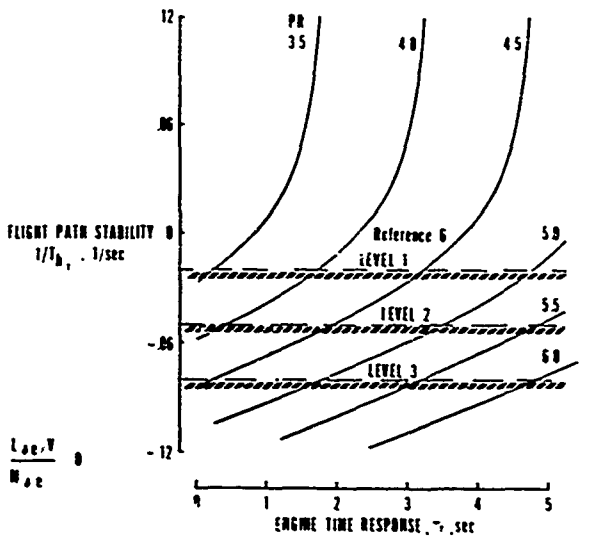


FIGURE 5 COMPARISON OF TEST RESULTS WITH REFERENCE
6 FLIGHT PATH STABILITY REQUIREMENTS
(FROM REFERENCE 7)

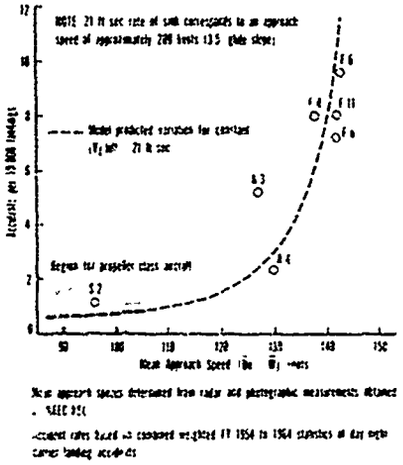


FIGURE 6 IMPLIED ACCIDENT COORDINATION OF REFERENCE 1 (FIGURE 12 OF REFERENCE 8)

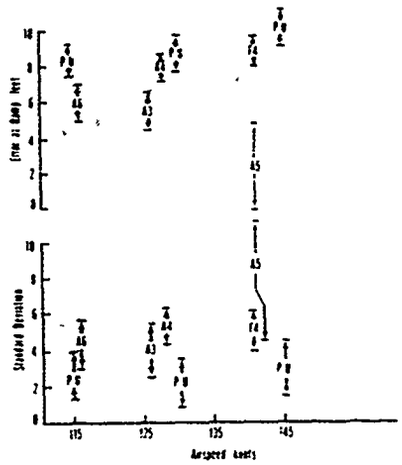


FIGURE 7 COMPARISON OF HEIGHT AT RAMP DATA (FROM REFERENCE 9)

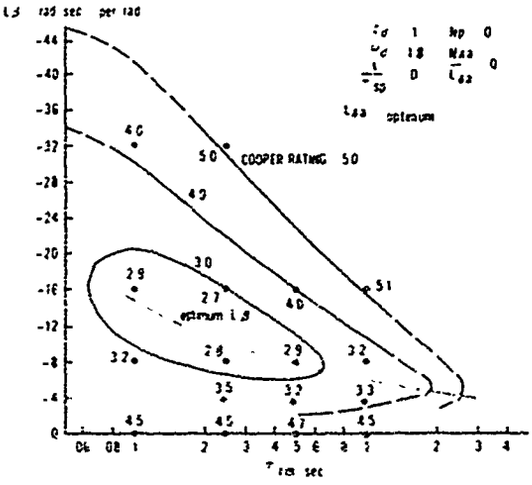


FIGURE 8 LATERAL FLYING QUALITIES BOUNDARIES (FROM REFERENCE 1)

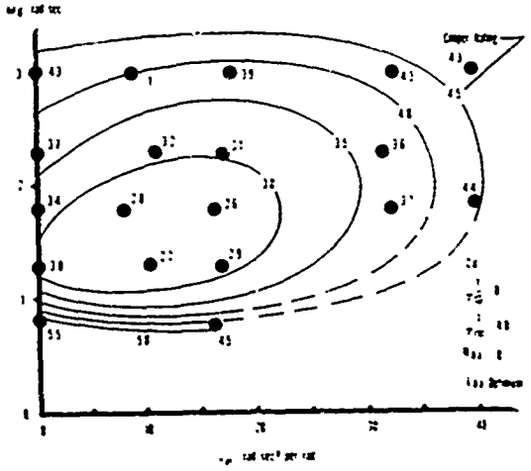


FIGURE 9 EFFECT OF [illegible] ON PILOT RATING AND LATERAL SUPPORT ON FLIGHT SIMULATOR (FROM REFERENCE 10)

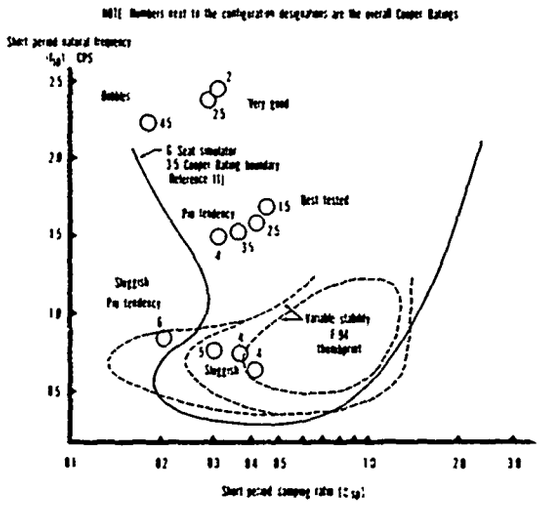


FIGURE 10 LAHS DATA COMPARED WITH REFERENCE(11) DATA (FROM REFERENCE 12)

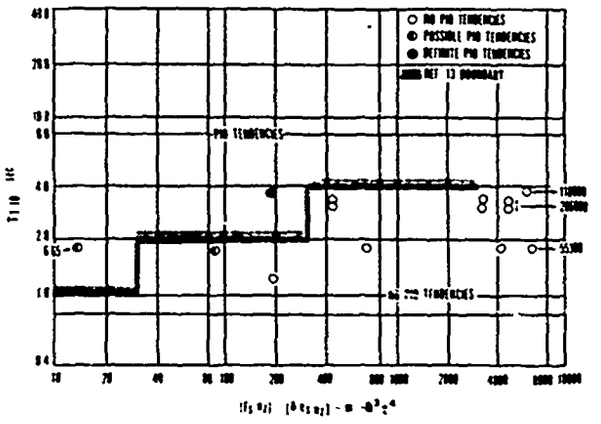


FIGURE 11 COMPARISON OF NADC SIMULATOR RESULTS WITH REFERENCE 13 BOUNDARY (FROM REFERENCE 14)

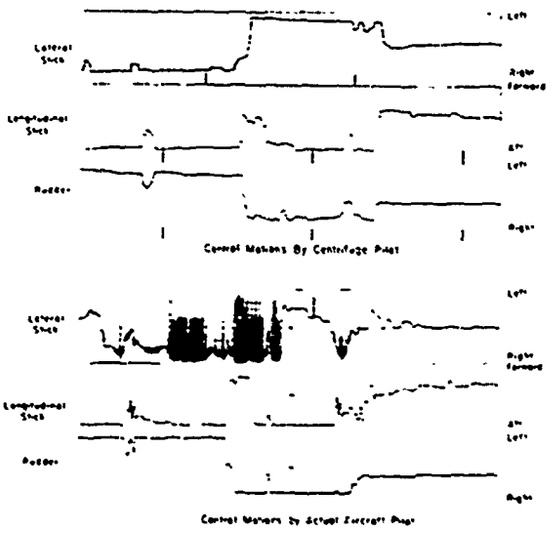


FIGURE 12 COMPARISON OF AIRCRAFT AND SIMULATOR PILOT CONTROL ACTIONS (FROM REFERENCE 15)

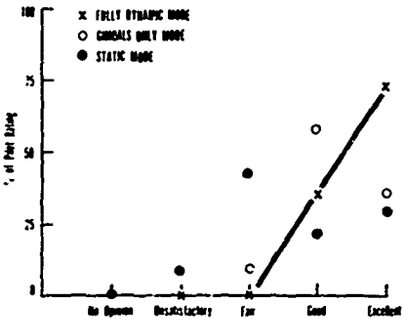


FIGURE 13 RATING OF SPIN SIMULATOR MODES (FROM REFERENCE 16)



FIGURE 14 X-22A VARIABLE STABILITY AIRCRAFT

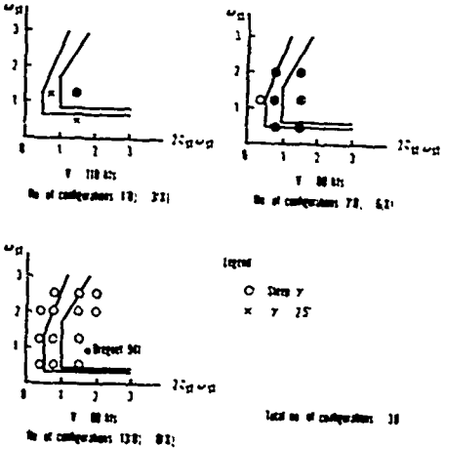


FIGURE 15 X-22A FLIGHT PROGRAM EVALUATION CONFIGURATIONS

LEAD DISCUSSION

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Mr Siewert's paper has reviewed a very wide-ranging research programme on flying qualities requirements. To do it justice would require more time and space than a lead discussor is allowed, so some selection is necessary. The first part of the paper is concerned with the particular requirements of carrier-deck-landing aircraft and is the topic on which this reviewer feels best qualified to comment. The second half of the paper, on the other hand, is not strictly concerned with Naval aviation (although the work was sponsored by the US Navy) but touches on a variety of topics, any one of which could become the subject for heated debate between experts.

The cause and cure of pilot induced oscillation problems in low-altitude, high speed flight, is such a topic. Mr Siewert himself has made a significant contribution in this field, but, as he says, the soundness of his proposed criterion is still in dispute. The later simulator data from NADC (Reference 14) confirms the proposed criterion, as Figure 11 shows, but there is flight data, from the Air Force Flight Dynamics Laboratory, for example, that reports unacceptable PIO tendencies in conditions well inside the "no PIO tendencies" zone of Figure 11. This later work deals with the effects of higher order control system dynamics and so should be comparable with the F-8D data.

It would be interesting to hear Mr Siewert's views on this situation. It does seem to us, in RAE that reviewing and correlating other workers' handling qualities data is just as important as producing new data. Any proposal for a new criterion simply must take account of all earlier data, unless there are good strong reasons for rejecting some of it.

Just a brief word on the spin simulator results before getting on to the more strictly Naval aspects of the paper. The results which Mr Siewert reports are certainly encouraging, and the objectives very worth-while. One suspects that the numbers of aircraft lost during spin investigations and in training are comparable with those for genuine inadvertent spins in Service. It is not clear from Figure 12 whether the simulated spin refers to a particular aircraft, or is simply a typical example. We believe that the F-4, for example, can show a variety of spin characteristics, requiring different recovery actions. If such a training simulator can teach the pilot how to recognise what type of spin he has to contend with, real progress will have been made. But, is it thought that the input data, particularly the rotary derivatives, and at extreme angles of attack and sideslip, will be good enough to reproduce these various forms of spin correctly?

The first half of Mr Siewert's paper deals with problems that are more familiar to this reviewer, as a one-time member of a small group that was formed in RAE in 1943. It was abundantly clear then that the carrier deck landing manoeuvre was, as Mr Siewert says "the most demanding and dangerous of all routine aircraft operations". Landing accident rates were frighteningly high in those early days - up to 25% on some early war-time operations - and there was a desperate need to help designers to produce better deck landing characteristics, as well as to see if procedures could be improved.

This small group studied the Naval pilot's problems throughout the whole period of change-over from propellers and tail-wheels to jets and tricycle gears, through new deck-landing techniques, angled decks and the introduction of the first optical glide path indicator - the mirror landing aid.

When we began this work, handling qualities research, as such, had scarcely been born, so we started with the simple observation that some aircraft had a good reputation for deck landing, others were rated "bad". Accident statistics helped in this grading process, but experienced pilot opinion was heavily relied upon. The problem then seemed simple enough - to find what characteristics made the pilots happy, and what must be avoided.

First, a simple framework of rules was drafted. In the handling area, these were concerned with items such as the lift and trim changes due to power adjustment, the time to climb from one glide path and settle on a higher one, the time to bank and stop at a new angle and the time to perform a sidestop manoeuvre, and so on. Then, by direct measurements on several samples each of the "good" and "bad" aircraft, we attempted to put numbers to these requirements.

This was elementry stuff, of course, and no dramatic changes in the state of the art were expected or realised, though we collected a lot of data on what went on during actual deck landings. But today's emphasis on the detailed parameters, derivatives and coefficients which define these manoeuvres contrasts strongly with our former pre-occupation with the manoeuvres themselves. There seems to me to be some danger of losing sight of what, exactly, the pilot needs to be able to do. The definition of frequencies, damping ratios, control powers, time constants, etc, is of immediate help to the designer, but do they necessarily define a good deck-landing aircraft, and does failure to meet one or more of these criteria necessarily define a bad one? This question becomes particularly relevant as control systems become more complex (e.g. manoeuvre demand etc.).

The question being asked is whether the precise tasks against which the pilot ratings are assigned, and the acceptance standards for the finished product, are sufficiently closely related to what the good typical deck-landing aircraft should be capable of doing. In order to be sure that the criteria now being developed are really relevant to the real deck-landing task, one would like to see a lot more data from

actual landings on the nature of the longitudinal and lateral manoeuvres that are now required, and on the pilot's inputs and responses. Simulation, both ground-based and in-flight, is a valuable tool, but one would like to see more evidence of validation using real operational experience.

Great care has obviously been taken to make the variable stability Navion experiment as realistic as possible. But, of course, several features must have been omitted. The "deck" did not move nor did it have "hard" edges. Real turbulence generated by the ship is intense but very localised, not uniform throughout the approach. The prescribed approach path is just clear of it - but only just. The mean sink rate of 11 ft/sec on the approach meant that the Navion could not carry on to touch down as a real Navy aircraft could have done. A wave-off, or at least a flare had to be performed, and the data of Figure 7 suggest that this was already under way at the ramp, the Navion being higher than usual at that point.

This suggests that the evaluation proper must have concluded before reaching the ramp, and have been confined to the 30 seconds or so of steady approach. This, of course, is very short by conventional approach assessment standards. A lot would depend on the evaluation pilot's skill in making an accurate turn on to the final glide path. Were deliberate errors introduced here, to force some element of manoeuvring during the final 30 seconds? Only average pilot ratings are quoted in the paper. Could poor ratings be related to the amount of manoeuvring that was demanded? It does seem to us that this is an evaluation exercise where more than ordinary care is needed to define the task precisely. This is particularly so, I suggest, when comparing the results of real or simulated deck-landing studies of desirable characteristics with those from ground-based simulators. You cannot reproduce the "tight-rope act" environment of an actual deck-landing in a simulator, but, against this, the assessment period can be made to last as long as the pilot wishes. If it is too long, he may apply different standards. For instance, we found, when first looking at the problem of flight on the back-side of the drag curve, back in 1950, that all our Naval jet aircraft then landed happily with quite marked negative speed stability, (time constants of 20 seconds or less), whereas their shore-based counterparts were much less tolerable. It was argued that some speed divergence did not matter too much for the short final carrier approach, but did bother the pilot on a long straight approach for a couple of minutes or more, ashore.

The above remarks are not intended to decry the value of the impressive amount of data that the Navion experiments have produced. Much of it shows gratifying agreement with Mil Spec 8785. But without careful scrutiny of all the quoted references, the message in some of the examples, given by Mr Siewert is not too clear. At first sight, Figure 2, for instance, implies that, given the freedom to chose the optimum stick force per 'g', almost any combination of frequency and damping can be made acceptable - all the points get a rating of 4.0 or better. The Navion used values from 3 to 18 lb/g in the simulated carrier approach tests, yet all received about the same rating - 2.6 to 3.5. What should the designer aim for?

It would be surprising if the importance of manoeuvring force gradient (stick sensitivity) in the carrier approach has not already been studied, as it has been in relation to the low-altitude, high speed phase. There are obvious differences in the two tasks, and perhaps one of the more important is the duration - the carrier approach lasts only 30 seconds or so, whereas the LAHS task could, in principle, go on for hours. But it is interesting to note the pilots' comments about "nose bobbling" in both the limiting cases illustrated in Figures 2 and 10. They occur at frequencies differing by a factor of about 5. The quoted explanation of the pilot's problem in the carrier approach case is that the stick force per g was not the optimum in the ground-based simulator tests, whereas the Navion pilots could choose the best force gradient. In the sense that the "nose bobbling" tendencies in the ground-based simulator were not reported in flight when higher stick force/g levels were used, these results seem consistent with the principle of the PIO criterion. It would be interesting to know whether further analysis of the carrier approach requirements along these lines has been made or is proposed.

On the whole, however, the trends indicated by the Navion tests all look reasonable. It is particularly reassuring to see that attention is drawn to the importance of engine thrust response - there is a potential problem area here, which engine designers need warning about. Unfortunately, this question of thrust control seems to fall into one of those "grey" areas, between the airframe and engine designers' spheres of responsibility.

Finally, one comes back to accident rates, which is what this work is really all about. The rates are still too high, but not so high, surely, that we can treat them like any other statistic, and seek some correlation with a simple parameter like approach speed, as was attempted in Reference 8. Every accident is an individual event, separately investigated and a prime cause determined. Even if all the data on Figure 6 referred to heavy landings and undercarriage failures only, there would be no reason to expect any correlation with approach speed over a range of aircraft. The specific studies with the Navion, to which Mr Siewert refers (Reference 9) shows that, other things being equal, approach speed, per se, does not affect the accident rate. Many other factors affect the risk, and some of these factors can change the accident rate with no change to the aircraft at all. The angled deck and mirror landing aid, together, reduced the rate to 1/3 its former value, and these innovations were introduced in the time period covered by the data in Figure 6.

The present Paper has been concerned with flying qualities, seeking improvements that will reduce these risks. The optima we are looking for are certainly elusive - they may even be non-existent - so how does one know when to stop?

OPEN DISCUSSION

R.O. Anderson, AFFDL, USA

We have looked at some of the F-8 data that Mr. Siewert mentioned using paper pilot approach. For the power approach configurations, the Paper Pilot predictions of pilot rating were in quite good agreement with the F-8 results. For the low altitude, high speed cases however, the machine ratings were very nearly constant, but real pilot ratings varied quite a lot. It seemed that pilot rating was almost directly correlated with total short period damping, and we are now using this trend to predict ratings when the short period natural frequency is high, and the damping ratio is small, say, less than three-tenths.

R.F. Siewert, U.S. Navy

Beware that the F-8 data is not classical second order.

R.P. Harper, Cornell Aero, USA

Could Mr. Wanner or Mr. Deque comment on the backside during approach shown in Mr. Siewert's Fig. 5 with respect to the Concorde?

J-C. Wanner, France

The figure 5 seems to be very close and I don't see any large disagreement.

W. Bihrle, Grumman, USA

We found that we could put the pilot well on the backside and surprisingly the pilots had little difficulty. We did this experiment on a moving base simulator. At the time we were missing engine audio cues and therefore this was a conservative result.

Regarding Mr. Siewert's comments about being diabolical, we really were trying to be diabolical. We first establish the validity of the parameter ω^2_n/N_{Z_α} and then we restricted ourselves to values which would be involved during the landing task.

A few points regarding ω^2_n/N_{Z_α}, (1) the lower boundaries are unique values and apply throughout the flight regime, because it is based on the threshold value of human perceptibility of angular acceleration, and (2) damping ratio per se, anything over .15, plays a very small function in terms of the ability to perform control tasks.

H.A. Mooij, NLR, Netherlands

I agree with Mr. Bihrle's comments.

What about direct-lift-control? .and N_Z/α and $\frac{1}{T_{\theta 2}}$.?

R.F. Siewert, U.S. Navy

The direct-lift-control is only a vernier control in our application. The debate between N_Z/α and $\frac{1}{T\theta_2}$ is still underway.

I.L. Ashkenas, Systems Technology, Inc., USA

The issue of $1/T\theta_2$ versus n_{z_α} which has been raised is something I don't want to get involved with here. However, I would like to point out that there is an alternative explanation for Mr. Siewert's Fig. 6 which shows a model-predicted accident probability versus $1/T\theta_2$ rather than versus approach speed (as in Fig. 6). The historical trend of $1/T\theta_2$ has been down while approach speed has been going up. The physical significance of $1/T\theta_2$ is that it theoretically constitutes a measure of the path-following bandwidth or time-response. Accordingly, low values imply larger path-following errors, greater dispersions and increased accident probability. Furthermore, in some special tests conducted at NATC, Patuxent, we actually measured the lags in manual following of a quasi-randomly disturbed optical beam for a variety of service aircraft. The results were consistent with theory in that aircraft with low values of $1/T\theta_2$ exhibited larger lags than those with high values.

RECENT NASA HANDLING QUALITIES RESEARCH

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SUMMARY

A comprehensive review of NASA research results documented since the mid-1960's and some recently completed programs on aircraft handling qualities are presented. In addition to handling qualities research pertaining to vehicle stability and control characteristics, investigations related to specialized piloting tasks, cockpit displays, and environmental factors are summarized. The background leading to NASA's handling qualities research activities is discussed, and programs that have received major emphasis are indicated. For general aviation aircraft, the survey includes investigations aimed at improving handling qualities by incorporating increasingly sophisticated stability augmentation and display systems, simplifying the approach and landing task for relatively inexperienced pilots, and establishing the basic effects of turbulence. Research on the specialized piloting problem of steeper instrument approaches for noise abatement and investigations with a representative first generation aircraft are reviewed in the section on subsonic jet transports. Supersonic cruise aircraft programs include a variety of simulation studies related to supersonic transport designs and flight tests with the XB-70 aircraft. Investigations of high angle of attack loss of control problems and a flight study of direct lift control utilization for formation flying and aerial refueling are discussed in the review of tactical military aircraft research. The section on powered-lift STOL aircraft summarizes the flight research investigations with eight experimental aircraft and the supporting ground-based simulation studies. For VTOL aircraft, the survey includes research on the handling qualities of helicopters, hovering and low-speed characteristics of jet VTOL's, displays and advanced stabilization systems for IFR approaches to an instrument hover, and flight tests of experimental aircraft.

1. INTRODUCTION

The purpose of this paper is to review NASA's recent research on aircraft handling qualities. Where appropriate, the review will include the background which led to various handling qualities research activities, will indicate the programs which received major emphasis and the manner by which individual investigations were related to an overall effort, and will outline some of the primary program results and conclusions. Although representative data will be presented, it is not an objective of this review to discuss in detail any single research investigation or group of studies. Such information can be obtained from the references cited.

Classically, handling qualities research has emphasized the aircraft's stability and control characteristics, and research results for the most part have been formulated in terms of vehicle responses to pilot control inputs or parameters related to aerodynamic stability. In recent years, however, the introduction of sophisticated augmentation systems and cockpit displays, the renewed recognition of the importance of atmospheric turbulence and other environmental factors, and the delineation of specialized piloting tasks have resulted in an expanded concept of handling qualities. In Reference 1, Cooper and Harper define handling qualities as "those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role". They also point out that, in addition to stability and control characteristics, the task, pilot's stress, cockpit interface, and aircraft environment are factors that influence handling qualities. This broad definition of handling qualities is used to establish the scope of NASA's research which will be reviewed in this paper.

Handling qualities research documented since the mid-1960's forms the primary basis for this paper. In addition, the review includes some programs that have been completed but not yet fully reported and several that are still underway. The paper is organized according to an aircraft type/mission categorization and discusses NASA's research for general aviation aircraft, subsonic jet transports and supersonic cruise vehicles, tactical military aircraft, powered-lift STOL aircraft, and VTOL vehicles.

2. GENERAL AVIATION AIRCRAFT

In the early 1960's, NASA initiated a flight evaluation of a representative cross section of general aviation aircraft. One of the primary objectives of this investigation was to assess the handling qualities of this class of aircraft for a variety of operations, with particular empnasis on instrument flight and ILS approaches in adverse weather conditions. The seven general aviation aircraft used in this study included both high- and low-wing configurations and were single- and twin-engine powered. As reported in Reference 2, the evaluations by a large sample of pilots indicated that, for visual flight and during instrument flight in smooth air, the handling qualities were satisfactory. However, atmospheric turbulence degraded the handling qualities, the effect being most noticeable during ILS approaches where the increase in pilot workload made precise instrument tracking difficult even for experienced instrument-rated pilots. At about the time the seven general aviation aircraft flight evaluations were being completed, a separate flight investigation was being conducted (Reference 3). This investigation showed that with the aid of a simple wing-levelling stability augmentation system, a non-instrument-rated pilot was capable of sustained instrument flight and limited radio navigation, permitting recovery to visual flight conditions from an inadvertent instrument situation. These two flight studies pointed out the importance of the instrument flight operation in turbulence and indicated the potential benefits of augmentation systems. The results of these studies were used to form the basis for most of NASA's recent general aviation handling qualities research programs.

A concentrated effort has been underway for several years to investigate possible improvements in the handling qualities of general avaiation aircraft by incorporating increasingly sophisticated stability augmentation and display systems. Flight evaluations have been made with a six-place, low-wing, twin-engine aircraft that is representative of personal-owner general aviation aircraft involved in instrument flight operations. The initial study investigated the use of cockpit-displayed angle of attack information during low-speed flight operations, including take-offs and climbs, maneuvers, and both visual and instrument approaches. As reported in Reference 4, the flight evaluation exposed certain fundamental complications with this display that tended to negate some of the expected advantages. For ILS instrument approaches, the use of the angle of attack display did not significantly alter either the pilot's workload or the degree of accuracy with which the task could be performed. In the next phase of this program, a yaw damper combined with an aileron-to-rudder interconnect for turn coordination was tested. The evaluation included flights with the yaw-damper-interconnect system operating concurrently with the aircraft's basic autopilot in both the heading-hold and wings-leveler modes. Although the system improved the lateral-directional handling qualities of the basic aircraft and both autopilot modes during visual and instrument flight in light-to-moderate turbulence, and reduced the pilot's workload during ILS instrument approaches, the improvement in the pilot's overall performance of the ILS approach task was not significant. The yaw damper was effective in reducing aircraft motions during stalls and simulated engine failures, and provided the pilot with more time to take corrective actions. Reference 5 documents this flight investigation.

The most recently completed research in this program evaluated rate and attitude command control systems and advanced displays. The command control systems were installed in the pitch and roll axes. During the investigation with the rate system, the flight tests were conducted with a rate damper in the yaw axis. During the study of the attitude command system, a yaw-heading-hold control loop incorporating an automatic cutout switch for turning maneuvers was incorporated in addition to the yaw damper. In both cases an aileron-to-rudder interconnect was utilized for turn coordination. The advanced displays included a horizontal situation indicator with a course deviation bar and an attitude indicator with flight director command bars and both glide slope and localizer error information. Figure 1 shows the increasingly significant handling qualities improvements achieved in these tests. As reported in Reference 6, the combined use of the advanced displays and attitude command control system transformed the representative general aviation aircraft into a vehicle that bordered on being perfect from a handling qualities standpoint during ILS approaches in turbulence. Other effects of the command control systems, including gust alleviation and responses during stalls and after sudden engine failures, were evaluated and are discussed in Reference 6.

As part of its general aviation program, NASA is sponsoring investigations by several universities and research groups. The investigations are aimed at improving the performance and control characteristics of light aircraft and simplifying the approach and landing task for relatively inexperienced pilots. These programs, still in progress, are considering revised aerodynamic configurations and new aerodynamic control devices. Reference 7 reviews the status of one effort that includes a new wing design with spoilers for lateral control to eliminate adverse yaw effects and, by symmetrical deflection, for direct lift flight path control during the landing approach. Another program, described in Reference 8, concerns the design of a light aircraft that would fly at a constant pitch attitude and would require a minimum of pilot commands for satisfactory operation. In a third program, spoiler/dive brake systems are being studied for flight path control during the total landing task including approach, flare, touchdown, rollout, and go-around. Design characteristics of several spoiler controllers and results from preliminary flight evaluations are reported in Reference 9. Figure 2 presents the range of pilots' ratings of their touchdown point accuracy obtained during early VFR investigations to optimize a single lever integrated throttle-spoiler controller. These tests established desirable design characteristics of the flight path control system and indicated the potential benefits from utilization of spoilers.

A basic investigation of the effects of turbulence on handling qualities has been in progress under NASA sponsorship for several years. Although not specifically directed toward general aviation aircraft, the study has used a variable stability light aircraft and is most appropriately reviewed in this section of the paper. In this program,

in-flight evaluations have been made to determine the independent and interacting effects of turbulence-induced aerodynamic disturbances and aircraft dynamic response parameters. The first investigation, involving the lateral-directional mode, used an IFR heading control task and studied the influence of the magnitudes of roll and yaw disturbances, turbulence spectral bandwidth, and correlation between roll and yaw disturbances. During this phase of the program, the aircraft's roll damping, directional stability, Dutch roll damping ratio, and aileron yaw characteristics were selectively varied. Reference 10 summarizes the lateral-directional investigation, which is reported in detail in Reference 11.

In the more recent study, reported in References 12 and 13, an ILS approach task was used to determine the effects of turbulence on longitudinal handling qualities. Variations in the magnitudes of both pitch and heave disturbances, turbulence bandwidth, short period dynamics, and lift curve slope were evaluated. Figure 3, shows the significant influence of the pitch disturbance magnitude on pilot ratings. In addition to presenting experimental data, both References 11 and 13 include closed-loop pilot-aircraft systems analyses which substantially support the pilot rating results and the flight test performance and workload data.

NASA's recent general aviation program has included a university team's review of the NACA/NASA-generated literature that has been published since 1940 and is considered applicable to the design of light aircraft. The survey of published information on performance, stability and control, and handling qualities is contained in Reference 14.

3. SUBSONIC JET TRANSPORTS

Recent NASA handling qualities research related to subsonic jet transports has been concentrated primarily in two areas – the special piloting problem of steeper instrument approaches for noise abatement, and handling qualities investigations with a representative first generation subsonic jet transport. The background and reasons for each of these programs are different and will be reviewed separately.

NASA initiated preliminary flight studies of steeper approaches with conventional fixed-wing aircraft in the early 1960's. The interest at that time was for potential reduction of noise under the approach path and reduced terminal area airspace requirements. The tests used three widely different aircraft – a C-47, T-33 and DC-8F – to determine the capabilities of both aircraft and pilots to make steeper-than-normal instrument approaches, to establish the maximum glide slope for operational use, and to isolate problem areas. Special equipment used in the program generated straight glide slopes for most of the approach followed by flare path guidance to touchdown. As reported in Reference 15, the investigation indicated that the maximum operational glide slope for the three aircraft was 6 degrees. This angle allowed a margin for steepening the flight path without airspeed increases to take care of gusty conditions, wind shear, and other inadvertent flight path deviations. Although the pilots felt that 6-degree instrument approaches with flare path guidance could be flown consistently down to 100-foot altitudes, there was careful qualification in Reference 15 that this conclusion was based on the clear weather and good visibility conditions of the tests.

The increased awareness in the mid-1960's of the subsonic jet transport noise problem in the vicinity of airports brought about an intensified NASA program on steeper approaches. Since experimental measurements indicated that the larger portion of the total noise reduction was caused by the reduced engine power associated with the steeper approaches, the program became an investigation of flight procedures for approaches at reduced power settings that would be safe for day-to-day operations by pilots of average skill. Two factors influenced the next research effort that was undertaken. First, to be operationally practical, the steeper approach profiles had to be within the capability of a wide spectrum of jet transports; second, the day-to-day operations, unlike the preliminary tests noted above, had to include bad weather conditions. Consequently, six jet transports ranging from a twin-engine executive aircraft to a four-engine intercontinental commercial transport were used to investigate single- and two-segment steeper approach profiles under simulated 200-foot-ceiling instrument flight conditions. The aircraft varied with regard to the type of flight director display installed, autopilot capability for coupled approaches, and availability of an autothrottle. A progress report on these tests is contained in Reference 16, and the final results are documented in Reference 17. Although the flight evaluations of more than 600 approaches confirmed the earlier result that 6 degrees was the maximum usable glide slope and was within the capability of each aircraft tested, the program essentially concluded that the pilot's tracking performance and overall workload on the steeper approaches were unacceptable for day-to-day routine use.

Reference 16 reported observations representing an extrapolation of the then-current work. One of these was an indication that improved methods of flight path control were needed. This led to a separate flight evaluation of the use of direct lift control as an aid to flight path control during the steeper approaches. Using an available US Navy F-8C aircraft with a DLC system modified from the configuration previously used in carrier landing studies, these tests indicated favorable effects of DLC (especially when used in conjunction with automatic speed control) on piloting performance and workload for both single- and two-segment steeper approaches. The results of this flight study are reported in Reference 18

The research program reported in References 16 and 17 used basically unmodified operational jet transports. In order to determine the importance and benefits of various possible aids to the pilot for improving his tracking performance and reducing his workload, a major combined simulator study and flight investigation with a highly modified

research jet transport was undertaken. The systems evaluated in this program included specialized pitch flight director computations, an autothrottle, automatic pitch trim follow-up, a pitch rate-command/attitude-hold system, a cathode-ray tube integrated display, direct lift control and lateral-directional stability augmentation. In both the simulator and flight tests, single-segment, two-segment, and deceleration approach profiles were used, the latter two being evaluated by a total of 11 pilots from NASA, the FAA, and a commercial airline. Reference 19 presents preliminary results of a portion of the total program. Additional information is contained in References 20 and 21, and the complete investigation is documented in Reference 22.

It was determined from this research that two-segment noise abatement approaches could be flown in the modified jet transport with the same precision as a conventional instrument landing approach without a significant increase in the pilot's workload. The relative importance of the systems evaluated in the tests was established for the two-segment approaches, and information was obtained about the piloting problems for the other noise abatement approaches. It must be noted, however, that in this program a complete evaluation of noise abatement approaches under adverse operational conditions, including bad weather and equipment failures, was not made.

The most recently completed NASA research related to steeper approaches involved flight studies of an alternate concept for providing flight path guidance information to the pilot. A graphic vertical situation display with a pictorial analog of the glide slope profile and an aircraft symbol with attached velocity vector was tested in a small twin-engine aircraft. The method by which the display was implemented is described in Reference 23, and the test results are summarized in Reference 24.

In the mid-1960's interest in very large subsonic jet transports for both military and civil airline use led to a NASA program on the landing approach handling qualities of the response characteristics expected for such aircraft. Results from the ground-based and in-flight simulator study are reported in Reference 25. During the same time period in which this investigation occurred, NASA research on the handling qualities of supersonic transport designs was underway. Although the published literature did not contain extensive flight measured data and associated pilot evaluations for operational transports, one of the design objectives for the large subsonic transports and the supersonic transports was that their handling qualities should be as good or better than those of the jet transports then in service. The availability of a first generation jet transport led to a recent NASA flight program aimed at documenting its handling qualities and response characteristics to provide a data base for comparisons with future proposed handling qualities criteria.

As part of the documentation program and because of its importance in transport design, the lateral control capability needed for maneuvering during approaches and landings was investigated. By mechanically limiting the pilot's control wheel rotation, the roll control power available to him was varied. Simulated lateral offset approaches were performed at altitude in addition to simulated instrument approaches to a 200-foot visual-breakout altitude with a subsequent 200-foot offset correction and actual landing. The results of the investigation are reported in Reference 26, which also includes comparisons of the experimental data with several proposed roll criteria and with the results of related studies. As shown in Figure 4, the two test techniques did not produce the same results for reduced roll control power configurations, indicating that the actual approaches were more demanding than the simulated maneuvers at altitude.

In the main documentation program, four pilots evaluated the handling qualities of the four-engine jet transport under VFR conditions while performing typical transport operational maneuvers within the aircraft's normal operating flight envelope. At specific flight conditions, pilots also rated individual aircraft response modes, such as the phugoid, short period, spiral and Dutch roll, as well as the longitudinal and lateral maneuvering control characteristics. The results of the flight evaluations and comparisons of the experimental data with various handling qualities criteria and requirements are reported in Reference 27.

Reference 28 documents the results from a flight investigation of generalized roll requirements for transport aircraft in cruise flight. The study was performed with a modified Jet Star general purpose airborne simulator incorporating a model-controlled variable stability system and was the first handling qualities research effort using this in-flight simulator. At the time the investigation was performed, the aircraft was not cleared for low altitude operations with the variable stability system functioning; consequently, the flight evaluations were formed for only the up-and-away cruise condition. Figures 5 and 6 show some of the results obtained in the investigation of a wide range of roll time constants and levels of roll control power. Extensive comparisons of the experimental data with the results of other tests and with several flying qualities specifications and proposed criteria are contained in Reference 28.

4. SUPERSONIC CRUISE AIRCRAFT

NASA's research efforts on the handling qualities of supersonic cruise aircraft have involved two types of investigations, namely, a variety of simulation studies concerned with different potential problem areas related to several flight regimes and flight testing of a large supersonic aircraft. The primary impetus for this research was the commercial supersonic transport development programs.

The supersonic transport simulation studies performed by NASA in the early 1960's were generalized investigations of stability and control characteristics that might result in handling qualities significantly different from those

of the first generation subsonic jet transports. At that time, NASA's theoretical and experimental aerodynamic programs were exploring the performance capability of several supersonic transport configurations, including fixed-geometry delta-wing designs and variable-sweep configurations. The evolutionary nature of the aerodynamic studies limited the availability of detailed stability and control data for the simulation programs. Early handling qualities efforts included the ground-based simulation (Reference 29) of variations in longitudinal parameters for a delta-wing design and a combined ground-based and in-flight simulation investigation of lateral-directional characteristics of variable-sweep configurations, both studies being concerned with the instrument approach and visual landing task. Reference 30 summarizes the experimental results from the lateral-directional tests, with a more detailed description of the program and additional analyses of the results documented in Reference 31. The lateral-directional investigation was supported by the theoretical pilot-vehicle analyses reported in Reference 32.

By mid-1960 the fixed-geometry and the variable-sweep designs were still in contention for the US supersonic transport development, and a major NASA in-flight simulation program was undertaken to investigate the acceptability of the handling qualities of each design for instrument landing approaches. The test configurations included the unaugmented aircraft responses for both designs and the characteristics expected from different stability augmentation system mechanizations. The variable-sweep design was also evaluated with an aft center of gravity location and for an emergency landing with the wing in its cruise-sweep position. Reference 33 describes the program and presents correlations of the experimental data with military flying qualities specification requirements and several proposed handling qualities criteria for transport aircraft.

Also underway during the mid-1960's was a joint NASA-FAA study directed at the interactions and problems associated with supersonic transport flights operating under air traffic control systems procedures. A NASA ground-based simulator was linked by telephone lines to an FAA air traffic control facility simulator, and both departures and arrivals were made under ATC control. The investigation resulted in experimental data on several potential operating problems, including aircraft overspeeds as reported in Reference 34 and 35, and also indicated flight path control difficulties for the pilot during supersonic climbs and descents. The benefits of a more sensitive pitch attitude indicator and vertical flight path command guidance information for supersonic operations are reported in Reference 36. Thrust management problems noted in Reference 36 also provided additional motivation for the general simulation study (Reference 37) which investigated the use of displays presenting rate of change of speed, potential flight path angle, and potential rate of climb for improved thrust control by the pilot.

Recent NASA simulation programs related to supersonic transports have been primarily concerned with the take-off and final landing flare maneuvers. Reference 38 reports the results of a fixed-base simulator study on the influence of different ground-effect characteristics during the landing flare of a delta-wing supersonic transport configuration. As shown in Figure 7, the pilots' evaluations were influenced by the magnitude of the control force required to flare the aircraft and by whether the nose-down trim change in ground effect was apparent prior to flare initiation. The investigation documented in Reference 38 included pilots' assessments of the ground effect characteristics for both a subsonic jet transport and an ogee-wing modified F5D-1 aircraft for comparison purposes.

Ground-based simulation programs on supersonic transport take-off characteristics have been underway by NASA since the mid-1960's, initially with a fixed-cockpit and more recently with a large amplitude moving-base simulator. Although the factors of primary interest in take-off simulations are usually considered to be aircraft performance characteristics, handling qualities have an influence on the pilot's task performance. Earlier research, reported in Reference 39, established the requirements for valid take-off simulations and achieved successful duplication of take-off certification tests using characteristics of a subsonic jet transport. Preliminary results from the study of take-off characteristics for delta-wing and variable-sweep supersonic transport configurations are contained in Reference 40, and a detailed description of the fixed-base simulation program for a double-delta design is presented in Reference 41. The most recently reported effort relates to a joint NASA-FAA program with British and French participation that was aimed at the development of certification criteria for supersonic transport take-off. Reference 42 presents some of the results from the moving-base simulator investigation that has involved reference performance, abused and operational take-offs. The simulator's use in developing an accepted airworthiness requirement for the minimum climbout speed with one engine inoperative is discussed in Reference 42, and data are presented on pilot action times during simulated refused take-offs.

A systematic parametric study of minimum longitudinal handling qualities for transport-type aircraft at cruise conditions was recently performed in flight with the modified Jet Star general purpose airborne simulator. Although the investigation was not directed specifically at supersonic transport handling qualities, the results are considered to be potentially applicable to certain failure mode situations for such aircraft. The pilots' evaluations of the effects of control column feel characteristics, short period damping, and static stability, including negative static margin levels, were made under daylight VFR conditions in smooth air. These evaluations included assessments of several maneuvers as well as typical transport cruise tasks. Figure 8 presents the primary study results that were obtained with a constant pitch control effectiveness and a constant force-deflection gradient. The data indicate that for the conditions of the evaluations a transport could have acceptable handling qualities for failure mode operations with some static instability if the damping was sufficient. Several test conditions near the minimum stability boundary were reevaluated in the flight investigation by changing the control feel gradient and gearing and it was found that the basic control characteristics used in the primary evaluations were generally within the range of values selected as best by the pilots.

During the 1960's NASA participated with the USAF in joint flight tests of the XB-70, a large supersonic cruise aircraft. In the early envelope-expansion flight testing of this aircraft, an emergency occurred at a Mach number of 2.6. During the ensuing deceleration and descent, a low frequency unstable pilot-induced lateral-directional oscillation was experienced when the stability augmentation system was turned off. Reference 43 discusses the events leading to the pilot-induced oscillation and presents an analysis of this handling qualities problem. The preliminary handling qualities evaluations made during the initial XB-70 flights are reported in Reference 44 which also contains comparisons of the experimental data with several proposed handling qualities criteria for transport aircraft. In the late 1960's, an extensive research program was performed with the XB-70, emphasizing aerodynamic, propulsion, and structure technologies and some handling qualities problems. Although the study of landing approach handling qualities was not a primary objective in this program, data were obtained from approaches and landings made at various approach speeds and with different glide slope angles and lateral offsets. Reference 45 summarizes the flight experiences with the XB-70 during landing approaches and presents the handling qualities data acquired during the tests.

The primary results from pilots' evaluations of the XB-70's handling qualities throughout the entire flight envelope are summarized in Reference 46 and compared with various handling qualities criteria based on different stability and control parameters. Figure 9 shows the trend of pilot ratings for two piloting tasks with the parameter determined by the longitudinal short-period natural frequency and the normal acceleration change per unit angle of attack. This was found to be the best parameter for correlating XB-70 longitudinal ratings, including those for an accurate altitude and speed hold task performed during sonic boom tests. Reference 46 also presents data on the roll rates experienced in various flight phases during routine XB-70 flying which indicate that the highest roll rates occurred in landing approach maneuvers. A more detailed statistical survey of the XB-70's responses and control usage is reported in Reference 47.

5. TACTICAL MILITARY AIRCRAFT

Two reviewable programs involving research on handling qualities of tactical military aircraft were conducted during the 1960's by NASA. The first involved investigations related to loss of control at high angles of attack and post-stall spin-entry behavior. In the second program, flight evaluations were made to study the potential benefits of direct lift control in formation flying and aerial refueling.

Concern about the relatively poor handling qualities of several tactical military aircraft at high angles of attack and their poor stall and spin characteristics led to a recent NASA research program involving wind tunnel tests, analyses, and simulation. Flight time histories illustrating the directional divergence, or "nose slice", response experienced with a swept-wing fighter at angles of attack near the stall are presented in Reference 48. This report contains static wind tunnel test results for the basic aircraft and also for configuration modifications aimed at delaying or eliminating the instability. In addition, it presents an analysis indicating the dynamic characteristics of the observed "nose slice" divergence. The essential character of the divergence was reproduced in the investigation (Reference 49) that indicated a fixed-base simulator could be used to study stall and spin characteristics of fighter aircraft. A description of a recently developed ground-based simulator suitable for tactical military aircraft handling qualities research is presented in Reference 50.

The extensive mid-1960 interest in direct lift control as a means of improving longitudinal handling qualities during landing approaches of Naval carrier aircraft and large jet transports was the motivation for a NASA flight investigation of the potential application of DLC in the up-and-away flight regime. A variable-stability fighter was modified so that in addition to their use for roll control the ailerons could be deflected symmetrically as DLC flaps. Flap actuation was integrated with the pilot's control stick, and the flap-horizontal-stabilizer interconnect ratio was selected by the pilot to achieve the best overall response. The first series of flight tests indicated that the pilot's vertical stationkeeping task during formation flying could be eased significantly by using the integrated DLC controller. These tests were followed by an evaluation of the effect of direct lift control and pitch damping augmentation on the precision and ease of performing the in-flight refueling task. Actual hookups with a jet tanker were made using the probe-and-drogue refueling method. Figure 10 presents some of the results obtained for one pilot during the hookup period. Both pilots involved in the tests noted a definite improvement with either pitch rate augmentation or direct lift control over the basic aircraft, and one remarked that the integrated DLC controller was slightly superior.

6. POWERED-LIFT STOL AIRCRAFT

During the 1960's, NASA's handling qualities research related to powered-lift STOL aircraft was centered about flight tests of a variety of experimental aircraft. For the most part, the ground-based simulation programs performed during this time period directly supported the flight investigations, with simulators being used in several instances to study handling qualities problems experienced during initial flight evaluations. Recent research has concentrated on exploring the handling qualities and stability augmentation system requirements of new experimental STOL aircraft under development and STOL transport configurations which incorporate powered-lift concepts not previously flight tested.

Eight powered-lift STOL aircraft were tested and evaluated in flight by NASA. These were the Stroukoff YC-134A, Lockheed NC-130B, Ryan VZ-eRY, Breguet 941, Shin Meiwa UF-XS, Boeing 367-80, Convair Model 48 and DeHavilland C-8A. The results from most of the flight investigations and supporting ground-based simulation studies are documented in References 51 to 63. The aircraft had gross weights ranging from under 3,000 pounds to over 150,000 pounds; wing loadings from 23 to over 65 pounds per square foot; and approach speeds from 40 to 90 knots. The majority of the tested aircraft were powered by turbo-propeller engines, although two were powered by reciprocating engines and one was a jet transport prototype modified with a boundary layer control system which provided some degree of powered lift. In the flight evaluations and simulation studies, the landing approach task received major emphasis. With some of the aircraft (e.g., References 51, 54, 56 and 60), only VFR approaches were made because of marginal capabilities of the aircraft or lack of adequate displays. Others were flown on simulated instrument approaches, and one (Reference 63) was evaluated during normal and steep ILS approaches in actual IFR weather. In view of the extensive correlation and analysis of the results from these test programs (Reference 64), the individual flight and simulation studies will not be reviewed in this paper.

The increased interest in powered-lift STOL aircraft for commercial air transportation that occurred in the late 1960's brought about a review and re-examination of NASA's experiences with such aircraft and resulted in the development of the airworthiness guidelines and criteria contained in Reference 64. This report emphasizes the characteristics of powered-lift STOL aircraft in the landing-approach mode that would be required for safe and consistent routine civil operations in a wide variety of weather conditions. Three aspects are considered: the low-speed performance envelope and safety margin restrictions, take-off and landing field lengths, and handling qualities. The handling qualities criteria presented in Reference 64 are divided into two groups – those for aircraft responses to pilot control inputs and those for stability and damping to limit the aircraft's response to external disturbances. For both groups two criteria levels are proposed – one for satisfactory operation and a second for safe operation. The handling qualities items are expressed in terms of parameters that are easily recognized and appreciated by the pilot and readily evaluated in flight tests for compliance.

Reference 64 also presents and discusses the experimental data that substantiate each of the recommended criteria. Figure 11 shows the flight tests results used to develop the criteria on lateral-control cross coupling, and Figure 12 indicates the flight and ground-based simulator data that support the proposed levels for spiral stability. Although criteria for many of the important handling qualities factors are presented in Reference 64, sufficient experimental data were not available to develop quantitative criteria for several significant facets of powered-lift STOL aircraft handling qualities, and the report discusses those items that require additional research.

There are several powered-lift concepts for turbofan STOL jet transports that have not yet been flight-tested in experimental aircraft. Among these are the externally-blown flap and the augmentor wing. Both of these concepts have received considerable emphasis in NASA's recent research program (Reference 65) which resulted from the increased interest in civil powered-lift STOL transports. A large portion of the recent aerodynamic, propulsion, noise, and handling qualities research has been oriented toward new experimental aircraft and configuration designs with these powered-lift concepts. References 66 and 67 present the results of simulation studies of the handling qualities of two transport configurations incorporating externally-blown flaps. These investigations of the instrument approach task have been oriented toward determining the stability augmentation required to achieve satisfactory handling qualities, and the benefits of direct lift control and autothrottles. In the Reference 67 study, the visual landing task was included in order to evaluate the ground-effect characteristics expected for the externally-blown flap configuration.

7. VTOL AIRCRAFT

Since the early 1960's NASA's handling qualities research on VTOL aircraft has included major efforts on ground-based and in-flight simulation studies, display investigations, and flight tests with experimental aircraft. Recent helicopter handling qualities research has been rather limited, and emphasis has been primarily on research oriented toward non-rotary wing VTOL concepts. Although work has been done on hovering and low-speed visual flight, most of the recent research has concentrated on IFR terminal area operations and has followed very closely the considerations and recommendations made by Reeder in the mid-1960's and reported in Reference 68.

References 69 to 71 present results from early 1960 flight handling qualities investigations with three different helicopters. One of these, the 13,000 pound tandem-rotor transport helicopter reported in Reference 69, had been selected for use as a variable-stability aircraft. Before the modifications were made, several of its unaugmented stability and control characteristics were evaluated to determine the applicability of V/STOL handling qualities specifications to a helicopter of its size and configuration. The question of the effect of a helicopter's size on handling qualities criteria also led to flight tests of a one-man helicopter with a gross weight of approximately 500 pounds (Reference 70) and an evaluation with a 30,000 pound single-rotor helicopter having variable control sensitivity and angular rate damping in the pitch and roll axes (Reference 71).

Recent helicopter handling qualities research has centered on hingeless rotor systems and compound helicopters. Initial flight tests, documented in Reference 72, were performed with a rudimentary hingeless rotor system installed on a standard Army observation helicopter. Both a turbine-powered helicopter with a more

refined hingeless rotor system and a teetering-rotor helicopter were then used in a flight investigation on the handling qualities factors limiting the performance of simulated nap-of-the-earth tactical maneuvers. As reported in Reference 73, the initial angular response characteristics, particularly about the roll axis, and the sensitivity of the height control had significant influences on the pilot's ability to rapidly maneuver the helicopters over the various test courses. Results from flight evaluations of a hingeless rotor compound helicopter, one of several experimental high-speed rotary-wing aircraft tested in recent years, are documented in Reference 74,

Research on VTOL hovering and low-speed handling qualities under visual flight conditions, performed in the early and mid-1960's, were accomplished using two variable stability aircraft, the X 14A and the CH-46B helicopter, and a ground-based 6 degree-of-freedom motion simulator. Major emphasis was placed on control power considerations because of their significant influence on the design of jet VTOL aircraft. Reference 75 presents the results from an X-14A flight test investigation of the effects of lateral control power, control sensitivity, and rate damping on the pilot's performance of precision hover and maneuvering tasks. X-14A flight data were correlated with initial 6-degree-of-freedom simulator results, and the simulator was then used to investigate lateral handling qualities during hover and low-speed maneuvers with acceleration, rate, and attitude control systems. As reported in Reference 76, the study indicated that the attitude control system realized the most favorable pilot ratings and was evaluated as satisfactory at lower lateral control power levels. Additional information on the effects of simulated disturbances and the influence of control non-linea .s contained in Reference 77.

Pilot evaluations of control power and damping for both the roll and pitch axes, obtain· rom the X-14A and the 6-degree-of-freedom simulator, are presented in Reference 78 which also reports on the effects of decreasing the degrees of simulator motion. Figure 13 shows that at least 2 degrees of motion freedom were required to obtain results essentially similar to the flight data when roll axis maneuvers were rated. The X-14A and the 6-degree-of-freedom simulator were also used to investigate a direct side force system for low-speed lateral maneuvering. As reported in Reference 79, satisfactory handling qualities were achieved at lower roll control power levels for a simple lateral-offset maneuver, but the system was not preferred by the pilots for the more complex maneuvering tasks evaluated. Additional data from tests with the X-14A, including the effect of the roll control system time constant, are contained in Reference 80.

Research performed with the variable stability CH-46B helicopter on precision hover and low-speed visual flight tasks included the investigation of control power and sensitivity effects for the pitch, roll, and yaw axes reported in Reference 81. Height control considerations, including pilot evaluations of thrust-to-weight ratio, height control sensitivity, vertical damping and lifting system response time delay, were also studied. As noted in Reference 82, the results indicated that the task involving acceleration and climbout from hover imposed a more stringent requirement on the thrust-to-weight ratio than the deceleration to arrest the descent rate at the end of a landing approach. Consideration of simultaneous attitude control usage, a matter of particular importance for VTOL aircraft with reaction control systems, was also investigated with the CH-46B helicopter. The results of the flight study of various maneuvering tasks are contained in Reference 83. Another program using the variable stability helicopter was a study of on-off controllers for pitch and roll control. Initial results of the effects of control power level, rate damping, out-of-trim conditions, static stability, and simulated disturbances are contained in Reference 84, and Reference 85 documents the complete flight investigation. Related handling qualities data obtain .d from flight tests of a lunar landing research vehicle are reported in Reference 86.

In the mid-1960's Reeder pointed out the need for greatly improved displays in order to achieve successful VTOL terminal area operations under instrument weather conditions. A NASA research program was initiated to evaluate a variety of displays with the eventual aim of achieving approaches, decelerations to hover, and vertical descents to touchdown under instruments in zero-zero conditions. Various information display concepts for VTOL aircraft instrument landings are categorized and described in Reference 87 which serves as a basic guide to the individual flight tests of increasingly sophisticated display systems performed with a helicopter as the test vehicle. The first display incorporated a vertical situation flight director indicator, a horizontal situation indicator, and small vertical scale instruments for airpseed, altitude, and several other measurements. As reported in Reference 88, four configurations of the guidance-attitude elements of the display were evaluated. With the best system, satisfactory guidance along a 6-degree glide slope could be maintained at airspeeds below that for minimum power. Although instrument approaches to a 50-foot br ·kout and visual slowdowns to hover could be flown with fairly high repeatability, the operational use of the test displays would require considerable pilot training. The task of reducing speed under instrument conditions was generally too difficult with the cross-pointer type displays. Displays subsequently evaluated in this program included a moving-map instrument (Reference 89), a closed-circuit television system (Reference 90), a contact-analog (Reference 91), and a system incorporating both moving-graph and moving-map pictorial situation displays (Reference 92). Although vertical landings with the test helicopter have been accomplished under simulated zero-zero conditions using the real world display of the closed-circuit television system, this task has not been accomplished successfully with any of the other display systems evaluated.

Inflight simulation studies oriented toward IFR terminal area operations have been underway with the variable stability CH-46B helicopter since early 1960. The initial tests in this c . .uing program were related to stability and control characteristics, and the more recent investigations have con. ntrated on command

augmentation control systems and display concepts, with the eventual aim of successfully performing safe IFR curved decelerating approaches to an instrument hover and landing. The recent studies have been closely associated with the display evaluations discussed previously. Reference 93 describes the results of flight simulations in which variations in directional static stability and damping, dihedral effect, and directional control sensitivity were evaluated in both VFR descending approaches and hooded instrument approaches on a 3-degree glide slope. Effects of changes in longitudinal characteristics, including angle-of-attack stability, speed stability, pitch damping, and longitudinal control sensitivity, were then evaluated during IFR up-and-away maneuvers performed with the variable stability CH-46B helicopter. The results of these tests are reported in Reference 94 and compared with data from other longitudinal handling qualities investigations in Reference 95.

Recent CH-46B flight evaluations, aimed at developing a capability of instrument decelerating approaches to hover, have been made with the helicopter's electronic equipment being used to mechanize command augmentation control systems and flight director display logics. Constant speed, constant 6-degree glide slope instrument approaches to 50-foot altitude have been included in the program to serve as a basis for comparison with the decelerating approaches. In the constant speed tests reported in Reference 96, the control-display configuration included attitude command stabilization in pitch and roll, automatic turn-following in yaw, a moving map instrument and flight director commands for pitch, roll and power presented on an attitude director indicator. Although with this system the pilot could perform acceptable constant speed approaches on a consistent basis using relatively small control inputs, the task of tracking three flight director commands tended to detract from his ability to scan the remaining instruments, and he had some doubts as to the overall status of the approaches. References 97 and 98 report the results of the recent flight evaluations of the instrument decelerating approaches made along a 6-degree glide slope, and also describe instrument hover tests performed to establish the constant flight director gains used. During the initial testing when the flight director logics were being developed, a glide slope dropout problem was encountered that was found to be related to the helicopter's power-required characteristics. As shown in Figure 14, glide slope tracking performance improved when a body-mounted normal accelerometer signal was used instead of the height control position signal in the flight director logic for power commands. Even with this improved logic, the pilot's workload was very high, and the tests indicated the need for better integration of displayed command and situation information.

Recent NASA flight tests with experimental VTOL aircraft have investigated configuration-oriented handling qualities factors, with emphasis on low-speed characteristics affecting terminal area instrument flight operations. The five tested aircraft, representing four different VTOL concepts, were the tilt-wing CL-84 and XC-142A, the vectored jet thrust Kestrel, the lift fan XV-5B, and the mixed jet propulsion DO-31. They had different degrees of sophistication in the displays and stability augmentation systems installed, and consequently, the ability to simulate instrument approaches varied. The Kestrel, a single-place aircraft with no augmentation, represented one end of the spectrum, and the DO-31, a two-place aircraft with attitude command stabilization and IFR displays, represented the other end. Flight evaluations of the CL-84 were performed in the mid-1960's, and tests of the other four aircraft were only recently concluded.

The abbreviated flight-test evaluation of the CL-84, reported in Reference 99, was concerned primarily with the handling qualities in the hover and transition modes of flight and did not include simulated instrument approaches. However, characteristics that might affect glide path control during terminal area instrument operations were investigated. The handling qualities of the CL-84 in hover, transition, and cruise were considered good by the NASA pilots, although low normal-velocity damping was experienced at a low approach speed which affected the aircraft's open loop rate of descent stabilization following a slow decrease in power. In the XC-142A flight program, two stability augmentation-display configurations were evaluated in tests that included complete terminal area operations initiated by instrument penetrations in the cruise configuration. As noted in Reference 100, modifications in the stability augmentation from a rate system to a low-gain attitude system and changes from conventional flight director displays to VTOL flight director logics significantly improved the low-speed instrument approach capability. The XC-142A pilots also evaluated the minimum comfortable altitude for breakout from a simulated instrument approach to a visual landing, and Figure 15 shows that the results were affected by both the approach speed and the glide slope angle.

The XV-5B flight program, summarized in Reference 101, emphasized simulated precision instrument landing approaches and investigated the effects of variations in aircraft deck angle, deceleration schedule, and powered-lift management on the handling qualities during approaches that included decelerations along the glide slope to a spot hover. The pilot preferred a deck angle parallel to the glide slope during the approach rather than a deck-level altitude, and with the preferred technique used the powered-lift collective control to correct glide slope errors while maintaining near zero angle of attack with the longitudinal pitch control. It was also found in the XV-5B tests that the pilot's workload was reduced if the deceleration schedule was delayed until the aircraft was well established on the glide slope. Basic operational aspects of VTOL instrument approaches, derived from the most recent NASA flight studies with experimental VTOL aircraft including the Kestrel and DO-31, are outlined in Reference 102.

In the last several years the status of a major portion of NASA's VTOL aircraft handling qualities research, particularly the programs involving display evaluations, in-flight IFR simulations, and experimental aircraft flight tests, has been reported in papers presented at various technical society meetings. These reports, References 103

to 107, have summarized the highlights of much of NASA's VTOL terminal area research work and have indicated the strong interaction between displays, stability augmentation systems, and basic airframe characteristics on the handling qualities of VTOL aircraft.

8. CONCLUDING REMARKS

Primarily, this paper has considered the past with regard to NASA's handling qualities research. Many of the programs reviewed in the paper are continuing, and others are currently underway. Research on general aviation aircraft will continue to emphasize improved stability augmentation systems, displays, and automatic coupling with guidance/navigation systems to achieve complete IFR capability in adverse weather conditions, and will explore new methods for improving light aircraft handling qualities to aid the relatively inexperienced pilot. Subsonic jet transport research will emphasize super-critical wing technology. Related handling qualities efforts will increase as more refined aerodynamic configuration data become available and super-critical wing experimental aircraft enter extensive flight testing. NASA's handling qualities research related to supersonic cruise aircraft will include continuing activities to develop improved certification criteria for supersonic transports and expanded research on strategic military aircraft. Tactical military aircraft research will emphasize the handling qualities problems occurring at high angles of attack during maneuvering conditions, and STOL aircraft research will center about new configuration concepts and experimental aircraft incorporating augmentor wings, externally-blown flaps, and lift fans. A wide variety of VTOL aircraft handling qualities research will continue, emphasizing terminal area instrument flight operations and the improvements needed in displays, command guidance information, and stability augmentation systems to achieve an instrument decelerating approach to hover capability. Expanded activities on new rotary-wing aircraft concepts and special helicopter piloting tasks will also be included. The importance of the pilot is recognized in NASA's overall aeronautics program, and handling qualities research will remain a significant part of the total research effort in the future.

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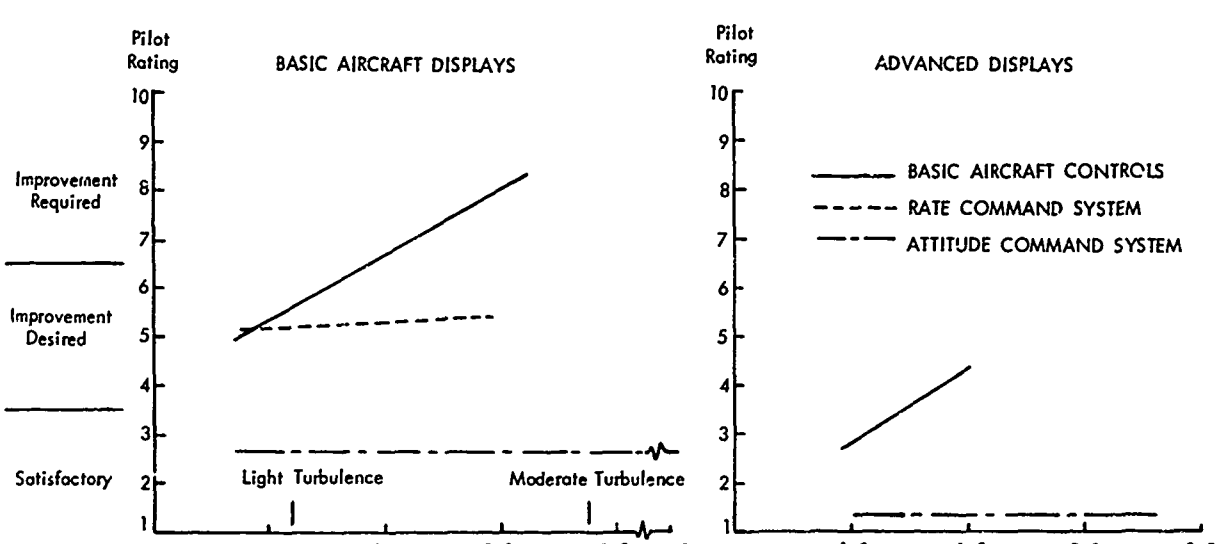


Fig.1 Pilot ratings of ILS approach task with a general aviation aircraft

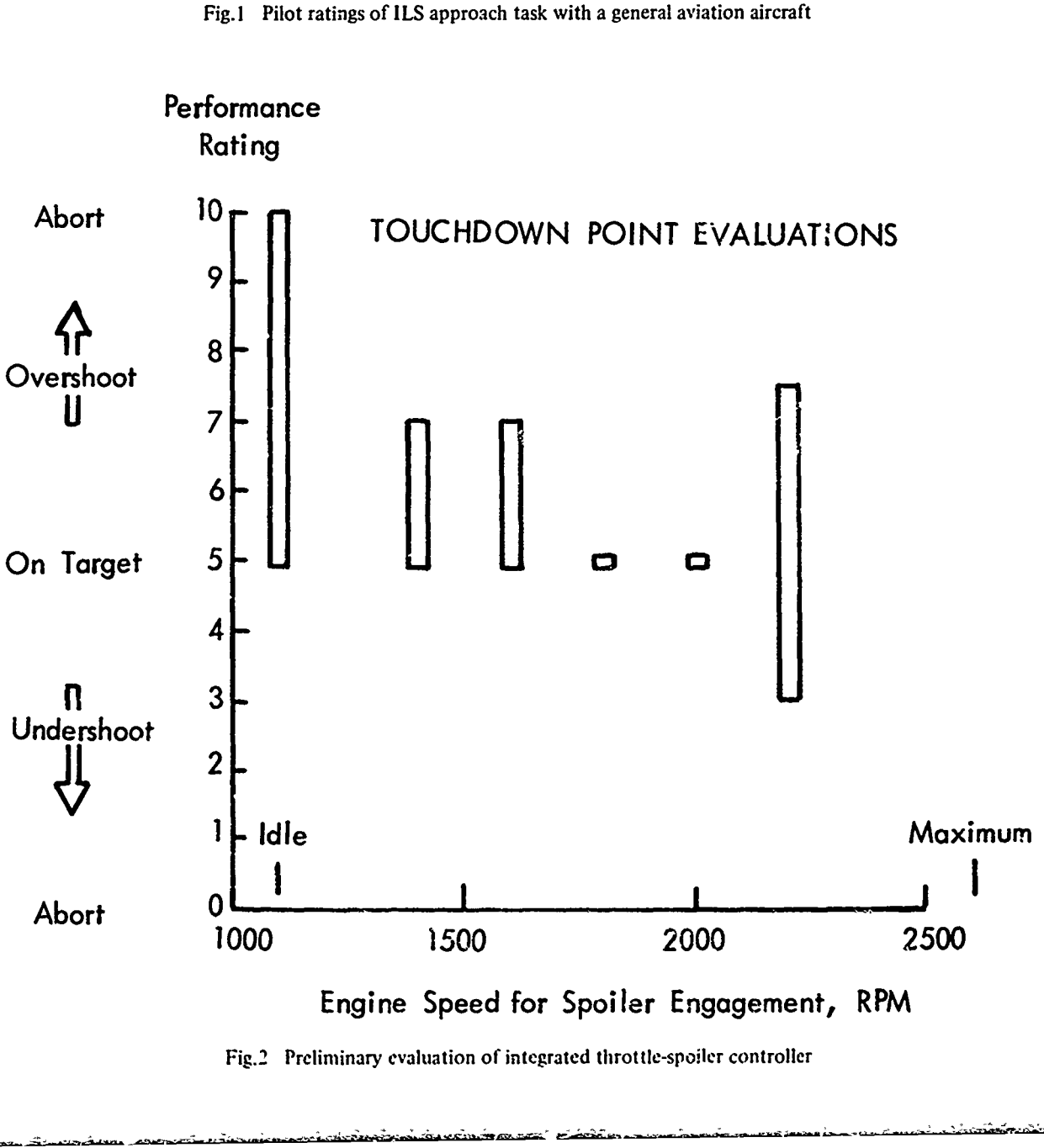


Fig.2 Preliminary evaluation of integrated throttle-spoiler controller

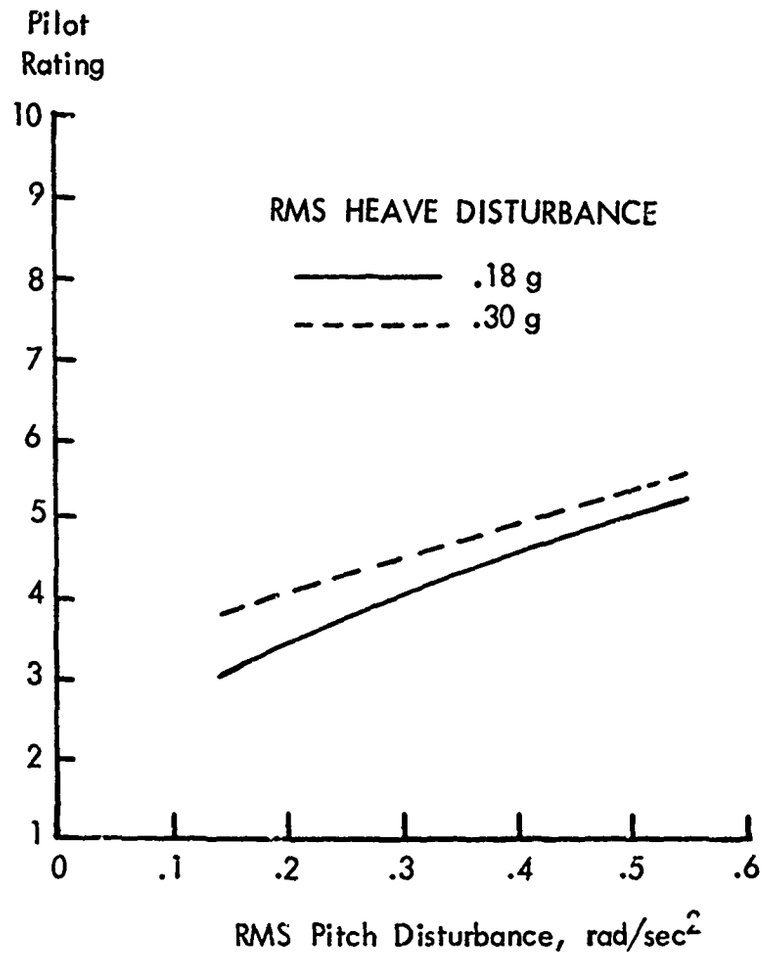


Fig.3 Effect of turbulence disturbances on pilot ratings

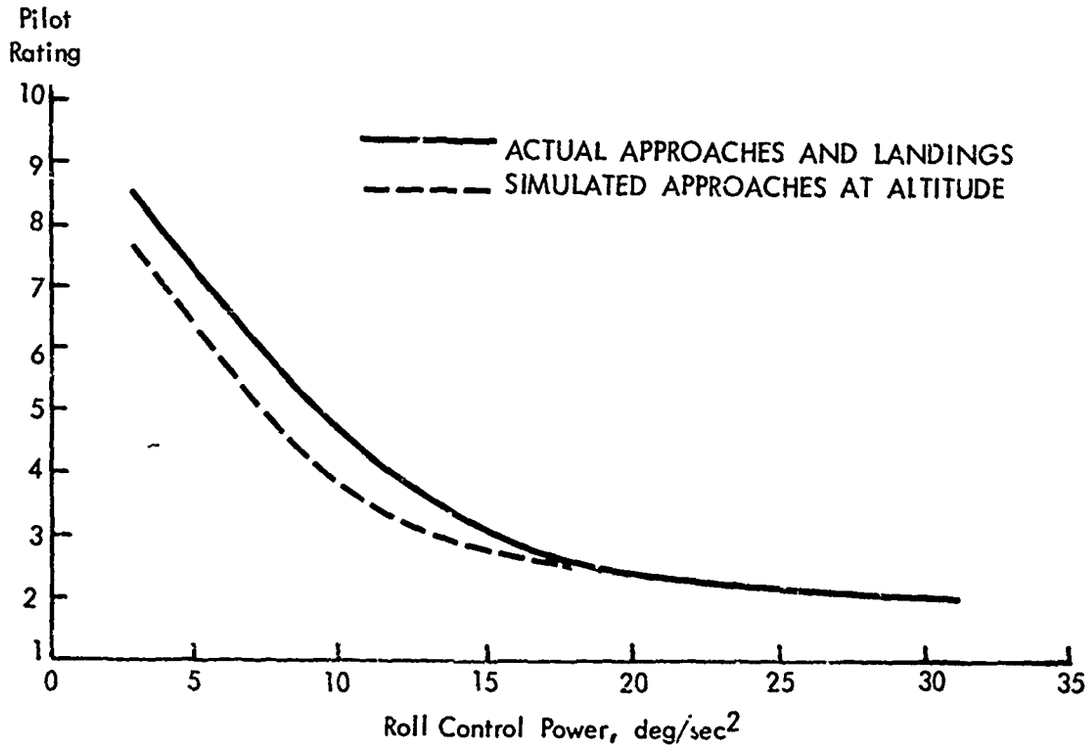


Fig.4 Results from subsonic jet transport landing approach evaluations

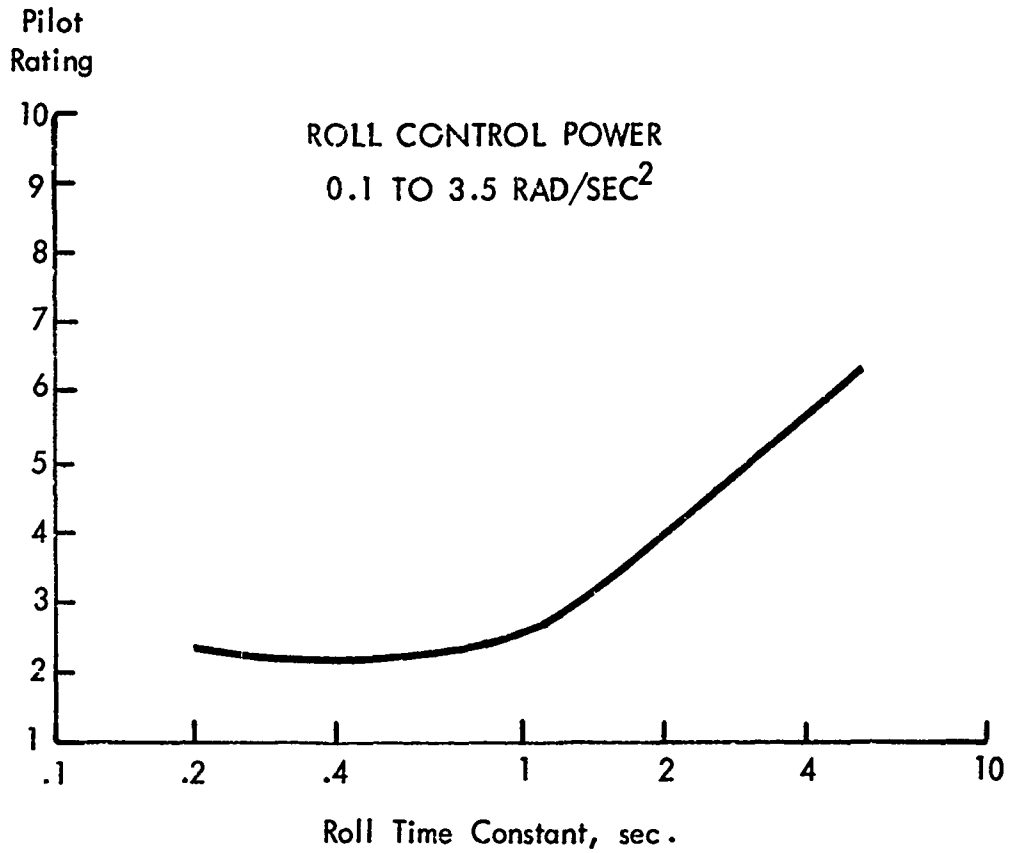


Fig.5 Pilot ratings of transport aircraft roll time constant for cruise flight

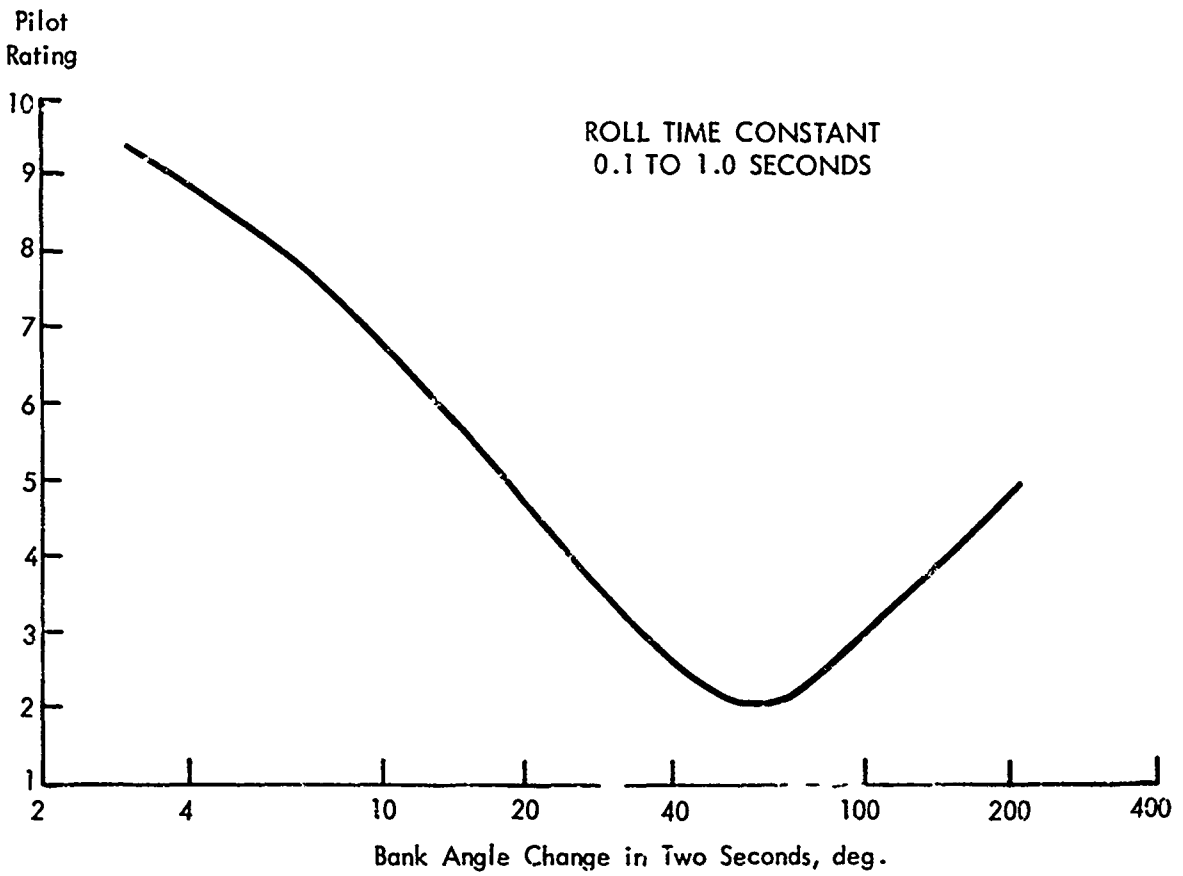


Fig.6 Pilot ratings of transport aircraft roll response for cruise flight

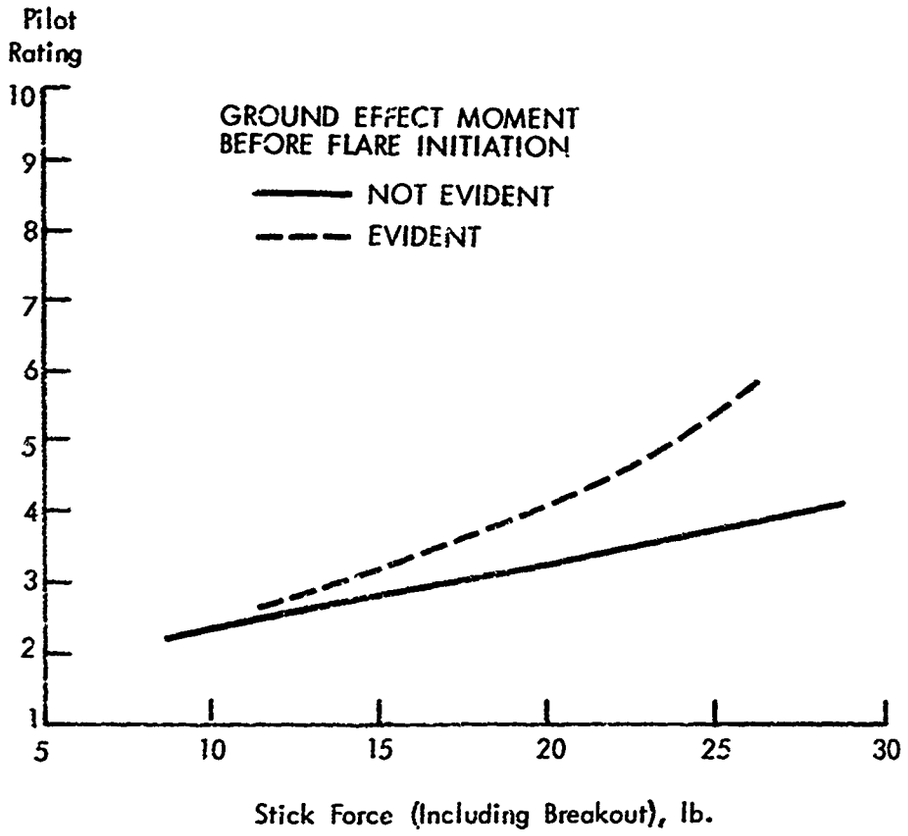


Fig.7 Fixed-base simulate results from large aircraft ground-effect evaluations

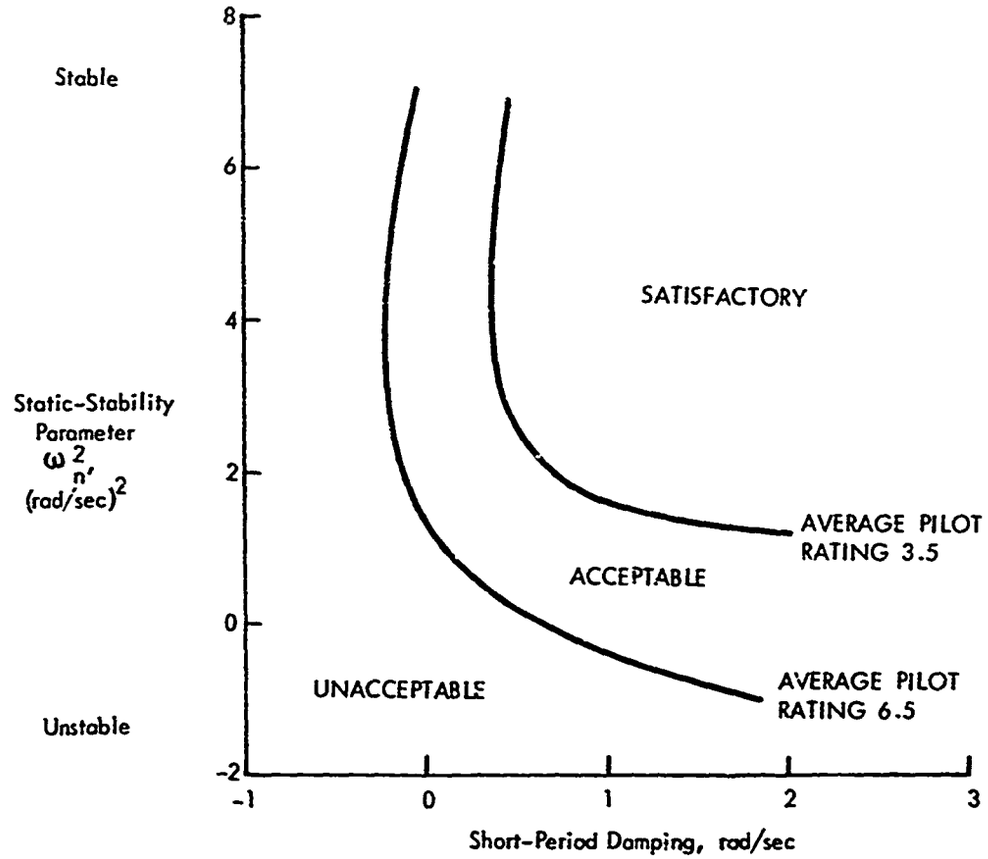


Fig.8 Evaluation of transport aircraft longitudinal handling qualities

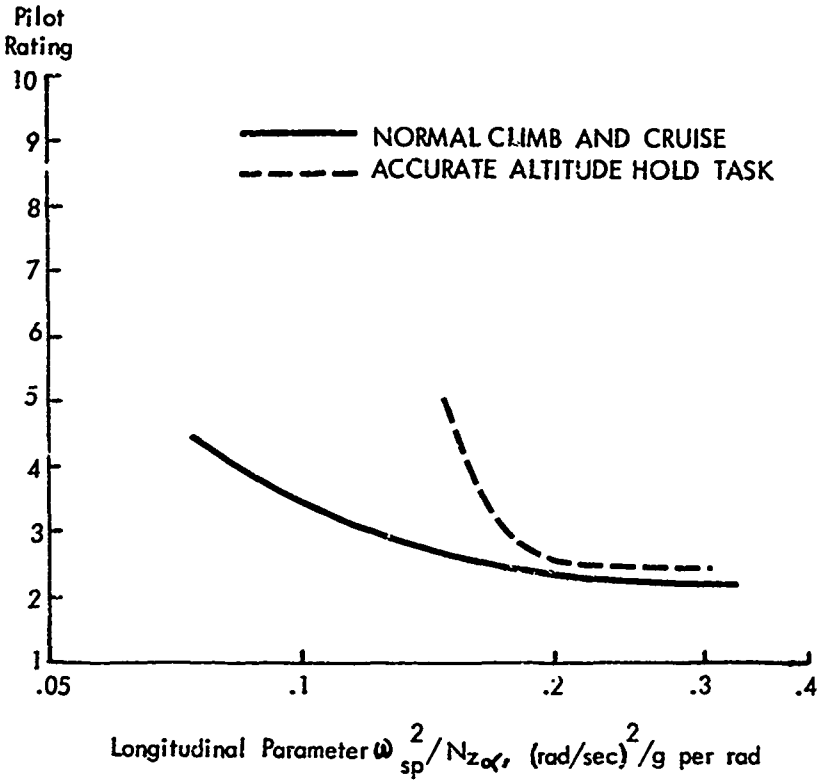


Fig.9 Results from XB-70 flight tests

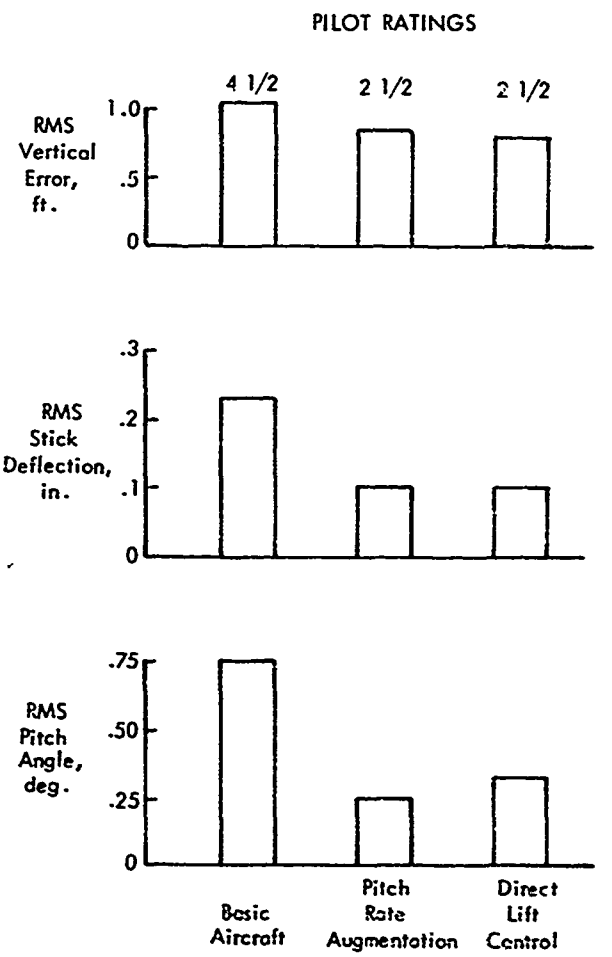


Fig.10 Evaluation of in-flight refueling task with a fighter aircraft

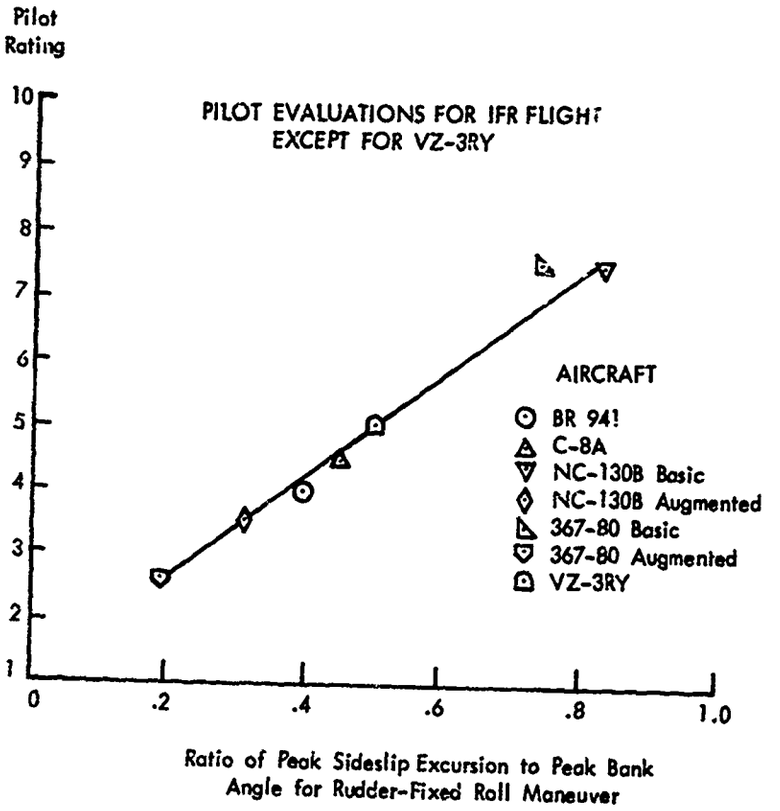


Fig.11 Pilot ratings of lateral-control cross coupling for STOL aircraft

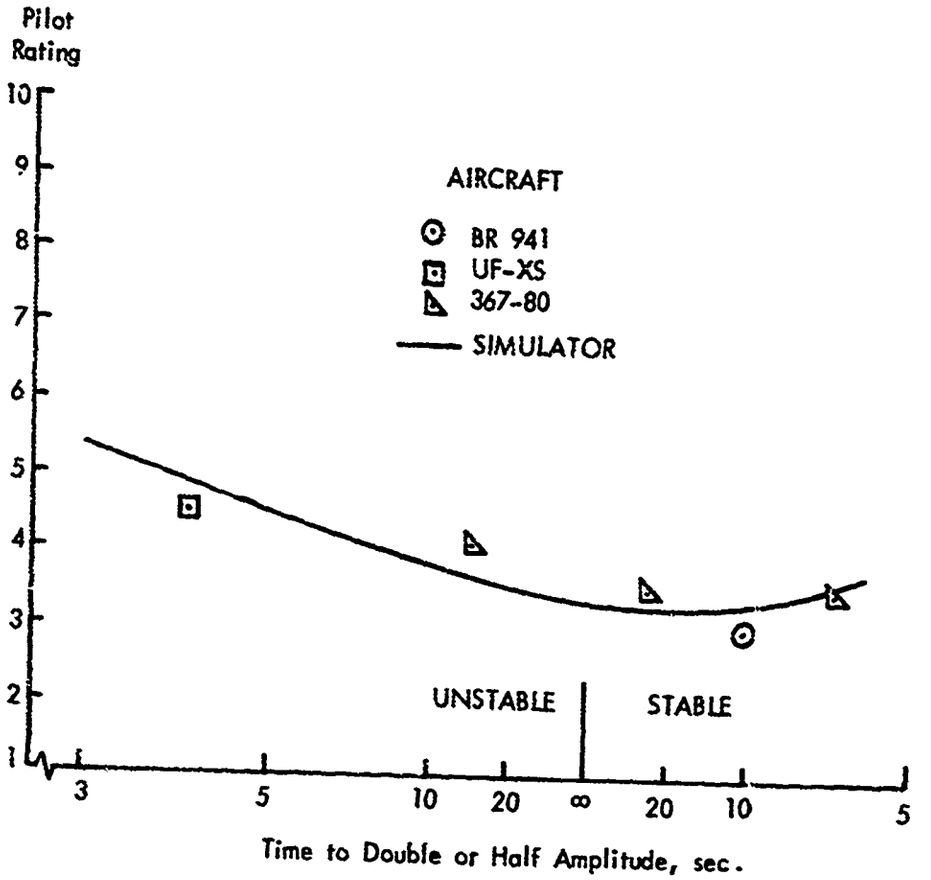


Fig.12 Variation of pilot ratings with spiral stability of STOL aircraft

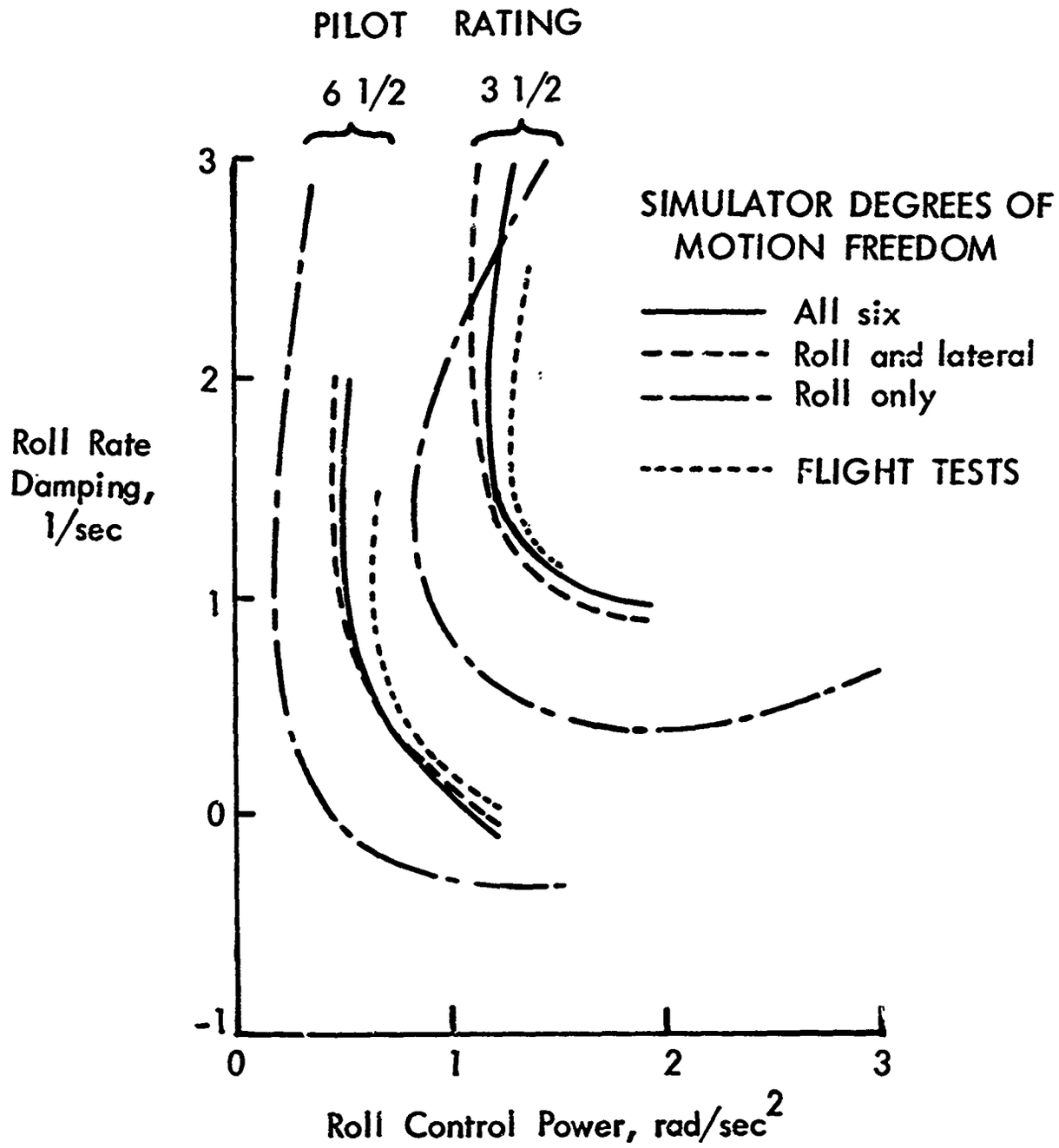


Fig.13 Effect of simulator degrees of motion freedom on pilot ratings of VTOL hover task

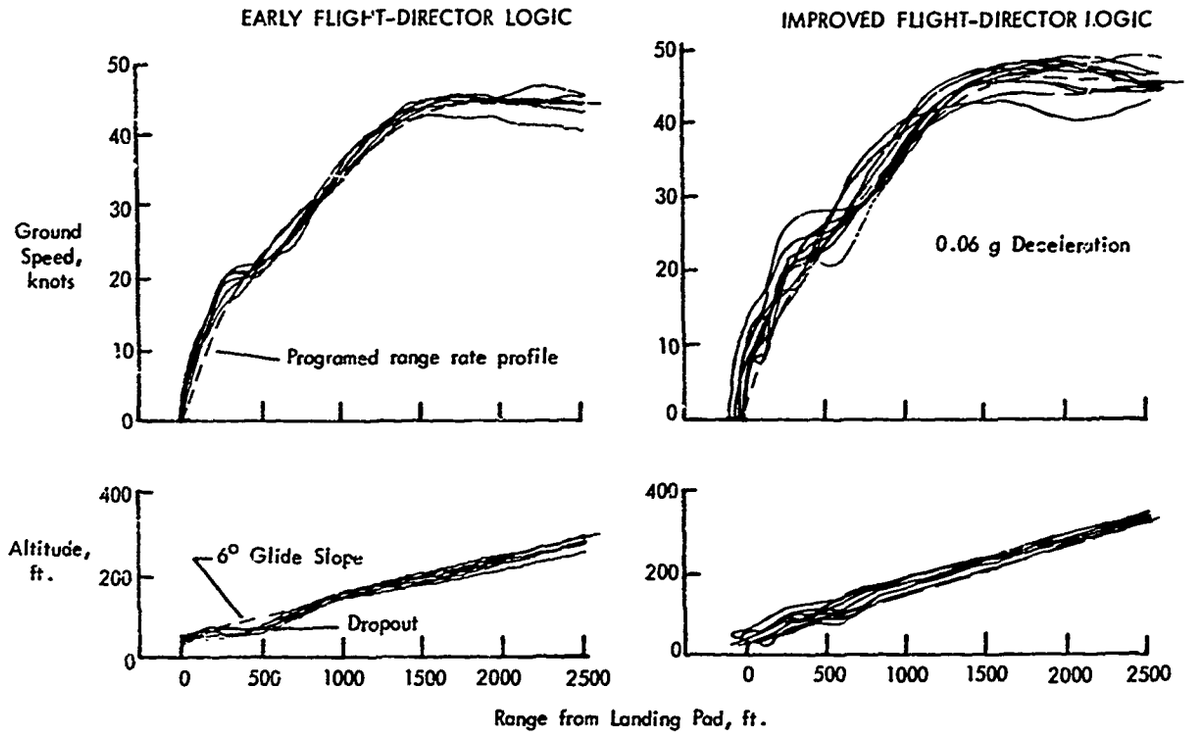


Fig.14 Pilot tracking performance during IFR decelerating approaches to an instrument hover

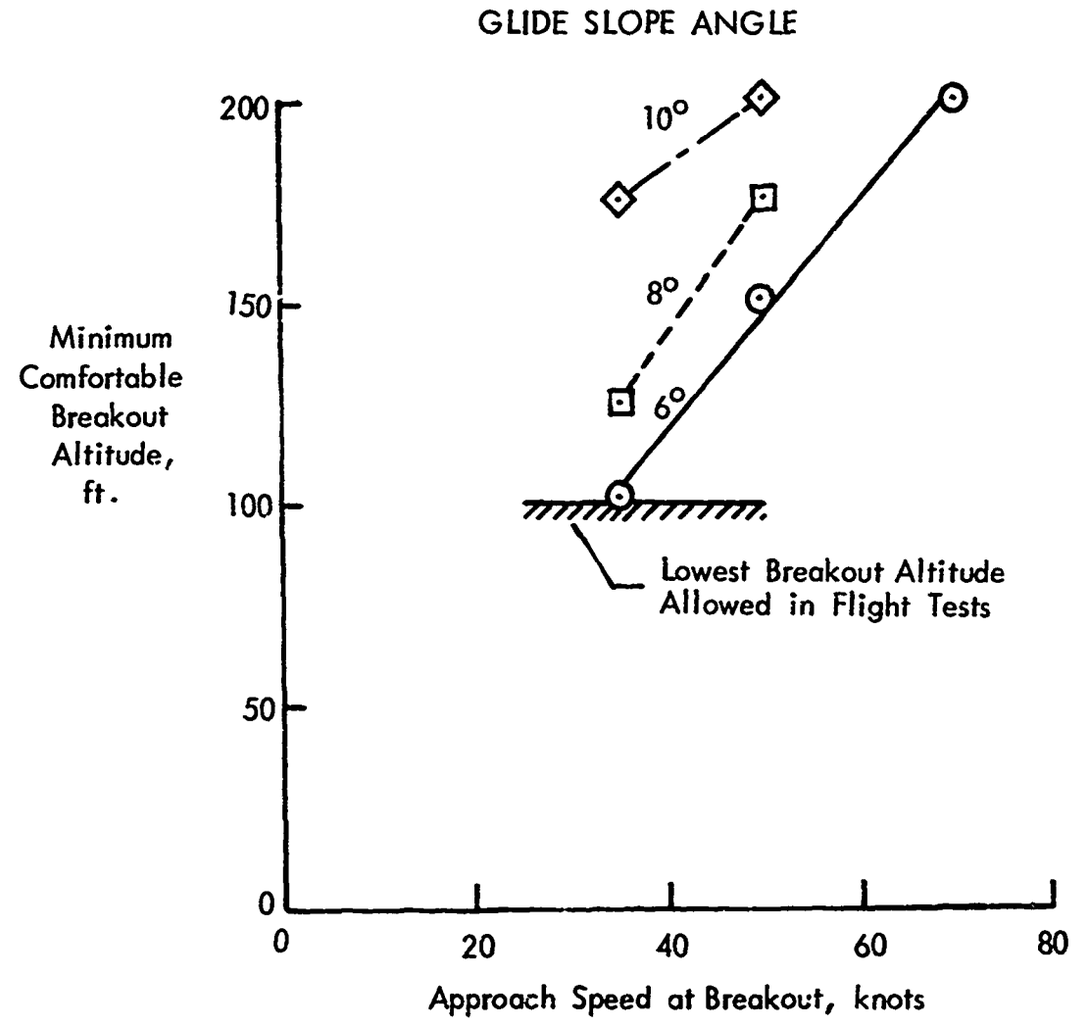


Fig.15 Results from simulated in-flight IFR landing approaches with a VTOL aircraft

LEAD DISCUSSION

by
Domenico Covelli
FIAT Sez. Velivoli
10146 Torino, Italy

To comment on the great amount of research on handling qualities carried out by NASA in the last ten years and presented to us by Mr. Wasicko is a rather hard task considering I have only ten minutes to do it.

Therefore I will expose only some considerations on this paper with the intention of raising a useful discussion by the present delegates to the Meeting.

A first consideration: we can say that the research work conducted by NASA has been addressed especially to find out new evaluation criteria or new requirements for handling qualities, stressing the pilot's ability to perform the required task. Therefore we can define such handling qualities criteria as "task oriented". I completely agree with this principle which is understood in the definition of handling qualities given by Cooper and Harper and mentioned in Mr. Wasicko's paper.

But if we consider, as an example, a typical task which has been the subject of many investigations, namely the approach and landing task, we realize that despite the great evolution in aircraft in terms of performance, physical dimensions and aerodynamic configuration, this task has remained practically the same - that is, follow a straight path with more or less slope with respect to the ground, holding the speed constant. This was valid for a DC-3, as now for a Jumbo Jet or a Concorde. But if the task is the same, and I assume also the pilots are the same, why new criteria?

Obviously we have to recognize that if the task is the same the conditions under which the task must be performed have changed, as for example the approach speed, the behaviour of the modern aircraft under external disturbances, and the presence of new augmentation systems and sophisticated pilot displays. We have to conclude, in a rather obvious manner, that the handling qualities criteria are determined not only by the task but also by the conditions under which the task is performed.

But if we look at the evolution of handling qualities criteria and at the enormous quantity of research studies which have determined this evolution, my feeling is that at least until today, the purpose of this research was to solve the immediate problems that were brought about by changing the task conditions rather than an attempt to solve the more general problem of the interaction between man and machine. The approach followed could be defined as a pragmatic way to attack the problem and one which gave us results of limited application. It would be very difficult to extrapolate the results of this handling qualities research even to similar aircraft but operating in different conditions until we get more accurate knowledge about the role of the pilot in accomplishing the task.

I don't want to say that the importance of the pilot has been ignored. In fact, there are well known studies conducted by Messrs. Ashkenas and McRuer of S.T.I. and by others with the purpose of describing pilot behaviour by a mathematical model, not just to replace the pilot with a "paper pilot", but because modern servomechanism theory can be very useful in understanding pilot behaviour and in the interpretation of the pilot's assessment. I appreciate very much this new approach because I feel it is a first attempt to solve the general problem.

I would like to conclude with an expression of appreciation for the NASA research on aircraft handling qualities, pointing out the need for synthesis work aimed at getting a better understanding of the interaction between the pilot and aircraft to get the maximum benefit from this impressive research.

OPEN DISCUSSION

D. Davies, ARB, UK

What are the contributions of all the research to civil aviation? This is really a plea to research, not to get too far ahead, but to aid civil aviation with the problems which are presently causing difficulties.

J. Wykes, NAR, USA

My comment is to reiterate that technical people need time to do their jobs and do them correctly.

C.B. Westbrook, AFFDL, USA

The trade-offs encountered during the development of aircraft are numerous and what we don't have is any clear-cut incentives for the designer or procurement activity to judge what he is willing to pay for. We need this in the early stages of the development, not after the aircraft is flying.

J. Teplitz, FAA, USA

I agree with Mr. Davies. It was only recently that FAA could fund research. Our programs are for the benefit designer and the standards for civil application.

Sqn Ldr D.C. Scouller, RAF/ETPS, UK

It is clear from discussion that spin characteristics are causing difficulty with modern military aircraft. Would anyone tell me whether it is possible to build an aircraft specifically for spin research since this is an area in which knowledge is poor. I suggest such a vehicle would require variable control power, variable stability and variable inertia characteristics.

J. Gallagher, Northrop Aircraft, USA

The new VSS fighter aircraft that USAF is undertaking could be designed to investigate various areas of stall and spins.

PANEL DISCUSSION

THEME: WHERE DO WE GO FROM HERE?

Chairman: P. Lecomte, Aerospatiale, Toulouse, France

K.H. Doetsch, DFVLR Institut fur Flugfuhrung, Braunschweig, Germany
O.H. Gerlach, Delft University of Technology, Delft, Netherlands
W.T. Hamilton, The Boeing Company, Seattle, Washington, USA
D.M. McGregor, National Research Council, Ottawa, Ontario, Canada
J.B. Scott-Wilson, Hawker Siddeley Aviation Ltd, Woodford Aerodrome, England
J-C. Wanner, Service Technique Aeronautique, Paris, France

Introduction by P. Lecomte

We have spent three days discussing various aspects of handling qualities criteria and requirements, trying to outline where we stand. I think that the presentations and discussions have brought into light certain numbers of points of view, sometimes consistent, sometimes conflicting. These have been identified as a large number of uncertainties or problem areas. Finally, the only absolutely sound requirement was and still is, the aircraft should be safe and efficient for an average pilot. So the problem exists for the contracting agency which has to insure that he is spending the money he has for a product which will meet its objectives. But he does not want to spend too much money by being unduly exacting to the product. The problem exists for the authorizing authority, who has the duty of being sure that the aircraft will be sufficiently safe in service, but on the other hand, he does not want to prohibit the progress of public transport. The problem exists for the designer who has to design, and build an aircraft to meet, to some extent, unknown requirements or insufficiently defined requirements and on the other hand that if they are too much defined his freedom to make a successful aircraft will be very limited. And finally a problem for the people in charge of acceptance to check with the products they have in hand to see if they meet the objectives.

J.B. Scott-Wilson

I was very tempted to start getting involved with criteria and requirements. After thinking about it, it seems to me that there was a broader picture emerging from the course of our meeting here. This is a very unique meeting because we have researchers, certificators, and contractors all looking with different views on the same topic. In my office, I have two books - one is BCAR's (British Civil Airworthiness Requirements) and the other is AvP 970 which is actually three books and slightly bigger than the BCAR's. As far as BCAR's are concerned they provide me with a very clear guide which I know was based on experience, and I know it is international and in addition I know that it is updated very frequently. We have heard from Mr. Andrews that AvP 970 is going to be updated, from Mr. Wanner that they would probably use 8785 and thanks to Mr. Westbrook I have read MIL-F-8785. I noted that from 8785 that from 1954 to 1968 apparently it was unaltered.

I think the difference between what the civil people do and what the military people do is very significant. I know that if I have a question on the civil side, I can ring somebody up at ARB and they will explain the requirement to me. On the military side, the situation isn't so clear, and I do believe that one thing that emerges from this meeting is the need for much clearer integration, across the western world, of military requirements. I think there is a big field here where a lot could be done, instead of each country or service doing his little bit, I think that a common standard could cover a large part of the requirements. This would have the benefit of being updated regularly and allowing each country to comment and feed into it their experience. For instance, the V/STOL requirements we have MIL-F-83300, from the United States Air Force and AGARD produced 577 as a compendium of experience of the various NATO countries. I think that it is true to say that it (AGARD 577) has a wider background of data than was available to go into 83300. So here is another case where more cooperation and integration could well produce a better standard of requirements. Another facet which comes out of the civil requirement, is that civil people are very aware of the importance of performance to the contractor and that handling qualities and performance are very closely integrated. Certainly more closely than that indicated in 8785B. Don't let's separate performance and handling qualities.

On turbulence, we are having a meeting in the Spring of 1973 on flight in turbulence. My impression is that the clear air turbulence situation is making big studies. But in the V/STOL case, quite close to the ground, we still have a fair way to go to really establish the right sort of models from enough measures. In particular, to identify the worse possible case in the way of gusts either due to hot spots in the atmosphere or flow around buildings.

The third comment is on simulation. I just wonder if we put enough fear content into our simulations. I heard two comments regarding situations where the pilot was frightened and that it must have an impact on his workload capability. How we put this in, I don't know, but certainly, the difference between flying a simulator and flying something where you know you are in highly dangerous position, must produce a different human reaction.

D.M. McGregor

In working with the AGARD committee on handling qualities and looking into AGARD 577, it seems that the main problem was coming up with reliable data in a useful form. This was the basic reason it took so long to come out. As Mr. Harper pointed out earlier in the week the pilot rating without pilot comments are virtually useless, because you can't possibly tell why the pilot rated it so. Thus my plea is that

we should try to come up with some standard way of gathering information and even more important a standard way of presenting the information and recording it. The evaluation maneuvers contained in the back of AGARD 577 are an attempt to do this and try to at least get V/STOL aircraft assessed a particular way. Seth Anderson has been asked by the Flight Mechanics Panel to act as the central clearing house for any comments regarding AGARD 577 and its updating.

The main problem in the V/STOL area seems to be the lack of information about instrument flying criteria. We don't seem to be clever enough right now at combining various aspects of handling qualities, display requirements, and the man-machine system under these conditions.

AGARD can operate in a standardizing role. In one of two ways it has started right now in a working group chaired by Prof. Gerlach of the Netherlands which is going to look into simulation. Part of their responsibility is coming up with a standardized model of the atmosphere for take-off and landing simulations, standardization of ILS noise, maneuvers for simulator handling qualities evaluations and the providing of data for reference aircraft.

O.H. Gerlach

I think our main gap of knowledge can be described as follows: The final judgment of the acceptability handling qualities parameters is based on the pilot's opinion. We are still far removed from the situation where we have a full and satisfactory understanding of the way in which the pilot arrives at his opinion and comments. The pilot workload seems to be the catchword. It occurs to me that the Flight Mechanics Panel could do something to fill this gap. Not new research, but to bring together the people involved to involve cooperation.

K.H. Doetsch

The requirements must be written so that they are directly translatable to the designer.

I think better monitoring for the pilot - the pilot should have available to him the information regarding the energy remaining, not only throttle, but also the energy in the form of kinetic energy.

An additional point, requirements must remain flexible. The way I did this in 43 was to give a discussion of what I meant by it. I think it is very important to have a good explanation of all of the requirements.

One should keep open numerical values that have to be achieved right up to the last moment of fixing the specification and mission of a particular aircraft. There are few figures that can be applied generally, those that apply to the human being. But most figures are really related to the mission and standard of training the pilot has had.

AGARD represents a very vast background of experience and this should be gathered continuously, updating and standardizing requirements.

W.T. Hamilton

I believe, first, from the standpoint of establishment of criteria and requirements, that we should arrive at very basic or fundamental criteria and based on these criteria we should then select requirements for the particular aircraft task we have in mind.

There is still room for investigation into the area of pilot opinion and comments. Another area I feel is important is in the area of establishing priorities for the various criteria and determining how to best achieve the most effective aircraft for the money available. This approach may force you to a point-designed aircraft, which will not have the versatility of the aircraft of the past.

J-C. Wanner

I shall propose three things about the problem criteria. I think that the approach made by Mr. Anderson is a very good one. If we use a more sophisticated model of the pilot, mainly if we take into account more than one degree of freedom. I think the pilot does not work at all like an autopilot. I did not insist enough yesterday on that point when I gave a description of my pilot model. All of the operation in each loop are fulfilled successively and the different loops are switched on successively. The successive switching on are not random, but are chosen by the brain in a way we have to study more precisely. Nevertheless I think that it is possible to build a model which, statistically, is consistent with the true pilot. This model should not be a representation of the pilot, but could be a tool to prepare new criteria. So I think we could try to build new criteria using this type of sophisticated pilot model.

On the other hand, I think it would be good to take into account in the criteria the presentation of the flight data to the pilot. It is evident that when, for instance we decrease the precision of the horizon, we make some modifications in the behavior of the pilot and it will change the pilot rating, even if the characteristics of the aircraft are not changed. What about the presentation of bank angle, pitch attitude with digital presentation? The aerodynamic characteristics would be the same, but the pilot rating would not. I think we have to increase our research on that point of view and try to include the problem of data presentation in the criteria. I don't know how to do it, but I think we have to look at that.

Another point, I think the longitudinal criteria are not very good for heavy aircraft. It seems that all existent longitudinal criteria are pretty good for fighters, but our studies have shown that for Concorde or Airbus the longitudinal criteria are very wrong. It would be necessary to improve this type of criteria, to take into account maybe not the weight, but the shape of the aircraft.

The area of workload needs to be defined. What we need is a common definition for workload.

DISCUSSION FROM FLOOR

Wunnenberg, Dornier, Germany

I would like to answer some of the questions of Mr. McGregor. He said that it was difficult to get data from actual VTOL aircraft, to get a better background of the AGARD report. This is true - it was very difficult to get this data. We got his proposal for maneuvers very early and we gave this proposal to our flight test people. We told them that we felt it was a good way to test handling qualities. But they said it was impossible to do with our money. They said with our money we could do about 1/10 of this catalogue. I think that one of the results that came out of the NASA-Dornier Corp testing of DO-31 was that the handling qualities of the hovering flight is not of great interest. These handling qualities are done by the automatic stabilization system. It is, of course, of interest for future work that you have to know the combination of the aircraft, automatic stabilization and pilot. The problems with VTOL were the transition and the power management during transition. I think the most important point in this field is to reduce the pilot workload. The workload during transition and under IFR conditions. We did a very few flights under simulated IFR conditions with the DO-31 and it showed that there is a big field of future research to improve the control devices and the displays for VTOL aircraft.

We have an idea of what future VTOL studies should be. That is to develop a new guidance and control system for the landing phase of VTOL aircraft; to prove all-weather capability especially for commercial aircraft and show how VTOL air traffic can fit into conventional air traffic. As we think that one of the advantages of VTOL aircraft is the enlarging the capability of existing airfields as this traffic can be separate from conventional aircraft.

McGregor, DRC/NAE, Canada

The catalogue of maneuvers in the back of AGARD 577 was meant to try to cover everything possible, so I can appreciate your flight test people shying away, especially in a jet lift vehicle.

K.H. Doetsch, Germany

Just one additional remark. If we start using black boxes, we do it in the proper way. The DO-31 was not developed to the stage it should be developed. For instance, to make the transition you have to separate axes again, you must really decouple the controls for the pilot. That can be done with black boxes but they must be reliable.

R.F. Siewert, U.S. Navy, USA

To Mr. Scott-Wilson and also to Prof. Doetsch on this business of 8785 and where it fits into the picture and flexible requirements. A little rundown of how we procure aircraft within the U.S. Navy. We start with 8785 in its present version as a point of departure and what we do is when we decide to buy a new attack aircraft, for example, is start with 8785 and strike out all the things that are not applicable to attack aircraft. Then we decide to add in new requirements, based on the latest criteria or data we have available or basedon our recent experience with our own aircraft. This we call a "type" specification, and is put out for the contractors for them to bid against; of course, the performance requirements, the structural requirements, everything is put in here. At the time we select an airframe manufacturer to build the airplane, we sit down, across table, and argue out the requirements and we finally arrive at what we call a "detail" specification which is the document signed by both parties and is the thing the aircraft is designed against. It is not 8785 as it sits on the shelf. So we do have the flexibility we build it into the system. The remark that 8785 (ASG), no "B" after it, 1954 version remained in its present state for so many years, this is not really true. Because Mr. Brynes S-3 airplane was essentially procured against 8785 ASG and the flying qualities requirements he has to meet are considerably different from those in the 1954 document.

To follow-up something Mr. Hamilton said that while safety is of paramount importance, the military aircraft has to go a step beyond. Somehow we should push toward translating Harper's pilot opinion ratings into mission performance, mission effectiveness, combat effectiveness, whatever the term has to be. We have to get a performance measure to translate from the flying qualities to the pilot opinion to the actual performance characteristics, not the lift drag characteristics but the ability to hit the target, etc.

Scott-Wilson, Hawker Siddeley, UK

One comment, I think there should be feedback of what you finally agree with your contract into the system that is producing the book (8785). This is what is continually happening in the civil world. They are continuously looking their requirements and they get their experience from operator, contractor feedback into the requirements as a living process. I think the military requirements have been far too much a case of we'll start with the book then we'll diverge away to where we want to go to and leave it at that. My plea was more that the military requirements could be much more valuable if it were a "living" document, that had the feedback into it from all of the people who are using it as a basis and that some mechanism whereby this could happen would improve its basic status considerably.

Deque, Aerospatiale, France

We have now in existence an assembly of criteria, for example, 8785 and on the other side we have aircraft flying every day. Would it not be possible for somebody to put the characteristics of these aircraft on the existing criteria. This could be quite helpful to the designers.

R.O. Anderson, AFFDL, USA

Regarding your question on comparing aircraft against the specs, yes we are trying to do that. The Air Force has sponsored several contracts along that line. The first was an attempt to compare the F-4 against MIL-F-8785B, that report is out. We are also looking at the F-111, F-5, and T-38.

Deque, Aerospatiale, France

I would like to see some civil aircraft too

D.P. Davies, ARB, UK

We all speak from nested interests so perhaps you will forgive my next comment. This is addressed to Prof. Doetsch, who made a plea to keep the numbers open. Certification authority people are not rigid, at least the ones I know, and we are flexible. But in the field of handling qualities there comes a time when you have to draw a line and firm up on the numbers. One good example is the minimum stick force to pull "g" on big transport airplanes. Over the years, and I am in favor of this development, very large airplanes have become lighter and lighter to fly. But it is necessary at sometime to do something about the airline gorilla who is quite ignorant in the way he flys his airplane. Now when you are in a horse trading agreement on today's airplane you can say the book says 50 lb (50 lb to pull "g") taking into account the actual weight of the airplane in the flight condition, where the stick force per "g" is least. Now if someone offered me airplane at 47 lbs to pull "g", I couldn't argue, because what is 3 lbs in 50 lbs. But if we compromise and give in on that, then the next contractor comes and says mine is only 42 lbs. How do you feel about that? So you go on and say what's another 5 lbs so you give that away. If you go on like this you are guaranteeing a slow degradation over the years. If you don't do something to stop it you'll get an airplane where a 3 lb pull force will be enough to take the wings off, - now that's absurd. There will come a time when you'll have to draw a line and stick to it.

Prof. Doetsch, Germany

I would agree with you on one point, that those requirements that are really necessary for safety, should not be negotiated.

Bernotat, Germany

I agree fully with Mr. Scott-Wilson, Prof. Gerlach and Mr. Wanner that pilot workload measurements is a very important area. But I have learned that there is a lot of research work going on outside of the aeronautical field. There is a Dutch scientist who has been working on this for ten years now and is only concerned with this topic. There is no success up to now. So we shouldn't believe that making up a working group of aviation medicine, guidance and control, and our panel would help us in a very short time to get useful results.

Gerlach, Netherlands

I suggest that we don't go straight away and form another working group, probably wouldn't help very much. What I'm proposing is that we take stock of what is going on elsewhere. We need to have the information and within AGARD we just haven't got it. This is a situation which need not exist and what I would like to see is some means of collecting the information and how we go on, or whether we give the problem to other people. I'm not sure that others will deal with the workload problem in the way we would need it.

Scott-Wilson, Hawker Siddeley, UK

Thank you gentlemen. As you recall at the start of the meeting I said you are all specialists and let's talk. Well you certainly did that and I thank you very much indeed for that. I would also like to particularly thank those of you that prepared papers and those people who prepared lead discussions, and all of those who were session chairmen and the interpretors.

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