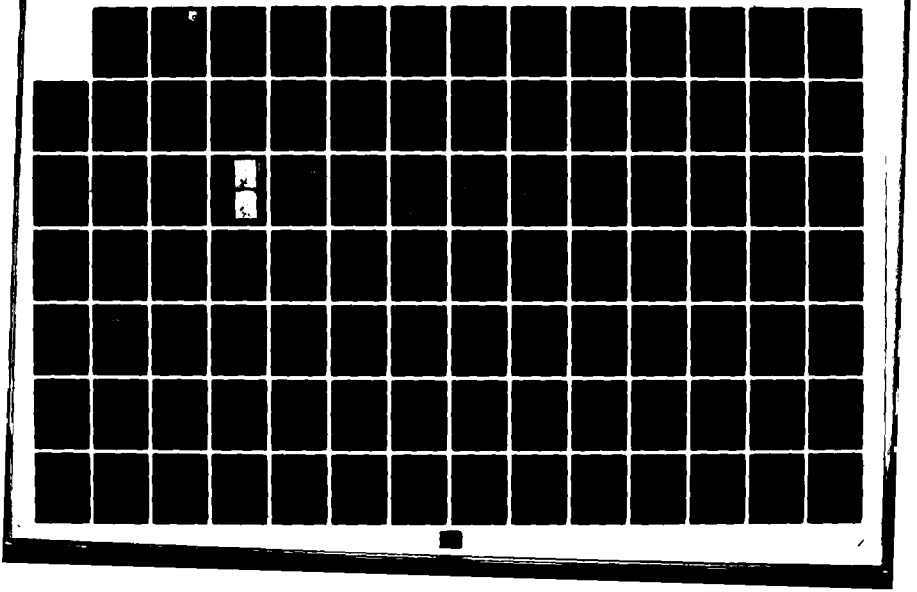
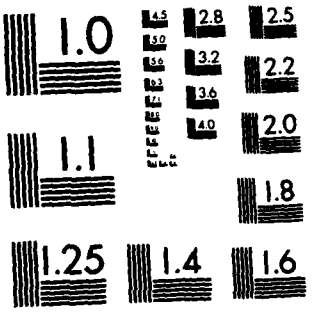
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DESIGN CRITERIA FOR THE FUTURE OF FLIGHT CONTROLS

PROCEEDINGS OF THE FLIGHT DYNAMICS LABORATORY FLYING QUALITIES AND FLIGHT CONTROL SYMPOSIUM 2-5 MARCH 1982

STANLEY G. FULLER
DAVID W. POTTS

CONTROL DYNAMICS BRANCH
CONTROL SYSTEMS DEVELOPMENT BRANCH
FLIGHT DYNAMICS LABORATORY

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JULY 1982

TECHNICAL REPORT AFWAL-TR-82-3064
Interim Report - March 1980 to March 1982

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		MIL-F-9490

20 ABSTRACT (Continue on reverse side if necessary and identify by block number)

Proceedings are reported of a symposium held in Dayton, sponsored by the Flight Dynamics Laboratory during 2-5 March 1982. The symposium was planned and ran by the Flight Control Division, specifically the Flying Qualities Group and the Control Techniques Group as part of an ongoing effort to revise and upgrade both MIL-F-8785C, "Military Specification, Flying Qualities of Piloted Airplanes", and MIL-F-9490D, "Flight Control System-Design, Installation and Test of Piloted Aircraft, General Specification For."

Specialists from both the flying qualities and flight control system

disciplines were gathered in Dayton from both industry and government agencies. Formal and informal presentations, plus workshop discussions, were structured around proposed draft versions of the new Flying Qualities MIL-Standard and Handbook and the new Flight Control Systems MIL-Specification and Handbook. This report contains a record of the presentations and discussions as submitted by the individual authors.

FOREWORD

This report contains the proceedings of the AFWAL-sponsored symposium on the revision efforts of the Flying Qualities and Flight Control Specifications held at the Dayton Stouffer's Plaza Hotel March 2-5, 1982. The papers contained herein were prepared by various authors. The report editors were Captain Stanley G. Fuller of the Control Dynamics Branch and Captain David M. Potts of the Control Systems Development Branch of the Air Force Flight Dynamics Laboratory, Air Force Wright Aeronautical Laboratories (AFWAL/FIGC and AFWAL/FIGL, respectively). Symposium chairmen were Captain Fuller and Captain Potts.

Flying Qualities related work covers the time period of March 1980 through March 1982. It was performed under Program Element 62201F, Project 2401, Task 05, Work Unit 32. Flight Control work was performed under Program Element 62201F, Project 2401, Task 02, Work Unit 68.

Mr Robert J. Woodcock of the Control Dynamics Branch deserves special appreciation for his efforts reviewing and evaluating draft copies of both the Flying Qualities and the Flight Control System Specifications. His inputs greatly aided in establishing the groundwork and direction for the symposium discussions and workshops. Additionally, special thanks go to Miss Robin Ardrey and Miss Wendy Hoffman of Stouffer's Dayton Plaza Hotel for their assistance and coordination of the many details of the symposium.

A

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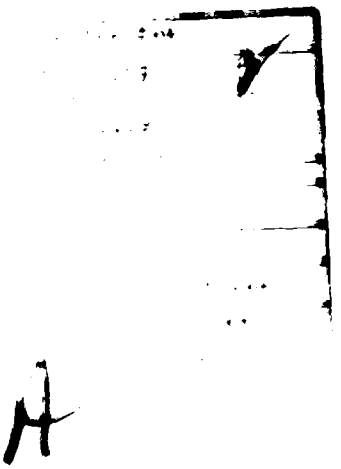
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Section I.
INTRODUCTION



I. INTRODUCTION

MIL-F-8785C, "Military Specification, Flying Qualities of Piloted Airplanes, and MIL-F-9490D, "Flight Control System-Design, Installation and Test of Piloted Aircraft, General Specification For" have been undergoing extensive modifications for the past several years. Recently, efforts have been ongoing to restructure both specifications into Standard/Specification and Handbook format as a result of an Aeronautical Systems Division (ASD) directive.

An AFWAL/FIG-sponsored symposium/workshop was held to bring together government and industry representatives directly concerned with development, use or application of either MIL-F-8785 or MIL-F-9490. As an integral part of the review cycle, a primary objective of the symposium was to solicit comments and objections/endorsements for the proposed revisions. A unique objective of the combined nature of the symposium was to foster interaction between the flying qualities engineers and the flight control system designers and to help establish a communications interface, a much needed process when considering today's highly augmented systems. Formal and informal presentations were solicited on both MIL-F-8785C and MIL-F-9490D revision drafts. Working sessions were structured to investigate the revision efforts from three different standpoints: specification revision and validation, high-technology interface with the specifications and flight testing and related experience. The comments and discussions are critical components of continued efforts with Systems Technology, Incorporated (STI), responsible for the revision of MIL-F-8785C and Northrop Corporation, responsible for the revision of MIL-F-9490D. Comments and discussion points will be used by the respective to implement changes and additions to their respective draft versions of the documents. These final reports will then be subjected to an Air Force evaluation and necessary changes, deletions and additions will be accomplished. Publications of the new Standard/Specification and Handbooks will follow.

This report presents the papers as submitted by the individual authors from both government and industry. In addition, moderators were appointed for each working session to guide and record specific comments. Review and summaries were detailed by the Chiefs of the Flight Dynamics Laboratory branches responsible for the specifications and are included in Section V along with several other summary papers. Other related symposium results are detailed in Section VI. Finally, a list of attendees and their affiliations is given in the Appendix.

Section II.
DISTINGUISHED SPEAKER REVIEWS

OPENING REMARKS FOR THE FLIGHT CONTROL SYMPOSIUM

Robert R. Rankine, Jr., Colonel, USAF
Commander, Air Force Wright Aeronautical Laboratories (AFWAL)

Good morning, ladies and gentlemen. Welcome to the "Design Criteria for the Future of Flight Controls" Symposium. It is a pleasure for me to be able to open this conference and extend my wishes for a most successful interchange on behalf of the Air Force Wright Aeronautical Laboratories and Wright-Patterson Air Force Base. Much work and effort has gone into the planning and coordination of this week's activities. I'm sure the Symposium will be a tremendous success.

The pace of technology is setting new world records almost daily. We in the Military must learn to utilize and employ such breakthroughs in the strategic realm to maintain our position as Leader of the Free World. This constant change puts new constraints and challenges to those of us in the military hardware business, and to those who govern the requirements that such hardware must meet. As a result, the military standards and specifications for weapons systems acquisition have been the subject of continuing work. As a whole, government, industry and research groups, whom you assembled here today represent, are to be commended for your unparalleled support of the goal of better and more useful specifications through this transitory period. I feel that the movement toward new formats and styles for requirements, as evidenced by both the Flying Qualities STANDARD and HANDBOOK and the Flight Controls SPECIFICATION and HANDBOOK will greatly settle much of the confusion which is in existence today. And this trend will make your jobs, whether in industry, or in the government, whether in design and manufacture, or in procurement, much easier. More important, we will have the tools which are needed in order to incorporate the technological advances sure to affect our futures. We trust your discussions here this week will be important steps toward these goals. We are depending on your success; we are confident of no other result.

Our keynote speaker became a recognized expert in the areas we will be discussing before he moved on to broader responsibilities. He is a graduate of the University of Illinois, where he received his Bachelor of Science in Aeronautical Engineering in 1954. He later received his Masters of Science from George Washington University. After serving with the United States Army as a fixed-wing aviator until 1958, our speaker joined the Columbus Division of Rockwell International. In 1966, he joined the staff of the Naval Air Systems Command, where he held several positions related to aircraft development and research and technology program planning. He led Navy participation in the formulation of the landmark Flying Qualities Specification, MIL-F-87858. In 1979, he served as Staff Specialist for Aeronautics Technology at the Pentagon, responsible for tri-service aeronautics technology programs and insuring a close relationship between the Department of Defense and the National

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Aeronautics and Space Administration. Earlier this year he was appointed Director, Engineering Technology in the Office of the Under Secretary of Defense for Research and Engineering, where he has management responsibility for a wide range of vehicle and weapons technology programs in the Department of Defense.

It is a distinct pleasure for me to introduce Mr. Raymond F. Siewert.

KEYNOTE ADDRESS
Design Criteria for the Future of Flight Controls Symposium
Raymond F. Siewart, Director, Engineering Technology
Office of the Under Secretary of Defense for Research and Engineering, The Pentagon

Thank you, Bob. Good morning.

Ladies and gentlemen, I must apologize right from the start because I woke up this morning with a rather severe cold; so my normal monotone voice is going to be even more so, I am afraid, but I'll try to get my points across. I don't think all is lost though. Last night I was reading Mark Russell's book, Presenting Mark Russell. For those of you who may not be familiar with Mark, he is a political satirist who for years has performed in the Marque Lounge in the Shore Hotel in Washington. And I noted this quote that I think fits very well today: "Adult candidates speaking at a political banquet can make you yearn to hear the clergyman's opening prayer all over again; so, if there's some consolation, maybe the dullness will allow someone to find religion."

The other thing I have to mention is if you'll note in the program, the Air Force is trying to get me in trouble with this title "Honorable." Not that I'm "dishonorable," but it seems that in the hierarchy where I work in Washington, the title "Honorable" is reserved for Assistant Secretaries. Now you know we have Secretaries, Deputy Secretaries, Under Secretaries, Assistant Secretaries, and Deputy Assistant Secretaries, and Deputy Under Secretaries. The Navy, I think, has done the best of anybody in this area because they have one position listing in the DOD directory as the Associate Deputy Secretary and he's not "Honorable."

I'm very pleased to be with you this morning and share some of my thoughts on this subject. When Dave Potts called me last fall and asked me to deliver the keynote address at this meeting, I readily agreed. Those of you who have known me through the years--and there are many out there I was pleased to meet again--you know that I am never shy about stating my views on this subject. However, after I hung up the telephone, two questions hit me. First, what really is a keynote address; and second, how does it fit in with a symposium on military specifications. The first thing I concluded was that a keynote address does not require viewgraphs, and for a bureaucrat from Washington not to use viewgraphs is tough. But then, to get a better answer to my question, I did what all us good engineers do: I consulted an authoritative reference, in this case Webster's Dictionary, which defines a keynote address as "a speech that sets forth the main line of policy" and that really had me thinking. Since last fall, I've been very involved with the Office of Science and Technology Policy, trying to develop an aeronautical policy for research policy for the 80's and 90's, and we still have yet to come to an agreement as to what the policy issues are. So when one talks policy, it's very nebulous. Then how do you bring this question of policy to this meeting? Well, I dug back in history a little bit, and if we go back to the mid 70's, we find what I term the "anti-specification era" within DOD. There's no wonder that this anti-specification feeling existed when you consider that the specification for white cotton pillow cases was some 22 pages long. And the specification for men's white cotton shorts was over 25 pages. In addition, it was felt and documented to some extent that applications of these elaborate specifications inhibited flexibility and resulted in costs, excessive costs, for a wide variety of materiel.

Hence, we adopted the concept of tailoring specifications. The currently proposed MIL-Standards and MIL-Handbooks represent the efforts by the Air Force to tailor the specifications in our areas of interest. Whether this radical departure in specification format is required or justified, I believe, is a matter of debate. The present flying quality specification MIL-F-8785C provides the mechanism to alter any or all the requirements contained therein, and that's right there on the first page about three paragraphs down. We should realize that this document is the result of years of effort to understand and define the flying qualities of aircraft that are necessary for proper performance of specified missions. I want to get back to this point of missions again. MIL-F-8785C represents the thoughts of the best technical minds in the business, although to the nonspecialist, it probably appears to be appallingly complex. This apparant complexity results from a real effort to deal with a multi-dimensional problem in a rational manner rather than from the capricious and arbitrary decisions the specification writers are frequently suspected of being guilty of.

We should also realize that military specifications, particularly those similar in nature to specifications which form the basis of this meeting, serve many roles. First, they can and do form a portion of the contractual documents in any aircraft procurement. In this role, they must be legally correct, as straightforward as possible, and contain only pertinent requirements. Second, they serve as guides, not only during the procurement process, but also in-between procurements when they sit on the shelf representing the best guidance available for future aircraft designs. Obviously, in this role, specifications should be updated regularly to reflect the latest knowledge and lessons learned. Finally, they provide the common ground to facilitate communications between the developer and procuring activity. The specifications serve in the communications role to transfer the results of our research and technology division in flight control areas to the industry. With regard to the communications role, I believe that the new format will result in increased communications at least an order of magnitude greater than we have experienced in the past, just to arrive to that common ground.

Hopefully, we now all share a common understanding of this thing we call MIL-SPEC, and I would like to get more specific about handling qualities and flight control. This is a rather unique area in the engineering community. We attempt to identify a set of parameters and assign values of those parameters such that we can identify a good airplane. But what is good? To me, it means that the pilot-aircraft combination must be able to perform the designed missions with a high probability of success. For example, if the design is a tactical aircraft, there should exist the capability to kill enemy targets in the air or on the ground with high probability. If it is a strategic aircraft, it must have good range payload capability to be a stable launch platform. But as a transport, obviously, long duration flights must be accomplished without undue crew fatigue. Underlying all this is an inherent requirement for safety and survivability, particularly for certain critical flight phases, such as take-off, landing or high-angled attack maneuvering. The unique nature of all this is that we have very little direct correlation between those aircraft parameters we select and mission effectiveness, which of course raises the question, "How does one determine whether the airplane is good or bad?" In the last analysis, this will have to remain where it has been since airplanes began to fly, i.e., based on a considered judgment of the men who operate the airplane--knowledgeable and motivated pilots.

With these thoughts in mind, I believe it might be enlightening to see how far we have progressed in this business. In 1907, the first specification for military aircraft was prepared. The handling qualities requirements for this observation airplane were stated in one sentence. During this trial flight of one hour, it, the aircraft, must be steered in all directions without difficulty and at all times under perfect control and equilibrium. From that original requirement, we have progressed through a variety of documents up to the present flying qualities specification, MIL-F-8785C, which contains 93 pages of requirements and related information. We are now proposing a new format wherein we will fill in 44 pages of blanks with data drawn from a 620-page handbook. The question is, "Have we made progress in assuring good aircraft in the future?" I believe the answer is doubtful. We are still not smart enough to be sure that strict compliance with requirements of the flying qualities specification will ensure a good airplane, nor can we be certain that noncompliance will inevitably result in a bad airplane. I am sure that we all know of several examples of both situations: therefore, I will not take time now to tell my favorite war story. And I've got a few.

In reflecting on the current situation, I believe there are many factors that impact the future of flight control specifications. First is the fact apparent to us all, namely that new military aircraft development programs are becoming fewer and farther apart. As a result, we don't have the operational feedback to tell us how well or how poorly airplanes designed to our present specifications measure up. Secondly, when a new aircraft devleopment is initiated, there is that drive by all concerned to make the new aircraft significantly more capable than its predecessor. As airplanes become more capable, they also become more complex. This increase in complexity is nowhere more apparent than in the control system. The result is that modern control systems lead to the situation wherein the flying qualities become more difficult to describe. Many flying qualities are specified in terms of basic modal characteristics of airplane dynamics. This was a fundamental and rational approach when airplanes flew like airplanes. But the newer control systems incorporating prefilters, forward loop compensation, and crossfeeds are being used on many current aircraft. These artifacts do increase system order and we need to increase the effects and requirements. However, one questions the need to increase the order of the system to the extent that has been experienced recently. Is all this compensation required for good flying qualities? Or is it being done because we like to display our technical cleverness? And this cleverness can be easily implemented today through the extensive use of digital flight control computation schemes. In this case, I agree with the airplane design philosophy of William Allen, former president of the Boeing Company, which is, simplicate and add lightness. All of the above notwithstanding, we recognize that increased capability leads to some increase in complexity.

In flying qualities, this has led to the concept of equivalent systems as an attempt to utilize the existing data base for a broad range of control system mechanizations. However, as noted on page 61 of the Draft MIL-Handbook, as we consider configurations with dynamics that depart more and more from the classical order form, more and more judgment will be required in defining the appropriate equivalent system parameters in accessing compliance with the requirements. I believe that the question for all of us to consider on reflecting on that paragraph is "How amenable is the system we work in, i.e. not the control system, to developing and applying

the requirement judgment?" I don't know. I believe that this question becomes even more germaine if we examine the potential impact of some of our current flight control research and technology programs. We are stressing the integration of the flight control with the fire control, weapons system, propulsion system, navigation system. We will shortly fly an F-16 aircraft that will be capable of any independent modes of motion. When this capability is integrated with subsystems mentioned above, then a serious question in my mind is, "How do we specify the flying qualities?" With all due respect to John Hodgkinson, I don't believe the equivalent system concept will be adequate. Finally, I would like to share with you some observations about this specific meeting. One of the stated purposes of this symposium is to bring the handling qualities and flight control specialists together in the same room. But are we thinking together about the subject at hand? A cursory review of the two standards documents indicates that both specifications set requirements on airplane response to control system failure. While these requirements do not seem to be in conflict, and although they could be lacking proper coordination in filling in the blanks, they do tend to be confusing because of the use of different terminology. And why do we have to specify the same thing in two different places? It is stated in the preface of the Handbook that a primary objective of the Mil-Standard and Handbook is to accommodate highly augmented airplanes. After going through some of the documents, I'm afraid that result may encourage contractors to offer highly augmented airplanes. It will take a great deal of skill and judgment (there's that word judgment again) to fill in the blanks so that on the one hand, reasonable assurance of adequate flying qualities exists while on the other, we can allow for proper flexibility during negotiation and procurement process. Somewhere in this process, we must examine the impact on program cost. Showing compliance with all the requirements is no trivial matter.

In conclusion, I'd like to share with you some thoughts I have about aeronautical technology as a discipline. I believe that we are at a crucial point in the evolution of this technology as far as manned aircraft are concerned. I'm speaking primarily of military aircraft, tactical aircraft. We are meeting here for three and a half days to review specifications that may be obsolete before they are published. For example, can we really separate flying qualities and flight control? Yet, we are talking about two separate documents. How do we address other elements of the aircraft such as the propulsion system which will be thought more and more as part of the flight control? I don't know how many are representing engine companies here today. An interesting question, "How many here represent engine companies today?" Yet, we're talking about that as a part of flight control. How do they feel about that? How are we going to get them in bed with us? How do we cope with design concepts of the future such as independent modes of motion and integrated control. These are perplexing questions, and underlying all of them is the growing feeling that maybe we have to take a new look at what constitutes flight control criteria. I hope that during these next three and a half days you'll have an opportunity to debate these and other questions, and through your wisdom provide guidance for future directions in this technology. Thank you.

OPENING REMARKS - DINNER BANQUET

Robert C. Barlow, Colonel, USAF
Director, Flight Dynamics Laboratory

Good evening ladies and gentlemen. On behalf of the Flight Dynamics Laboratory, let me welcome you to the Flight Control Symposium Dinner Banquet.

I know that the conference has been a success so far. The interface achieved in the formal sessions and the informal workshops has already proven the invaluable progress possible when both the Flying Qualities and Flight Control communities jointly tackle the problems exposed by today's highly technical Air Force. I wish you continued success this week; more important, I hope you've gained some valuable insight for continued success in your own individual responsibilities.

It is my distinct pleasure this evening to introduce you to a man who is eminently qualified to address this conference. Flying Qualities and Flight Controls were among the many important aspects of the systems the Aeronautical Systems Division managed under his leadership and guidance. He played a major role in the effort to transition to more streamlined requirements and specifications. In fact, it was during his tenure as the ASD Commander that the principle of using the STANDARD and HANDBOOK for aircraft procurement developed. Further, he forewarned the research and development community of the problems associated with too rapid an entrance into high-technology hardware without the supporting data base, technical requirements and design criteria and specifications. We in the Flight Dynamics Laboratory share his concerns.

James T. Stewart began his illustrious military career in 1941 as an Aviation Cadet at Brookes Field, Texas. He was commissioned in the United States Army Air Corps Reserves and awarded wings in 1942. He obtained his Bachelors Degree in Aeronautics from the University of Michigan and later his Masters of Business Administration from George Washington University.

General Stewart held varying responsibilities during World War II. He transitioned to the B-17, became an Instructor Pilot, and later commanded the 508th Bombardment Squadron, England. He completed two combat tours during his European assignment.

After returning to the states, General Stewart continued to affect aircraft development and operational use, pioneering jet aircraft piloting techniques for long-range cruise and dive-bombing. His abilities led him overseas again, this time to the Far Eastern Air Force Headquarters, Tokyo, where he was a key planner in F-84 nuclear delivery capability.

General Stewart returned to Air Force Headquarters for several positions before being assigned to the Office of the

Secretary of the Air Force. He was involved in the US Space Program, serving as Vice Director, Manned Orbiting Laboratory. He later went to the Air Force Systems Command as Deputy Chief of Staff, Systems. In 1970, General Stewart assumed command of the Aeronautical Systems Division, Wright-Patterson Air Force Base, a position he retained until his retirement from the Air Force.

General Stewart's numerous decorations and awards include the Air Medal, awarded seven times, the French Croix de Guerre, the Distinguished Flying Cross, awarded twice, the Distinguished Service Medal, The Legion of Merit with one Oak Leaf Cluster and the Bronze Star Medal. He is also the author of the book, "Airpower - The Decisive Force in Korea."

Ladies and gentlemen, may I present, General James T. Stewart.

DINNER BANQUET COMMENTS

James T. Stewart, Lieutenant General, USAF(Ret)
Former Commander, Aeronautical Systems Division

Several months ago, when Captain Fuller invited me to your dinner tonight, I accepted immediately. After all, what better way to warm the cockles of an old soldier's heart than by offering him free cocktails, a free dinner, and the opportunity to swap war stories with old friends!

Of course, nothing ever really is free, and there was a small hook hidden in the bait--namely, that I "sing for my supper!" And when I learned the title of the "song," the wisdom of accepting Fuller's invitation began to appear highly questionable.

In fact, last month, when I began to think seriously about words to go with the melody, there was a reaction similar to the punch line of one of my all-time favorite stories--which, incidentally, seemed quite appropriate for this gathering, since the key figure possesses outstanding inherent flying qualities and a superb flight control system.

Visualize, if you will, a dove, a lark and a duck perched atop a split-rail fence, with a giant American Bald Eagle soaring majestically back and forth above them. Suddenly, the eagle swooped down, grabbed up the dove, and disappeared over the horizon. The eagle returned in about ten minutes, deposited the dove gently on the fence, and resumed his circling in the sky above. The little dove preened all over, and proclaimed for all the world to hear, "I'm a dove, and I'm in love!"

Then, the eagle swooped down again, grabbed up the lark, and disappeared over the horizon. Again the eagle returned in about ten minutes, deposited the lark gently on the fence, and resumed his majestic flight above. The little lark preened all over, and proclaimed for all the world to hear, "I'm a lark, and I've been sparked!"

Suddenly, the great eagle dove down a third time, grabbed up the duck, and disappeared over the horizon. This time, the eagle didn't return for about twenty minutes, and--with both looking somewhat bedraggled--plunked the duck on the fence, and ever-so-slowly climbed back up into the afternoon thermals. The duck first shook it's head from side to side, then shook all over, and proclaimed for all the world to hear, "I'm a drake, and there's been a terrible mistake!".....

Believe me, I understood that drake's reaction! I began to feel it had been a "terrible mistake" to agree to talk about subjects as tough as flying qualities and flight control systems; in the presence of in-depth technical expertise, without benefit of having attended any of your sessions, and with my background, the final nail is in the coffin.

Of course, as an active pilot for close to 40 years, I have most of the flying fraternity's usual prejudices and misconceptions, and I am--or was--an aeronautical engineer, but unfortunately majored in structures and aerodynamics. And finally, I'm not in as close touch with the technical community as five years ago when I retired to the retail world of toasters and crockpots.

So, after assessing my qualifications--or lack thereof--to be your speaker tonight, I discussed my dilemma and solicited advice from some of my old Wright-Patterson competitors. I didn't get too many specifics, but did get a lot of free advice. Probably, the best came from Fred Ball, AGD's Chief Engineer, who said, "Man, you're in trouble. Dance around a lot, and keep it brief!"

So far, I'm following Fred's advice quite well. I see by my watch that I've now danced around for almost 5 of the 25 minutes allocated for this purpose, and only mentioned the purpose of your Symposium twice! Seriously, for the next 20 minutes or so, let me offer some thoughts on flying qualities and flight control systems, and also some cautions on the preparation and use of specifications and handbooks.

To start with, let's delve back into history for a few minutes, and see how we got to where we are today.

Surprisingly, to me, despite the many technology advancements in the 19th century--electricity, steam, machinery of all kinds--except for balloons, man did not make much progress in winged flying until the late 1800s. I am referring here, of course, mostly to the hang-glider research and flight-test experimenting by Germany's Otto Lilienthal. Although Lilienthal's hang-gliders were more conventional in planform than the modern generation, his basic approach was essentially the same--namely, to use an inherently stable form, and control it in pitch and yaw by subtle weight shifting. Unfortunately, Lilienthal encountered some of the same control problems that have claimed numerous modern enthusiasts and was killed in an accident in 1896. At the time of his death, he was developing an ingenious body harness connected to an aft elevator for better pitch control--which might have prevented his untimely demise. Fortunately, for the world of aviation, Lilienthal was a great documenter of his work. And that's the first lesson for this evening: take the time to thoroughly and accurately document your work.

As an aside, not too much progress was made in powered, controlled flight for a couple of hundred years because most men were too preoccupied with the flight of birds. Even Lilienthal believed that powered flight would first be realized with some form of wing flapping.

It wasn't until many years later that man finally determined that a bird, even while gliding, is a highly unstable vehicle, using it's eye and brain to make continuous and minute corrections to its pinions and tail feathers. Today, thanks to rate-sensing

gyros, accelerometers, pressure sensors and digital computers to provide a basis for artificial stability. I suppose we could make a reasonably close copy of a gliding bird--if there were a need to do so.

But as a further bit of trivia, high-speed photography finally showed why man's early attempts to achieve powered flight by wing flapping were on the wrong track. It, of course, is not the simple motion that it appears to be to the naked eye, but rather a complicated figure-eight pattern at the tips, coupled with something else again inboard.

If you engineers think writing specs and handbooks for today's aircraft is difficult, try writing flying qualities, flight control system and structural specifications and handbooks for the wing system of my great American bald eagle.

And, then, along came two bright bicycle builders, who after fooling around with unmanned and manned gliders, and putting over the writings of Lilienthal and Chanute, came to the conclusion that man's approach to powered controlled flight was mostly wrong. They concluded that propellers were the right source of power--which weren't all that new, by the way: man-made propellers and windmills having been around for about 600 years then. They also concluded that the right approach--the one intended--was to design a totally unstable vehicle with an integral flight control system of a forward elevator, aft rudders and wing warping for lateral control.

And, as attempts to duplicate their machine, on the 75th anniversary of powered flight in 1978 proved out, they had indeed succeeded in building a wildly unstable vehicle in pitch--thanks to the front elevator and short moment arm--and almost equally unstable in yaw, again thanks to a short moment arm.

Why the Wright brothers went to wing warping rather than ailerons for lateral control is unclear in their writings. Perhaps, it was the last hangover from man's long-time enchantment with birds. But, the important thing is that it did fly under its own power, and with a certain amount of control over where it went!

While this approach was successful, it was soon determined that flying qualities and the flight control system needed considerable improvement if the pilot was to do anything with an airplane--other than to try to keep up with its gyrations. Thus, Signal Corps Specification Number 486, in December 1907, required a trial endurance flight of one hour which returned to the starting point and landed without damage. The spec further stated that the craft "must be steered in all directions without difficulty, and at all times under perfect control and equilibrium."

That one-page specification stood virtually unchanged until 1943 when the Army Air Force issued a single specification,

[illegible], entitled "Stability and Control Requirements for Airplanes." About half of this document was devoted to the flight tests required to demonstrate compliance with the requirements. In hindsight, it was done sufficient that it used [illegible] the data available through flights.

This specification was released in 1954 (as MIL-F-8785) and contained an exceptionally proven, but still with great emphasis on the evaluation criteria to prove compliance. A major change occurred in 1969, with the issue of MIL-F-8785B, with many of the requirements now based on "good-in-the-loop" considerations, with known levels of flying qualities, and recognition of different levels of pilot workload and task performance. This document established the baseline flying qualities/flight control system requirements for the F-15, B-1 and other current high-performance aircraft.

Unfortunately, by now, MIL-F-8785 had grown to 80 pages, with a supporting document of 600 pages+ for any from the 1969 signal change one page specified probably led to more complexity in several other specs that really was needed.

The last version emphasized high angle of attack requirements--all of which sort of leads up to where you are today--trying to accomplish all that is known, and sort it out so that ultimately aircraft can fly flying qualities and flight control system requirements to the intended mission.

But let's go back into history and talk about capabilities for a few minutes more.

After the Wright Brothers' success with a vehicle inherently unstable in all axes, there was an immediate turn-around to the inherently stable airplane--dihedral in the wings, long moment arms for aft-mounted vertical and horizontal stabilizers, a center-of-gravity at about 25% of the mean wing chord--all of which could be designed and/or overcome by mechanically actuated, conventional ailerons, rudders and elevators.

There wasn't too much progress for the next fifty years or so. Although there were many lessons learned about flying qualities and control systems. For example, the torque from rotary engines in British Sopwiths and French Nieuports often resulted in wild, spinning departures from controlled flight at high power settings and high angles of attack. World War I designers never could develop enough control authority to overcome the problem, so smart pilots just stayed away from that flight regime, if possible. The problem finally disappeared when the rotary engine passed on into oblivion.

I suspect Snoopy's problem in coping with the Red Baron and rotary engines would be easily solved today with a flight control system a la the F-16. Just feed engine power and angle of attack data into the FCS computer and prevent the old Sopwith from ever flying into a departure situation!

One other tid-bit from World War I engineering might be useful if any of you ever have a need to specify flying qualities of a tail-plane. And, that is: use forward, not reverse stagger on the wings if you hope for stall recovery! And don't laugh at the possibility of a comeback by the tail-plane. I note that our beloved Congress, in all its aeronautical wisdom has the Air Force building some turbo-prop powered P-51's for evaluation.

Air racing before World War II developed some flight control and flight characteristics innovations which, like many other racing advancements, lay dormant for many years. For example, the Boyton-Wright Airplane Company entered a racer in the last Gordon Bennett Trophy Race in Paris in 1920. Very sophisticated for its time, the Boyton-Wright Racer was a high-wing monoplane with a retractable landing gear a la the Grumman Navy fighters of the 1930s. Most interesting, however, was the use of cambered leading and trailing edge flaps to provide the increased lateral control authority needed for closed-course racing.

In the thirties, considerable attention was placed on controls and flying qualities of smaller and slower aircraft.

For example, there was a safety competition, encouraged by the Government, to develop small stall/spin-proof airplanes. For the most part, this was accomplished by using very low-speed, gentle-stalling airfoils and by limiting elevator authority.

The well-known small Druopa tried to further simplify flying by coupling the rudder and the ailerons. The result, however, was what the designer should have expected--a sloppy flying airplane at all but one design point.

French designer Henri Mignet gave the world a negative lesson in flying qualities and flight control systems with his famous --and infamous-- Pou de Ciel, which literally translated meant Flying Louse, but was affectionately known as the Flying Flea by its amateur builders. Henri despised ailerons, so the Flea didn't have any. Fortunately, for Henri, the turned-up wingtips and a large rudder combined for such a strong roll-coupling that it turned reasonably well. Mignet didn't believe in elevators either, so he didn't include any; pitch control was achieved by changing the angle of incidence of the upper, forward wing. Unfortunately, if the incidence angle was increased too much, it increased the lift considerably on the lower, rear wing. This caused an ever-increasing negative pitch which led either to an outside loop--if the Flea was high enough--or a devastating dive into the ground. Needless to say, this resulted in the permanent grounding of the Flying Flea.

Somewhere around the start of World War II, elevator bob-weights were devised as a means of preventing two-fisted pilots from over-stressing transports or bombers which had overly light stick forces, or unacceptable stick-force gradients. Bob-weights, however, were an awful nuisance in straight-and-level flight in any kind of turbulence.

The jet era of the late forties and fifties introduced a whole host of flying quality and flight control system problems because of the great expansion of the flight envelope. Nevertheless, these didn't seem to be all that great many technology advances in areas core for the next twenty years. Namely, small stickforce gradients, powered-boosted controls, power-assist controls, stability augmentation systems to overcome the low stability problems, the use of spoilers and/or jet-vanes for high-speed roll control and many other band-aids to help the pilot make gradually less demanding.

Now, all the inclusions history has for a purpose. It, presumably, was an unanticipated evolution toward this result. Over the years, it has taught history not only fascinating but useful as well. The lesson, fascinatingly, is pervasive throughout the ages. Whenever we had a problem, I always used to advise young ADP engineers to consciously check history books before undertaking their studies. And for those of you too young to know what a slide rule was, that's a mechanical calculator somewhere between the Roman Abacus and today's pocket computers!

The introduction of flight control systems came with the introduction of the computer into the system. Combined with highly complex mechanisms, this gave pilot and designer access to more than a few of the new possibilities to make an airplane fly to the very limit of the aerodynamic capabilities. Conversely, for the first time, it was also now possible to artificially preclude the pilot from undesirable departures from controlled flight. Current examples of what can be done include the roll-rate system in the B-1 to bank the pilot and the attitude and the superb flight control system in the F-16.

There now are great computer possibilities and potentials in flight control systems. Because of the computer and all kinds of sensors, there is almost carte blanche for concepts of what aircraft--most of which are non-technological in nature.

For example, let's think about flying qualities for a moment--which, incidentally, should be viewed from two re-equipment--one, the inherent flying characteristics of the airframe and two, flying qualities brought about by flight control inputs. Will the aerodynamicists become overly complacent in various areas of the flight envelope simply because unnecessary airframe flying qualities can be covered-up with a do-it-all computerized flight control system?

Is so much attention focused on very high speed and great maneuverability throughout the flight envelope, that what has been learned over the last 40 years for the 300 miles per hour and less range, is largely neglected or forgotten?. I will wager anyone here a steak dinner that the next generation trainer does not end up with a simple, power-assisted, mechanical flight control system.

Is so much being demanded from Flight Control Systems and Flying Qualities, in terms of perfection across the flight envelope, that insufficient attention is focused on the primary mission? To digress, the worst airplane I ever encountered, as far as primary mission flying qualities were concerned, was the C-125 Assault Transport in the late 1940s. The C-125 was a high-wing, fixed-gear, tri-motor configuration, with an aft loading ramp ala the C-140. The C-125 generally met the stability and control requirements of Army MIL Spec C-1815--in normal take-offs and landings, in climb at about 120 knots, and in cruise at a zippy 140 knots. Unfortunately, at assault landing speeds, with power on, it had virtually no pre-stall warning, and would unexpectedly quit flying with unpredictable violent departures. None of the usual band-aid fixes, such as air guides, air fences, stall strips or fillets cured any of it's deadly characteristics; and the 25 or 30 C-125s built were finally consigned to the Mechanics School at Sheppard. Not enough attention was paid to flying characteristics in the primary mission part of the flight envelope.

Back to the concerns. As a long-time pilot, I'm delighted to see more attention focused on workloads and tasks. But designers shouldn't become so engrossed in these subjects that insufficient attention is paid to his (the pilot's) strong and weak attributes. For example, the human brain digests visual cues very well. Sound inputs are a distant second, and you can pretty well forget about the rest of the human sensors.

The community seems to be focusing on a single specification/standard for all aircraft. Would life be more manageable for the requirements writers, designers and evaluators if there were five or six separate classes for the various generic kinds of aircraft?

And finally, I think you should be very concerned about the application of the MIL-PRIME formatted specification. The concept of having a shopping list that covers the waterfront, and then selecting from that list, and filling in the blanks to tailor a flying qualities/flight control system spec to each new system is great. However, the application isn't all that easy.

I would remind you of the 375 series of Air Force Regulations on System Program Management. About 20 years ago, they grew out of and were designed to guide system acquisitions as complex as the ICBM Programs. The concept--sound familiar? --was to selectively tailor them for systems of lesser programs. The only problem was that most Directors of lesser programs didn't have the depth of experience required to do selective tailoring, so they applied the whole sheet. I shouldn't have to tell you what the results were in many programs.

Well, the old familiar Timex tells me I have danced away most of my allotted time. So, in closing, let me just offer a couple of observations.

On the one hand, I stand in absolute awe at the knowledge, the capabilities and the possibilities in the flying qualities/flight control system arena. And what you are doing in your Symposium is important to further advancement. But, on the other hand, were I the Commander of ASD at this moment, I would be concerned about guarding against sophistication for sophistication's sake.

What it all adds up to is a tough road ahead for most of you here--a never ending series of difficult choices between requirements, capabilities and costs.

Speaking of difficult choices brings to mind the young fellow whose wealthy aunt in Brazil died and named him a principal heir. He sold everything and went to Brazil for the reading of the will. The will stipulated that he had his choice of her coffee plantation or her nut farm. He chose nuts. Shortly thereafter, the price of coffee tripled and the bottom fell out of the nut market. He lost everything. He sold his new, gold Seiko to buy an airline ticket back to the States. At the airport, he had to choose between Los Angeles and New York as a destination. He chose Los Angeles. The New York plane was a brand-new Boeing 747. The Los Angeles plane was a 1928 Ford Trimotor--which incidentally had reasonably good flying qualities, and a very simple, reliable and low-cost flight control system. Well, over the Andes, an outboard engine fell off and the over-loaded Ford began to lose altitude. Our hero made his way forward to the cockpit, and offered to bail out to lighten the aircraft if the pilot would give him a parachute.

"OK," said the pilot, "but anyone who bails out of this airplane has to wear two parachutes!"

So, he buckled them on and jumped. He decided to use the seat pack and yanked the ripcord handle. But, alas, the cable was rusted and pulled apart. Frantically, he pulled the chest-pack ripcord. That parachute came out and blossomed. But, almost immediately, the rotted shroud lines parted, and he plummeted toward the earth. Somewhat desperate at this turn of events, he frantically screamed out,

"St Francis! Save me! Save me!"

A great hand reached down from the sky, grasped him by the wrist, and gently stopped his death plunge toward the rocks below. And a deep, pleasant voice inquired,

"St Francis Xavier, or St Francis of Assisi?"

Thank you again--my pleasure to have been here tonight.

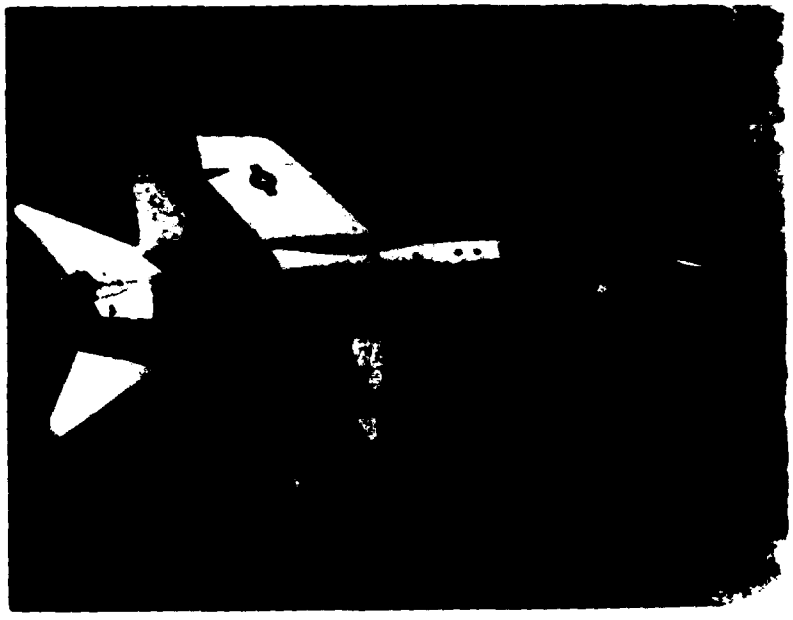
SECTION III.
FORMAL PAPERS

NEW DIRECTIONS IN FLIGHT CONTROL REQUIREMENTS

Marle Hewett
Northrop Corporation

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NEW DIRECTIONS IN FLIGHT CONTROLS REQUIREMENTS



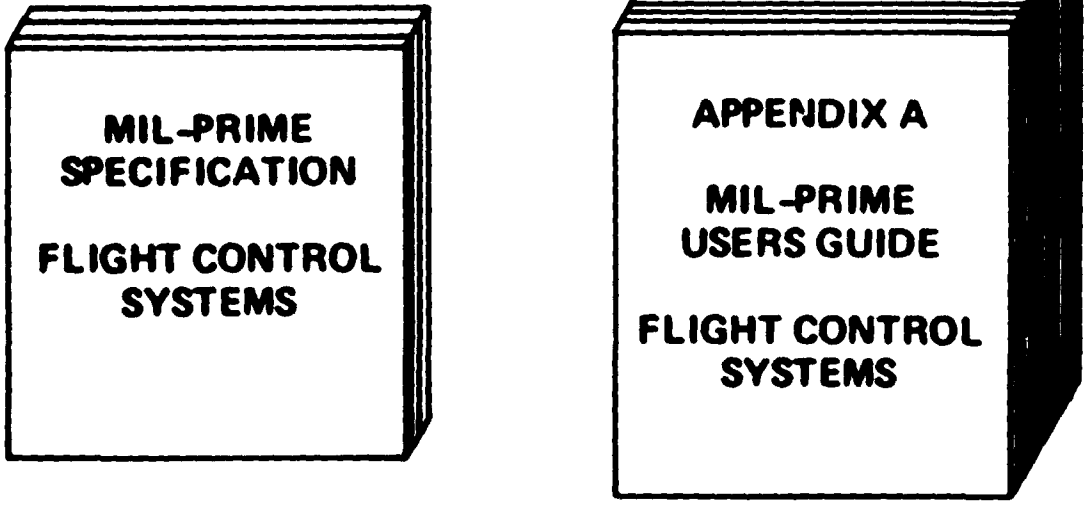


NORTHROP

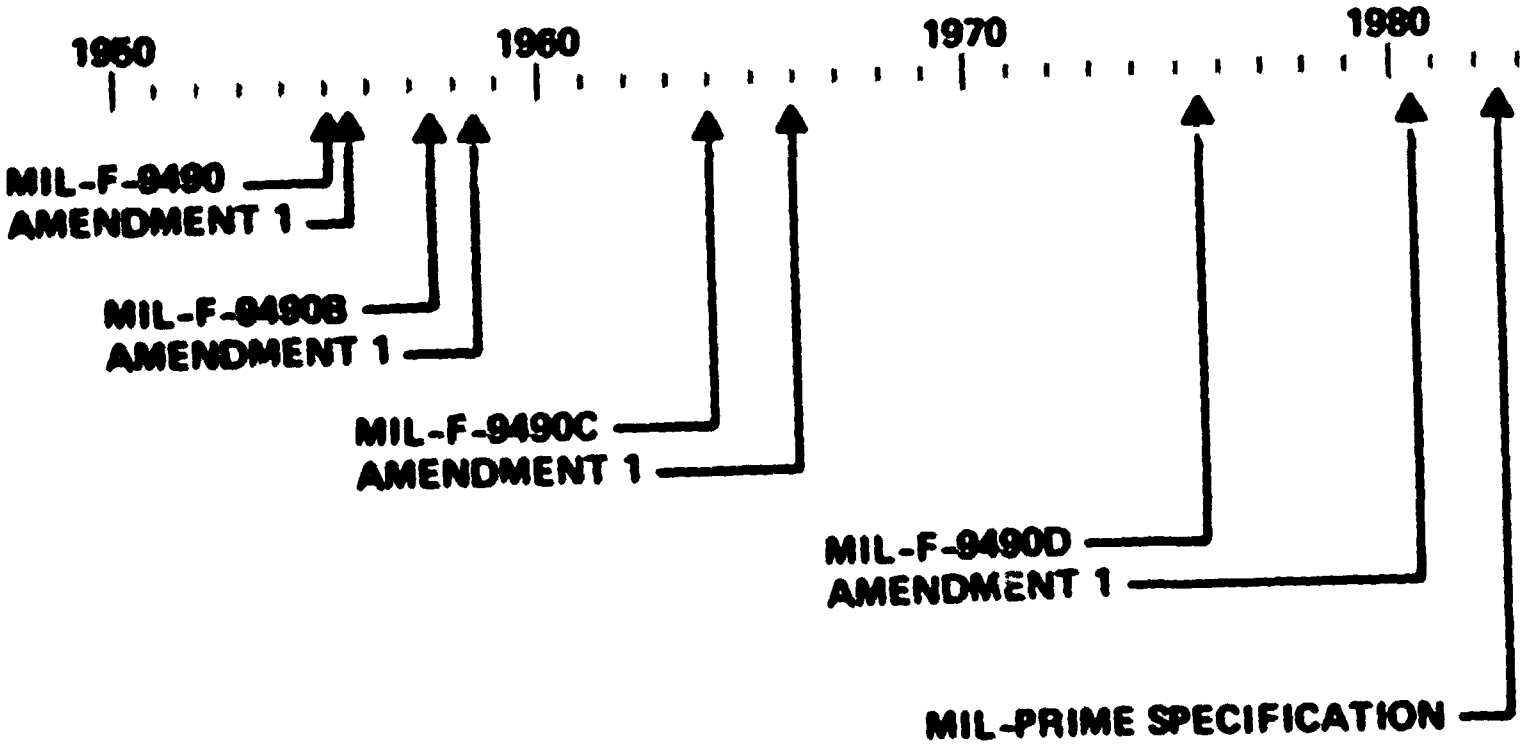
CONTRACT: F33615-80-C-3610

TITLE: UPGRADING OF MIL-F-9490, GENERAL SPECIFICATION FOR FLIGHT CONTROL SYSTEMS

PURPOSE: REPLACE MIL-F-9490D AND ITS ATTENDANT USERS GUIDE WITH A MIL-PRIME SPECIFICATION AND ASSOCIATED USERS GUIDE



HISTORY OF MIL-F-9490 DEVELOPMENT



OBJECTIVES OF THE CONVERSION OF MIL-F-9490 TO A MIL PRIME SPECIFICATION

- SIMPLIFY THE SPECIFICATION
- ELIMINATE REFERENCES TO SUB-TIER SPECIFICATIONS
- STANDARDIZE SPECIFICATION FORMAT
- FORCE A TAILORING OF THE SPECIFICATION TO THE OPERATIONAL AND PERFORMANCE REQUIREMENTS OF A GIVEN PROCUREMENT
- ELIMINATE DETAIL DESIGN REQUIREMENTS
- EMPHASIZE THE USE OF THE HANDBOOK

FORMAT COMPARISON:
MIL-PRIME VS MIL-F-9490D

MIL PRIME SPECIFICATION

SECTION	TITLE	PAGE COUNT
1	SCOPE	2
2	APPLICABLE DOCUMENTS	1
3	REQUIREMENTS	22
4	VERIFICATION PROVISIONS	13
5	PREPARATION FOR DELIVERY	½
6	NOTES	½
		39

MIL-F-9490D

SECTION	TITLE	PAGE COUNT
1	SCOPE	2
2	APPLICABLE DOCUMENTS	5
3	REQUIREMENTS	60
4	QUALITY ASSURANCE	7
5	PREPARATION FOR DELIVERY	½
6	NOTES	5½
		80

MIL-PRIME EXCERPTS

1. SCOPE

1.1 SCOPE. THIS SPECIFICATION ESTABLISHES PERFORMANCE, OPERATIONAL, VERIFICATION AND QUALITY ASSURANCE REQUIREMENTS FOR THE FLIGHT CONTROL SYSTEM OF THE _____ _____ AIR VEHICLE. THIS SPECIFICATION ADDRESSES THE SPECIFIC OPERATIONAL NEEDS WHICH THIS FLIGHT CONTROL SYSTEM MUST SATISFY IN ORDER TO MEET MISSION REQUIREMENTS.

1.2 APPLICABILITY. THE FLIGHT CONTROL SYSTEM SHALL MEET ALL THE REQUIREMENTS CONTAINED HEREIN EXCEPT THOSE CONTAINED IN PARAGRAPHS OR SUBPARAGRAPHS MARKED NOT APPLICABLE (N/A).

1.3 USE. THIS SPECIFICATION CANNOT BE USED FOR CONTRACTUAL PURPOSES WITHOUT FILLING IN THE BLANKS CONTAINED HEREIN AFTER A DETAILED REVIEW OF THE MISSION REQUIREMENTS. SUPPLEMENTAL INFORMATION RELATING TO THE PERFORMANCE AND OPERATIONAL REQUIREMENTS OF FLIGHT CONTROL SYSTEMS IS CONTAINED IN APPENDIX A. THAT INFORMATION AND DATA MAY BE USED IN FILLING IN THE BLANK FLIGHT CONTROL SYSTEM SPECIFICATION.

MIL-PRIME EXCERPTS (Continued)

3.4.1 CONTRACTOR REQUIRED DOCUMENTATION AS SPECIFIED IN THE CONTRACT THE FOLLOWING DOCUMENTATION WILL BE PERIODICALLY UPDATED BY THE CONTRACTOR DURING THE DEVELOPMENT AND TEST CYCLE OF THIS FLIGHT CONTROL SYSTEM

A. FLIGHT CONTROL SYSTEM DEVELOPMENT PLAN (REF APPENDIX A 40.4.1)

B. FLIGHT CONTROL SYSTEM FCS QUALIFICATION AND INSPECTION REPORT (REF APPENDIX A 40.4.3.2)

C. FLIGHT CONTROL SYSTEM ANALYSIS REPORT (REF APPENDIX A 40.4.3.1)

D. FLIGHT CONTROL SYSTEM FINAL TEST REPORT (INCLUDES GROUND AND FLIGHT TEST RESULTS) (REF APPENDIX A 40.4.3.2)

E. FLIGHT CONTROL DESCRIPTIVE REPORT. THIS REPORT SHALL PROVIDE A GENERAL DESCRIPTION OF THE FLIGHT CONTROL MECHANIZATION AND OPERATION

F. AT THE TIME SPECIFIED BY THE CONTRACT, A REPORT SUMMARIZING THE "LESSONS LEARNED" BY THE CONTRACTOR IN MEETING THE FCS REQUIREMENTS AS DEFINED BY THIS SPECIFICATION SHALL BE SUBMITTED IN A FORMAT EASILY USED IN UPDATING THE FCS APPENDIX A.

FORMAT COMPARISON:
MIL-PRIME VS MIL-F-9490D

MIL PRIME SPECIFICATION

SECTION	TITLE	PAGE COUNT
1	SCOPE	2
2	APPLICABLE DOCUMENTS	1
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4	VERIFICATION PROVISIONS	13
5	PREPARATION FOR DELIVERY	½
6	NOTES	½
		39

MIL-F-9490D

SECTION	TITLE	PAGE COUNT
1	SCOPE	2
2	APPLICABLE DOCUMENTS	5
3	REQUIREMENTS	60
4	QUALITY ASSURANCE	7
5	PREPARATION FOR DELIVERY	½
6	NOTES	5½
		80

MIL-PRIME EXCERPTS (Continued)

2.0 APPLICABLE DOCUMENTS

2.1 ISSUES OF DOCUMENTS. THE FOLLOWING DOCUMENTS, OF THE ISSUE IN EFFECT ON THE DATE OF INVITATION FOR BIDS OR REQUEST FOR PROPOSAL, FORM A PART OF THIS SPECIFICATION TO THE EXTENT SPECIFIED HEREIN:

SPECIFICATIONS

MIL-F-8785 FLYING QUALITIES OF PILOTED AIRPLANES, GENERAL SPECIFICATION FOR

MIL-F-83300 FLYING QUALITIES OF PILOTED V/STOL AIRCRAFT

STANDARDS

PUBLICATIONS

(COPIES OF THESE SPECIFICATIONS, STANDARDS, AND PUBLICATIONS REQUIRED BY CONTRACTORS IN CONNECTION WITH SPECIFIC PROCUREMENT FUNCTIONS SHOULD BE OBTAINED FROM THE PROCURING ACTIVITY OR AS DIRECTED BY THE CONTRACTING OFFICER.)

FORMAT COMPARISON: MIL-PRIME VS MIL-F-9490D

MIL PRIME SPECIFICATION			MIL-F-9490D		
SECTION	TITLE	PAGE COUNT	SECTION	TITLE	PAGE COUNT
1	SCOPE	2	1	SCOPE	2
2	APPLICABLE DOCUMENTS	1	2	APPLICABLE DOCUMENTS	5
3	REQUIREMENTS	22	3	REQUIREMENTS	60
4	VERIFICATION PROVISIONS	13	4	QUALITY ASSURANCE	7
5	PREPARATION FOR DELIVERY	½	5	PREPARATION FOR DELIVERY	½
6	NOTES	½	6	NOTES	5½
		39			80

MIL-PRIME EXCERPTS (Continued)

3.1.2.1 AFCS FUNCTIONAL PERFORMANCE. FOR THE AFCS FUNCTIONS INDICATED BELOW THE FOLLOWING SPECIFIED PERFORMANCE SHALL BE PROVIDED UNLESS OTHERWISE SPECIFIED. THESE REQUIREMENTS APPLY IN SMOOTH AIR AND INCLUDE SENSOR ERROR AND SHALL EXHIBIT A DAMPING RATIO (APPENDIX A SECTION 20.3) OF AT LEAST ____ CRITICAL FOR NONSTRUCTURAL AFCS CONTROLLED MODE RESPONSES. SPECIFIED DAMPING REQUIREMENTS APPLY ONLY TO THE RESPONSE CHARACTERISTICS FOR PERTURBATIONS AN ORDER OF MAGNITUDE GREATER THAN THE ALLOWABLE RESIDUAL OSCILLATION.

3.1.2.1.1 ATTITUDE HOLD. _____

3.1.2.1.2 HEADING HOLD. _____

3.1.2.1.3 HEADING SELECT. _____

3.1.2.1.4 ALTITUDE HOLD. _____

3.1.2.1.4.1 BAROMETRIC ALTITUDE STABILIZATION. _____

3.1.2.1.4.2 STABILIZATION OF ALTITUDE ABOVE THE TERRAIN. _____

3.1.2.1.5 MACH HOLD. _____

3.1.2.1.6 AIRSPEED HOLD. _____

3.1.2.1.7 CONTROL STICK (OR WHEEL) STEERING. _____

3.1.2.1.8 HOVER HOLD. _____

3.1.2.1.9 VERNIER CONTROL FOR HOVERING. _____

3.1.2.1.10 GROUND SPEED HOLD. _____

3.1.2.1.11 _____. _____

MIL-PRIME FORMAT - REQUIREMENTS

3. REQUIREMENTS
   - 3.1 SYSTEM REQUIREMENTS
     - 3.1.1 GENERAL FCS PERFORMANCE REQUIREMENTS
     - 3.1.2 AUTOMATIC FCS FUNCTIONAL REQUIREMENTS
     - 3.1.3 MANUAL FCS REQUIREMENTS
   - 3.2 "ILITIES"
     - 3.2.1 RELIABILITY
     - 3.2.2 MAINTAINABILITY
     - 3.2.3 SAFETY & OPERABILITY
     - 3.2.4 FCS TEST
     - 3.2.5 INVULNERABILITY
     - 3.2.6 COMPUTATIONAL METHODS & SOFTWARE
     - 3.2.7 HARDWARE
     - 3.2.8 MECHANIZATION
     - 3.2.9 INSTALLATION
     - 3.2.10 ENVIRONMENT
     - 3.2.11 CONTROLS & DISPLAYS
     - 3.2.12 ROTARY WING REQUIREMENTS
     - 3.2.13 GENERAL REQUIREMENTS

MIL-F-9490D FORMAT - REQUIREMENTS

3. REQUIREMENTS
   - 3.1 SYSTEM REQUIREMENTS
     - 3.1.1 MFCS PERFORMANCE REQUIREMENTS
     - 3.1.2 AFCS PERFORMANCE REQUIREMENTS
     - 3.1.3 GENERAL FCS DESIGN
     - 3.1.4 MFCS DESIGN
     - 3.1.5 AFCS DESIGN
     - 3.1.6 MISSION ACCOMPLISHMENT RELIABILITY
     - 3.1.7 QUANTITATIVE FLIGHT SAFETY
     - 3.1.8 SURVIVABILITY
     - 3.1.9 INVULNERABILITY
     - 3.1.10 MAINTENANCE PROVISIONS
     - 3.1.11 STRUCTURAL INTEGRITY
     - 3.1.12 WEAR LIFE
   - 3.2 SUBSYSTEM AND COMPONENT DESIGN REQUIREMENTS
     - 3.2.1 PILOT CONTROLS & DISPLAYS
     - 3.2.2 SENSORS
     - 3.2.3 SIGNAL TRANSMISSION
     - 3.2.4 SIGNAL COMPUTATION
     - 3.2.5 CONTROL POWER
     - 3.2.6 ACTUATION
     - 3.2.7 COMPONENT DESIGN
     - 3.2.8 COMPONENT FABRICATION
     - 3.2.9 COMPONENT INSTALLATION
   - 3.3 ROTARY WING PERFORMANCE & DESIGN

EXAMPLES OF DELETED PARAGRAPHS

THE FOLLOWING PARAGRAPHS HAVE BEEN DELETED BECAUSE THEY REFER TO DETAIL DESIGN REQUIREMENTS:

3.2.1.1.3 ALTERNATE OR UNCONVENTIONAL CONTROLS. IF PILOT'S CONTROLS OTHER THAN THE CONVENTIONAL CENTER LOCATED STICKS, W-TYPE WHEELS, RUDDER PEDALS, TRIM CONTROLS AND INDICATORS, WING INCIDENCE CONTROL, WING SWEEP CONTROL, LANDING FLAP CONTROL AND INDICATOR, SPEEDBRAKE CONTROL, AND AUTOMATIC FLIGHT CONTROL PANELS SPECIFIED IN AFSC DESIGN HANDBOOK DH 2-2, DN 2A5, ARE UTILIZED, DEMONSTRATION OF THEIR ADEQUACY AND SUITABILITY IS REQUIRED PRIOR TO INSTALLATION IN AN AIRCRAFT.

3.2.6.3.1.1 TORQUE TUBES. TORQUE TUBES SHALL HAVE A MINIMUM WALL THICKNESS OF 0.035 INCH AND SHALL BE SEAMLESS, EXCEPT THAT STEEL TUBES, SEAM WELDED BY THE ELECTRICAL RESISTANCE METHOD, MAY BE USED.

EXAMPLES OF DELETED PARAGRAPHS

THE FOLLOWING PARAGRAPHS HAVE BEEN DELETED BECAUSE THEY REFER EXCLUSIVELY TO A SUBTIER SPECIFICATION:

3.2.1.1.5 TRIM CONTROLS. ELECTRICAL TRIM SYSTEM SWITCHES OF THE FIVE-POSITION, CENTER OFF, TOGGLE TYPE SHALL BE IN ACCORDANCE WITH MIL-S-9419. CONTROL STICK GRIPS IN ACCORDANCE WITH MIL-G-25561 SHALL ALREADY HAVE THE TRIM SWITCHES, CONFORMING TO MIL-S-9419, INSTALLED. THREE POSITION TRIM SWITCHES SHALL BE APPROVED SWITCHES SIMILAR OR EQUIVALENT TO THE MIL-S-9419, MIL-S-3950 OR MIL-S-6743 SWITCHES.

3.2.4.2.2 GEARED MECHANISMS. ALL GEARED MECHANISMS USED IN MECHANICAL COMPUTER COMPONENTS SHALL MEET THE REQUIREMENTS OF MIL-G-6641.

3.2.4.2.3 HYDRAULIC ELEMENTS. HYDRAULIC COMPUTING ELEMENTS SHALL BE DESIGNED IN ACCORDANCE WITH MIL-C-5503, MIL-H-8775, MIL-G-8890 OR APR 1281, AS APPLICABLE. MIL-V-27162 SHALL BE USED AS A GENERAL GUIDE FOR THE DESIGN OF CONTROL VALVES USED IN HYDRAULIC COMPUTING COMPONENTS.

FORMAT COMPARISON: MIL-PRIME VS MIL-F-9490D

MIL PRIME SPECIFICATION			MIL-F-9490D		
SECTION	TITLE	PAGE COUNT	SECTION	TITLE	PAGE COUNT
1	SCOPE	2	1	SCOPE	2
2	APPLICABLE DOCUMENTS	1	2	APPLICABLE DOCUMENTS	5
3	REQUIREMENTS	22	3	REQUIREMENTS	60
4	VERIFICATION PROVISIONS	13	4	QUALITY ASSURANCE	7
5	PREPARATION FOR DELIVERY	½	5	PREPARATION FOR DELIVERY	½
6	NOTES	½	6	NOTES	5½
		39			80

MIL-PRIME EXCERPTS (Continued)

4.0 VERIFICATION PROVISIONS

4.1 SYSTEM REQUIREMENTS. THE FLIGHT CONTROL SYSTEM COMPLIANCE WITH EACH OF THE APPLICABLE REQUIREMENTS OF THIS SPECIFICATION SHALL BE VERIFIED USING ONE OR MORE OF THE FOLLOWING METHODS:

A. ANALYSIS: _____.

1) PILOTED SIMULATIONS: _____.

B. INSPECTION: _____.

C. TEST: _____.

1) GENERAL TEST REQUIREMENTS: _____.

2) LABORATORY TESTS: _____.

3) AIRCRAFT GROUND TESTS: _____.

4) FLIGHT TESTS: _____.

5) SOFTWARE VERIFICATION TESTS: _____.

MIL-PRIME EXCERPTS (Continued)

4.1.1.2 RESIDUAL OSCILLATIONS. FCS INDUCED AIRCRAFT OSCILLATIONS REQUIREMENTS AT ALL CREW AND PASSENGER STATIONS SHALL BE VERIFIED BY_____.

4.1.2.1 AFCS FUNCTIONAL PERFORMANCE. THE SPECIFIED DAMPING RATIO FOR NONSTRUCTURAL AFCS CONTROLLED MODE RESPONSES SHALL BE VERIFIED BY_____.

4.1.2.1.1 ATTITUDE HOLD (PITCH, ROLL, YAW). COMPLIANCE WITH THE ATTITUDE HOLD REQUIREMENTS SHALL BE DEMONSTRATED BY_____.

MIL-PRIME USERS GUIDE - FORMAT

3.X.X REQUIREMENT REPEATED FROM THE SPECIFICATION

- RATIONALE
- GUIDANCE
- LESSONS LEARNED

4.X.X VERIFICATION REPEATED FROM THE SPECIFICATION

- RATIONALE
- GUIDANCE
- LESSONS LEARNED

APPENDICES

APPENDIX A - USERS GUIDE

APPENDIX B - DERIVATION OF RELIABILITY REQUIREMENTS FROM ACTUAL FIELD STUDY EXPERIENCE DATA

APPENDIX C - METHODS OF DETERMINING COMPONENT OR SUBSYSTEM RELIABILITY INCREASES REQUIRED TO COMPENSATE FOR BLIND REDUNDANCIES

APPENDIX D - A BIBLIOGRAPHIC COMPILATION OF TERRAIN FOLLOWING LITERATURE REFERENCES

APPENDIX E - DELETED USERS GUIDE MATERIAL FROM MIL-9490

OBJECTIVES OF THE CONVERSION OF MIL-F-9490 TO A MIL PRIME SPECIFICATION

- SIMPLIFY THE SPECIFICATION
- ELIMINATE REFERENCES TO SUB-TIER SPECIFICATIONS
- STANDARDIZE SPECIFICATION FORMAT
- FORCE A TAILORING OF THE SPECIFICATION TO THE OPERATIONAL AND PERFORMANCE REQUIREMENTS OF A GIVEN PROCUREMENT
- ELIMINATE DETAIL DESIGN REQUIREMENTS
- EMPHASIZE THE USE OF THE HANDBOOK

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

AN OVERVIEW OF THE PROPOSED MIL STANDARD AND HANDBOOK

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1. INTRODUCTION

This paper presents an overview of a recently completed version of the proposed MIL Standard and Handbook. The Standard/Handbook combination is intended to replace the existing Military Flying Quality Specification for Piloted Aircraft, MIL-F-8785C. A draft version was completed in December 1980 and has been distributed to the handling qualities community for review. Subsequent to this review, a revised version will be published as an AFWAL technical report. The official MIL Standard and Handbook will be published by the Air Force after making the revisions necessary to put it in a format acceptable to all potential procuring activities in the U.S. Armed Forces.

The basic philosophy behind the MIL Standard and Handbook is somewhat different than the existing MIL-F-8785C. Where the current specification lists a series of requirements which are to be applied to all aircraft, the new format requires the procuring activity to develop a customized "type specification" for each new aircraft or major aircraft modification. The basic Standard has no specific requirements and consists of a series of unnumbered statements which serve as an outline upon which to build a specification using criteria contained in the Handbook. The Handbook consists of a collection of handling qualities criteria. In cases where two or more viable criteria are available, both are presented with the pros and cons of each given to assist the user in selecting a specific criterion for a given application.

Experience has shown that MIL-F-8785C is used as much, if not more, as a design guide than a specification. It is expected that this will be even more prevalent with the MIL Handbook. In fact, we

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have attempted to organize the Handbook in such a manner as to enhance its usage as a design guide for handling qualities.

As might be expected, the task of deciding which of the many existing flying quality criteria should be included in the Handbook proved to be a formidable one. The following factors tended to dominate the decision process.

- Nearly all of the existing MIL-F-8785C criteria were retained. This was done primarily to make the transition to the new format with as little resistance as possible. Also, the existing criteria, in general, work very well for classical aircraft.

- Criteria which apply to highly augmented aircraft and which are in a reasonably well developed state were utilized.

- Criteria which are reasonably simple to apply were picked over more complex criteria. For example, the Neal-Smith criterion, which is judged to be extremely valuable for design guidance, nonetheless requires the variation of several pilot model parameters as well as judicious selection of a reference bandwidth. It was, therefore, not included in the present version of the MIL Handbook.

One possibility was to include all viable existing handling quality criteria, thereby establishing the Handbook as a DATCOM for handling qualities. This concept was rejected on the basis that marginal criteria would inevitably find their way into a MIL Standard.

In the following section of this paper we will discuss major differences between MIL-F-8785C and the Standard/Handbook.

B. [illegible] REVISIONS TO [illegible] QUALITY CRITERIA

1. Organization of Criteria

There is general agreement that the existing MIL-F-8785C specification works well for conventional aircraft, but needs considerable upgrading to account for the current generation of highly augmented

aircraft. A primary objective of the Standard/Handbook development was to establish a format which would allow the inclusion of criteria appropriate to highly augmented aircraft.

The MIL-F-8785 format was judged to be unacceptable because the existing criteria are organized according to classical aircraft "modes" such as phugoid, short period, etc. For augmented aircraft these modes are frequently suppressed, making it impossible to characterize aircraft responses according to specific modes. Hence, we have reorganized the specification in terms of responses along and about the aircraft axes. With this proposed organization, the sequence of major topics in the standard are as follows:

1) Flying Quality Requirements for Pitch Axis
2) Flying Quality Requirements for Vertical Flight Path Axis
3) Flying Quality Requirements for Longitudinal (Speed) Axis
4) Flying Quality Requirements for Roll Axis
5) Flying Quality Requirements for Yaw Axis
6) Flying Quality Requirements for Lateral Flight Path Axis
7) Flying Quality Requirements for Combined Axes
8) Flying Quality Requirements in Stalls, Departures, and Spins

Items such as control power, pilot-induced oscillation, trim authority, control forces, and displacements would all be covered under the appropriate heading for each axis of motion. This approach is applicable to all types of aircraft (i.e., all aircraft have 6 degrees of freedom), and hopefully will make application of future research results more direct.

We have departed from the organization by axis for stalls, departures, and spins because of the unique character and strong interaxis coupling that generally exists in this flight regime. In the draft version of the Standard/Handbook, stalls, departures, and spins were included under "combined axes". However, this approach seemed somewhat

[illegible], and a separate section is felt to be warranted for such an important issue.

4. Attainable Levels for Airplane Normal States
(Para. 1.3 MIL-F-8785C; Para. 1.7, MIL Handbook)

For the most part the MIL-F-8785C flying quality criteria are divided into three "Levels" of acceptability corresponding to the following definitions.

> Level 1 — Flying qualities clearly adequate for the mission flight Phase. Aircraft is satisfactory without improvement.
>
> Level 2 — Flying qualities adequate to accomplish the mission flight Phase, but some increase in pilot workload or degradation in mission effectiveness, or both, exists. Aircraft deficiencies warrant improvement.
>
> Level 3 — Flying qualities such that the airplane can be controlled safely, but pilot workload is excessive or mission effectiveness is inadequate, or both. Category A Flight Phases can be terminated safely, and Category B and C Flight Phases can be completed. Aircraft deficiencies require improvement.

In normal practice, the flying quality boundaries were obtained by fairing lines of constant Cooper-Harper pilot rating. Hence it was necessary to define equivalent definitions between the Cooper-Harper scale and the level definitions. Typically, a Cooper-Harper pilot rating of 1 to 3-1/2 defines Level 1, a Cooper-Harper rating between 3-1/2 and 6-1/2 defines Level 2, and a Cooper-Harper rating between 6-1/2 and 9-1/2 defines Level 3.

In the MIL Standard/Handbook, allowance is made for using the Cooper-Harper scale directly as the definition of Flying Quality Levels (see Fig. 1). Hence, the procuring activity has the option of applying the above level definitions or the Fig. 1 scale for various criteria in the Standard. However, it is our opinion that use of the Cooper-Harper scale results in a more consistent set of requirements. This becomes an important factor when compliance is to be shown via demonstration for some criteria and by analysis on others.

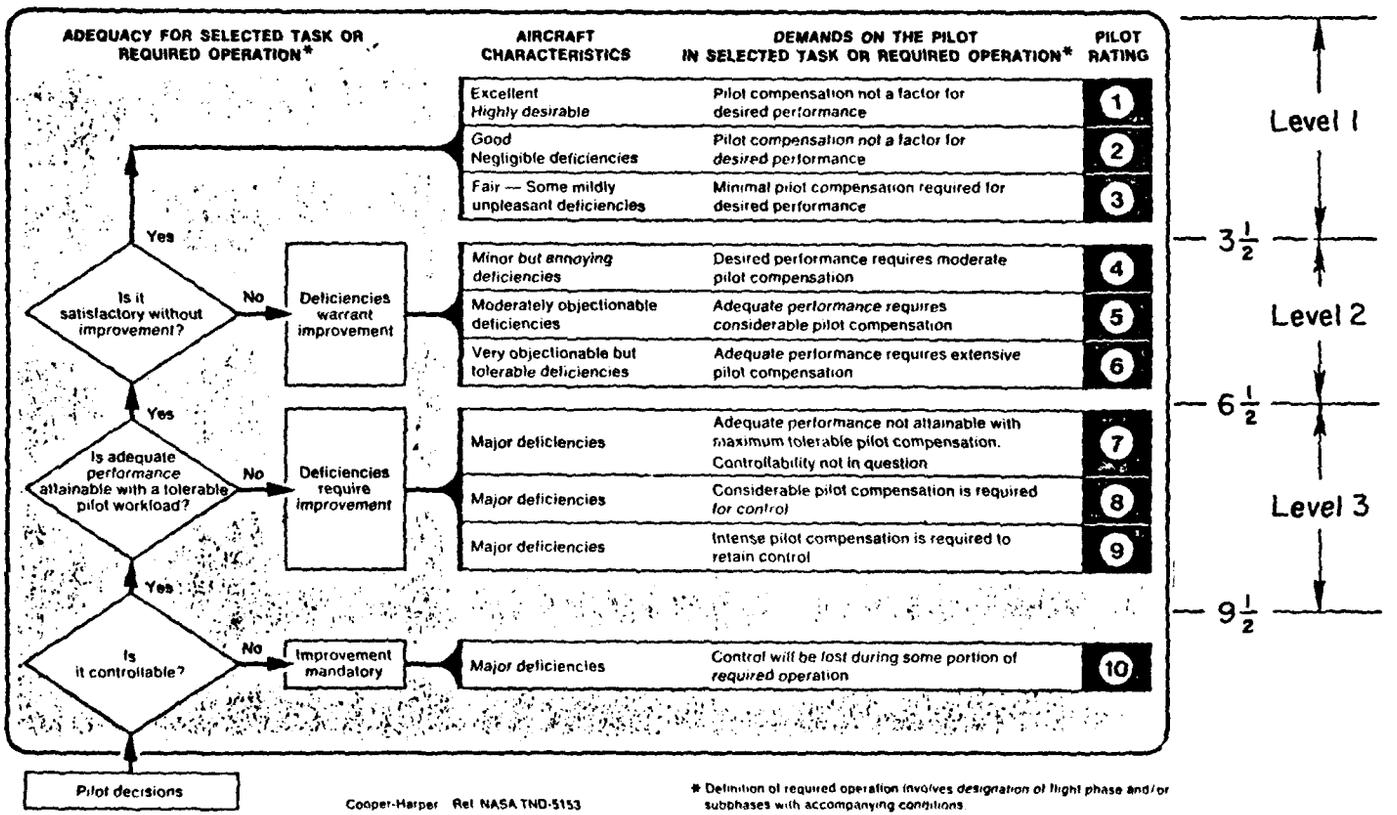


Figure 1. Definition of Flying Quality Levels

It is expected that flying qualities will degrade with increasing atmospheric disturbances and/or airplane failure states. To account for this, the Levels will be adjusted as a function of turbulence magnitude and aircraft failure states. These adjustments to the definition of flying quality Levels are to be used for those requirements where numerical values are not specifically stated. The adjusted Level definitions should not be construed as a recommendation to degrade flying qualities with increasing values of atmospheric disturbances. The effect of atmospheric turbulence on Levels is discussed in the following section.

3. Allowable Degradations in Flying Qualities in Turbulence (Not covered in MIL-F-8785C; Para. 4.3 in Standard)

The intent of this requirement is to insure that atmospheric turbulence is accounted for in a reasonable way. The adjustments in Level definitions are presented both in terms of adjectival phrases and Cooper-Harper pilot ratings in Tables 1 and 2 respectively. The definitions that use pilot ratings allow a more fine-grained distinction. This has been utilized to define a more appropriate degradation in flying qualities with turbulence. For example, the Level 1 definition in Moderate turbulence is 5-1/2 (as opposed to 6-1/2). The rationale for this is summarized as follows:

- Adequate performance should be obtainable with <u>considerable</u> compensation; <u>extensive</u> compensation is felt to be excessive for flight in moderate turbulence (see Fig. 1).
- During a several-year simulation effort to develop STOL airworthiness criteria for the FAA the evaluation pilots generally agreed that 5-1/2 represented adequate safety for normal operation (the standard σ_{u_g} used in that simulation was 4.5 ft/sec).

A Cooper-Harper rating of 7-1/2 was assigned to "severe" turbulence for Level 1 (see Table 2). This choice was based on the rationale that according to Table 3 control is momentarily lost in severe turbulence. This seems consistent with a pilot rating of 7-1/2 (Fig. 1), which is between "controllability not in question" and "considerable pilot

TABLE 1. DEFINITION OF LEVELS WHEN LEVELS ARE DEFINED BY ADJECTIVAL PHRASES IN PARA. 1.7

LEVEL	ATMOSPHERIC DISTURBANCES			
	LIGHT	MODERATE	SEVERE	EXTREME
1	Flying qualities clearly adequate for the mission Flight Phase	Flying qualities adequate to accomplish the mission Flight Phase, but some increase in pilot workload or degradation in mission effectiveness, or both, exists.	Flying qualities such that the airplane can be controlled safely, but pilot workload is excessive or mission effectiveness is inadequate or both. Category A Flight Phases can be terminated safely, and Category B and C Flight Phases can be completed	Flying qualities such that control can be maintained long enough to fly out of the disturbance
2	Flying qualities adequate to accomplish the mission Flight Phase, but some increase in pilot workload or degradation in mission effectiveness, or both, exists	Flying qualities such that the airplane can be controlled safely, but pilot workload is excessive or mission effectiveness is inadequate or both. Category A Flight Phases can be terminated safely, and Category B and C Flight Phases can be completed.	Flying qualities such that control can be maintained long enough to fly out of the disturbance	Flying qualities such that pilot can regain control after being upset
3	Flying qualities such that the airplane can be controlled safely, but pilot workload is excessive or mission effectiveness is inadequate or both. Category A Flight Phases can be terminated safely, and Category B and C Flight Phases can be completed	Flying qualities such that control can be maintained long enough to fly out of the disturbance	Flying qualities such that pilot can regain control after being upset	No requirement

TABLE 2. DEFINITION OF LEVELS WHEN LEVELS ARE DEFINED BY COOPER-HARPER PILOT RATING SCALE IN PARA 1.7

LEVEL	ATMOSPHERIC DISTURBANCES			
	LIGHT	MODERATE	SEVERE	EXTREME
1	[illegible]	[illegible]	[illegible]	Flying qualities such that control can be maintained long enough to fly out of the disturbance
2	[illegible]	[illegible]	Flying qualities such that control can be maintained long enough to fly out of the disturbance	Flying qualities such that pilot can regain control after being upset
3	[illegible]	Flying qualities such that control can be maintained long enough to fly out of the disturbance	Flying qualities such that control can be maintained long enough to fly out of the disturbance	No requirement

TABLE 3 (4.3). TURBULENCE CRITERIA FOR INFLIGHT EVALUATIONS

Intensity	Aircraft Reaction	Reaction Inside Aircraft
[illegible]	Turbulence that momentarily causes slight, erratic changes in altitude and/or attitude (roll, pitch, yaw). Report as light turbulence.* or Turbulence that causes slight, rapid and somewhat rhythmic bumpiness without significant change in altitude or attitude. Report as light turbulence.	Occupants may feel a slight strain against seat belts or shoulder straps. Unsecured objects may be displaced slightly.
[illegible]	Turbulence that is similar to Light turbulence but of greater intensity. Changes in altitude and/or attitude occur but the aircraft remains in positive control at all times. It usually causes variations in indicated airspeed. Report as light or moderate turbulence.* or Turbulence that is similar to Light turbulence but of greater intensity. It causes rapid bumps or jolts in normal aircraft attitude or altitude. Report as moderate turbulence.	Occupants feel definite strains against seat belts or shoulder straps. Unsecured objects are dislodged. Food service and walking are difficult.
[illegible]	Turbulence that causes large abrupt changes in altitude and/or attitude. It usually causes large variations in indicated airspeed. Aircraft may be momentarily out of control. Report as severe turbulence.*	Occupants are forced violently against seat belts or shoulder straps. Unsecured objects are tossed about.
[illegible]	Turbulence in which the aircraft is violently tossed about and is practically impossible to control. It may cause structural damage. Report as extreme turbulence.*	

* High altitude turbulence encountered above 15,000 feet MSL associated with thunderstorms should be reported as EXTREME turbulence regardless of the aircraft's reaction.

compensation required for control." This latter distinction also seems appropriate for Level 2 flying qualities in "moderate" turbulence (Table 2).

In some cases the expected actions due to turbulence are sufficiently extreme that pilot ratings are not appropriate. In these cases statements relating to controllability are used in both Tables 1 and 2.

The concept of accounting for degradations in flying qualities in a flying qualities specification was introduced in Ref. 1 and discussed at some length in the flying quality workshops held each year at the Flight Dynamics Lab. A primary objection has been that it is impractical to measure turbulence in flight test. However, it does not seem necessary to have an exact measurement of the disturbance to determine if handling quality problems occur when the aircraft is "moderately" disturbed. Hence, we elected to "borrow" a well-accepted scale defined by pilots for the PSD (see Table 3), which is published in the Airman's Information Manual. A review of Table 3 led us to believe that there are a sufficient number of quantitative descriptions to allow test pilots to define the turbulence environment. In addition, the details of the disturbance environment are known exactly.

b. Definition of Atmospheric Disturbance Term (Para. 3.7 MIL-F-8785C; Para. 3.1, MIL Standard)

The atmospheric disturbance model has been considerably simplified from the model in MIL-F-8785C. The philosophy being applied is based upon two fundamental premises: a) keep the analysis form simple; and b) use parameters that have direct relationships to aircraft dynamics or flying qualities. This requires a rational approach to the tradeoff between engineering convenience and physical correctness in disturbance models.

For the purposes of the Flying Qualities Standard, an engineering model of atmospheric disturbances is required. This engineering model may be considered as the simplest or minimum acceptable model that correctly identifies the primary parameters of particular interest. This

is in contrast to the objectives of basic research into meteorological phenomena or the physics of atmospheric dynamics.

The approach taken herein is to define a basic utility model that can be applied to most handling quality evaluations. For some applications, the resulting accuracy may exist to designate a specialized model. For example, if a high-fidelity model is required to reproduce very high-frequency effects, the von Karman model would be appropriate. A table of alternative turbulence models is given in the MIL Handbook (Ref. 4).

The basic utility model presented herein represents a major simplification from most flying qualities specifications. It consists of a random turbulence component with a single σ_{rms} of 3 ft/sec and a constant gradient wind shear. The random component is defined using the Dryden form because it is easy to implement and to vary the frequency spectrum of interest for handling qualities evaluations. It is noticed that most previous handling qualities investigations have utilized the Dryden form. It was decided to specify a single value of σ_{rms} on the basis of experience with a large number of piloted simulation handling qualities investigations. This experience showed that a σ_{rms} of 2.5 to 3 ft/sec is large enough to expose handling deficiencies. Such large values of σ_{rms} corresponding to severe turbulence generally do not add new information and tend to mask other primaries due to the extreme violence of the disturbances. A review of past handling quality investigations reveals that nearly all of the simulation pure handling turbulence cases used with a σ_{rms} in the vicinity of 2.5 to 3 ft/sec.

It is a recognized fact that the large amplitude, low frequency component of the turbulence model plays a dominant role in separating good and bad handling qualities. The problem with a random turbulence model is that the large wind shears occur at the critical point on only a few runs, resulting in inconsistencies in pilot ratings and comments. A discrete wind shear is defined in the current model to insure that all pilots will experience the critical input. When discrete shears are used, the σ_{rms} is decreased to 2.5 ft/sec to avoid cases where a large shear component of the random model adds to the discrete shear to give

an intermediate large total wind shear. The maximum wind shear magnitude is set according to the incremental flight path change capability of the aircraft up to a limit, i.e.,

$$\frac{\theta_{g_2} - \theta_{g_1}}{t_{g_2} - t_{g_1}} = \text{gpa} \leq \text{3.5 ft/sec}^2$$

The shear selection should be at least 10 sec and the shear should consist of an altitude of 10 ft for landing simulations. The zero wind or altitude should be set at the wind at touchdown to zero. As in the up direction be consistent at maximum wind speed and in the down direction at flight path. Intensity quantity the wind shear magnitude should not be required to exceed 3.5 ft/sec^2 (g pa of 0^{10}). At least four additional wind shear values are considered.

H_0	H_g	Shear Type
0	0	[illegible]
100'	100'	[illegible]
20'	20'	[illegible]
0	20'	[illegible]

The considered wind shear corresponds to corresponding to one half the altitude level of turbulence, i.e., σ_{h_g} = 5.7 ft/sec.

Finally, the independent variable in the shear model is time. This is done to insure that the shear is independent of aircraft trajectory and that the investigation when one shear occurring as a function of position or altitude in the real world can be reconstructed as a function of time.

The use of wind shear in landing quality evaluations is primarily to provide a disturbance that forces aggressive closed-loop pilot behavior. It is felt to be unnecessary to simulate vertical shears since the horizontal shear provides the aircraft both in airspeed and flight path. For specialized applications, such as the carrier landing bubble, a vertical shear should be included.

C. [redacted]

1. [redacted]

[redacted]

[redacted]

[

that placed closed-loop tracking in the pitch axis would be satisfactory. Hence, a separate requirement seems redundant. However, numerous comments from industry and government representatives indicated that a separate PIO criterion would be desirable. Specifically, the Neigh Smith PIO criterion has been suggested. It has been included in the draft version of the proposed MIL Handbook for industry review and response.

b. Pitch Control Forces and Deflections (Para. [illegible], MIL-F-8785C, Para. [illegible], MIL-Standard)

Some guidance for designing stability considerations has been added based on flight test results obtained at the USAF test pilot school. This is felt to be an excellent data base. However, it indicates that very high gradients such as found in the F-4B are unacceptable. This discrepancy should be resolved. Nonetheless a requirement for stability considerations has been suggested based on the test pilot school data.

c. Roll Axis Equivalent Systems (Para. [illegible], MIL-F-8785C, Para. [illegible], MIL Standard)

A comprehensive series of flight tests are presently conducted on the variable stability NT-33 to investigate the effect of higher-order system dynamics on lateral handling qualities ("LAHOS" for lateral higher-order systems). While the results have not yet been thoroughly analyzed, some preliminary findings are included here for design guidance. The effect of roll axis time constant is given in Fig. 2. Values of $1/T_R$ less than the Level 1 boundary were not tested. However, the data for $1/T_R$ greater than 1 supports the current boundary (T_R = 1.0 sec) up to a value of $1/T_R$ = 3 (T_R = 0.33). For $1/T_R$ greater than 3 the pilot ratings show a consistent degradation, a trend that is not included in the current requirement. The pilot comments for these cases center about excessive lateral divergence. Calspan is currently running frequency sweeps on all of the configurations which will be Fourier transformed to insure that the simulated dynamics are correct. The trend towards degraded pilot ratings for $1/T_R$ > 3 is not reflected in previous

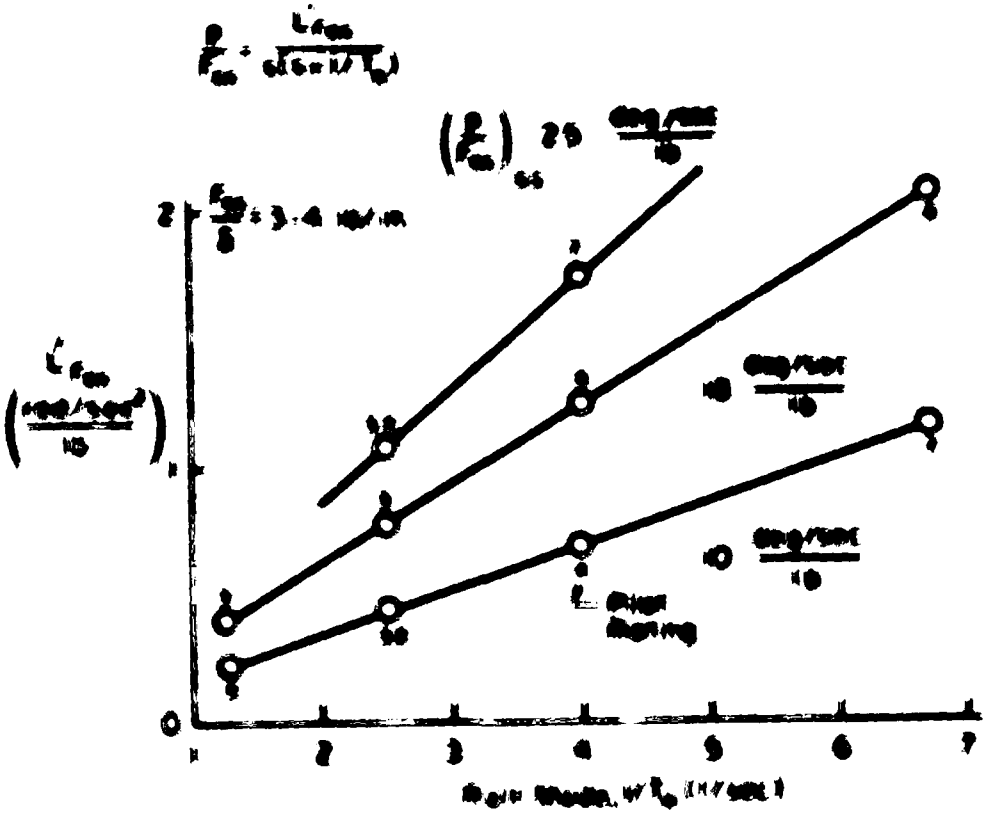


Figure 5. Effect of [illegible] — [illegible]
(Category A)

stimulation at flight test data. However, the ratings and comments from the [illegible] program may be evidence that an upper bound on $1/T_{R_2}$ does indeed exist. On this basis it is recommended that high-gain, high-authority roll rate augmentation systems be limited to a $1/T_{R_2}$ of 3 rad/sec. This design guidance should be upgraded to a recommended requirement if the dynamics used in the [illegible] program are validated.

The effect of equivalent time delay was found to be significant in the longitudinal axis (Para. 3.2.1.1). This result is seen to extend to the lateral axis in Fig. 5. In fact, for the demanding task used in the

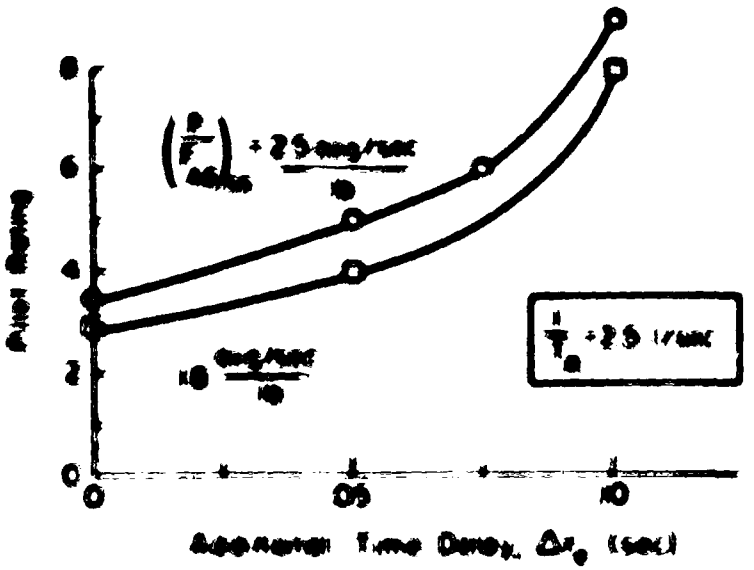


Figure 5. Effect of Time Delay — LATHOS

LATHOS program (side-to-side reflecting and bank angle tracking on the HUD), one time delay above the basic HQ=3.5 value resulted in Level 2 ratings. Hence there is some evidence that effective time delay may be more critical in the lateral than in the longitudinal axis.

Finally, we should consider the far-reaching design implications of the Fig. 5 data. If indeed the pilot ratings degrade for $1/T_\theta > 3$, an upper limit on the region of K/s response has been defined — a result that has not been observed in our human operator system.

5. Direct Force Control (Para. 3.6.1.1, MIL-F-8785C; Para. 3.6.1.2.1 and 3.7.1, MIL Handbook)

Two direct force control modes are included in the proposed Standard/Handbook: Wings Level Turn (Para. 3.6.1.2.1) and Lateral Translation (Para. 3.7.1). The criteria developed for these modes are based on handling and are discussed in some detail in the MIL Handbook (Para. 3.6.1.2.1). More data are required in order to extend these criteria to other direct force control modes.

6. Roll Command Augmentation (Para. 3.3.4.1.3, MIL-F-8785C; Paras. 3.5.9.1 and 3.3.10.3, Mil Standard)

The roll effectiveness requirements of this paragraph are written in terms of time to achieve a certain change in bank angle of 25 deg or more; that is, they correspond to large-control-input measures. The only explicit requirement dealing with roll responses for small inputs is stated in 3.5.4, "Linearity of Roll Response to Roll Controller," a purely qualitative requirement. This is a shortcoming in MIL-F-8785C and in the Standard. A need for some quantitative measure to assure acceptable roll response for small, fine inputs is needed. Such a measure is not currently available. However, design guidance based on current aircraft is provided.

For airplanes with classical, unaugmented, mechanical control systems roll sensitivity has not been found to be a problem. However, the modern use of high gain, high authority command augmentation systems (CAS) has led to problems with extreme sensitivity for small inputs. The cure has been to increase the roll-command-to-control-input gradient, p_c/δ_{ss} (or p_c/F_{ss}), for small inputs via a nonlinear stick shaping network. While such networks are commonly found on recent augmented aircraft, there is insufficient information to write a hard requirement that defines their limiting characteristics. However, design guidance is provided based on experience with specific aircraft.

D. FUTURE DIRECTION

The proposed Mil Standard and Handbook discussed herein should be considered a point of departure directed toward a more comprehensive set of requirements for highly augmented aircraft. In the short term, requirements are needed to develop a more extensive data base necessary to make refinements of many of the handling qualities criteria. However, in the long term it is our opinion that a more direct connection between the mission and the requirements is required. With the recent improvements in simulation technology, and better understanding of pilot workload assessment, it is becoming more practical to show compliance

via demonstration — the ultimate goal being to retain quantitative criteria for design guidance and to relegate compliance to simulation and flight test. Before such an approach is viable the following significant areas of research need to be accomplished.

- Establish a methodology for defining task elements of mission segments.
- Define critical disturbances for each task element.
- Establish methodology for normalizing pilots, that is, the following items should be transparent:
  1) Pilot background
  2) Interpretation of the pilot rating rating scales
- Establish simulator requirements for every defined task element where simulation is proposed.
  1) Instrumentation
  2) Motion
  3) Visual system

These tasks are formidable, and are not expected to be resolved for a considerable period of time. In the interim, we must continue to upgrade the quantitative flying quality criteria. The lessons learned from this exercise should provide the answers to many of the above areas of research, leading to a truly mission-oriented specification.

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1. Moorhouse, David J., Robert J. Woodcock, and Timothy P. Sweeney, "Discussion and Status of the Proposed Revision (1978) to MIL-F-8785B," Proceedings of AFFDL Flying Qualities Symposium Held at Wright State University 12-15 September 1978, AFFDL-TR-78-171, Dec. 1978.

COMMENTS AND QUESTIONS

Tom Cord, FDL: How does the Cooper-Harper means of defining flying qualities levels account for the adequate/desirable performance requirement?

Answer: It is possible to tie in the Cooper-Harper definitions with the more mission-oriented tone of the Standard and Handbook.

Naval Test Center: What is an adequate sample size for pilots?

Answer: More work is required for this issue to be resolved. Currently, three (3) seems to be a minimum.

Sam Craig: We need to make sure that an interface to crew station and human factors engineering exists as we move to a more mission-oriented approach and task definitions.

Tom Black, OSU: How do we account for turbulence response changes which are a function of aircraft design and physical parameters (wing loading, e.g., etc).

Answer: Evaluate total airplane response. Ride quality could possibly be tied in with performance.

John Schuler, Boeing: The Cooper-Harper rating of 9½ corresponding to the upper boundary of Level 3 seems high. 8½ seems to be a better value.

Answer: Good point.

AN ASSESSMENT OF MILITARY FLYING QUALITIES: A LOOK AT DESIGN CRITERIA FOR THE FUTURE

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BACKGROUND

In 1979, the Flight Dynamics Laboratory began a contracted effort with Systems Technology, Incorporated (STI) revising and updating MIL-F-8785C, "Flying Qualities of Piloted Airplanes" (Ref 1). The new format is to be consistent with guidelines set by the Aeronautical Systems Division (ASD). We will provide a choice of requirement forms and numerical values. Since specifications are to be only for hardware (e.g., the flight control system) the flying qualities requirements have been re-designated a MIL-Standard. A supporting MIL-Handbook accompanies it. Draft versions of the documents (Ref 2) were completed and reviewed by both government and industry representatives. The Air Force review began in late 1981 with AFWAL and ASD representatives. Findings will be combined and used by STI to complete an AFWAL Technical Report covering their work under this contract. This final report will be the foundation for a later tri-service review (Fall 1982) leading to a new MIL-Standard and MIL-Handbook, "Flying Qualities of Air Vehicles." This paper summarizes important findings and recommendations of the AFWAL/ASD review, mostly dealing with the structure of the specification or generalities concerning the requirements. It also highlights areas of emphasis which were discussed during the symposium.

ORGANIZATIONAL FORMAT

The transition to a new format or method of specifying flying qualities requirements naturally leads to confusion and some misapplication of the intent and detail of the requirements. Hence such a transition must be made as smooth and straightforward as possible. Already there is a recognized and documented wariness of the new Standard and Handbook style. Industry and government representatives may be apprehensive that some new requirements may overly restrict design, not assure mission capability, be too complex, voluminous, difficult to understand or to apply, not well-founded or substantiated,..... Some are not ready for a massive restructuring of either the documents or their own familiar flying qualities perceptions.

In 1976, the Office of Management and Budget issued Circular A-109 (Ref 3), stating that mission needs rather than technical requirements would govern future procurements. ASD application of this circular to their Standards and Specifications system has led to the MIL-Standard/Specification and MIL-Handbook style which calls for the new documents to be organized with several critical governing objectives in mind (Ref 4a):

a. Facilitate and "force" selective application (tailoring). This demands that the Standard and Handbook be capable of specifying requirements for future aircraft procurements, some of which may have unique dynamics and mission requirements. Blanks are to be filled in with pertinent requirements for each procurement.

b. State requirements in terms of parameters related to operational needs rather than dictating specific solutions (a long-standing rule that is given increased emphasis).

c. Transform the current general Military Specifications for nonhardware items into a MIL-STD according to MIL-STD-847A (Ref 5).

d. In an accompanying handbook, provide the rationale for each requirement. Show the need in terms of operational use, indicate the basis of the requirement and state the appropriate means of demonstrating compliance.

e. Guide the user in selective application of the requirements. We interpret this as an instruction to provide a "cookbook" to facilitate filling in the blanks as well as a compilation of background material to aid in choosing the form and numerical values, and to interpreting the implications of the requirements.

f. Present a compilation of "lessons learned." ASD envisions annual updating of this information.

With these goals in mind, ASD has developed a relatively rigid format (Ref 6) for both the general outline of the Standard and Handbook and the specific contents of the requirements and verification sections. Figures 1 and 2 highlight this format. This format is required for the Standard and Handbook. A limited degree of flexibility is permitted within this framework to account for the uniqueness of each Standard, although such excursions are to be minimized. Such an approach is intended not only to assure that the goals are met, but also to promote a consistency and uniformity among all Air Force Standards and Specifications.

STI has used an organizational format for the Handbook markedly different from the format now specified by ASD (Figure 3). Even so, most information needed for the requirements and verification sections and supporting rationale, guidance and lessons learned sections was contained in the draft documents. STI's approach was to emphasize specific details of each requirement and has the new format related to the former, more familiar specification (MIL-F-8785C). This information can be combined, simplified and restructured to fit ASD's standard format or placed in a supplemental appendix. Such a supplemental appendix might improve the transition process as well as preserve current information and background data which may not fit smoothly into the ASD structure. Reorganizing STI's structure is not seen as a major effort; it will be carried out by Flight Dynamics Laboratory engineers as an in-house project.

TECHNICAL FORMAT

In the process of revising, updating and publishing the flying qualities requirements, organization of the requirements must be considered. That is, how are the requirements presented and how will the buyer verify an aircraft's compliance with these requirements? Several options are possible, though to change for the sake of change is unwarranted. The Air Force review committee looked at three separate options and noted the disadvantages and advantages of each. A fourth format devised by the Boeing Company was used in the development of the YC-14 (Ref 48). It was not specifically evaluated by the committee, but is also listed in Figure 7 for reference and comparison. All formats suffer to some degree due to the complexity of the requirements. It was noted that any changes adopted, in either style or structure, will tend to make the specifications seem new and unfamiliar. It was further noted that none of the formats, including the current MIL-F-8785C format, arranged the requirements according to their relative order of importance (that will vary according to the mission, the design and the viewpoint). Specifics of the remaining options are discussed in turn.

MIL-F-8785C FORMAT (Fig. 6).

Advantages: Familiarity - Users of the new Standard and Handbook would be familiar, even if not comfortable, with the presentation and style of the requirements. As MIL-F-8785C is structured, grouping is by classical response mode, with control power requirements by axis; asymmetric thrust, static, etc., are separate topics.

Disadvantages: Reference to details several problems Boeing noted when trying to apply it to the design of the YC-14. Specifically, a flight control system designer must search through the entire specification to compile the requirements for each axis of control (10 separate sections for pitch control force and displacement). The organization is more by abstract concept than by design factors relating to stability and control or flight control system design. Additionally, although not necessarily related to the specific format of the requirements, they found the requirements tended to favor a rate-command type of system. Imposing the same requirements on an attitude-hold system compromised the system design and degraded its performance. Further, there are not adequate requirements for other manual control modes, such as airspeed select/hold.

MODIFIED BY SEPARATE AXIS (Fig. 9):

Advantages: Readiness - The present draft is in this structure and reviewing individuals are now relatively familiar with the material, having just finished their initial evaluations.

Single-point analysis - Controls, turbulence and other inputs are now located in the same section, giving designers the ability to simply handle requirements for all inputs at the same time.

Disadvantages- Complexity - Some of the requirements needed to be repeated for other response axes. Only format inconsistencies can keep down repetition in the requirements for controllers, which often affect more than one response. For example, the Standard and Handbook call out roll-axis and yaw-axis control for ground test in accordance to the separate requirements, 3.3.1.2 and 3.6.3.2. Mil-F-8785C defines the requirements in one paragraph, 3.3.1.3, The "Guidance for Application" paragraph of section 3.3.1.2 notes, "This requirement is identical to Paragraph 3.6.3.2 in the yaw axis, specified wind speeds should agree for both. The statement is duplicated as a result of organizing the Mil-Standard by axis, since both roll and yaw axis responses are effected in ground test." MTI felt that such redundancy is beneficial, forcing the designer to look at a broader picture of the requirements, thus leading to a better design. An inconsistency is that a number of requirements are actually organized by principal control axis rather than response axis.

Cross-coupling - A side-effect to the disadvantage of the requirements format being complex is that there is a large possibility for discrepancies in filling in the blanks in the Standard, particularly when the requirements are interrelated or similar, but presented as separate requirements and sections.

Responses affected - Pedal responses to one controller are scattered throughout the Handbook. That is, effects of inputs through the throttle, for example, might be in several different locations because that controller generally excites axes to several axes of response. Similarly, the roll, yaw and sideslip components of the Dutch roll appear in three different places. This tends to be confusing and hard to manage from a design point of view.

ORGANIZED BY CONTROL/INPUT (Fig. 8)-

Advantages- Cross-coupling - This approach highlights the effects of control and pedal cross-coupling in the design stage.

Pilot-centered - The structure seems rational from a pilot's point of view. Aircraft response and compliance with the requirements is verified for each input. Further, each input is uniquely handled, a benefit to the design engineer. All inputs are individually considered, whether they be inputs from the control system, from atmospheric disturbances, or other sources.

Adaptability - Response from inputs can be evaluated as a function of the input's origin. For example, response to control-stick steering could have different requirements than response to atmospheric disturbances. Though both responses might still be in the same axis, the modal characteristics might differ.

Disadvantages- Scattered requirements - Organizing the Mil-Standard in this format would tend to place requirements for one response axis in several different sections, to the extent that responses are not decoupled.

Separation - As with STI's draft standard and handbook, this format also separate requirements for nodes that can be assigned by more than one controller.

ALTERNATE CRITERIA

The difficulty of generalizing flying qualities has fostered the development of numerous criteria. Over the years, some of these criteria have been incorporated into the requirements and some of them have not. For example, consider the Neal-Smith criterion (Ref 2), which proposes boundaries for fighter maneuvering dynamics, or CP (Ref 3), time-domain boundaries for a combination of weighted pitch rate and normal acceleration. Table I lists several alternate criteria with specific examples concerning capabilities, limitations of application to higher-order systems, ease of interpretation and important features. All of these criteria have been developed since the issue of MIL-F-8785B (Ref 4). Only the Equivalent System approach has been incorporated into MIL-F-8785C though many are discussed in the new background information and User's Guide (AIDS) (Ref 10). Still, the Neal-Smith recommendations continue to be used to gain insight into an aircraft's flying qualities. Reference 11 details its use in the F-16 development program and Reference 12 covers the application of the criteria to the development of an augmentation system for the F-4E. Use of the CP criteria has waned in the past decade since it has been found to correlate poorly with actual flying qualities evaluations (Ref 13). Even so, it has been and is still being used as a tool in some aircraft developments, the most recent being the experimental STOL/Maneuver/Digital Fly-by-Wire Technology Demonstrator program (Ref 14).

TABLE I. ALTERNATE SHORT-PERIOD CRITERIA AND COMMENTS

Criterion	Description	Limitations & Applications	Comments
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]

These two criteria are indicative of much of the research work which has gone into the development of the flying qualities requirements. A recent AGARD Flight Mechanics Panel on Flying Qualities has also yielded several other criteria which have potential, it must be noted, however, that many of the criteria have limitations either because of their application or because of the access data base from which they were derived (Ref 16).

There are several conclusions which one might glean as one peruses the alternate criteria for flying qualities requirements. First, many of the criteria have been developed from a single source of data. The Neal-Smith data (Ref 7) have been thrown into the criteria "hopper" and processed and processed and processed. It is interesting that no configuration with a damping ratio less than 0.3 received a level 1 rating, although the criteria of MIL-F-8785C is 0.35. This is the reason for the comment in Ref. 17. Serious questions concerning proposed criteria were expressed by more than one attendee of the above-mentioned AGARD conference due to this single load of most, two of three) data sources). Though the development of criteria is important, it is just as important to the flying qualities community, whether it be government or industry, to see the development and acquisition of a older and more current data base. Especially important to any one thrusts into this area is the consideration of flight control system effects on flying qualities now that the emphasis for the future seems to be on digital systems, computers, filters, more complex augmentation, etc.

A second conclusion might concern the high priority which engineers have placed on research and development of longitudinal requirements. Nearly all alternate criteria have focused on the pitch axis or some portion of the pitch response. Some efforts have investigated the flight path response as well. This is in contrast to the lateral-directional realm where roll and yaw responses must be considered and the classical notions of controllers and surfaces not only effect the primary response of the aircraft but couple together and have secondary effects as well. STI has compiled some information concerning lateral-directional alternate criteria and included it in their proposed handbook. The criteria STI proposed included a bandwidth requirement and a turn coordination parameter (Ref 8, pp 398-410 and pp 439-458). The highly successful use of an equivalent systems approach to higher-order systems in the longitudinal axis gives hope that a similar approach is possible in the lateral-directional axis. One of the papers presented at the symposium concerned very research into the development of a lateral-directional equivalent systems approach. Additionally, both Hodgkinson (Ref 16) and the new background information and User's Guide for MIL-F-8785C (Ref 10) contain information related to lateral-directional equivalent systems. Still, more emphasis is needed.

Technology has introduced multi-function switches, displays and modes into the cockpit for today's and tomorrow's aircraft. Any information, from the aircraft's mechanical status to computer-generated displays of the outside world, can now be made readily available to the pilot. Such technology improvements have

impacted flying qualities, primarily in the negative sense, because of an increase in workload. The question remains, "Can the pilot still accomplish his primary task? Especially when he is confronted by many fish, low stability, foul weather, high speed at low level, etc.?" A pilot recently commented, "Will you function well when surrounded by 28 indicators, 27 switches with 83 different positions and 56 pushbuttons? How about during low-level ingress in the world of SAMs, AAAs and guns?" (Ref 17). Further, when discussing some of the new aircraft equipment and controllers, "Anyone who's played the piccolo will appreciate the new autopilot hand control." What this leads up to is another deficiency in flying qualities research which branches into two related areas. The first area concerns pilot workload in both flying and "side" tasks, and just how his workload affects his rating is a quantifiable number. One of the papers summarized the recent Pilot Workload Symposium held at Edwards AFB. Human factors engineers are working with biomedical researchers and investigating everything from a pilot's eye-blink rate to his heart pulse to see if correlations between activity and pilot rating exist. Still, understanding and measures of workload are poor and the door is wide open for effort and research. Related to this is the fact that the role of the pilot is subtly changing. He are no longer only flies a fighting, cargo-carrying, etc. machine but also must manage a complicated system of computers, weapons and instruments. This directly impacts the flying qualities community. The Air Force review found a painfully obvious lack of such information, not only in the SPO staff but also in general reference.

A caution concerning the statistical sensitivity of alternate criteria is in order. In the past, the tendency is for individuals to judge a criterion as a Company A criterion or a Company B criterion. With no requirement having perfect correlation, and the small data base, acceptance is influenced by an individual's background and experience. Further, reluctance has been observed in employing any pilot model or pilot rating in the requirements. No one criteria is sufficient; a judicious selection of criteria need to be chosen for a given design, based on an understanding of the many factors involved. We cannot afford to continue to see current aircraft flying qualities deficiencies as exhibited by the F-16, the Tornado, the F-18 and the Space Shuttle. Deficiencies several recent papers have diagnosed as generic in nature to today's development efforts (Refs 18, 19).

SPECIAL ISSUES

Communication. Numerous articles, proposed revisions and related materials concerning the contracted effort with SPO were forwarded to industry on a continuing basis throughout the time span of the development effort. These distributions culminated with the distribution of the proposed Standard and Handbook in December 1981. Of the many solicitations for comment and suggestion, only a few responses were received. However, we have been gratified by the large attendance at recent meetings related to flying qualities.

Another concern in this area has to do with the perceived lack of communication between the flying qualities and flight control system communities. The problem includes differing terminology, definitions, perceptions, etc., all of which have an effect on an aircraft's development. This was confirmed during the AF review of both the proposed flying qualities specification and the proposed flight control system specification by individuals involved in both efforts. Further, several comments at the Dayton symposium highlighted the fact that engineers from the disciplines rarely get together to address issues applicable to both communities. Meetings and conferences where individuals from both communities can gather, such as the recent Dayton symposium, will go a long way in helping to improve this concern.

Equivalent Systems. One of the major revisions of MIL-F-8785 has been the inclusion of an equivalent system approach to higher-order systems. The preceding article briefly determines requirement compliance by evaluating equivalent model parameters, such as short-period frequency, damping and the associated equivalent time delay. A frequency response-matching computer program developed by the McDonnell-Douglas Corporation called DYFF (Ref 18) may be used. Compliance verification by this method is not intended to unnecessarily restrict either the flying qualities or the flight control system engineers in their pursuit of the optimum blend of filters, compensators, integral control techniques, feedback and feed-forward loops, etc., in today's high-technology spectrum. Rather, it is envisioned in order to keep these involved in the design loop aware of the fact that the final goals of their designs must be capable of superior performance while achieving excellent flying qualities. Though end to end time, recent development efforts have not met these two goals satisfactorily (Ref 18).

The equivalent systems approach is not a magical tool. Nor may it be the best way to assure excellent flying qualities. Presently, however, it is the law of the specification and it will be used. The papers presented at the symposium were weighted toward this highly controversial topic in order to highlight gaps and weaknesses in this approach and to indicate areas needing more emphasis. There are problems with the method. Augmentation of today's aircraft has expanded into the digital realm and application of this approach may be neither straightforward nor simple. Questions concerning sample rate, aliasing, resolution, etc. need answers, especially if the trend away from analog systems continues in order for designers to correctly apply and interpret flying qualities requirements. Nevertheless, for present production digital systems at least, response is sufficiently conventional that present flying qualities requirements may be applied.

Further validation and more data for adequate lateral-directional equivalent systems has already been mentioned, but is again emphasized as a special issue. Direct force and full six-degree-of-freedom control further accentuate the needs and the range of application which future developments must address.

Another concern here concerns the handling of the [illegible] in the current longitudinal axis equivalent systems technique. The Air Force Review determined that whether or not this term should be fixed at zero depended primarily on test and control technique, therefore, both approaches have existing and should be used by the designer (see Ref 10). Related to the present equivalent systems program is the [illegible] parameter. A by-product of the analysis, this parameter gives an indication of how well the unaugmented system matches the higher-order system chosen. It is not an indication of how closely a pre-fixed rating will match the actual rating, in Reference 20, some high-valued discrepancy occurred for configurations with [illegible] between the predicted and actual ratings and some low-valued discrepancy were associated with configurations having a good agreement of predicted and actual ratings. Clearly, problems of interpretation exist in the equivalent systems approach and further research and development is still greatly needed. Response matching has been shown to be most critical in the vicinity of the bandwidth (or crossover) frequency of the pilot-vehicle system.

Atmospheric Disturbances. It is common knowledge that a good test of an aircraft's flying qualities occurs when that aircraft encounters gusts, wind shears and turbulence. Pilot rating vary with the intensity of disturbance. There is also the question of combinations such as shifting and gusting. The requirements in MIL-F-8785B were the first attempt to quantify this concept but they left a sizeable gap in the total atmospheric disturbance-effects picture. The actual requirements were qualitative in nature and were considered critical in scope and application. MIL-F-8785C attempts improvement by modifying and expanding the list of disturbances, but its requirements remain generally qualitative due to the incomplete data base.

The whole issue of atmospheric disturbances leads to some related concerns. It is the aircraft itself, without the pilot, which is to be governed and to which the requirements therefore apply. In the range of linear response, aircraft characteristics do not vary with disturbance intensity. However, increasing intensities of atmospheric disturbances tend to increase pilot workload and degrade task accomplishment. Subjective pilot ratings degrade in a consistent fashion, unless the pilot is told to mentally compensate for the effects of the disturbance. This leads to the second concern, the relationship that exists between Cooper-Harper pilot ratings (Ref 11) and the level of flying qualities. MIL-F-8785C handles this issue by using both qualitative and quantitative assessment when addressing atmospheric disturbances; an option is given to have the numerical requirements on aircraft parameters apply in the more likely disturbances, and the qualitative requirements account for the degradation in the subjective pilot rating. Specific details of this method of correlation and the changes which were incorporated in the transition from MIL-F-8785B to MIL-F-8785C are included in Reference 15.

STI has proposed a somewhat different relationship of the levels to the subjective Cooper-Harper rating scale and qualitative descriptions. Specifically, to calm air and "light" disturbances, level 1 applies to Cooper-Harper ratings less than 3.5, level 2 applies to ratings from 3.5 to 6.5, and level 3 applies to ratings from 6.5 to 9.5. The draft Handbook proposes allowing these relationships to slide depending on the severity of the disturbance. In effect, this is very similar to an early proposal for MIL-F-8785C but it met considerable resistance and was shelved. Table VI diagrams the sliding scale as proposed by STI in terms of numerical terms. Table III tabulates the adjectival terms as currently stated in MIL-F-8785C. Comparing Tables II and III to the definitions of the Cooper-Harper ratings, the major change from MIL-F-8785C to the STI proposal is for moderate and severe disturbance. 6.5 has become 7.5, 9 has become 9.5. It should be noted that the disturbance inputs are not necessarily real-world dynamics, but rather mathematical models having the capability to expose handling quality deficiencies.

TABLE II. DEFINITION OF LEVELS
NUMERICAL COOPER-HARPER RATINGS (PROPOSED BY STI)

1				
2				
3				

TABLE III. MIL-F-8785C DEFINITION OF LEVELS -- ADJECTIVAL TERMS

1				
2				
3				

Failure States. Another issue to which the Air Force review team gave special emphasis concerned analysis techniques for determining the failure states to be considered. The two methods currently in use by industry are a generic analysis technique and a probability calculations technique. Generic failure analysis assumes that a component will fail, and determines the state of the aircraft and compounding events which follow the failure. Statistical calculations determine the probability of an aircraft component failing. MIL-F-8785C now specifies the latter to be used to analyze. Both methods are presented in the draft Handbook. Proponents of the generic analysis dismiss the "numbers game" of the statistical approach and complain of the large size of an analysis of a complex system. Proponents of the statistical analysis want a generally applicable approach that can catch all items of significance, and trust that the answer will at least be of the right magnitude. What is of concern to the government is the cost and quality trade-offs which occur when using/supporting the two methods. Another concern is the interface with the flight control system specification, currently Reference 11, which also has reliability requirements which are related to flying qualities. Clearly a failure modes and effects analysis is needed. The question here is how to determine which failures to include in that analysis. A possible solution to the argument concerning validity of either of the two methods would be to use both methods in a complementary fashion. Still to be determined is just how to take advantage of both techniques, maximizing their strengths and minimizing their weaknesses.

Closed-loop Criteria. Arguments for and against the inclusion of closed-loop criteria in the flying qualities requirements are equally valid and convincing. Attempts to define accurate pilot models and closed-loop criteria have spanned many years, with recent work by Levison (Ref 13a) and Ross (Ref 14), the earlier "Paper Pilot" research of Anderson (Ref 15) and the pioneering and continuing work at AFFDL (McRuer, Jex,.....) to name a few. Though such approaches are not widely accepted for specification use, there is a trend to use similar analysis techniques more and more in the design process. With the current Air Force initiatives being directed toward development of Integrated Fire and Flight Control (IFFC) and Night Low-Weather Attack (NLWA), flying qualities engineers are analyzing new situations and finding the need to include pilot-in-the-loop considerations when designing for mission effectiveness. Also to be considered are display dynamics, presentation options and how best to automate functions in order to achieve an optimum balance of manual and automatic control. The review team found a rather primitive state of art in these areas. If more emphasis is not placed on these areas in the near term, efforts may turn out to be catch-up rather than methodical and planned; this could severely limit the needed overall ability to keep flying qualities a control part of the design process.

FINDINGS & RECOMMENDATIONS

The Air Force review team concluded their evaluation of the STI draft Standard and Handbook after spending nearly three months in detailed discussions and appraisal. Their findings were

a. Systems Technology, Incorporated is to be commended for their efforts in restructuring and formating the military flying qualities requirements into a MIL-Standard and Handbook. The detailed descriptions herein and the mere volume of the documents attest to the scope of the effort.

b. AFWAL's Flight Dynamics Laboratory, specifically the Flying Qualities Group of the Flight Control Division acts effectively in conjunction with the Flight Stability and Control Group of the Aeronautical Systems Division to manage the flying qualities specification and its requirements. It is responsible for both the relevance and the currency of the requirements, and must see to it that the scope of the requirements are adequate for future acquisitions. In order to accomplish this task effectively, it is imperative that feedback from industry and government users be received on a timely basis. Further, more in-depth communication between flying qualities and flight control system engineers must occur.

c. Numerous technical areas were highlighted which need further research. Some of these areas are the subjects of present-day in-house and contracted Flight Dynamics Laboratory efforts. Some are subjects of other contracted and in-house research efforts: Navy, Army, NASA, etc. Some were discussed during the symposium. Finally, others are in need of initial research efforts. Important areas mentioned by the review team, with some recent or current AF/AF-sponsored work indicated parenthetically are:

1. Requirements for aircraft having six-degree-of-freedom control (see also AFWAL-TR-81-3027)

2. Unstable aircraft configurations and relaxed static stability effects (see also AFWAL-TR-82-3014)

3. Pilot station location and related effects (see also AFWAL-TR-81-3118)

4. Sidestick controller requirements (see also AFFDL-TR-79-3126)

5. Force gradients compatible for men and women pilots (currently under study by the US Air Force Aeromedical Research Laboratory at Wright-Patterson Air Force Base. A strength standard is currently being considered by AF management.)

6. Requirements for aircraft which fly in specialized portions of the flight envelope such as STOL

7. Lateral-Directional dynamics: better definition and broader data base (see also AFWAL-TR-81-3171)

9. Further development of alternate criteria

10. Time domain criteria

It is hoped that this partial listing of critical flying qualities research areas will become the subject of much future effort as we strive to develop design criteria for the future.

To further the usefulness and impact of the flying qualities requirements, the groundwork for an Air Force validation study is being laid. This study will go beyond comparing a present-day aircraft with the requirements. Rather, it will task the contractor to identify the critical requirements which drove either the cost or the performance in the development of a vehicle. Costs and benefits of either meeting or not meeting the requirements will then be identified through the use of simulation or flight test data. The object will be to identify the cost-effectiveness of the flying qualities requirements and the most important contributors to a vehicle's design.

CONCLUSION

The events, papers and discussions of the "Design Criteria for the Future of Flight Controls" Symposium have been of great value to all participants. They will directly impact the future usefulness and application of the new MIL-Standard and Handbook, "Flying Qualities of Air Vehicles." Our driving goal is to design and build aircraft with superior mission effectiveness. It is imperative that we, the engineers from both industry and the government, work together to attain this difficult, but achievable goal.

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Section [redacted]

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Section [redacted]

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Supplemental Appendices

Figure 1. ASD Standard and Handbook General Structure

STANDARD

4.0 REQUIREMENTS

4.1.1 Requirement Title. Words describing the requirement with ___blanks___ where numerical values are to be inserted.

4.1.2

4.1.3

.

.

End of Requirements

5.0 VERIFICATION REQUIREMENTS

5.1.1 Verification Requirement Title. Words describing the verification method with ___blanks___ where information is to be inserted.

5.1.2

5.1.3

.

.

End of Verification Requirements

HANDBOOK

40. REQUIREMENTS

50. VERIFICATION REQUIREMENTS

4.1.1 Requirement. Words repeated from the Standard.

RATIONALE

Words describing the reasons for the requirement.

GUIDANCE

How to choose values for filling in the blanks.

LESSONS LEARNED

Successes and failures concerning this requirement.

5.1.1 Verification Requirement. Words repeated from Standard.

RATIONALE

Words describing verification style and reasons.

GUIDANCE

Words telling how to apply the verification method.

LESSONS LEARNED

Successes and failures from past experience.

4.1.2

5.1.2

4.1.3

5.1.3

.

.

End of Requirements/Verification Subsections.

Figure 2. Standard and Handbook Subsection Style

STANDARD

Section 1 Scope and Definitions
2 Applicable Documents
3 Requirements and Quality Assurance
4 Atmospheric Disturbances
5 N/A
6 Notes

HANDBOOK

Section 1 Scope and Definitions
2 Applicable Documents
3 Requirements
A. Reason for Requirement
B. Related MIL-F-8785C Requirement
C. Statement of Requirement and Recommended Value
D. Rationale Behind Requirement
E. Guidance for Application
F. Demonstration of Compliance
G. Supporting Data
H. Lessons Learned
4 Atmospheric Disturbances
5 Notes

Figure 3. STI Proposed Standard and Handbook General Structure

1.0 SCOPE
1.1 Scope
1.2 Application
1.3 Classification of Airplanes
1.3.1 Land- or Carrier-Based Designation
1.4 Flight Phase Categories
1.5 Levels of Flying Qualities

2.0 APPLICABLE DOCUMENTS
2.1 Issues of Documents

3.0 REQUIREMENTS
3.1 General Flying Qualities
3.1.1 Operational Missions
3.1.2 Loadings
3.1.3 Moments and Products of Inertia
3.1.4 External Stores
3.1.5 Configurations
3.1.6 State of the Airplane
3.1.7 Operational Flight Envelopes
3.1.8 Service Flight Envelopes
3.1.9 Permissible Flight Envelopes
3.1.10 Application of Levels
3.1.11 Interpretation of Subjective Requirements
3.2 Longitudinal Flying Qualities
3.2.1 Longitudinal Stability with Respect to Speed
3.2.2 Longitudinal Maneuvering Characteristics
3.2.3 Longitudinal Control
3.3 Lateral-Directional Flying Qualities
3.3.1 Lateral-Directional Mode Characteristics
3.3.2 Lateral-Directional Dynamic Response Characteristics
3.3.3 Pilot-Induced Oscillations
3.3.4 Roll Control Effectiveness
3.3.5 Directional Control Characteristics
3.3.6 Lateral-Directional Characteristics in Steady Sideslips
3.3.7 Lateral-Directional Control in Crosswinds
3.3.8 Lateral-Directional Control in Dives
3.3.9 Lateral-Directional Control with Asymmetric Thrust

Figure 4. MIL-F-8785C Format (Ref 1)

3.4 Miscellaneous Flying Qualities
3.4.1 Dangerous Flight Conditions
3.4.2 Flight at High Angles of Attack
3.4.3 Cross-Axis Coupling in Roll Manoeuvres
3.4.4 Control Harmony
3.4.5 Buffet
3.4.6 Release of Stores
3.4.7 Effects of Armament Delivery and Special Equipment
3.4.8 Transients Following Failure
3.4.9 Failures
3.4.10 Control Margin
3.4.11 Direct Force Controls
3.5 Characteristics of the Primary Flight Control System
3.5.1 General Characteristics
3.5.2 Mechanical Characteristics
3.5.3 Dynamic Characteristics
3.5.4 Augmentation Systems
3.5.5 Failures
3.5.6 Transfer to Alternate Control Modes
3.6 Characteristics of the Secondary Flight Control System
3.6.1 Trim System
3.6.2 Speed and Flight-Path Control Devices
3.6.3 Transients and Trim Changes
3.6.4 Auxiliary Dive Recovery Devices
3.7 Atmospheric Disturbances
3.7.1 Form of the Disturbance Model
3.7.2 Medium/High-Altitude Model
3.7.3 Low-Altitude Disturbance Model
3.7.4 Carrier Landing Disturbance Model
3.7.5 Application of the Disturbance Model in Analyses
3.8 Requirements for Use of the Disturbance Models
3.8.1 Use of Disturbance Models
3.8.2 Qualitative Degrees of Suitability
3.8.3 Effects of Atmospheric Disturbances

4.0 QUALITY ASSURANCE
4.1 Compliance Demonstration
4.1.1 Analytical Compliance
4.1.2 Simulation
4.1.3 Flight Test Demonstration
4.2 Airplane States
4.2.1 Weights and Moments of Inertia
4.2.2 Center-of-Gravity Positions
4.2.3 Thrust Settings
4.3 Design and Test Conditions
4.3.1 Altitudes
4.3.2 Special Conditions
4.4 Tests at Specialized Facilities

Figure 4(continued). MIL-F-8785C Format (Ref 1)

5.0 PREPARATION FOR DELIVERY

6.0 NOTES
6.1 Intended Use
6.2 Definitions
6.2.1 General
6.2.2 Speeds
6.2.3 Thrust and Power
6.2.4 Control Parameters
6.2.5 Longitudinal Parameters
6.2.6 Lateral-Directional Parameters
6.2.7 Atmospheric Disturbance Parameters
6.2.8 Terms Used in High Angle-of-Attack Requirements
6.3 Interpretation of Pole Limits of Table V.
6.4 Gain Scheduling
6.5 Engine Considerations
6.6 Effects of Aeroelasticity, Control Equipment and Structural Dynamics
6.7 Application of Levels
6.7.1 Level Definitions
6.8 Regulated Documents
6.9 Marginal Indicia

Figure 4(concluded). MIL-F-8785C Format (Ref 1)

1.0 SCOPE AND DEFINITIONS
1.1 Scope
1.2 Application
1.3 Airplane Classification and Operational Missions
1.4 Flight Phase Categories
1.5 Flight Envelopes
1.5.1 Operational Flight Envelopes
1.5.2 Service Flight Envelopes
1.5.3 Permissible Flight Envelopes
1.6 State of the Airplane
1.6.1 Airplane Normal States
1.6.2 Airplane Failure States
1.6.3 Airplane Special Failure States
1.7 Levels of Flying Qualities

2.0 APPLICABLE DOCUMENTS

3.0 REQUIREMENTS
3.1 General Requirements
3.1.1 Loadings
3.1.2 Moments and Products of Inertia
3.1.3 External Stores
3.1.4 Configurations
3.1.5 Allowable Levels for Airplane Normal States
3.1.6 Allowable Levels for Airplane Failure States
3.1.7 Dangerous Flight Conditions
3.1.8 Interpretation of Subjective Requirements
3.1.9 Interpretation of Quantitative Requirements
3.1.10 Quality Assurance
3.2 Flying Quality Requirements for Pitch Axis
3.2.1 Pitch Axis Response to Pitch Controller
3.2.2 Pilot-Induced Pitch Oscillations
3.2.3 Residual Pitch Oscillations
3.2.4 Vertical Acceleration at Pilot Station
3.2.5 Pitch Axis Response to Secondary (Throttle, DLC, etc.) Controllers
3.2.7 Pitch Axis Response to Other Inputs
3.2.8 Pitch Axis Control Power0
3.2.9 Pitch Axis Control Forces
3.2.10 Pitch Axis Control Displacements
3.3 Flying Quality Requirements for Vertical Flight Path Axis
3.3.1 Vertical Axis Response to Attitude Change
3.3.2 Vertical Axis Response to Designated Flight Path Controller
3.3.3 Vertical Axis Response to Atmospheric Disturbances
3.3.4 Vertical Axis Response to Other Inputs
3.3.5 Flight Path Control Power
3.3.6 Flight Path Controller Characteristics

Figure 5. Control Axis Format - STI Proposed (Ref 2)

3.4 Flying Quality Requirements for Longitudinal Axis (Speed)
3.4.1 Speed Response to Attitude Changes
3.4.2 Speed Response to Speed Controller
3.4.3 Speed Axis Response to Atmospheric Disturbances
3.4.4 Speed Axis Response to Other Inputs
3.4.5 Speed Axis Control Power
3.4.6 Speed Axis Controller Characteristics
3.5 Flying Quality Requirements for Roll Axis
3.5.1 Roll Axis Response to Roll Controller--Conventional Aircraft and Rate Command Augmentation
3.5.2 Pilot-Induced Roll Oscillations
3.5.3 Residual Roll Oscillations
3.5.4 Linearity of Roll Response to Roll Controller
3.5.5 Lateral Acceleration at Pilot Station
3.5.6 Roll Response to Yaw Controller
3.5.7 Roll Axis Control in Crosswinds
3.5.8 Roll Axis Control in the Presence of Other Inputs
3.5.9 Roll Axis Control Power
3.5.10 Roll Axis Control Forces and Displacements
3.6 Flying Quality Requirements for Yaw Axis
3.6.1 Yaw Axis Response to Yaw Controller
3.6.2 Pilot-Induced Yaw Oscillations
3.6.3 Yaw Axis Control in Crosswinds
3.6.4 Yaw Axis Response to Other Inputs
3.6.5 Yaw Axis Control Power
3.6.6 Yaw Axis Control Forces
3.7 Flying Quality Requirements for Lateral Flight Path Axis
3.7.1 Bandwidth Requirement for Direct Side Force Control
3.8 Flying Quality Requirements for Combined Axis
3.8.1 Cross-Axis Coupling in Roll Maneuvers
3.8.2 Crosstalk Between Pitch and Roll Controllers
3.8.3 Control Harmony
3.8.4 Stalls
3.8.5 Departures and Spins
3.9 Flying Quality Requirements in Atmospheric Disturbances

4.0 ATMOSPHERIC DISTURBANCES
4.1 Definition of Atmospheric Disturbance Model Form
4.2 Application of Disturbance Models
4.2.1 Application of Disturbance Models in Analyses
4.3 Allowable Flying Qualities Degradations in Turbulence
4.4 Requirements for Airplane Failure States in Turbulence

Figure 5(concluded). Control Axis Format - STI Proposed (Ref 2)

1.0 SCOPE
1.1 Scope
1.2 Application
1.3 Flight Phase Categories
1.4 Degrees of Suitability
1.5 Levels of Flying Qualities

2.0 APPLICABLE DOCUMENTS
2.1 Handbook

3.0 REQUIREMENTS
3.1 General Requirements
3.1.1 Operational Missions
3.1.2 Loadings
3.1.3 Configurations
3.1.4 State of the Aircraft
3.1.5 Flight Envelopes
3.1.6 Application of Levels
3.1.7 Dangerous Flight Conditions
3.1.8 Control Compatability and Harmony
3.1.9 Adjustable Controls
3.1.10 Augmentation Systems
3.1.11 Trim Systems
3.1.12 Buffet
3.2 Response to Pitch Controller
3.2.1 Short-Term Dynamics for Pitch Controller
3.2.2 Long-Term Response to Pitch Controller
3.2.3 Residual Oscillations
3.2.4 Pitch Control Power
3.2.5 Pitch Controller Characteristics
3.3 Response to Longitudinal Controllers
3.3.1 Transient Response to Longitudinal Controllers
3.3.2 Steady-State Response to Longitudinal Controllers
3.3.3 Longitudinal Control Power
3.3.4 Longitudinal Controller Characteristics
3.4 Response to Normal Path Controller
3.4.1 Transient Response to Normal Path Control
3.4.2 Steady-State Response to Normal Path Control
3.4.3 Normal Path Control Power
3.4.4 Normal Path Controller Characteristics
3.5 Response to Roll Controller
3.5.1 Short-Term Dynamics
3.5.2 Long-Term Response to Roll Controller
3.5.3 Residual Oscillations
3.5.4 Roll Control Power
3.5.5 Characteristics of Roll Controllers

Figure 6. Controller/Input Format (Proposed)

3.6 Response to Yaw Controllers
3.6.1 Short-Term Dynamics
3.6.2 Long-Term Response to Yaw Controller
3.6.3 Yaw Control Power
3.6.4 Characteristics of Yaw Controllers
3.7 Response to Lateral Path Controller
3.7.1 Transient Response to Lateral Path Controller
3.7.2 Steady-State Response to Lateral Path Controller
3.7.3 Lateral Path Control Power
3.7.4 Characteristics of Lateral Path Controller
3.8 Other Responses
3.8.1 Response to Atmospheric Disturbances
3.8.2 Response to Guidance Commands
3.8.3 Response to Stores Release, Armament Drop or Discharge
3.8.4 Response to Configuration Change Command
3.8.5 Response to Control Mode Switching
3.8.6 Response to Failures
3.9 Stall/Post-Stall Characteristics
3.9.1 Flight at High Angles-of-Attack
3.9.2 Stalls
3.9.3 Post-Stall Gyrations and Spins

4.0 ATMOSPHERIC DISTURBANCES
4.1 Definition of Atmospheric Disturbance Model Form
4.1.1 Steady Wind
4.1.2 Wind Shear
4.1.3 Free Air Turbulence
4.1.4 Ship/Terrain Wake
4.1.5 Aircraft Wake
4.2 Definition of Atmospheric Disturbance Model Parameter Dependence
4.2.1 Amplitude
4.2.2 Time/Frequency
4.2.3 Space
4.2.4 Interdependence
4.3 Application of Disturbance Models
4.3.1 Use of the Disturbance Models in Analyses
4.3.2 Quantitative Levels of Disturbance

Figure 6 (continued). Controller/Input Format (Proposed)

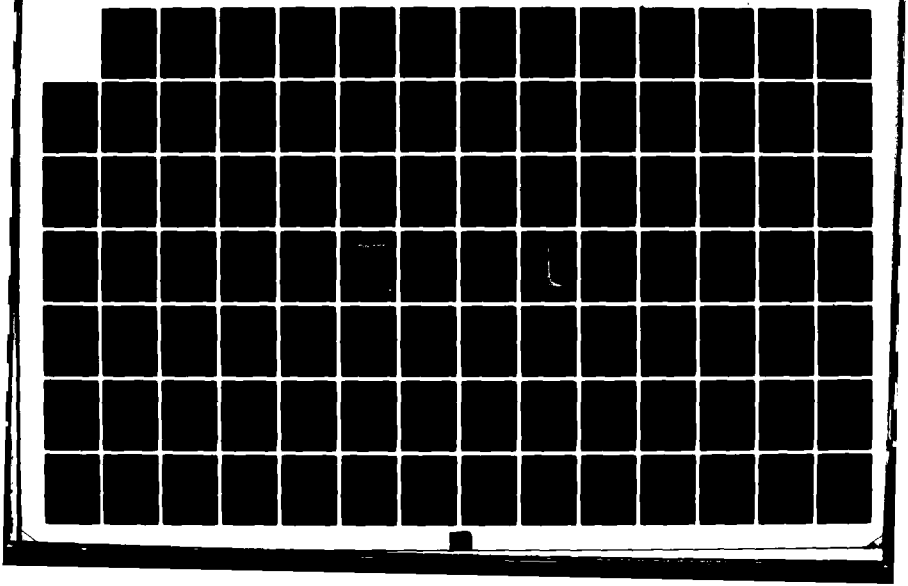
5.0 QUALITY ASSURANCE
5.1 Compliance Demonstration
5.1.1 Analytical Compliance
5.1.2 Simulation
5.1.3 Flight Test Demonstration
5.2 Airplane States
5.2.1 Weight and Moments of Inertia
5.2.2 Center-of-Gravity Positions
5.2.3 Thrust Settings
5.3 Design and Test Conditions
5.3.1 Altitudes
5.3.2 Special Conditions
5.4 Tests at Specialized Facilities

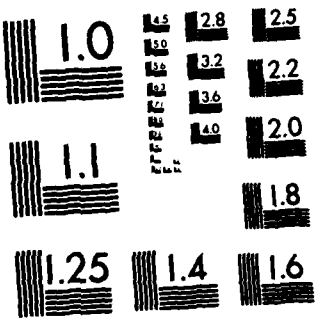
6.0 NOTES
6.1 Intended Use
6.2 Definitions
6.2.1 General
6.2.2 Speeds
6.2.3 Thrusts and Power
6.2.4 Control Parameters
6.2.5 Longitudinal Parameters
6.2.6 Lateral-Directional Parameters
6.2.7 Atmospheric Disturbance Parameters
6.2.8 Terms Used in High Angle-of-Attack Requirements
6.3 Interpretation of Fs/a Limits of Table V
6.4 Gain Scheduling
6.5 Engine Considerations
6.6 Effects of Aeroelasticity, Control Equipment and Structural Dynamics
6.7 Application of Levels
6.7.1 Level Definitions
6.8 Related Documents
6.9 Marginal Indicia

Figure 6 (concluded). Controller/Input Format (Proposed)

AD-A121 423 DESIGN CRITERIA FOR THE FUTURE OF FLIGHT CONTROLS PROCEEDINGS OF THE FLIG..(U) AIR FORCE WRIGHT AERONAUTICAL LABS WRIGHT-PATTERSON AFB OH

UNCLASSIFIED S G FULLER ET AL. JUL 82 AFWAL-TR-82-3064 F/G 1/2 NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

3.1 GENERAL REQUIREMENTS AND DEFINITIONS
- 3.1.1 Operational Philosophy
  - 3.1.1.1 Operational Modes
  - 3.1.1.2 Flight Phase Categories
  - 3.1.1.3 Operating Margins
  - 3.1.1.4 State of the Aircraft
- 3.1.2 Configurations and Loadings
- 3.1.3 Flight Envelopes
  - 3.1.3.1 Operational Flight Envelopes
  - 3.1.3.2 Service Flight Envelopes
  - 3.1.3.3 Permissible Flight Envelopes
- 3.1.4 Flying Qualities Levels and Application
  - 3.1.4.1 Aircraft Normal State Flying Qualities
  - 3.1.4.2 Aircraft Failure State Flying Qualities
- 3.1.5 Atmospheric Environment
  - 3.1.5.1 Mean Wind
  - 3.1.5.2 Turbulence
  - 3.1.5.3 Discrete Gust Analysis
- 3.1.6 Flight Control Systems
  - 3.1.6.1 Primary Flight Controls
  - 3.1.6.2 Secondary Flight Controls
  - 3.1.6.3 Basic/Manual Modes and Subsystems
  - 3.1.6.4 Pilot-Assist/Automatic Modes and Subsystems
- 3.1.7 System Status Indication
  - 3.1.7.1 Advisory
  - 3.1.7.2 Caution Indication
  - 3.1.7.3 Warning System

3.2 LONGITUDINAL FLYING QUALITIES
- 3.2.1 Control Power
  - 3.2.1.1 In-Flight Maneuvers
  - 3.2.1.2 Take-Off
  - 3.2.1.3 Landing
  - 3.2.1.4 Stall Recovery
  - 3.2.1.5 Trim Authority
- 3.2.2 Control Forces and Displacements
  - 3.2.2.1 Column Travel
  - 3.2.2.2 Breakout Forces
  - 3.2.2.3 Maneuver Force and Displacement Gradients
  - 3.2.2.4 Minimum Stick Forces
  - 3.2.2.5 Maximum Stick Forces
- 3.2.3 Stability and Response Characteristics
  - 3.2.3.1 Minimum Damping
  - 3.2.3.2 Pitch Rate Characteristics
  - 3.2.3.3 Pitch Attitude Hold
  - 3.2.3.4 Flight Path Characteristics

3.3 LATERAL-DIRECTIONAL FLYING QUALITIES
- 3.3.1 Control Power
  - 3.3.1.1 Roll Maneuvers
  - 3.3.1.2 Yaw Control
  - 3.3.1.3 Crosswind Takeoff and Landing
  - 3.3.1.4 Asymmetric Thrust
  - 3.3.1.5 Trim

Figure 7. Boeing YC-14 MIL Format (Ref 5b)

3.3.2 Control Force and Displacement
3.3.2.1 Control Travel
3.3.2.2 Breakout Forces
3.3.2.3 Control Forces
3.3.2.4 Turn Coordination
3.3.2.5 Control Sensitivity
3.3.2.6 Control Linearity
3.3.3 Stability and Response Characteristics
3.3.3.1 Roll Mode Response
3.3.3.2 Heading Control
3.3.3.3 Turn Coordination
3.3.3.4 Roll-Sideslip Stability
3.3.3.5 Roll-Sideslip Coupling
3.3.3.6 Pilot-Induced Oscillations
3.3.4 Stalls
3.3.5 Pilot-Assist Modes
3.3.5.1 Heading Hold
3.3.5.2 Heading Select
3.3.5.3 Automatic VOR/TACAN Navigation
3.3.5.4 Category II Landing Approach
3.3.5.5 Flight Director Modes
3.4 FLIGHT CONTROL SYSTEM DESIGN
3.4.1 General Design
3.4.1.1 Flight Deck Controls
3.4.1.2 Powered Control Systems
3.4.1.3 Fail Safety
3.4.1.4 Structural Load Path
3.4.1.5 Dissimilar Load Path
3.4.1.6 Residual Oscillations
3.4.1.7 Stability Margins
3.4.1.8 Endurance Life
3.4.1.9 Warmup
3.4.1.10 Failure Transients
3.4.1.11 Lightening Strikes and Static Atmospheric Electricity
3.4.2 Primary Flight Control System
3.4.2.1 Mechanical Flight Control Elements
3.4.2.2 Control Augmentation System Elements
3.4.2.3 Propulsion Control
3.4.3 Secondary Flight Control System
3.4.3.1 General Criteria
3.4.3.2 Trim Systems
3.4.4 Standby Flight Control System
3.4.4.1 Design Simplicity
3.4.4.2 Engagement
3.4.4.3 Override Capability
3.4.4.4 Isolation
3.4.5 Maintainability
3.4.5.1 Operational Checkout Provisions
3.4.5.2 Malfunction Detection and Fault Isolation Provisions
3.4.5.3 Maintenance Personnel Safety Provisions

Figure 7 (concluded). Boeing YC-14 MIL Format (Ref 5b)

FLIGHT CONTROL TO SATISFY FLYING QUALITIES

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Arvin/Calspan Corporation
Advanced Technology Center

INTRODUCTION

In the past, there has been a tendency to define flying qualities criteria independently of the methods used to design flight control systems that are to satisfy those flying qualities requirements. As a result, the flight control system designer has had to design to criteria that only nominally and incompletely considered the dynamic or other effects of a flight control system (as in MIL-F-8785B) or has had to use criteria that were never adequately verified or improved using experimental flight test methods (as in $C^*(t)$). The result has been flight control systems that satisfy the letter rather than the intent of the criteria or are nearly totally dependent on ground-based simulation for validation and evaluation. This has led to a succession of aircraft, starting with the F-111 (when quantitative requirements were first imposed) to the F-18 that have had problems relating in one way or another to flying qualities.

The purpose of this paper is to take a look at flying qualities from the flight control point of view. An attempt is made to assess the flying qualities requirements as they now exist and to try to suggest areas of the specifications that might be improved, or the format changed to decrease the possibility of misinterpretation by the flight control system designer. Finally, flight control system design methods that may be used to design systems are suggested that can satisfy flying qualities specifications as they now exist.

FLYING QUALITIES REQUIREMENTS

MIL-F-8785B(ASG) (Reference 1) is the classical flying qualities specification that summarizes and formalizes the lessons learned from a decade of simulator, and more importantly, experimental flight test using variable stability aircraft dedicated specifically to the definition of the specification. The language of the specification is that of the flight dynamicist and stresses such classical requirements as short period and Dutch roll natural frequency and damping ratios, eigenvector relationships such as ϕ/β and, of course, static or steady state requirements such as stick force per "g."

Often the flight control system designers tended to ignore the specification because the control system design techniques used, mainly Bode plot and root locus methods, stressed the use of compensation networks. Often these compensation networks were well within the passband of the vehicle dynamics itself, therefore giving rise to a higher order system response with significant residues in the compensation network poles excited by

the pilot during normal maneuvering. Because MIL-F-8785B did not address this problem, the next step was to evaluate the system using ground based simulators. Ground based simulators have motion and visual scene restrictions which have not predicted the PIO tendencies of the real aircraft. Perhaps the linear motion restrictions have led to concentration on the angular pitching motions of the vehicle. The problem is that when the pilot pulls back on the stick, he expects the vehicle to accelerate upward and change flight path, a most fundamental method of flying an aircraft. This basic vehicle aerodynamic behavior is generally not reproduced accurately on a ground based simulator. When coupled with a realization that no ground based simulator can reproduce the visual scene with absolute fidelity, the result has been control system designs with less than optimum flying qualities.

EQUIVALENT SYSTEM APPROACH TO FLYING QUALITIES EVALUATION

In an apparent attempt to make use of the many years of experimental research results embodied in 8785B, the next version of the flying qualities specification, MIL-F-8785C (Reference 2) made reference to an equivalent short period frequency and damping ratio. This subtle change in requirements appeared to be in deference to research being conducted by McDonell-Douglas (Reference 3 , 4) in which it was proposed to assess the flying qualities of an aircraft having a dynamically complex, high order flight control/airframe combination by approximating the high order system with a low order model. The flying qualities compliance evaluation would then be with respect to the lower order approximation, not the original system. The form of the proposed lower order model was given at that time by

$$\frac{\Delta\theta}{\delta_{F_s}}(s) = \frac{K_{q_e} e^{-As}\left(\tau_{\theta_e} s+1\right)}{s\left(\frac{s^2}{\omega_e^2} + \frac{2\zeta_e}{\omega_e} s+1\right)} \qquad (1)$$

In a memo by Rnaski (Reference 5), a number of possible problems associated with the mathematical model of Equation (1) and proposed analysis method were cited. Among these were:

1. The mathematical model did not contain a phugoid mode. Phugoid dynamics were easily evaluated from MIL-F-8785B.

2. Most control systems contained a prefilter or command augmentation compensation network. This kind of lag is generally associated with both analog and digital systems, while the transport delay is more often attributed to digital systems. Both can be evaluated but they are different in nature and effect and a differentiation should be made.

3. An equivalent system match should be made of $\frac{q}{\delta_{F_s}}(s)$ and $\frac{n_z}{\delta_{F_s}}(s)$ or $\frac{\alpha}{\delta_{F_s}}(s)$ simultaneously because the short period of an airplane

represented motions of two degrees of freedom of motion, while Equation (1) could imply that the aircraft may change pitch angle without a flight path change.

4. Time domain techniques of parameter identification are equally as accurate as frequency domain methods, require less flight time to gather data and do not require a Fourier transform pre-analysis step.

5. The zero of the pitch transfer function $(1/\tau_{\theta_2})$ should not be allowed to be "free" because this zero would always be equal to $s = +Z_\alpha$ in an aircraft that had coupled pitch-heave motions to a pilot command input, which results in the same short period natural frequency and damping ratio for $q/F_s(s)$ and $\alpha/F_s(s)$ responses of the vehicle.

With the exception of item 4, the proposed MIL Standard revision to MIL-F-8785C addresses each of the points listed above, but the inclusion of these provisions leads to other problems that will be encountered when attempting to use the equivalent system method of flying qualities evaluation.

EQUIVALENT SYSTEMS FROM A PARAMETER IDENTIFICATION VIEWPOINT

Four axioms of parameter identification have a significant effect on the results and should, therefore, be considered carefully.

- Motions - or input design
- Models - general form of the equations of motion
- Measurements - how many and which sensors?
- Methods - time or frequency domain

Motions and Models

The model form is incorrect by design. This means that the parameters of the equivalent system will then be very heavily dependent upon the input design, i.e. the motions of the vehicle that are to be used to extract the parameters of the equivalent system (see Reference 6, for instance). This means that the values of the parameters of the equivalent system that best match the vehicle response will be different for each and every different input time history injected by the pilot. In the frequency domain, this can be explained by noting that each input has a frequency spectrum associated with it, resulting in a different signal/noise ratio at each frequency and, therefore, a different measurement and plant noise covariance matrix. If the model form were exact, the band-limited white noise spectrum proposed for parameter identification would be close to optimum.

In an equivalent system analysis for short-period flying qualities evaluation, pitch rate and angle of attack models should be used rather than pitch rate and normal acceleration. There are three reasons for this:

1. The $n_z(t)$ response is station-dependent and nonminimum phase aft of the vehicle center of percussion.

2. Rotation corrections to angle of attack vane measurements $\frac{l_x}{g}\dot{\theta}$ can be made using pitch rate measurements but n_z measurement corrections should be made using the output of a rotary accelerometer.

3. Pitch rate and angle of attack are almost always minimum phase responses of the aircraft. This means that only amplitude matches are required; the phase angle that goes along with the resulting amplitude match, within the passband of considered data, is automatically defined by the Hilbert transformation.

Measurements

The MIL-Standard backup document includes an equivalent phugoid mode. In order to have a chance at an identification of a phugoid mode simultaneously with pitch and heave modes, at least three independent measurements, one for each degree of freedom of motion, are required. Otherwise, pole-zero cancellation or linear dependency problems can occur, particularly if the aircraft is heavily augmented. Because pitch angle and pitch rate are not usually sufficiently independent to enhance identifiability, a measurement of velocity change is usually required. The identification problem then becomes one of trying to decide how to weight the pitching motions to the heave motions to the velocity change motions of the vehicle. Not only is this problem not defined, it isn't even discussed in the MIL-Standard backup document.

Methods

Good alternatives to the frequency domain parameter identification method directed by the MIL-Standard handbook are available along with the free computer programs to perform the parameter extractions. Using time domain methods such as maximum likelihood, the actual pilot's inputs can be used, resulting in less flight time and semi-automatic weighting of the errors with no requirement for pre-processing, i.e., Fourier transform analysis. Because the results are obtainable in either transfer function or stability derivative form, an instant check with a time history or frequency domain envelope is possible. Finally, a transport lag is more easily and precisely defined in the time domain. There is no reason to exclude time domain parameter identification methods in equivalent system investigations and computer programs capable of doing the job both ways should be provided.

Specific Equivalent System Pitfalls

Figure 1 shows Bode plots that can be obtained from an aircraft that exhibits significant aeroelastic effects and the time histories that can result from the actual or equivalent system represented by the Bode plots. The Bode plots indicate that the rate gyro and normal accelerometer are likely co-located near an antinode of the lower frequency elastic mode shape. Because the signal picked up by the accelerometer is proportional to the mode shape while the rate gyro senses the derivative of the mode shape, a significant resonance of the response is evident in the accelerometer but not the rate gyro. The equivalent natural frequency of the pitch response would be quite different from that of the normal acceleration. In a case such as this, the signature of the n_z error, as shown in the time history response on the right in the figure, would be critical to the analyst in trying to assess the flying qualities. An equivalent system would mask these effects.

Not only will higher order system effects reduce the usefulness of equivalent systems, but lower order effects can also create problems. The equivalent system approach to flying qualities evaluation becomes questionable when some dynamics of the system become marginally observable, and this can happen with systems exhibiting behavior less than the fundamental second order. Consider the fundamental two-degree-of-freedom equations of motion given by

$$\begin{bmatrix}\dot{q}(t)\\ \dot{\alpha}(t)\end{bmatrix} = \begin{bmatrix}M'_q & M_\alpha\\ 1 & Z_\alpha\end{bmatrix}\begin{bmatrix}q(t)\\ \alpha(t)\end{bmatrix} + \begin{bmatrix}M_{\delta_e}\\ 0\end{bmatrix}\delta_e(t) \tag{2}$$

with a feedback control law

$$\delta_e(t) = -K_{11}q(t) - K_{12}\alpha(t) + \delta_{e_c}(t) \tag{3}$$

Incorporating the control law yields the closed-loop equations

$$\begin{bmatrix}\dot{q}(t)\\ \dot{\alpha}(t)\end{bmatrix} = \begin{bmatrix}M'_q - K_{11}M_{\delta_e} & M_\alpha - K_{12}M_{\delta_e}\\ 1 & Z_\alpha\end{bmatrix}\begin{bmatrix}q(t)\\ \alpha(t)\end{bmatrix} + \begin{bmatrix}M_{\delta_e}\\ 0\end{bmatrix}\delta_{e_c}(t) \tag{4}$$

which yields the characteristic polynomial

$$\Delta(s) = (s-M_q+K_{11}M_{\delta_e})(s-Z_\alpha) + M_\alpha - K_{12}M_{\delta_e} \tag{5}$$

in which $(s-M_q+K_{11}M_{\delta_e})$ represents the pitching mode, $(s-Z_\alpha)$ the heave or flight path mode while the term $M_\alpha-K_{12}M_{\delta_e}$ represents coupling between the flight path and pitching modes of motion of the aircraft.

The transfer functions relating the output response variables to the stick command input are given by

$$\frac{q}{\delta_{e_c}}(s) = \frac{M_{\delta_e}(s-Z_\alpha)}{\Delta(s)} \qquad \frac{\alpha}{\delta_{e_c}}(s) = \frac{M_{\delta_e}}{\Delta(s)} \qquad \frac{\dot{\gamma}}{\delta_{e_c}}(s) = \frac{M_{\delta_e} Z_\alpha}{\Delta(s)} \tag{6}$$

The transfer functions show that $1/\tau_{\theta_2} = +Z_\alpha$ and that in the steady state the attitude of the aircraft is perpendicular to the radius of curvature of a pullup maneuver.

If the feedback gain is chosen to decouple the flight path and pitch modes of motion, i.e., if K_{12} is chosen such that $M_\alpha - K_{12}M_{\delta_e} = 0$, $K_{12} = \frac{M_u}{M_{\delta_e}} = \frac{C_{m_u}}{C_{m_{\delta_e}}}$

the transfer functions become

$$\frac{q}{\delta_{e_c}}(s) = \frac{M_{\delta_e}}{s-M_q+K_{11}M_{\delta_e}} \qquad \frac{\alpha}{\delta_{e_c}}(s) = \frac{M_{\delta_e}}{(s-M_q+K_{11}M_{\delta_e})(s-Z_\alpha)}$$

$$\frac{\dot{\gamma}}{\delta_{e_c}}(s) = \frac{M_{\delta_e} Z_\alpha}{(s-M_q+K_{11}M_{\delta_e})(s-Z_\alpha)} \tag{7}$$

In this case, $\frac{q}{\delta_{e_c}}(s)$ exhibits a first-order response to an elevator command input and $1/\tau_{\theta_2}$ does not exist, so the argument of $1/\tau_{\theta_2}$ fixed or free is moot. The system is still second order and, in fact, all the dynamic parameters can be identified from the $\alpha(t)$ or $\dot{\gamma}(t)$ response of the system which always lags the pitch rate response by the term defined by the flight path mode.

Flight path and pitch rate response to a pilot stick command input can be made identical by feedback to a direct lift device from the output of a pitch rate gyro, i.e.

$$\delta_z = -K_{21}q(t) \tag{8}$$

yielding the closed loop equations of motion

$$\begin{bmatrix}\dot{q}(t)\\ \dot{\alpha}(t)\end{bmatrix} = \begin{bmatrix}M'_q & M_\alpha\\ 1-K_{21}Z_{\delta_z} & Z_\alpha\end{bmatrix}\begin{bmatrix}q(t)\\ \alpha(t)\end{bmatrix} + \begin{bmatrix}M_{\delta_e}\\ 0\end{bmatrix}\delta_{e_c}(t) \tag{9}$$

which yields the characteristic polynomial

$$\Delta(s) = (s-M_q)(s-Z_\alpha) - M_\alpha(1-K_{21}Z_{\delta_z}) \tag{10}$$

and transfer functions

$$\frac{q}{\delta_e}(s) = \frac{M_{\delta_e}(s-Z_\alpha)}{\Delta(s)} \quad \frac{\alpha}{\delta_e}(s) = \frac{M_{\delta_e}(1-K_{z1}Z_{\delta_z})}{\Delta(s)}; \frac{\dot{\gamma}}{\delta_e}(s) = \frac{M_{\delta_e}K_{z1}Z_{\delta_z}\left(s-\frac{Z_\alpha}{K_{z1}Z_{\delta_z}}\right)}{\Delta(s)} \tag{11}$$

which shows that the flight path no longer lags the pitch rate by the flight path mode term $s-Z_\alpha$. The $\frac{\dot{\gamma}}{\delta_{e_c}}(s)$ response has a numerator zero, different from Z_α. This term should be included in the lower order equivalent systems model.

If the pitch rate feedback to the direct lift device was chosen to decouple the pitch and path modes of motion, i.e., if $-1+K_{z1}Z_{\delta_z} = 0$, i.e., $K_{z1} = 1/Z_{\delta_z}$, the transfer functions become

$$\frac{q}{\delta_{e_c}}(s) = \frac{M_{\delta_e}}{s-M_q} = \frac{\dot{\gamma}}{\delta_{e_c}}(s); \quad \frac{\alpha}{\delta_{e_c}}(s) = 0 \tag{12}$$

This equation shows that pitch attitude is perpendicular to the radius of curvature both dynamically and statically, but neither $1/\tau_{\theta_2}$ nor Z_α appears to exist in the response of the aircraft to a pitch stick command input. So again, the question of whether $1/\tau_{\theta_2}$ is free or fixed is moot.

The system, however, is still second order and in this case, the remainder of the system dynamics are not observable unless the response to a command to the direct lift device is measured. In this case, the transfer functions relating pitch rate and angle of attack to a direct lift command become

$$\frac{q}{\delta_{z_c}}(s) = \frac{-Z_{\delta_z}M_\alpha}{(s-M_q)(s-Z_\alpha)} \; ; \; \frac{\alpha}{\delta_{z_c}}(s) = \frac{Z_{\delta_z}}{s-Z_\alpha} \tag{13}$$

The pitch rate response lags the angle of attack response by the pitch mode term $s-M_q$. A dilemma, therefore, exists for the flying qualities analyst trying to define a mathematical form of an equivalent system involving the short period response approximation of an aircraft that can be commanded by a moment-producing or a direct lift force-producing device.

DESIGN METHODS THAT DO NOT INHERENTLY INCREASE ORDER

Because the flying qualities of low order systems have been reasonably well mapped and because low order appears to be desirable, it seems well worth

while to investigate the use of those design techniques that do not inherently increase the order of closed loop systems. It is true that hardware realities such as actuators, sensors and structural mode filters will always result in a higher order system, but the design can be such that these elements contribute little within the pilot passband of interest. In fact, an airplane is structurally elastic, so the aircraft is always of infinite order, but the limited bandwidth of command excitation is such that the higher frequency modes are seldom excited to the extent that they have significant effect on the flying qualities (not ride qualities) of the vehicle.

Control system design,using any time domain, state space oriented method will not inherently increase the order of the closed-loop system compared to the bare airframe open-loop system. Basically, this is because the control law consists only of non-energy storage feedback gains. Among the more promising methods of control system design to satisfy flying qualities are:

1. Linear optimal control
2. Model-following methods
3. Pole placement/pole-zero placement methods
4. Robust observer techniques.

Linear Optimal Control

The basic properties of linear optimal methods as applied to flight control were described in detail in Reference 8 and repeated in different form and notation in many subsequent studies. The basic characteristic of linear optimal control is that whatever response variable or variables are included in the performance index tend toward the response of a Butterworth filter as the weighting of the response variable with respect to the control power is made very high. For aircraft control, it then becomes important to recognize or define those motion variables or time histories that may respond in the smooth and well behaved manner of a Butterworth filter responds. To illustrate, consider, as shown in Figure 5 (Reference 9) the two performance indices, the resulting migration of the closed-loop poles of the two degree-of-freedom aircraft representation as the weighting on the output variable becomes large with respect to the input and the resulting responses of the aircraft to a pilot step command input.

As shown in the sketch, the use of performance index (1) will lead to a response in angle of attack approaching that of a second order Butterworth filter while the use of performance index (2) will lead to a first-order response in pitch rate as the ratio q/r becomes large. Therefore, a flight control system designed on the basis of the first performance index will enable the pilot to change his angle of attack rapidly and smoothly by a stick input, allowing for enhanced aircraft maneuverability. The second performance index will yield an aircraft system that maneuvers sluggishly but allows for rapid and precise pitch rate control. Any combination of variables, such as $C^{*}(t)$, can be included in a performance index. However, if one recalls that $C^{*}(t)$ is nearly all pitch rate at low dynamic pressure flight conditions such as landing, the pilot will have difficulty accomplishing the landing maneuver if the vehicle has low Z_{α},with a tendency to overdrive the stick and subsequent "ballooning" should a touchdown not occur on the first try.

MODEL FOLLOWING

Model-following methods can be used in conjunction with optimal control (References 8, 10) or they can be designed directly (Reference 11). The model can be expressed implicitly as a weighting function of the performance index (Reference 8) or explicitly as a command augmentation computer that calculates the forces and moments to be applied to the aircraft to respond as the model. Reference 11 defines the explicit model-following design method while Reference 10 shows implicit model-following designs. In either case, the equations of motion of an "ideal model" having Level 1 flying qualities are extracted from MIL-F-8785B and a control system is designed to match the model responses as closely as possible. Because an airplane is completely controllable, one model response variable can be "exactly" matched for each independent control input, so optimal control is generally an unnecessarily complex and roundabout way to get to where you know you want to go. A performance index is useful mainly in those specific task-oriented situations where an exact model of the desired dynamics cannot be obtained from MIL-F-8785.

POLE PLACEMENT METHODS

The flying qualities specification rather precisely defines the range of phugoid and short period poles for Level 1 flying qualities. If the open-loop poles are known and the desired closed-loop poles specified, then pole placement techniques will directly yield the control law required for superior flying qualities. Generally speaking, all poles can be placed with one controller. If zeros are also to be placed, these must be done with a second controller. For instance, $1/T_{\theta_2}$ (Z_α) can be adjusted using n_z or angle of attack feedback to a direct lift device, while all poles can be placed using feedback to the elevator or moment-producing device.

The most direct way to devise a control law for pole placement is through the use of the phase variable transformation. The familiar equations of motion of the vehicle are expressed in matrix vector form as

$$\dot{x} = Fx + G\delta_e \tag{14}$$

where x represents a vector of aircraft motion variables such as $\Delta\theta$, θ, $\Delta\alpha$ and ΔV, and F and G are matrices of stability and control derivatives. A similarity transformation T is defined to transform Equation (14) above into the phase variable form

$$\begin{aligned} \dot{Z} &= F_O Z + G_O \delta_e \\ Z &= Tx \end{aligned} \tag{15}$$

where F_O and G_O are of the form

$$F_o = \begin{bmatrix} 0 & 1 & 0 & \cdots & 0 \\ 0 & 1 & 0 & & \\ & & & \ddots & 0 \\ 0 & & & & 1 \\ -a_o & -a_1 & \cdots & & a_{n-1} \end{bmatrix} \qquad G_o = \begin{bmatrix} 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix} \tag{16}$$

The last row of the matrix F_o is formed from the characteristic polynomial of Equation (14), i.e.:

$$D(s) = |Is-F| = s^n + a_{n-1}s^{n-1} + a_{n-2}s^{n-2} + \ldots a_1 s + a_o \tag{17}$$

The transfer function matrix of the aircraft equations of motion can be expressed as

$$(Is-F)^{-1}G = \frac{1}{D(s)} TS \tag{18}$$

where $s^T = [1 \quad s \quad s \quad \ldots\ldots \quad s^{n-1}]$ is an nxl matrix of ascending powers of the Laplace transform variable and T is the similarity transformation. Therefore, the rows of the matrix T are made up of the coefficients of the numerator coefficients of the transfer function of the response variables of the aircraft. If a desired characteristic polynomial, obtained from the MIL-F-8785 specification is given as

$$(s) = s^n + a_{n-1}s^{n-1} + a_{n-2}s^{n-2} + a_1 s + a_o) \tag{19}$$

then the feedback control law that will yield the desired closed-loop poles, such as short period and phugoid, is simply

$$\delta_e = -[a_o - a_o, \; a_1 - a_1, \; \ldots\ldots \; a_{n-1} - a_{n-1}]T^{-1}x \tag{20}$$

ROBUST OBSERVERS

The control law of Equation (20) above requires feedabck from as many independent measurements as poles of the system. For the longitudinal-vertical degrees of freedom of motion of the aircraft with relaxed static stability, it may be desirable to alter all four poles to meet the specification and restore the eigenvector relationships that exist in a more conventional aircraft. This can be done using robust output observers, a filter arrangement that has the effect of reproducing independent measurements of the dynamics of the airframe and, therefore, do not alter the phase and gain margins or robustness of the closed-loop system as compared to state feedback.

The observer theory of Luenberger specifies the conditions that must be satisfied for a filter to be an observer. The observer is of the form

$$\dot{z} = Az + By + Du \tag{21}$$

subject to the conditions

1) The matrix A yields a stable observer set.
2) A transformation T can be found such that $TF - AT = BH$
3) $TG = D$

where F, G and H are defined by the linearized equations of vehicle motion

$$\dot{x} = Fx + Gu$$

$$y = Hx$$

A robust observer must satisfy, in addition to the above conditions,

4) The observer poles, defined from $|Is-A| = 0$, must be selected from among the system transmission zeros, defined from $|H(Is-F)^{-1}G| = 0$.

5) The matrices H and T must constitute a nonsingular transformation M on x

$$\begin{bmatrix} y \\ z \end{bmatrix} = \begin{bmatrix} H \\ T \end{bmatrix} = Mx \tag{22}$$

such that the feedback control law can be defined as $u = -Kx = -KM^{-1}\begin{bmatrix} y \\ z \end{bmatrix}$

If a sixth condition can be satisfied

6) $TG = D = 0$

then the robust observer becomes a robust output observer requiring no input measurement for realization.

The transmission zeros are the key to the design method described above, for if the observer poles are selected from among the transmission zeros, the residues in the observer poles are zero to a command input. The observer itself is then unobservable and robustness compared to state feedback is preserved with no increase in the order of the response of the closed-loop system as compared to the open loop. This, then, satisfies the flying qualities axiom that, in general, the design technique should not introduce additional or higher order dynamics into the system. Output observers can, of course, be used to reconstruct a state such as the equivalent of an angle of attack measurement from a pitch rate measurement and this can be useful for measurement simplification or analytical redundancy purposes, but it is not at all obvious that this is a most effective way to use observers.

Figures 6 and 7 show examples of robust observer configurations that can place the poles of a statically unstable aircraft such as the AFTI-16 into the desirable short period and phugoid regions defined by MIL-F-8785.

Figure 3 a shows an output robust observer configuration using only one measurement, a rate gyro. As shown in the figure, it was necessary in this configuration to integrate the rate gyro output to obtain complete dynamic system observability. An alternative to integrating the rate gyro is shown in Figure 3b,, in which a δ_e measurement is used as an input to one of the observer poles. It should be stressed that the two observer networks shown in Figure 3 are only two of a possible near infinite set, and the process of going from one configuration to another is not merely a matter of block diagram manipulation.

Figure 4 shows an observer set using an angle of attack measurement rather than a rate gyro. The δ_e addition to the output measurement yields complete system observability without the need to differentiate or design a lead-lag network on the output of the angle of attack measurement, so the observer network will not increase the gust sensitivity of an aircraft. In general, all observers can be designed as lag or lag-lead networks to produce the added benefit of attenuating the feedback signals at the structural mode frequencies of the airplane.

CONCLUDING REMARKS AND SUMMARY

Since the introduction of MIL-F-8785B, a number of attempts have been made to extend flying qualities requirements into a region that would permit significant higher order system response behavior. The two major efforts, mainly $C^*(t)$ and the equivalent systems method, have not been shown to be effective predictors. Perhaps it is possible to develop both an equivalent system method and a response envelope time history method, but the present tools do not appear suitable and it will be necessary to map the higher order effects much more extensively than has been done to date. A versatile, high performance aircraft with independent force and moment control capable of rapidly and accurately simulating and mapping higher order dynamics is not yet available.

The flying qualities requirements of lower order, bare airframe rigid body dynamics are quite well known and are extensively documented. Because the more modern state-space-oriented control methods do not inherently increase the order of the closed-loop system as compared to the open loop, it seems that this time period represents a natural time period to link these design methods directly to the requirements of MIL-F-8785. A true union of flying qualities and flight control can be achieved with much higher assurance that total compatibility between the disciplines can be achieved. The result can only be superior flight control systems for the superior U.S. aircraft of the future.

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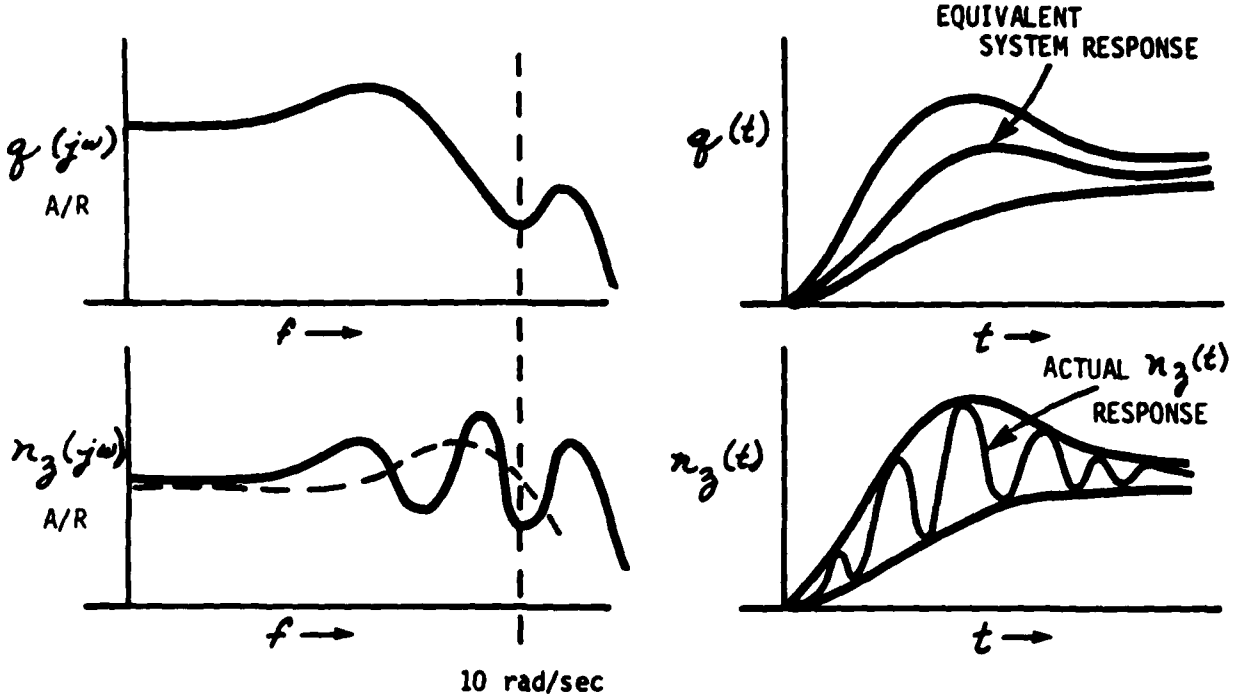


Figure 1. BODE AND TRANSIENT RESPONSES - AEROELASTIC AIRPLANE

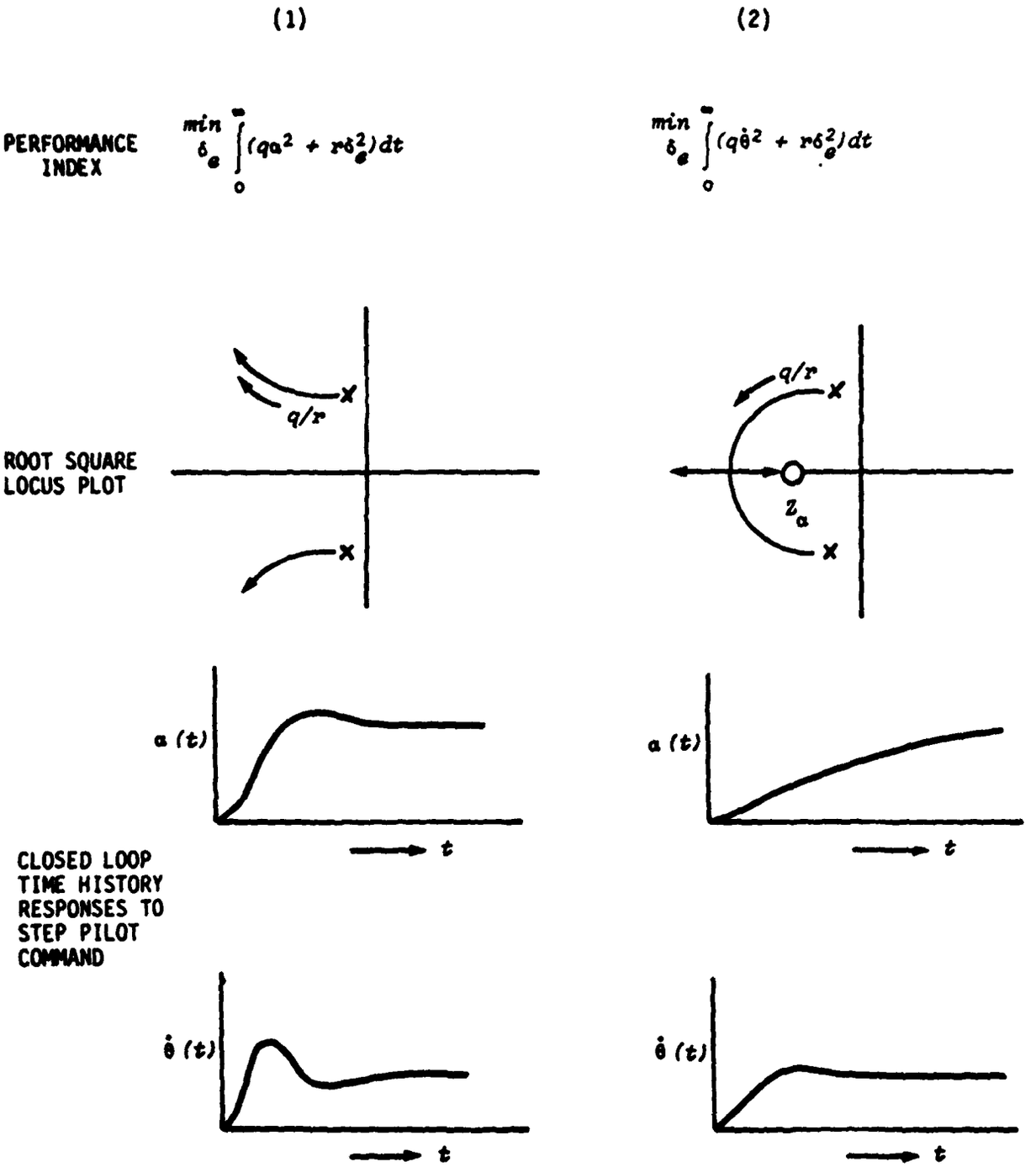


Figure 2. RESPONSE TO STEP COMMAND AS A FUNCTION OF PERFORMANCE INDEX

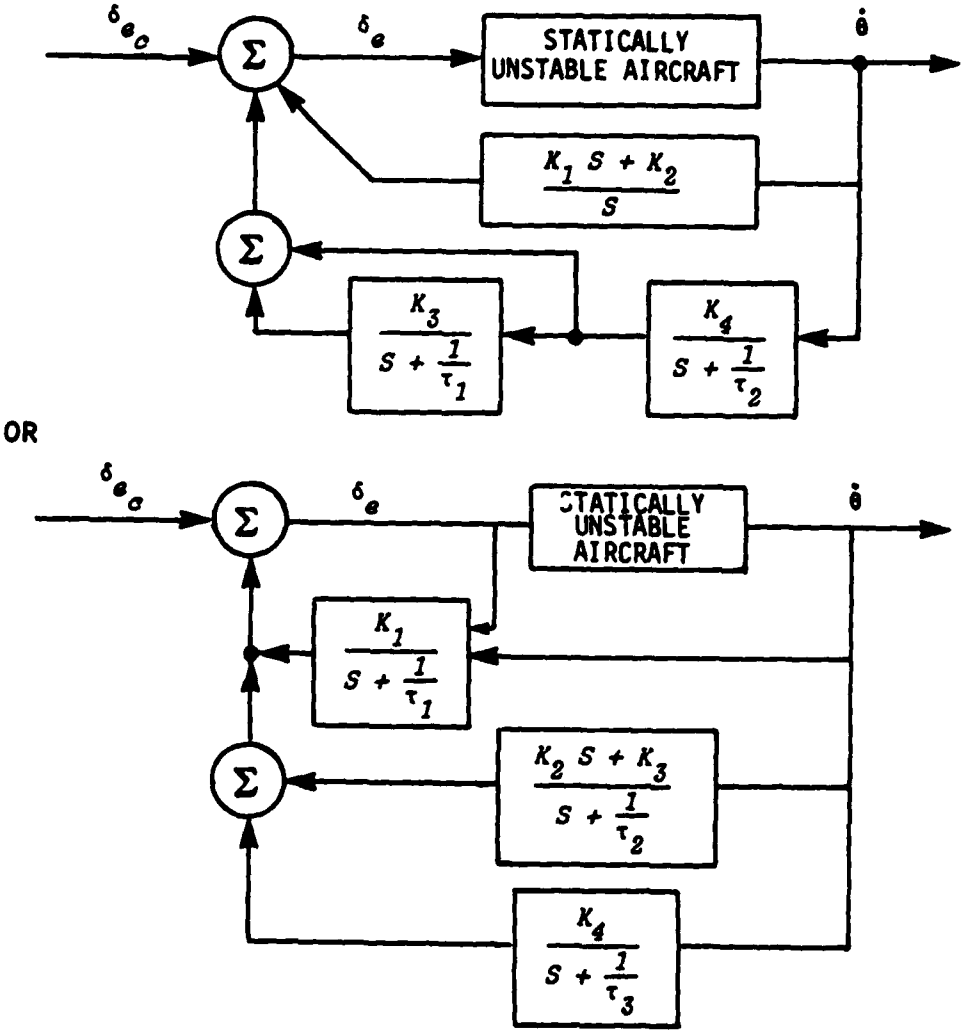


Figure 3. FLIGHT CONTROL USING PITCH RATE GYRO SYSTEM

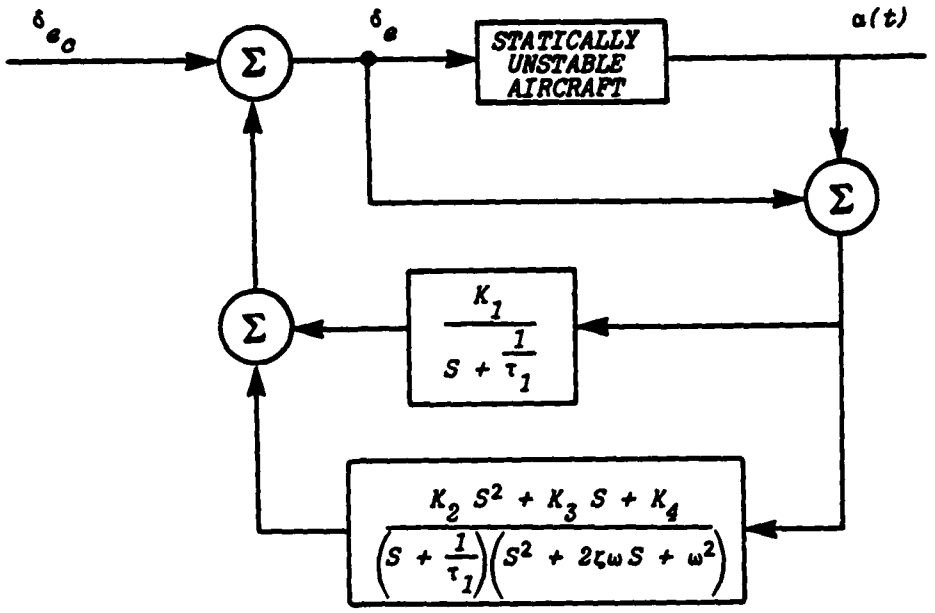


Figure 4. FLIGHT CONTROL SYSTEM USING ANGLE OF ATTACK FEEDBACK

COMMENTS AND QUESTIONS

Roger Hoh, STI: The equivalent systems approach may mask higher-order modes and imply that those modes are unimportant. If a mismatch occurs, it points out problem areas requiring further investigation.

Answer: Not necessarily. Some matches showing high values of mismatch have proven good. The converse has also been found--low mismatch value, yet a very poor match. Sensor location introduces problems.

Roger Burton, NATC: Does reliable data exist which has been validated by the equivalent systems method?

Answer: Yes. The B-1 was investigated at several design points during the envelope expansion phase. Both the NT-33 and the C-131 TIFS were used from an equivalent systems viewpoint.

EQUIVALENT SYSTEMS CRITERIA FOR THE FLYING QUALITIES MIL STANDARD*

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ABSTRACT

The flying qualities of fighter airplanes with modern augmented control systems are difficult to analyze using classical criteria. However, a new approach, the equivalent system method, reduces the high order dynamics of these airplanes to low order forms, which relate well to classical criteria when a requirement is also imposed on equivalent time delay. Recently, two developments have been proposed for the flying qualities MIL Handbook that yield more acceptable and useful equivalents. First, pitch rate and normal acceleration responses should be matched simultaneously. This eliminates the large variations in the numerator root of the pitch rate transfer function that can occur for pitch-rate-only matches. Second, mismatch envelopes have been developed for Maximum Unnoticeable Added Dynamics. These explain why large mismatches between high and low order systems were unnoticeable to pilots in a variable stability NT-33 simulation. The mismatch envelopes also emphasize the importance of a good match in the crossover region. They can be included in the match algorithm to penalize poor crossover region matches.

INTRODUCTION

"Equivalent systems" are now required for the Military Flying Qualities Specification MIL-F-8785C, Reference 1, applying to those

*Presented at the Joint Flying Qualities/Flight Controls Symposium sponsored by AFWAL/FDL, 2-5 March 1982, Wright-Patterson AFB, Ohio.

$$\frac{\dot{\theta}}{F_s} = \frac{K_{\dot{\theta}}\,(1/T_{\theta_2})e^{-\tau_{\dot{\theta}}S}}{[\zeta_{SP};\ \omega_{SP}]} \qquad \text{where } (1/T_{\theta_2}) \rightarrow S + 1/T_{\theta_2} \qquad (1)$$

$$[\zeta_{SP};\ \omega_{SP}] \rightarrow S^2 + 2\zeta_{SP}\omega_{SP}\,S + \omega_{SP}^2$$

The requirements specify ω_{SP} as a function of $n/\alpha = \frac{V}{g} L_\alpha$ where V is true speed and L_α is the aircraft dimensional lift slope parameter. For an augmented system, feedback to a single aircraft control surface (e.g., elevator) cannot change the numerator term $(1/T_{\theta_2})$, which is approximately L_α. This numerator term governs response ratios. For example, flight path angle, γ, lags pitch angle according to the relationship $\frac{\gamma}{\theta} = \frac{1/T_{\theta_2}}{(1/T_{\theta_2})}$, which is unchanged by feedback. There is therefore an excellent argument for fixing the $1/T_{\theta_2}$ value in pitch matching at its true value.

Suppose, however, that a first order lag prefilter with a break frequency approximating $1/T_{\theta_2}$ is the only augmentation effect added to an aircraft with short period flying qualities described by the above equation. Then the short period pitch response is exactly matched by:

$$\frac{\dot{\theta}}{F_S} = \frac{K_{\dot{\theta}}e^{-\tau_{\dot{\theta}}S}}{[\zeta_{SP};\ \omega_{SP}]} \qquad (2)$$

We can interpret this $1/T_{\theta_2}$ value as being effectively infinity, clearly not a realistic value for L_α. A correspondingly large n/α can be calculated using true speed and the gravitational constant. The specification requirements can then be applied, though in this case the parameters apply only to the pitch response and the large n/α does not define the response ratio. The specification

requirements specifying modal parameters, i.e., time constants, damping ratios, and natural frequencies. This means that whenever MIL-F-8785C is used for an aircraft whose linearized mathematical model is of high order, a matching procedure must be used to match the response with a low order, classical-appearing response. The parameters of the low order system will then be compared with the specification. The justification for this is contained in a number of reports and papers, including the Background Information and User Guide, Reference 2.

Recent developments which have become part of the proposed MIL Standard and Handbook answer two primary questions which have been raised concerning equivalent systems:

- o Why do unrealistic values of a fundamental aircraft parameter, L_α, occur in some equivalent systems?
- o What degree of mismatch is acceptable when comparing a low order equivalent against its high order counterpart?

UNREALISTIC L_α VALUES

In regard to the first question, the procedure we are proposing for the MIL Standard precludes unrealistic values. This procedure is also suitable for the current specification. The requirements for acceleration sensitivity and short period natural frequency, from MIL-F-8785B and C are involved. These are important requirements because they ensure that aircraft have sufficient rapidity in their attitude response at normal piloting frequencies.

The equivalent system form for short-term, small perturbation response to stick force is:

then clearly shows the flying qualities problems to be expected, as illustrated in Figure 1. Therefore, for systems resembling Equation (2), there is an excellent argument for allowing $1/T_{\theta_2}$ simply to optimize to an artificial value.

The outcome of these arguments is that matching the pitch response alone with $1/T_{\theta_2}$ free, though not actually misleading, is not allowed by the proposed MIL Handbook. The pitch and normal load factor responses are to be matched simultaneously. It will now be demonstrated that this method usually produces the same answers as matching pitch response alone with $1/T_{\theta_2}$ fixed.

Simultaneous Matching

To demonstrate the effects of simultaneous matching, we selected three groups of configurations from the variable stability NT-33 experiment of Neal and Smith (Reference 3). Each of Neal and Smith's groups had the same short period roots. We wished to focus on the effects of short period natural frequency, so we chose groups with good damping (nominally 0.7) and different frequencies. These groups were 1, 2, and 8, which had frequencies of nominally 2, 5, and 16 radians/second. Within each group, Neal and Smith added various high order terms which created configurations such as 1G, 2H, and 8C.

In some cases, the added terms changed the flying qualities drastically, even though the short period roots remained constant. This incidentally illustrated the unsuitability of using short period roots alone, without employing an equivalent system procedure.

We matched frequency responses of: the pitch response alone, with and without $1/T_{\theta_2}$ fixed; normal load factor alone; and both pitch and load factor simultaneously (weighted equally, and with

$1/T_{\theta_2}$ free). The equivalent system form was equation (1) for pitch, and the following for n_z:

$$\frac{n_z}{F_s} = \frac{K_{n_z} e^{-\tau_{n_z} S}}{[\zeta_{SP}, \omega_{SP}]} \qquad (3)$$

For groups 1 and 2 we matched in the range of 0.1 to 10 rad/sec and for group 8, 0.1 to 20 rad/sec.

When the only added high order term was the second-order actuator (ζ = .7, ω = 75 rad/sec) all of the matches were of course excellent. All of the responses produced the same values of ζ_{SP}, ω_{SP}, $\tau_{\dot{\theta}}$ and τ_{n_z}. However, when more lag was added, the parameters differed. For example, configuration 1G exhibited the changes shown in Figure 2 for pitch-alone matching. Some of the parameter variations in this figure appear large - for example, the numerator parameter more than triples. However, this is offset by a corresponding change in a denominator parameter. The specification parameters are not dramatically changed, and the predicted level does not change at all.

The configuration has too much lag, and the actual ratings were Level 2. This was predicted by the pitch alone match with $1/T_{\theta_2}$ free. Nevertheless, the $1/T_{\theta_2}$-free, pitch-only procedure was considered unsuitable for specification purposes. One reason was the tendency of $1/T_{\theta_2}$ to seek arbitrarily large values. Another reason was the confusion between the equivalent $1/T_{\theta_2}$ and the actual $1/T_{\theta_2}$. This confusion would be heightened when there

is an additional active control surface such as a canard or flaps for direct lift control (DLC). In this case, the flight path would not be coupled to the attitude response through the natural $1/T_{\theta_2}$ value.

The proposed MIL Handbook avoids this confusion, and provides a way of treating DLC and similar systems, by requiring pitch and normal load factor to be matched simultaneously. The term $1/T_{\theta_2}$ is then allowed to seek an optimum.

For configuration groups 2 and 8, which were fairly well matched, this produced the same answers as fixing $1/T_{\theta_2}$ in a pitch-alone match. When the matches are far worse than those obtained for 2H, $1/T_{\theta_2}$ can seek a slightly different compromise value. For example, simultaneous matching of configuration 1G produced a pitch mismatch of 151, and an equivalent $1/T_{\theta_2}$ of 1.6, versus the natural value of 1.25. But the remaining parameters were within 5% of the pitch-only, fixed $1/T_{\theta_2}$ match value. The pilot rating was 8.5, which the low short period frequency and large delay predict, in spite of the mismatch.

Apparently, in most cases, matching both pitch and normal load factor produces the same answer as matching pitch alone with the numerator fixed at the natural value.

Bischoff (Reference 4) has analyzed some operational aircraft with very poor matches. They have essentially confirmed the results described above.

THE QUESTION OF MISMATCH

In the configuration just described, 1G, the equivalent system parameters clearly show the reasons for the poor ratings. However, the equivalent system match is quite poor, as the frequency response of Figure 3 illustrates. This calls into question the reliability of the equivalent parameters.

In Reference 5 we introduced the idea of the sum-of-squares mismatch function, defined in Figure 4. When this was ten or less, we found the match quality visually acceptable. Mismatch was usually this small, particularly since we were able to reduce it if necessary by freeing $1/T_{\theta_2}$ in the pitch-alone match. On the other hand, when the mismatch function was large, the equivalent parameters were exaggerated to values which correctly indicated flying qualities problems.

In our later efforts to produce specification-worthy criteria, we needed to focus on mismatch as defining an acceptable degree of precision for equivalent systems. An exploratory study of mismatch was therefore performed in 1978, using the USAF/Calspan NT-33 (References 6, 7, and 8). High order longitudinal and lateral systems were evaluated, together with various low order equivalents. We chose the low order parameters to exhibit various types and amounts of mismatch when compared with the high order systems. By comparing pilot comments and ratings, we hoped to determine what level of mismatch would correspond to a noticeable difference in ratings.

However, flying qualities seemed equivalent regardless of mismatch level. We needed an explanation for this, since mismatch levels were often by design quite high - up to 200 in some cases. And the more recent requirement to match pitch and load factor simultaneously means that high mismatches will be more common.

Critical Added Pitch Dynamics

In 1979 and 1980 we performed a similar study of mismatch for V/STOL aircraft, using our ground based AV-8 simulator (References 9, 10). We suspected that evaluating high order systems and their low order equivalents would lead to the same inconclusive results obtained with the NT-33. This time, therefore, we progressively added high order terms to low order dynamics in order to build up mismatches in restricted frequency regions. We summarized the results by drawing frequency response envelopes around the "critical" added dynamics - the largest frequency response additions which did not cause a change in rating. Thus a frequency response mismatch within that envelope would probably not be noticeable to a pilot.

To establish envelopes for conventional CTOL aircraft, we reviewed the Neal-Smith and Landing Approach High Order System - (LAHOS) data. These are Reference 3 and 11 respectively. These studies evaluated the effects of several types of added dynamics on fighter handling qualities. By examining the pilot ratings, we defined the critical cases from these two experiments.

For example, Figure 5 shows the pitch frequency responses of a low order system (LOS), along with those from two high order systems (HOS) derived from it by adding different first order lead-lags. The higher frequency lead-lag addition in HOS

#1 causes no pilot degradation, but the lower frequency lead-lag addition in HOS #2 causes a definite degradation. In Figure 6 the mismatch from Figure 5 is plotted. (The mismatch is the difference between HOS and LOS, ie HOS-LOS). Based on pilot ratings from Figure 5, a HOS with a mismatch falling within the HOS #1 mismatch should have the same pilot rating as the low order system. At some mismatch between HOS #1 and HOS #2, a degradation in rating might be expected. HOS #1 therefore represents the critical added dynamics for the two first order lead-lag additions shown.

The process of finding the critical cases was readily performed in our V/STOL study because the experiment was designed with that in mind. The Neal-Smith and LAHOS programs were not run with this in mind, and therefore some inference was needed when interpreting the data. For example, the LAHOS phugoid caused no adverse comments and so was arbitrarily used to provide a tentative envelope of low frequency added dynamics.

In Figure 7, the frequency responses of the critical cases are plotted on a common Bode plot to obtain tentative envelopes (gain and phase) of Maximum Unnoticeable Added Dynamics (MUAD), for pitch dynamics.

The envelopes defined the pilot's frequency range of interest - the narrow region of the mismatch envelopes. The narrowing of the envelopes suggests that pilots notice much lower values of mismatch in this frequency range (essentially the crossover region) than at other frequencies.

Envelopes of Maximum Unnoticeable Added Dynamics

Envelopes were drawn by fairing smooth curves either through parts of the various critical added dynamics or tangent to them. The four envelope curves (an upper and a lower for gain and phase) were then matched by transfer functions, using an interactive matching program (Figure 8). The resulting transfer functions can be used for any frequencies and frequency ranges within the limits of 0.1 and 100 rad/sec. These transfer functions are (from Reference 12):

Upper Gain Envelope:

$$\frac{3.16S^2 + 31.61S + 22.79}{S^2 + 27.14S + 1.84}$$

Lower Gain Envelope:

$$\frac{.0955S^2 + 9.92S + 2.15}{S^2 + 11.60S + 4.95}$$

Upper Phase Envelope:

$$\frac{68.89S^2 + 1100.12S - 275.22}{S^2 + 39.94S + 9.99} e^{.0059S}$$

Lower Phase Envelope:

$$\frac{475.32S^2 + 184100S + 29456.1}{S^2 + 11.66S + .0389} e^{-.0072S}$$

A pitch rate response mismatch falling within the envelopes indicates that the low order equivalent system is satisfactory as a flying qualities tool. The envelope transfer functions have also been used as a design tool to predict whether a set of added dynamics will be noticed by a pilot.

Figure 9 compares the CTOL and V/STOL envelopes. These imply that the pilot's frequency range of interest was the same for aerial tracking, for demanding touchdowns, and for low speed and hover. In practice, matches for most configurations fall well within the relatively large match envelopes.

Mismatch Weighting

The envelopes show that the closest match is needed in the central crossover region. We modified our matching program to emphasize the match in this region. We weighted the match as an inverse function of the allowable mismatch at each match frequency (Figures 10 and 11). The weighting is therefore largest when the envelopes are narrowest. With these weighting factors, good matches can theoretically be obtained in the crossover region by sacrificing somewhat the quality of the match elsewhere.

In practice, the matches for most existing configurations are not affected dramatically by weighting factors. The situation may be different for aircraft with highly unconventional dynamics.

CONCLUSIONS

Two developments have been proposed for the flying qualities Military Standard. Because they are applicable to the current Military Specification, the developments respond to the question, 'Are today's specifications appropriate for tomorrow's airplanes?' (Reference 13).

First, longitudinal equivalent system matching of pitch and normal load factor simultaneously, with the pitch numerator free, is an acceptable match method. Second, the consequent, relatively large mismatches should fall within newly established envelopes which define acceptable precision of equivalent systems.

To put these two developments in perspective, it is evident that a computer program with the appropriate optimization, input and output options, dual response matching, mismatch weighting, mismatch envelopes, etc., will be a significant advantage in determining cost-effective equivalent systems. For most cases, however, matching pitch rate response to stick force with the numerator term remaining fixed will give adequate answers. This can, if necessary, be performed by hand.

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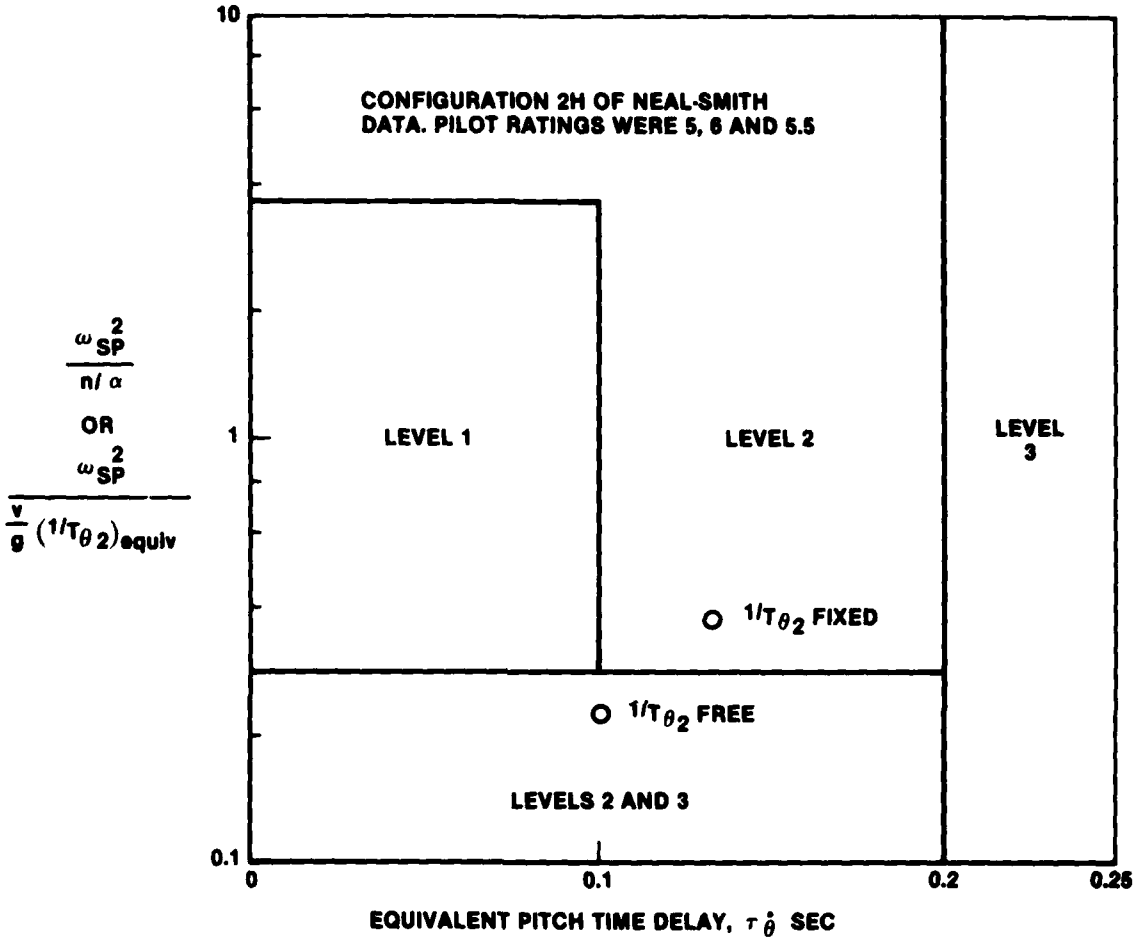
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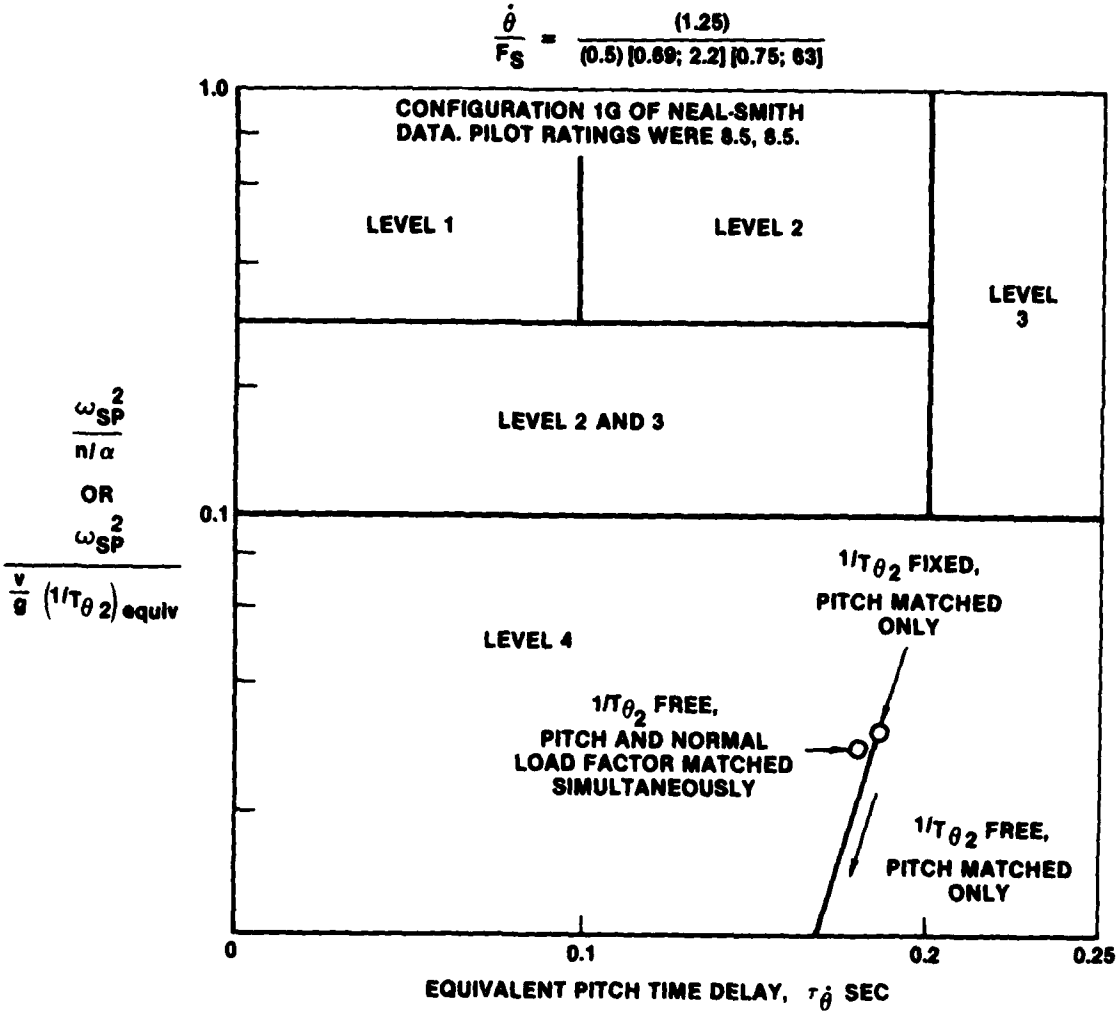
$$\frac{\dot{\theta}}{F_S} = \frac{(1.25)}{(2)\,[0.7;\ 4.9]\,[0.75;\ 63]}$$



ζ_{SP}	ω_{SP}	$\tau_{\dot{\theta}}$	$1/T_{\theta_2}$	n/α	$\frac{V}{g}\left(1/T_{\theta_2}\right)$	$\omega^2_{SP}/n/\alpha$	$\omega^2_{SP}/\frac{V}{g}\left(1/T_{\theta_2}\right)$	MISMATCH
0.8	2.8	0.13	1.25 (FIXED)	18.5	—	0.37	—	15.1
0.5	3.8	0.10	4.1 (FREE)	—	60.4	—	0.24	4.8

GP28-0170-2

Figure 1. Effect on Equivalent Parameters, and on MIL-F-8785C Correlation, of Fixing and Freeing Pitch Numerator Root in Matching Process. Pitch Response Alone Matched.



ζ_{SP}	ω_{SP}	$\tau_{\dot{\theta}}$	τ_{n_z}	$1/T_{\theta_2}$	n/α	$\frac{v}{g}\,1/T_{\theta_2}$	$\omega_{SP}^2/n/\alpha$	$\omega_{SP}^2/\frac{v}{g}\left(1/T_{\theta_2}\right)$	MISMATCH
PITCH MATCH ONLY									
0.74	0.78	0.184	—	1.25 (FIXED)	18.5	—	0.03	—	150
1.07	1.6	0.04	—	176 (FREE)	—	2601	—	0.0009	13
PITCH AND NORMAL LOAD FACTOR MATCHED SIMULTANEOUSLY									
0.75	0.82	0.176	0.188	1.60 (FREE)	—	23.6	—	0.29	140 ($\dot{\theta}$) 155 (n_z)

GP23-0179-3

Figure 2. Effect on Equivalent Parameters of Fixing and Freeing Numerator Root in Matching Process. Pitch Match Only, Compared with Pitch and Normal Load Factor Matched Simultaneously.

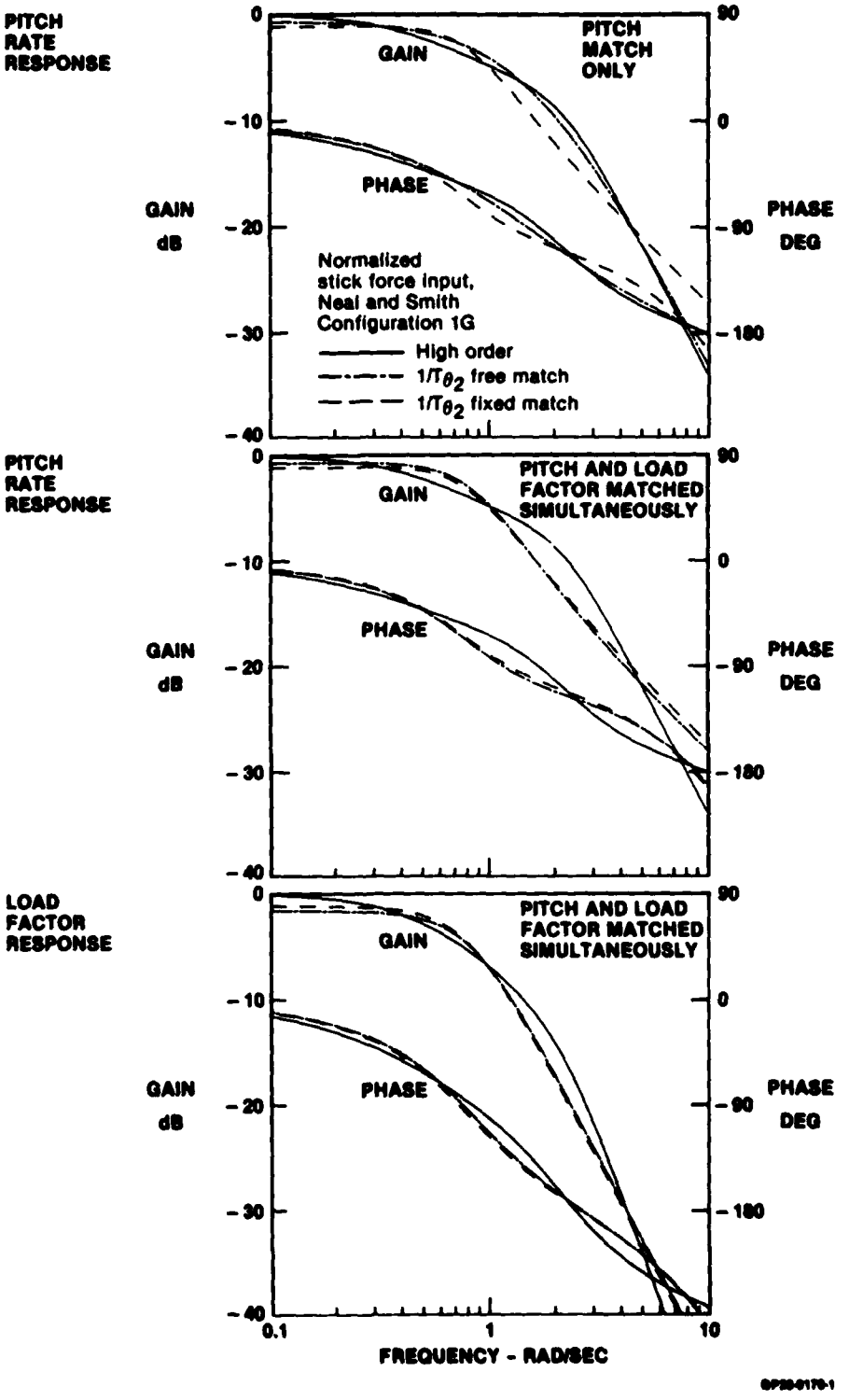
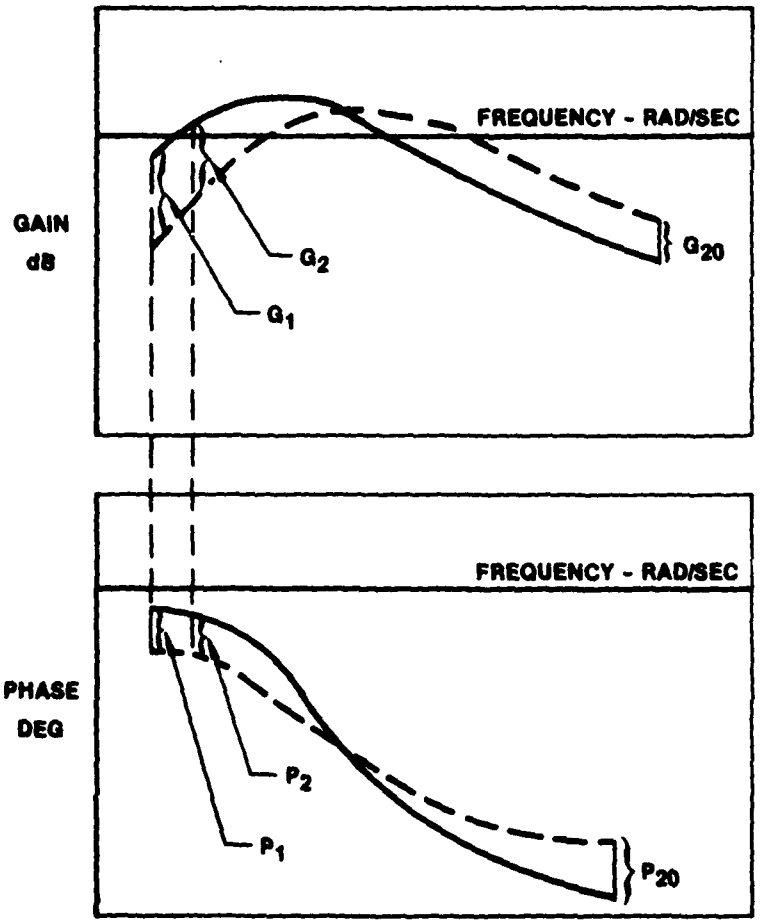


Figure 3. Configuration Showing Poor Match for Simultaneous Pitch and Normal Load Factor Matching



$$\text{COST FUNCTIONAL, IE MISMATCH} = \sum_{I=1}^{20} (G_I^2 + WP_I^2);\ W = 0.02$$

GP23-0179-4

Figure 4. Minimization Cost Functional in Digital Equivalent System Program

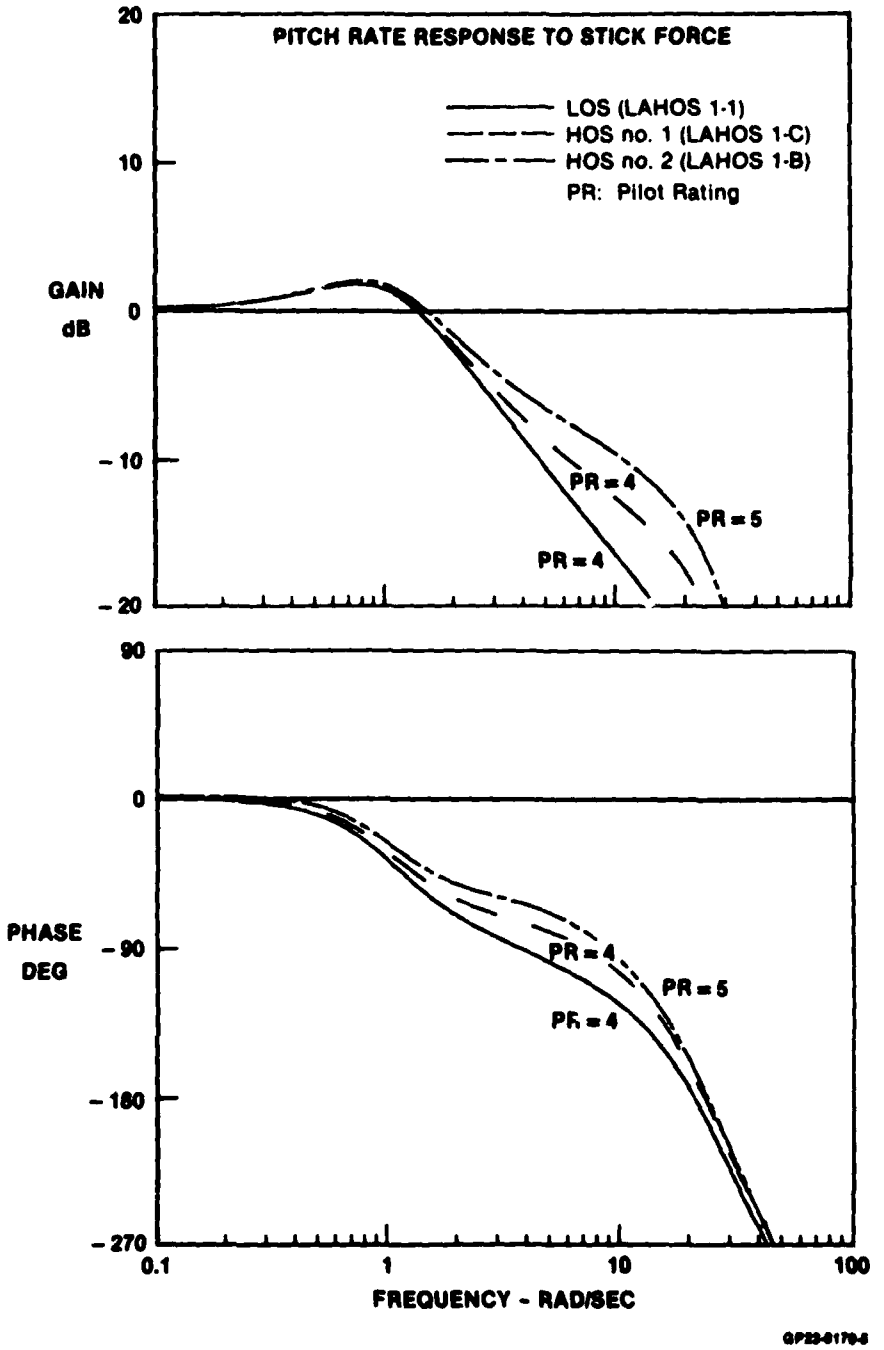


Figure 5. Addition of Unnoticeable and Noticeable Dynamics to a Low Order System (Example)

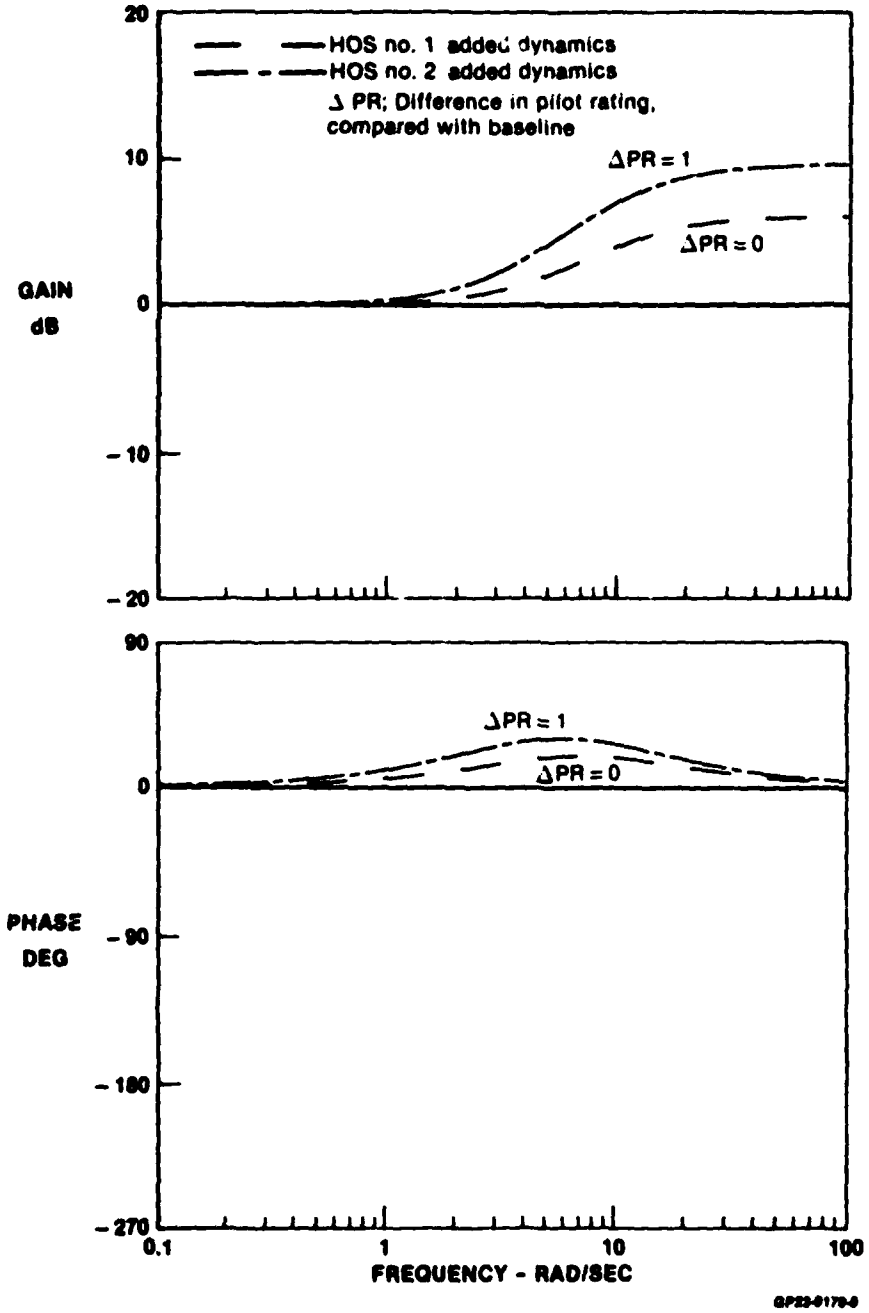


Figure 8. Mismatch from Unnoticeable and Noticeable Added Dynamics (Example)

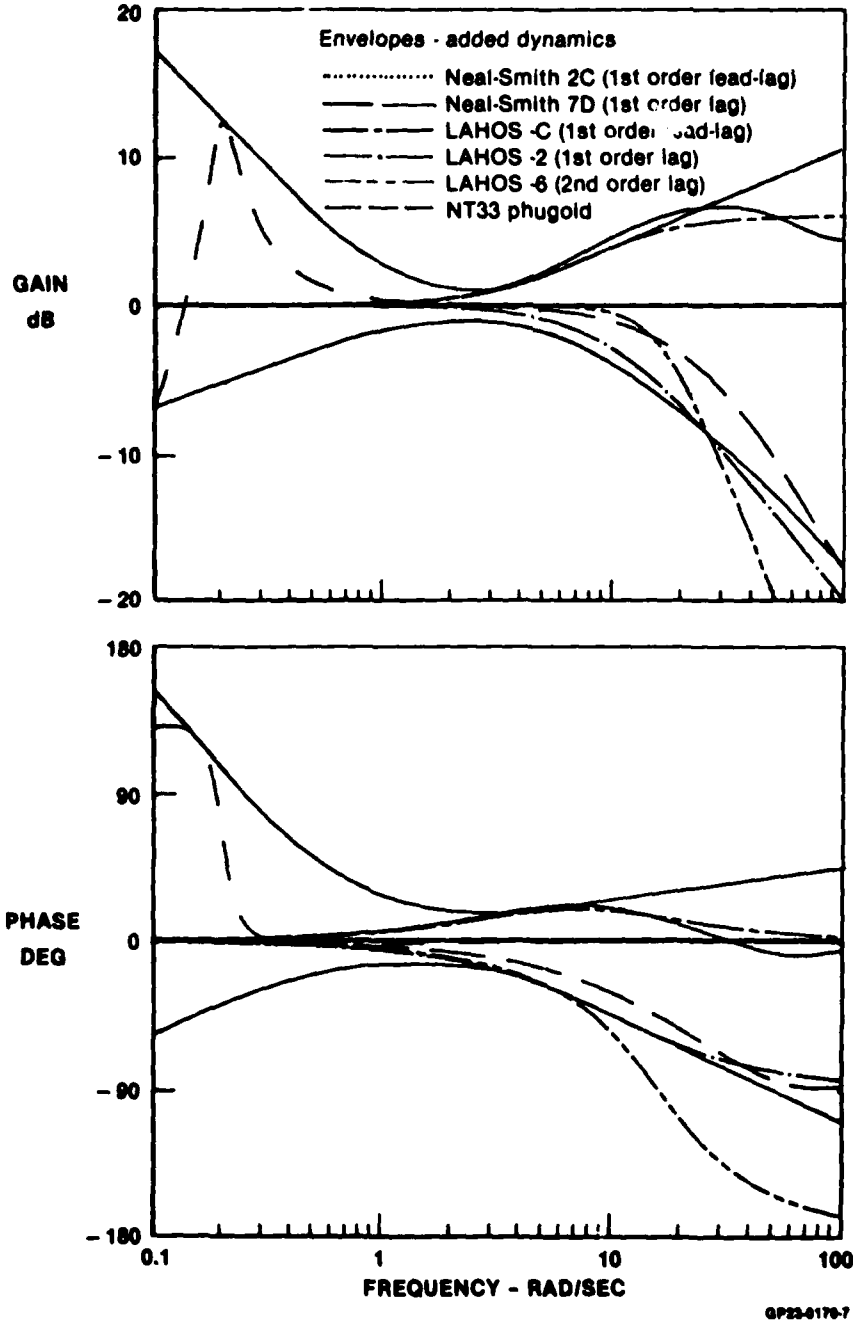


Figure 7. CTOL Critical Added Dynamics and Envelopes for Pitch Dynamics

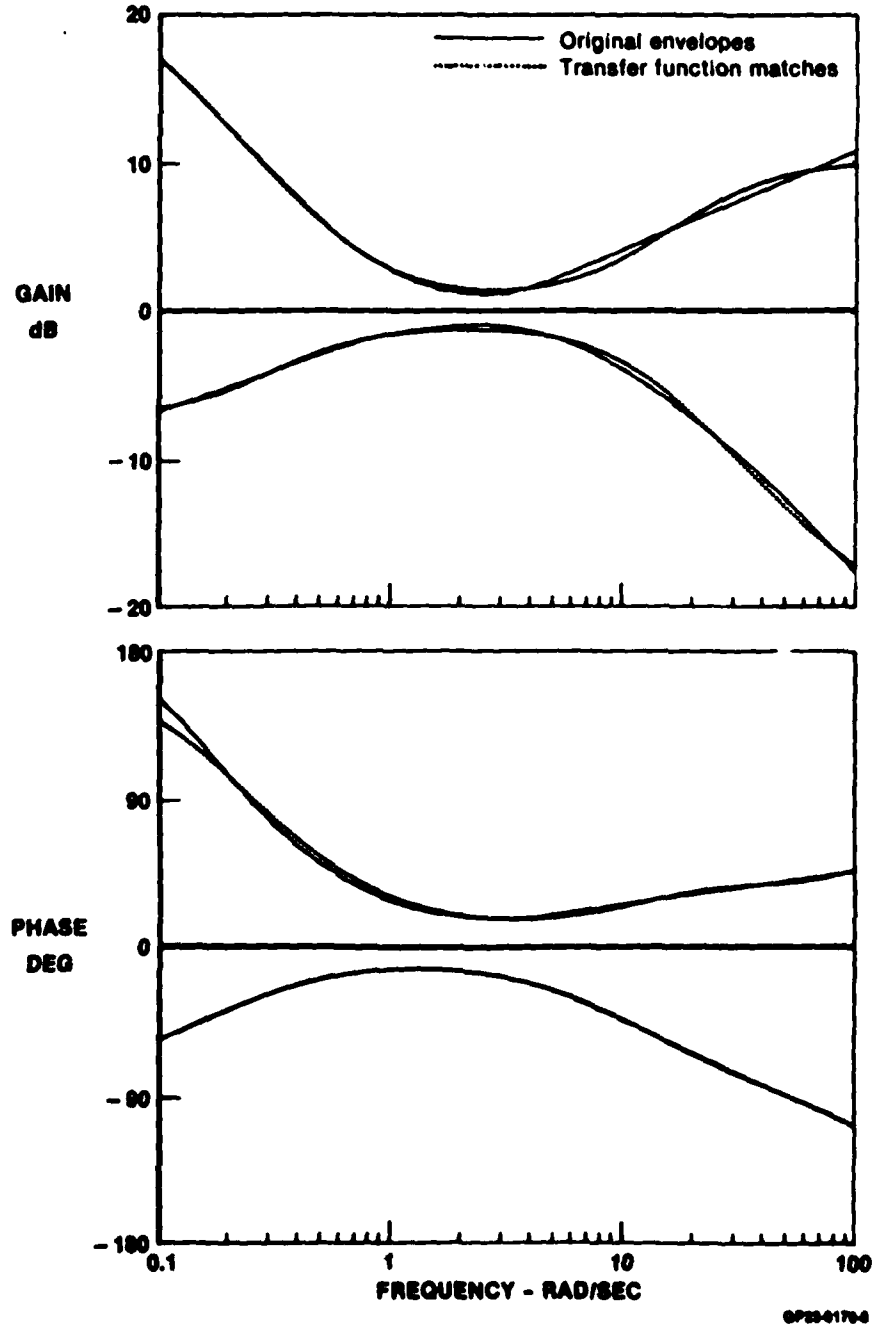


Figure 8. CTOL Envelopes and Transfer Function Matches

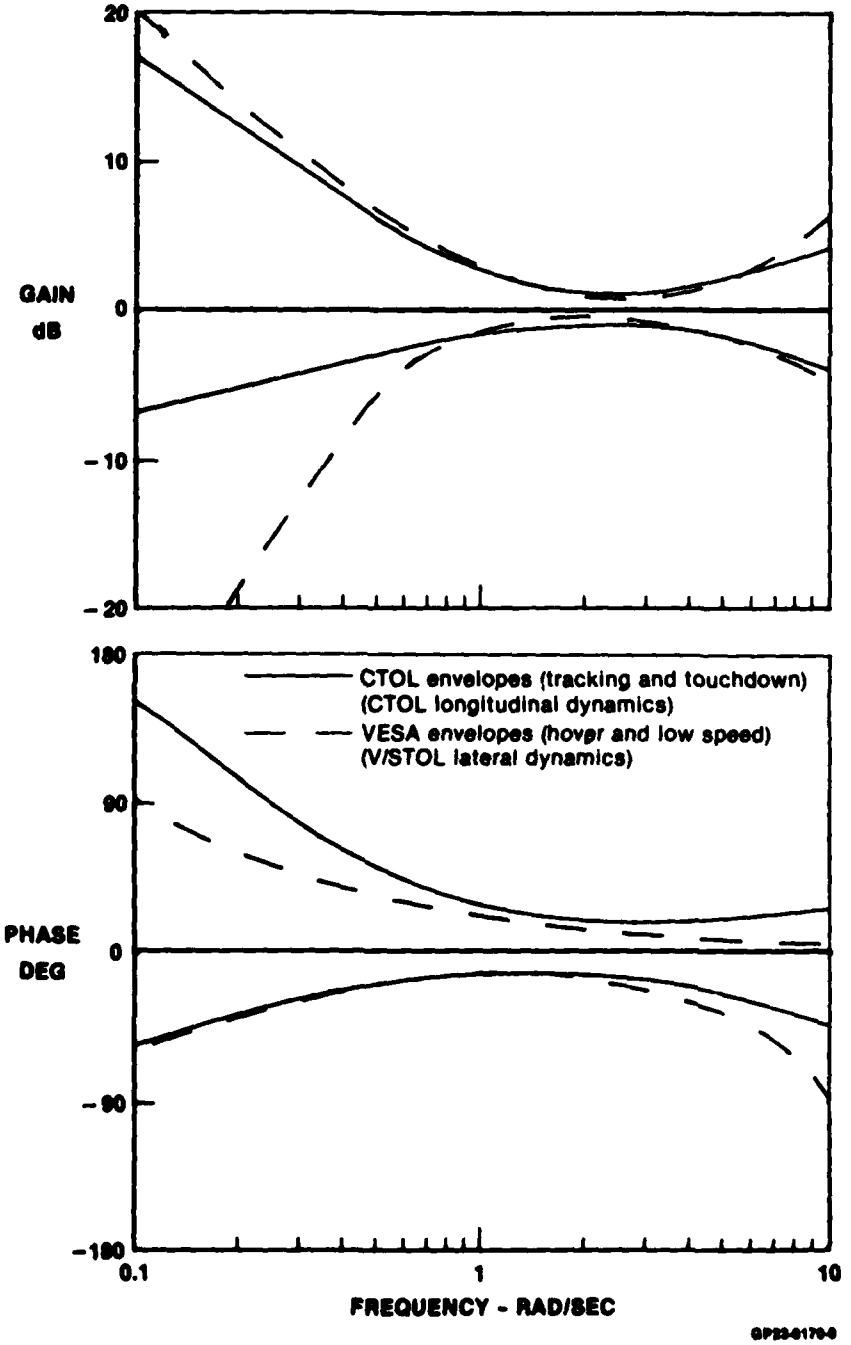


Figure 9. CTOL and VESA Envelopes of Maximum Unnoticeable Added Attitude Dynamics

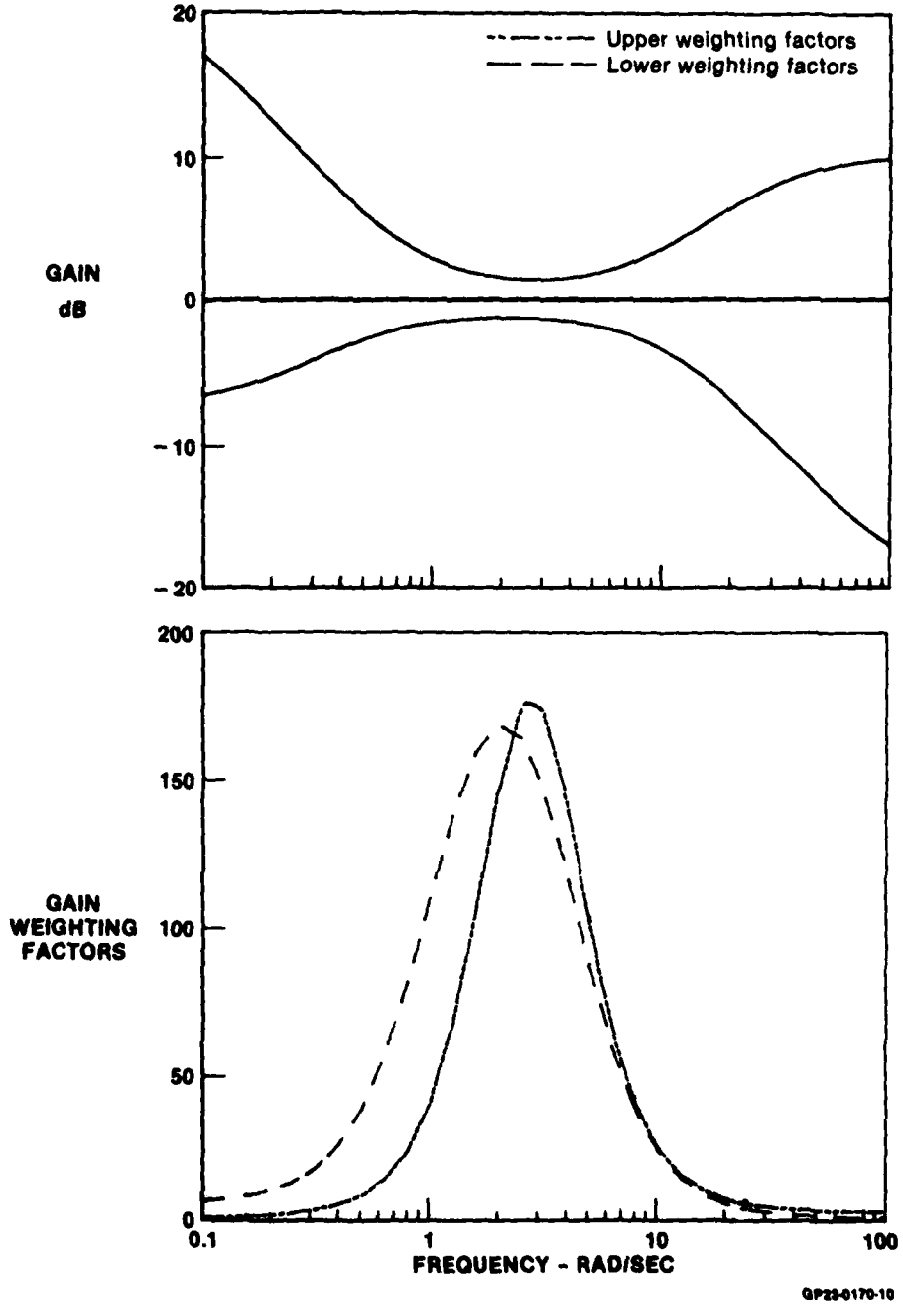


Figure 10. CTOL Envelopes of Maximum Unnoticeable Added Pitch Dynamics (Transfer Functions) and Associated Weighting Factors

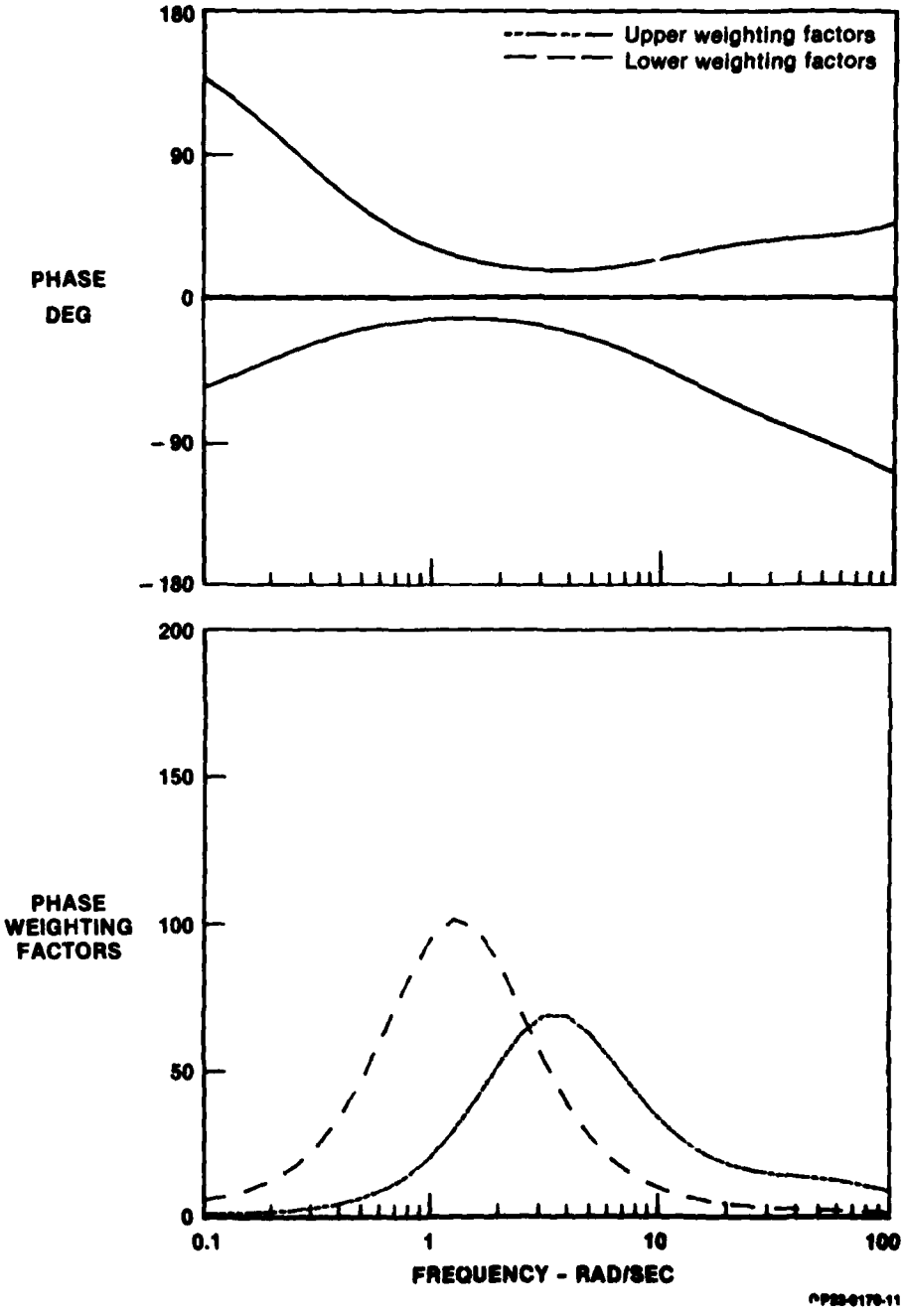


Figure 11. (Continued) CTOL Envelopes of Maximum Unnoticeable Added Pitch Dynamics (Transfer Functions) and Associated Weighting Factors

COMMENTS AND QUESTIONS

Dave Moorhouse, FDL: There has not been an Air Force decision on whether or not, when using an equivalent systems program, to fix or free L_α. There is valuable information which can be gained from both.

Answer: Both are possible with the McDonnell program.

Chick Chalk, Calspan: Do you have to fix L_α when matching both $\dot{\theta}$ and n_z?

Answer: No.

Sam Craig: The MIL-Specification/Standard is also design guidance. By your approach, you lose the option of influencing the wing design (i.e., $1/T_{\theta_2}$, n_z/α).

Bill Bihrle: We're losing the concept of CAP. Pilot-in-the-loop, the pilot moves the stick, creating an angular acceleration sensed by his inner ear. In the frequency domain, a 2nd order system may not be the best to match against. The time domain was initially used to discuss the threshold of the human operator.

ARVIN/CALSPAN

8 March 1982

HOW DESIGN CRITERIA HAVE CAUSED POOR FLYING QUALITIES FOR LANDING - C* AND PITCH RATE ENVELOPE CRITERIA APPLIED TO SPACE SHUTTLE

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CALSPAN IN-FLIGHT SIMULATION OF:

YF - 17

F - 18

AFTI - 16

SPACE SHUTTLE

FOUND COMMON PROBLEMS:

DIFFICULT TO LAND - TEND TO BALLOON AND LAND LONG

POOR INITIAL RESPONSE

TENDENCY TO PIO IN FLARE

PROBLEMS CAUSED BY DESIGN CRITERIA

A = Amplitude/Steady state amplitude

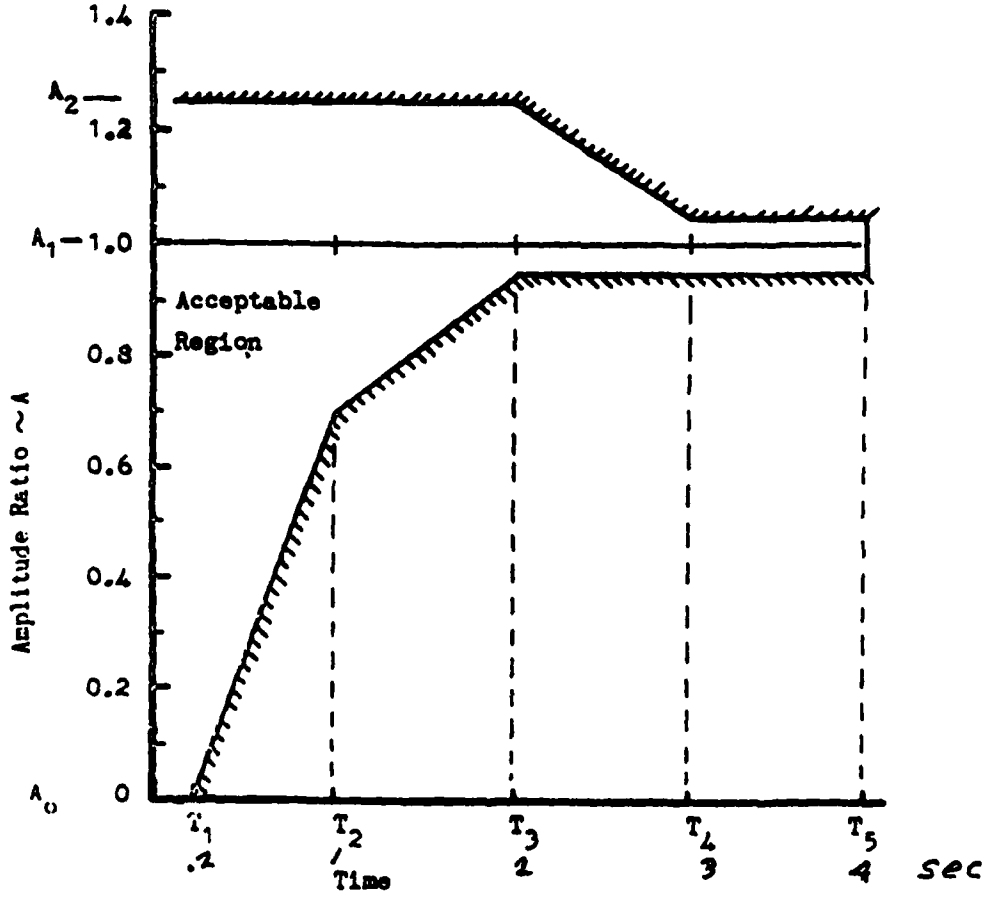


Figure 1.- Generalized transient response

Space Shuttle

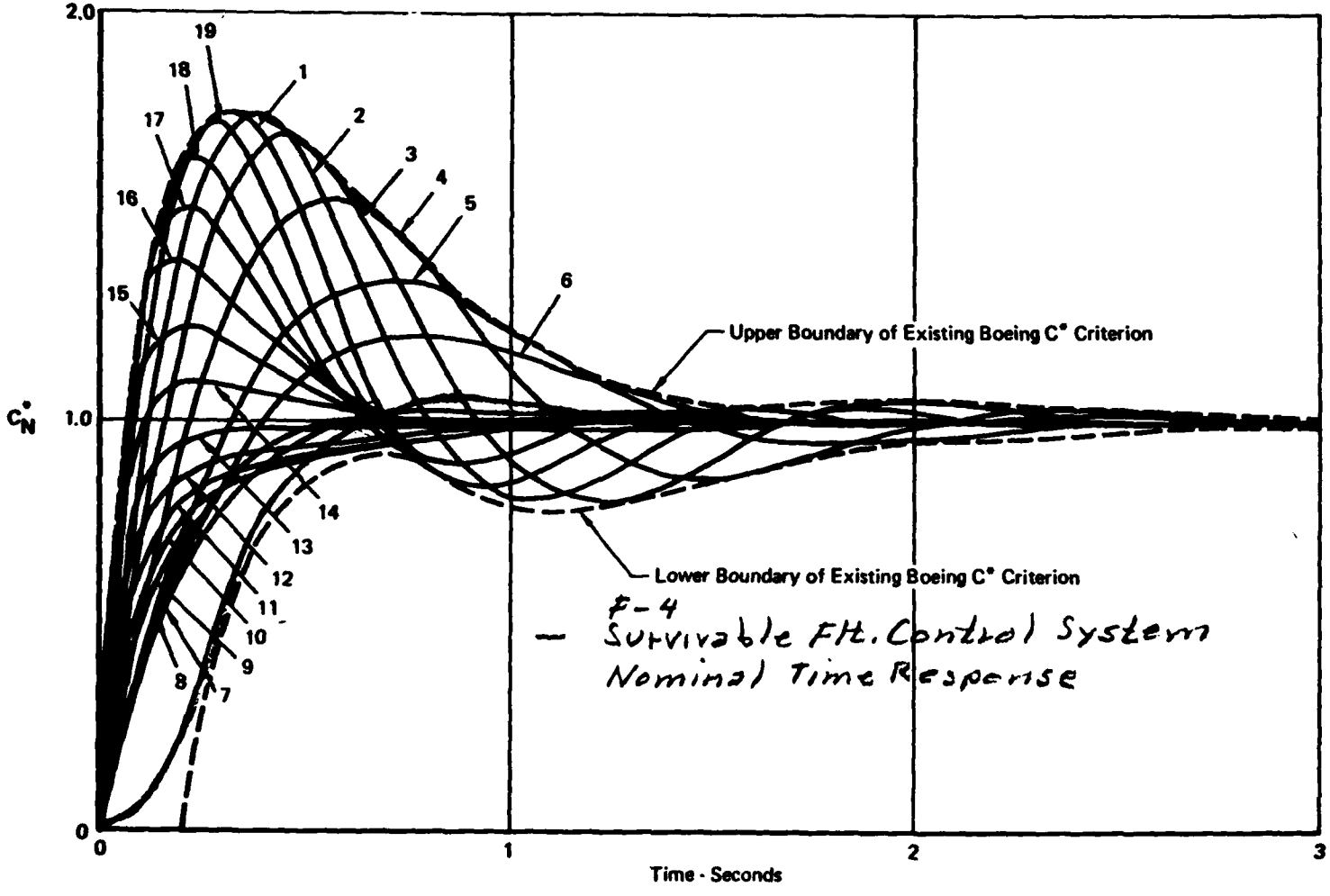


FIGURE 3
C* TIME HISTORY TRACES FOR CATEGORY 1

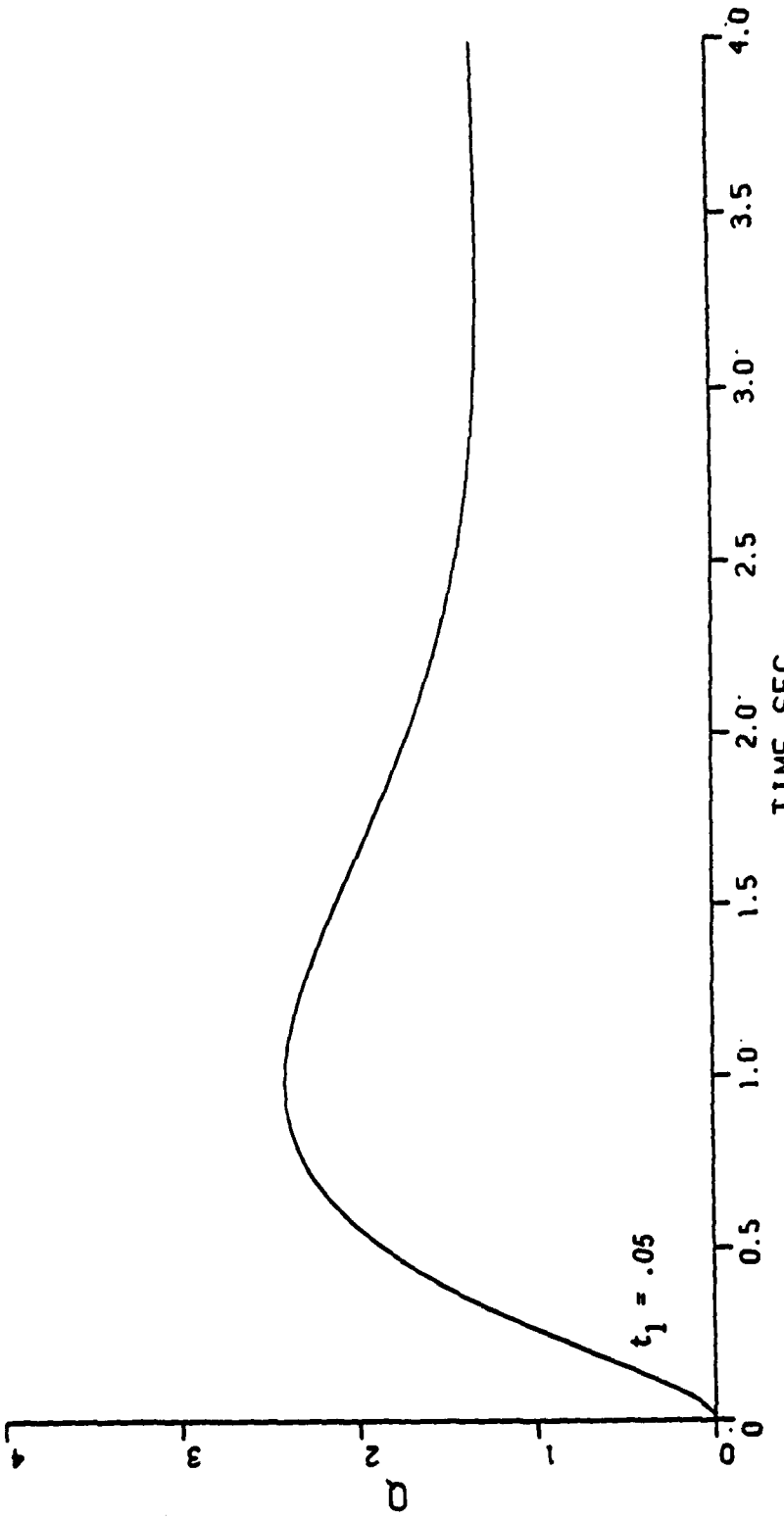
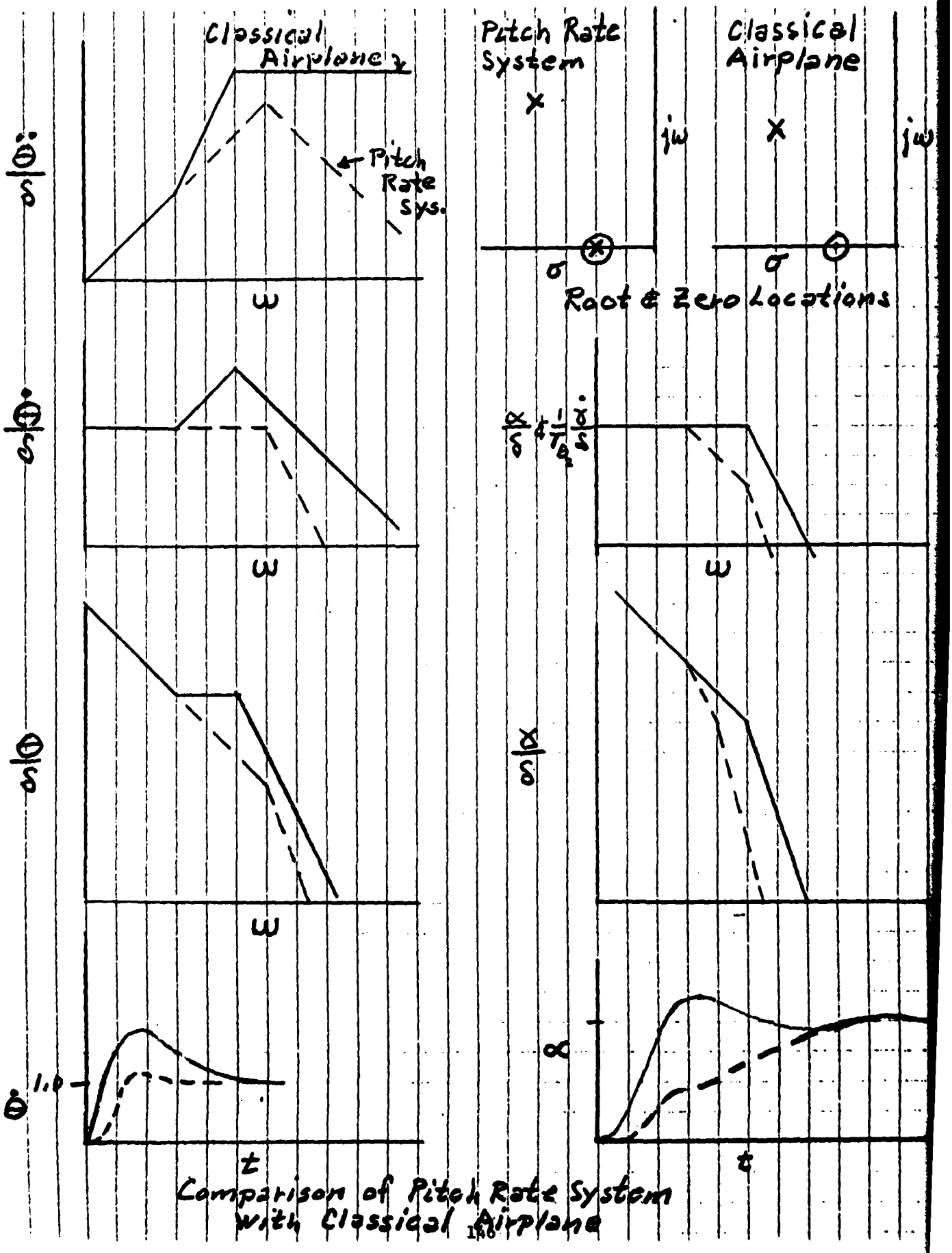
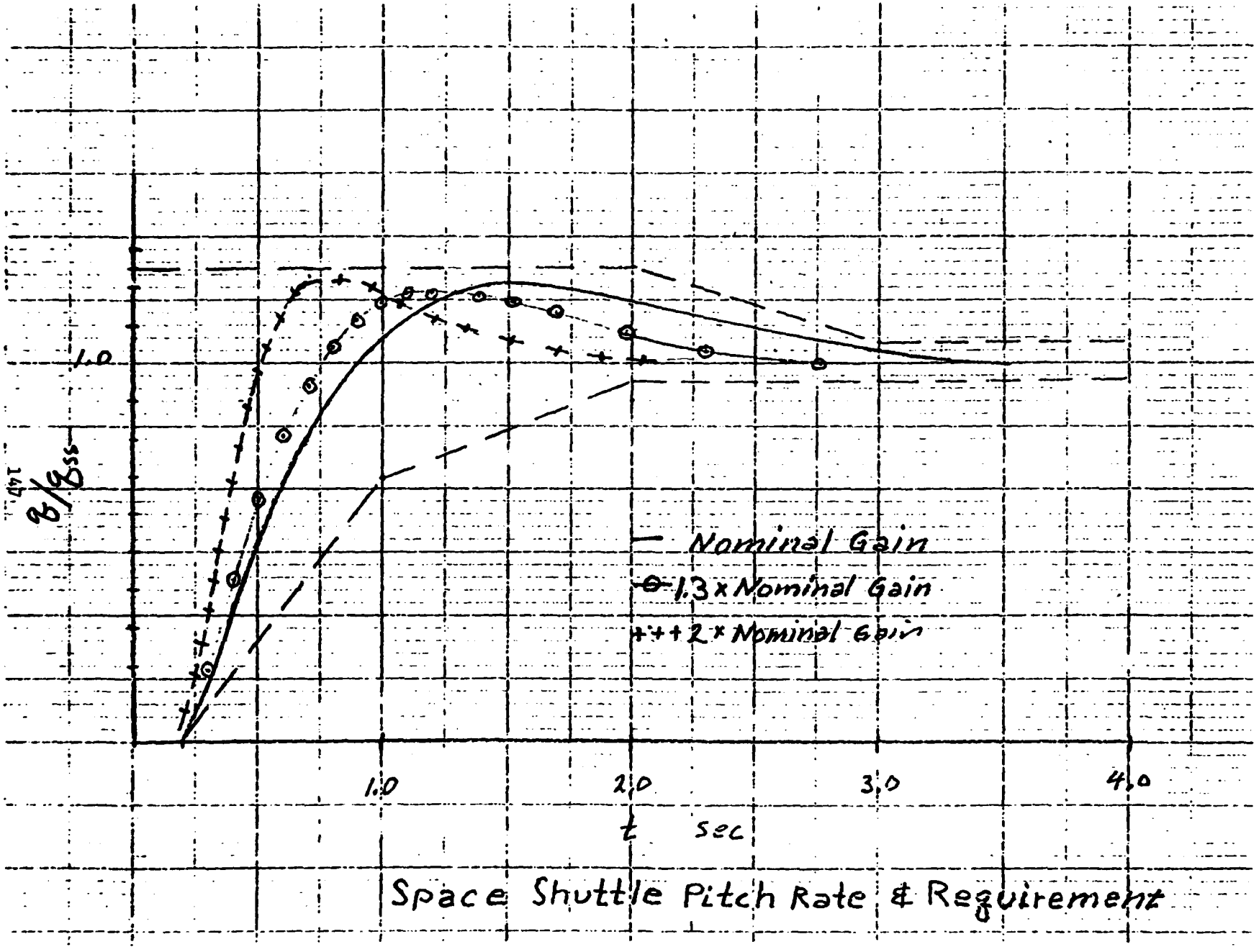


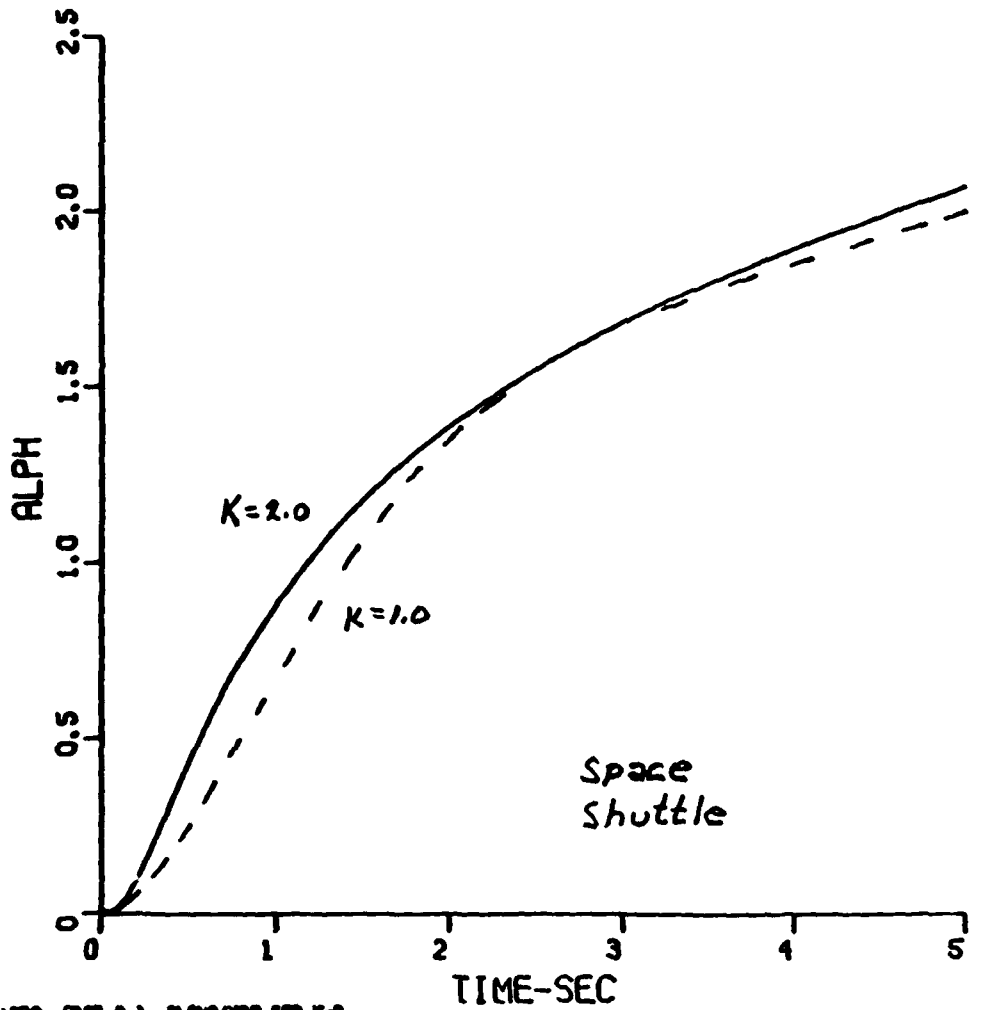
Figure 6. PITCH RATE RESPONSE



Comparison of Pitch Rate System with Classical Airplane



Space Shuttle Pitch Rate & Requirement



11 JAN 1979 CASE 2 1 ALPHA/BETA FOR K=2

Space Shuttle

$K = 1$

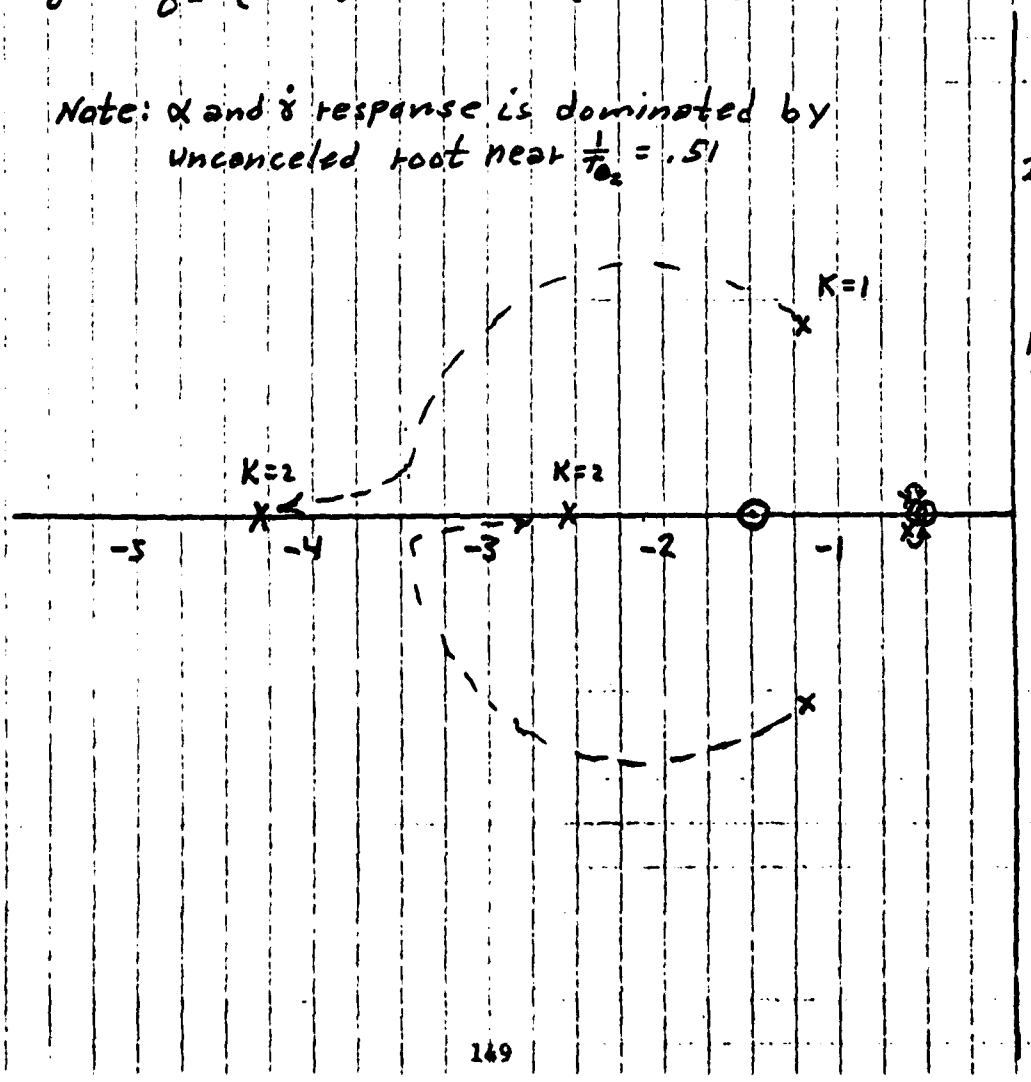
$$\frac{q}{q_c} = \frac{(s+.042)}{(s+.038)} \frac{(s+.51)(s+.59)}{\left[s^2+2(.98).595s+.59^2\right]} \frac{(s+1.49)}{\left[s^2+2(.69)1.70s+1.70^2\right]} \frac{e^{-\tau_1 s}}{(s+17.98)}$$

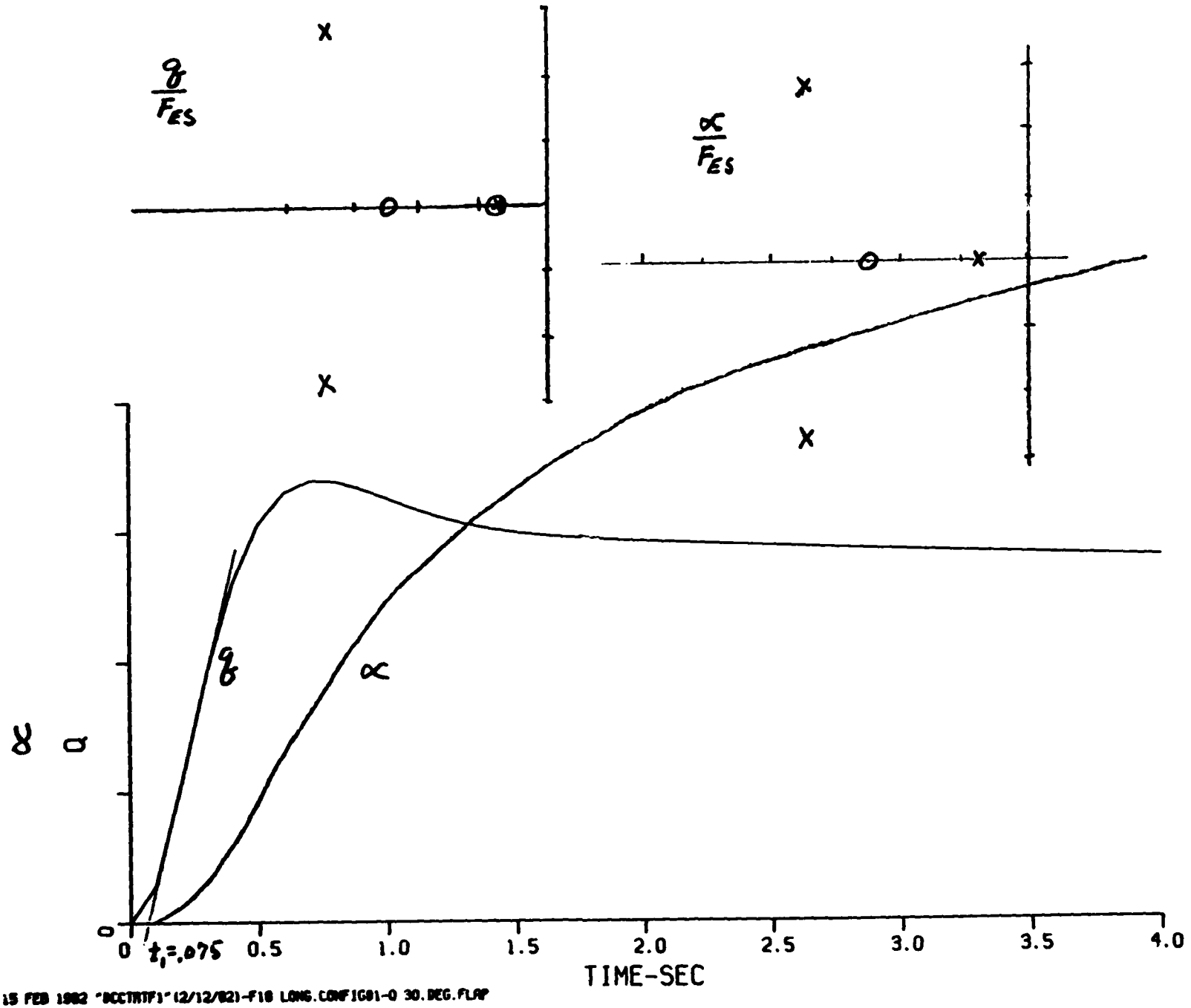
$K = 2$

$$\frac{q}{q_c} = \frac{(s+.042)}{(s+.040)} \frac{(s+.51)(s+.59)}{\left[s^2+2(.99).575s+.57^2\right]} \frac{(s+1.49)}{(s+2.54)(s+4.29)} \frac{e^{-\tau_2 s}}{(s+9.24)}$$

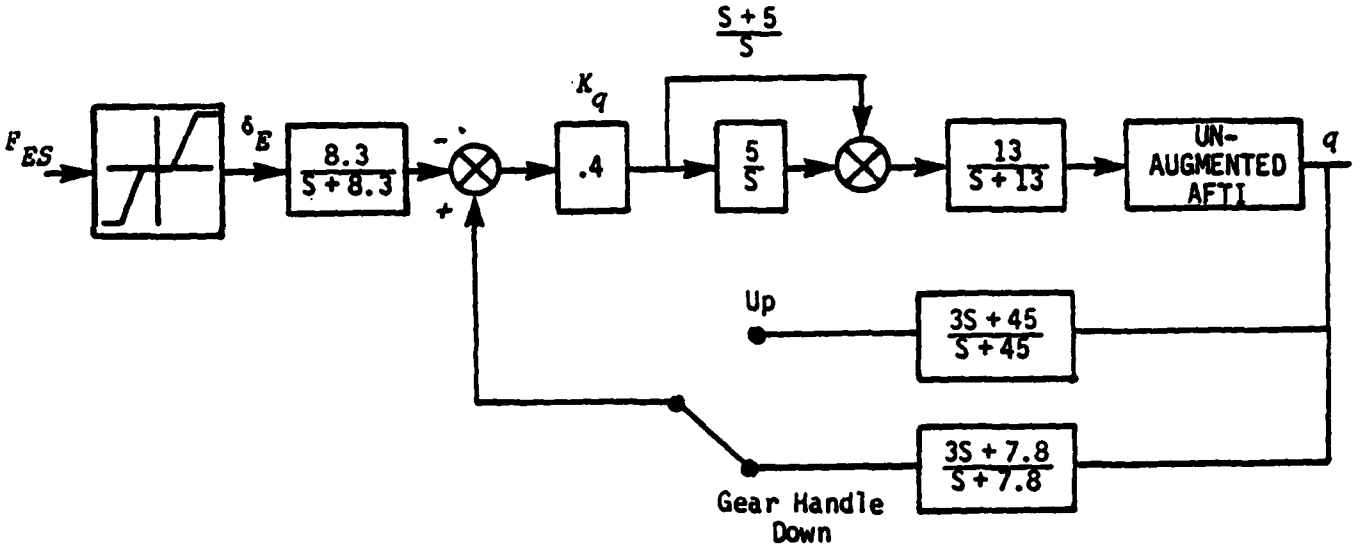
$$\frac{\alpha}{q_c} = \frac{q}{q_c} \frac{K_\alpha}{(s+.51)} \frac{\left[s^2+2(.11).14s+.14^2\right](s+5.9)}{s(s+.042)}$$

Note: α and $\dot{\theta}$ response is dominated by unconceled root near $\frac{1}{\tau_{\theta_2}} = .51$





15 FEB 1982 "DCCTRTF1" (2/12/82)-F18 LONG.CONFIG01-0 30.DEG.FLAP



$$\frac{q}{\delta_E} = \frac{90.25\ (S+.0326)(S+.588)(S+5)(S+7.8)}{(S+8.3)(S+.0208)(S+.757)(S+1.019 \pm 1.54j)(S+9.55 \pm 2.64j)}$$

Figure 1. AFTI-16 LONGITUDINAL IBU

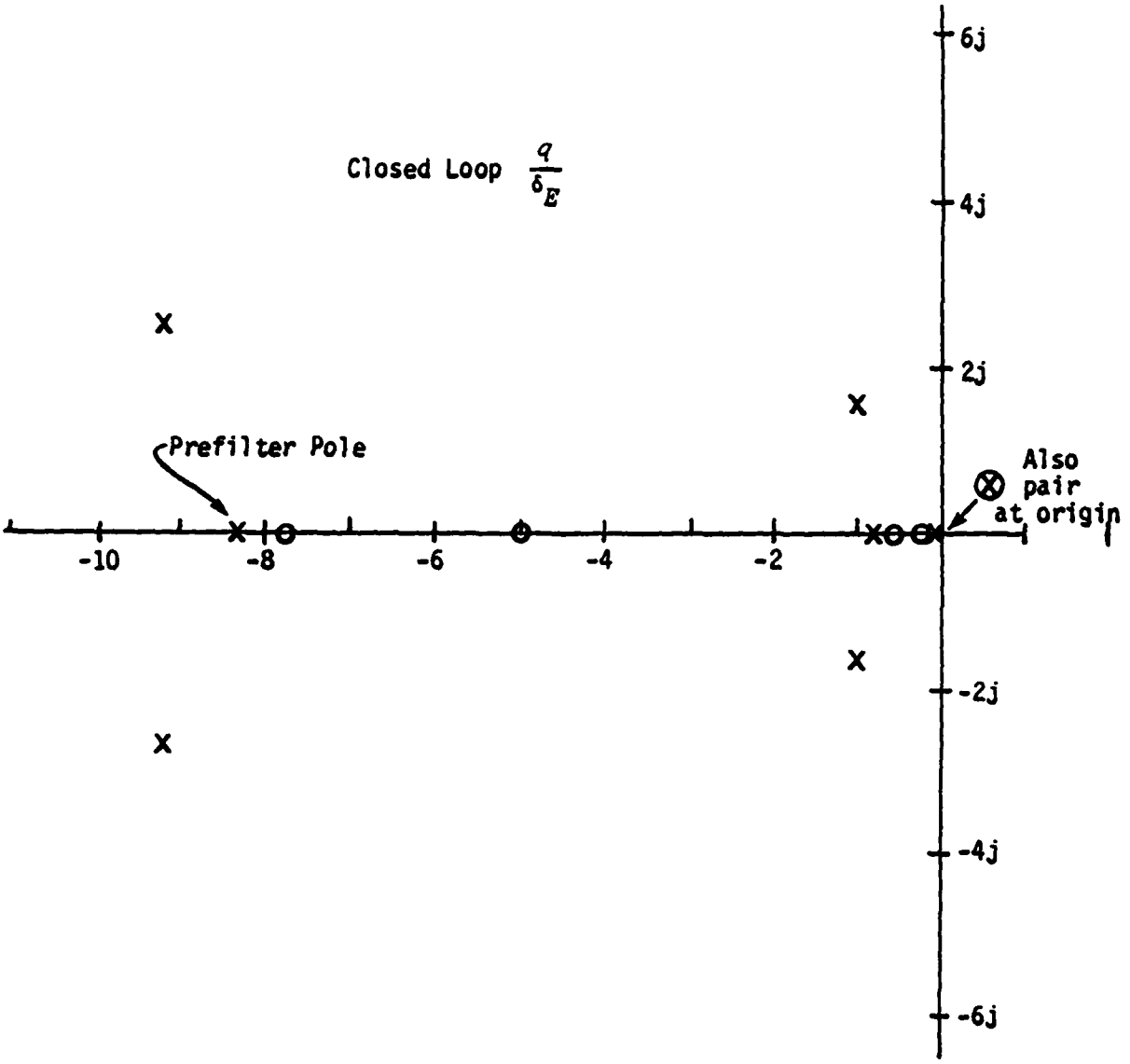


Figure 2. PITCH IBU POLE-ZERO CONFIGURATION

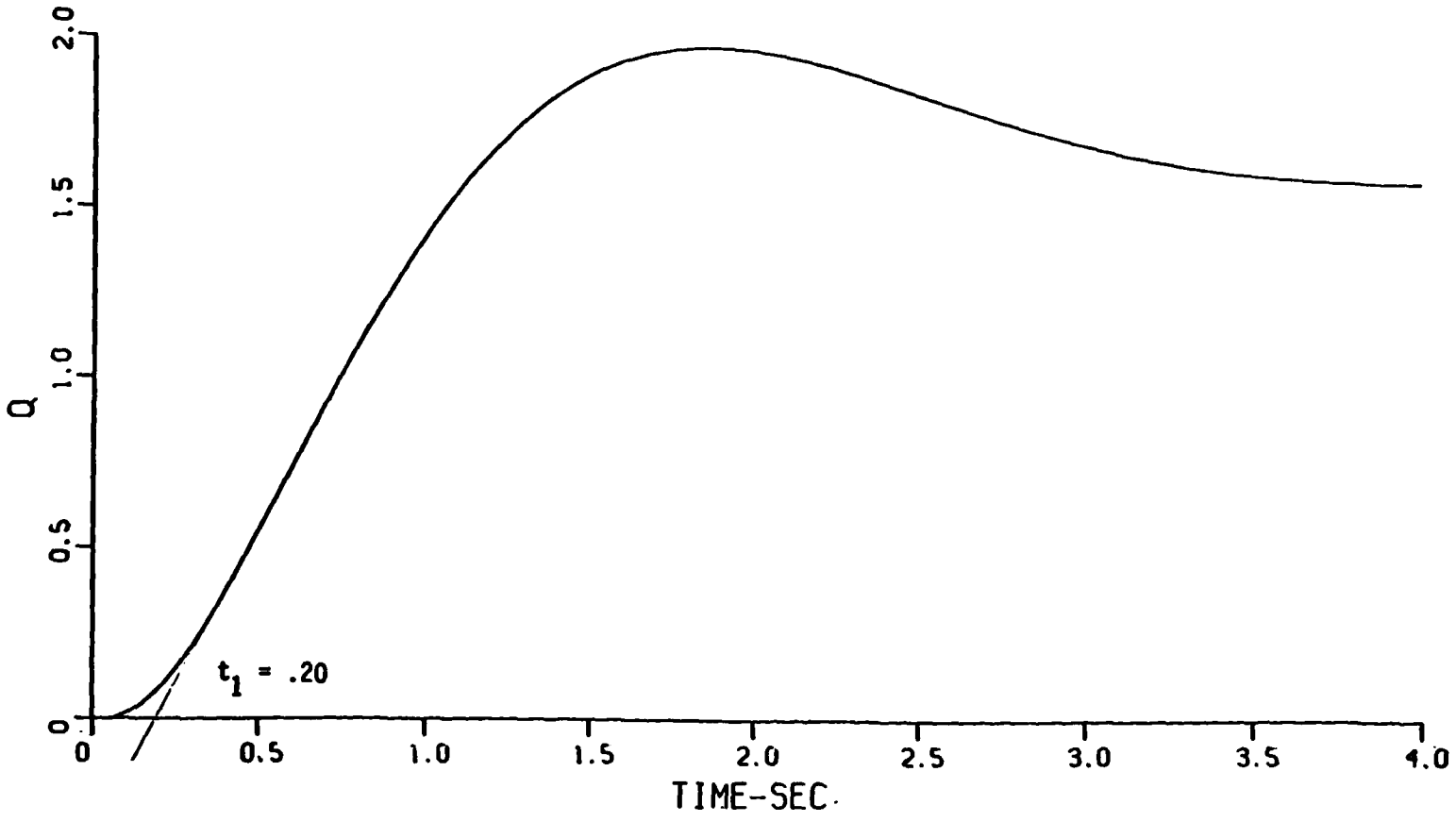
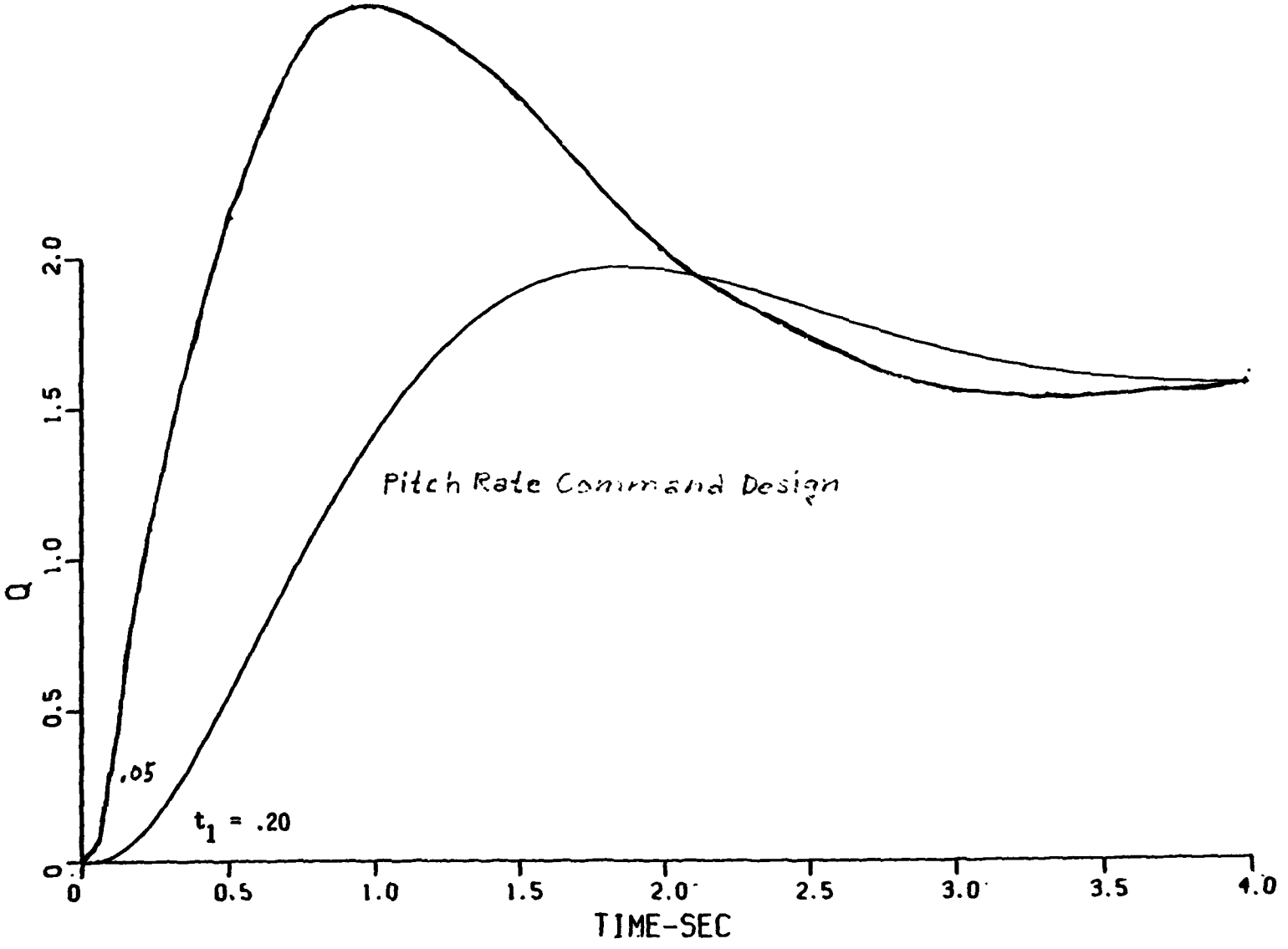
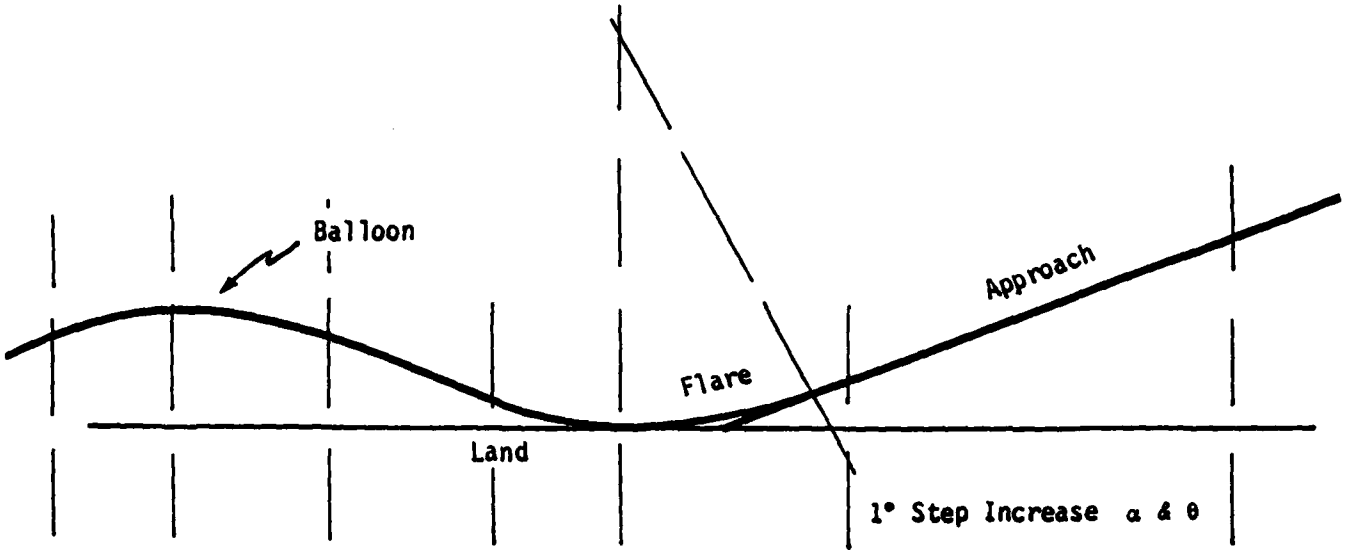


Figure 3. AFTI-16 PITCH IBU RESPONSE


Pitch Rate Command Design
Q
TIME-SEC
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
.05
t_1 = .20

$\theta = \gamma + \alpha$

	γ	θ	α	
Approach	$\gamma = -3°$	$\theta = 10°$	$\alpha = 13°$	δ_e = Trim
Flare	$\gamma \sim$ vary $-3° \rightarrow 0$	$\theta \sim$ vary $+10 \rightarrow 14°$	$\alpha = 14°$	δ_e = K Trim
Land	$\gamma = 0°$	$\theta = 13.2°$	$\alpha = 13.2°$	δ_e = Trim



$\theta = 14°$	$\theta = 14°$	$\theta = 14°$	$\theta = 14°$	$\theta = 14°$	$\theta = 11$	$\theta = 10$
$\alpha = 15°$	$\alpha = 14°$	$\alpha = 13°$	$\alpha = 13.5°$	$\alpha = 14°$	$\alpha = 14$	$\alpha = 13$
$\gamma = -1°$	$\gamma = 0°$	$\gamma = 1°$	$\gamma = .5°$	$\gamma = 0°$	$\gamma = -3$	$\gamma = -3$

Figure 14. APPROACH-FLARE-LANDING WITH A PITCH RATE COMMAND SYSTEM

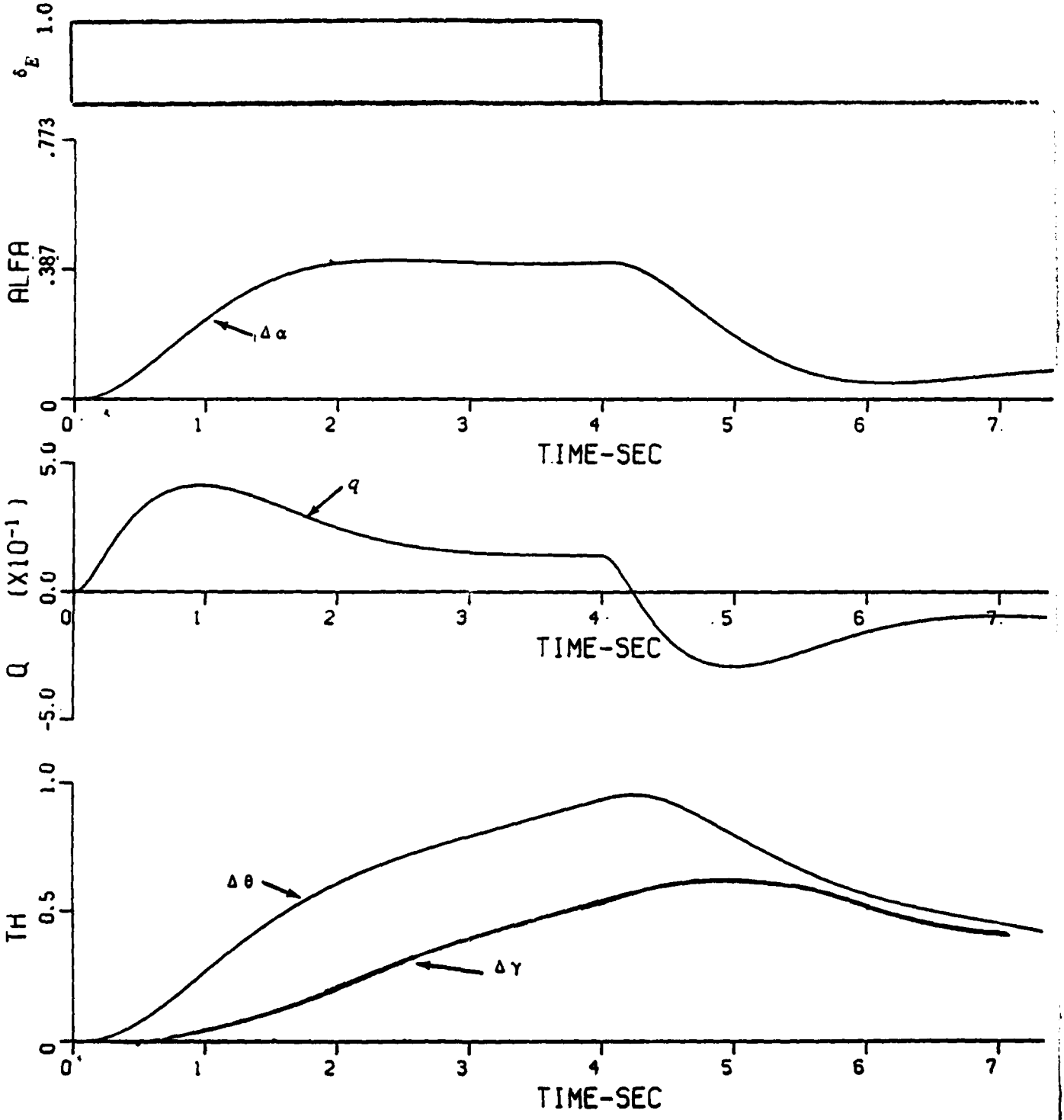


Figure 18. CALSPAN DESIGN α & q SYSTEM RESPONSE TO 4 SEC. STEP δ_E

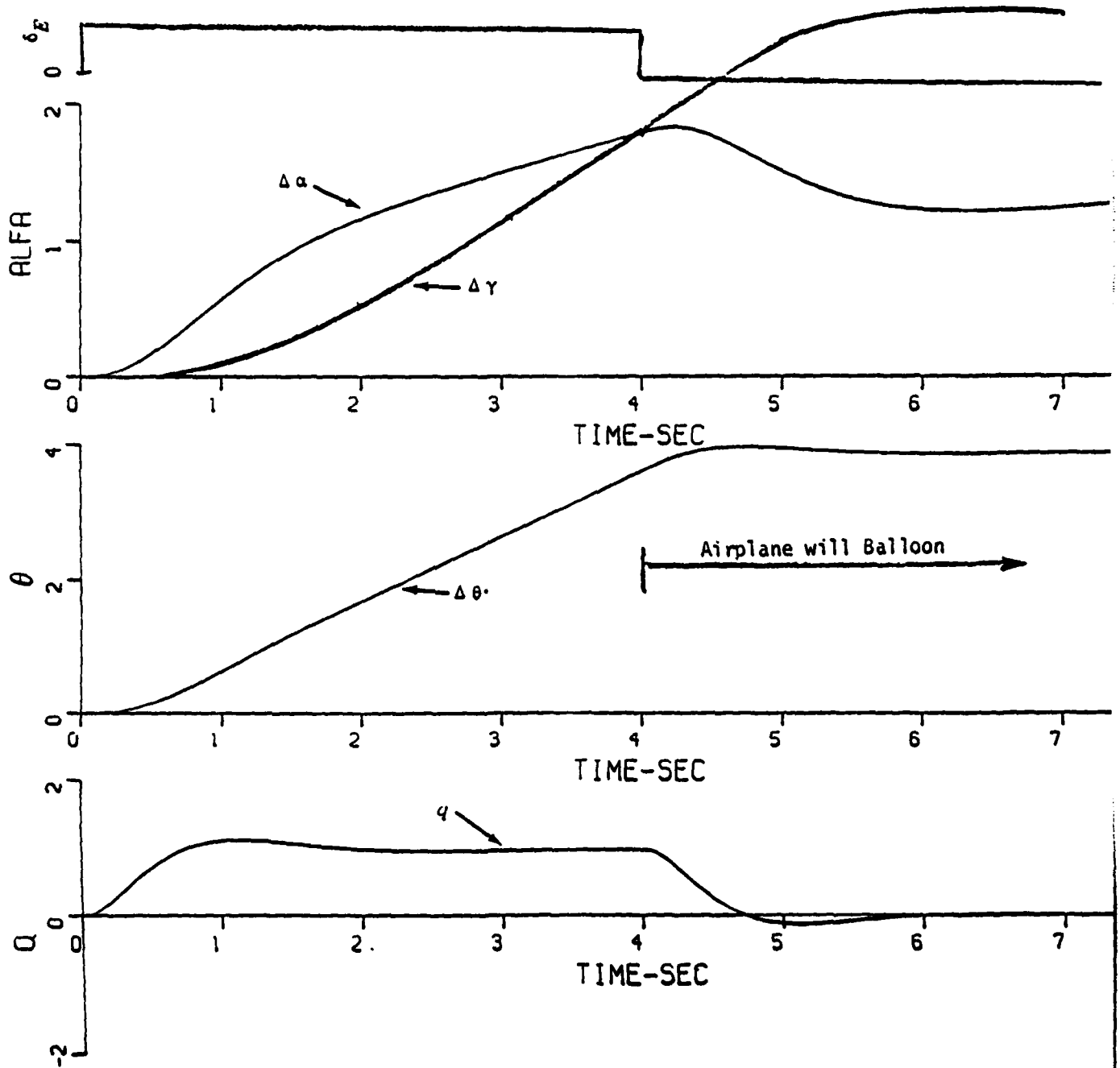


Figure 13. PITCH RESPONSE TO 4 SEC. STEP COMMAND

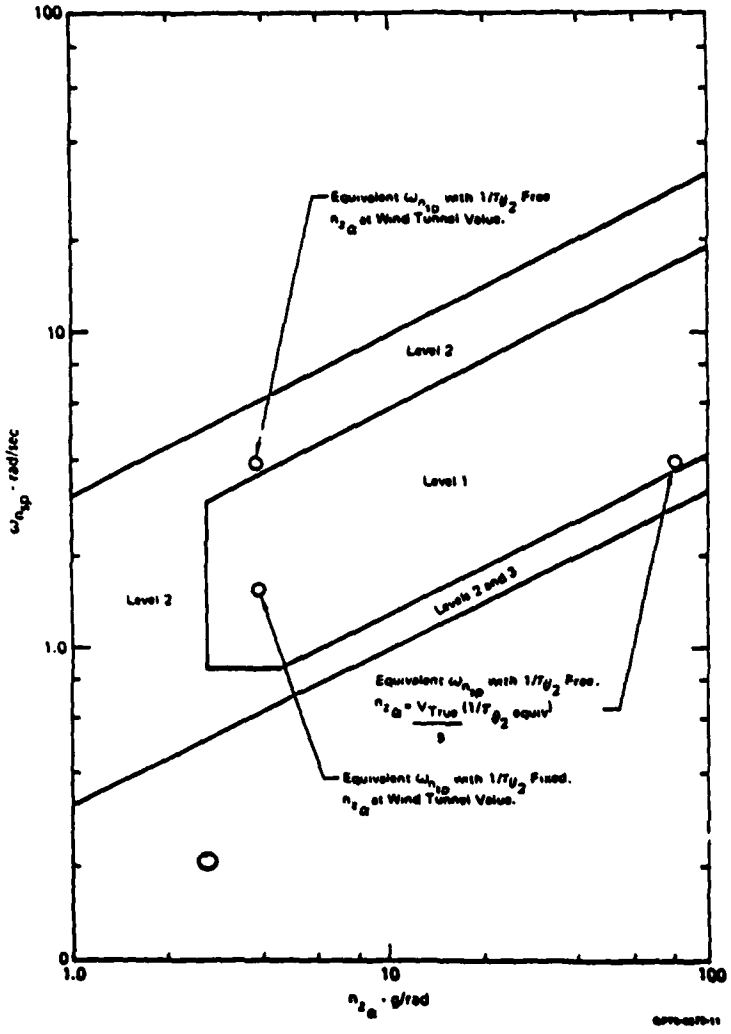
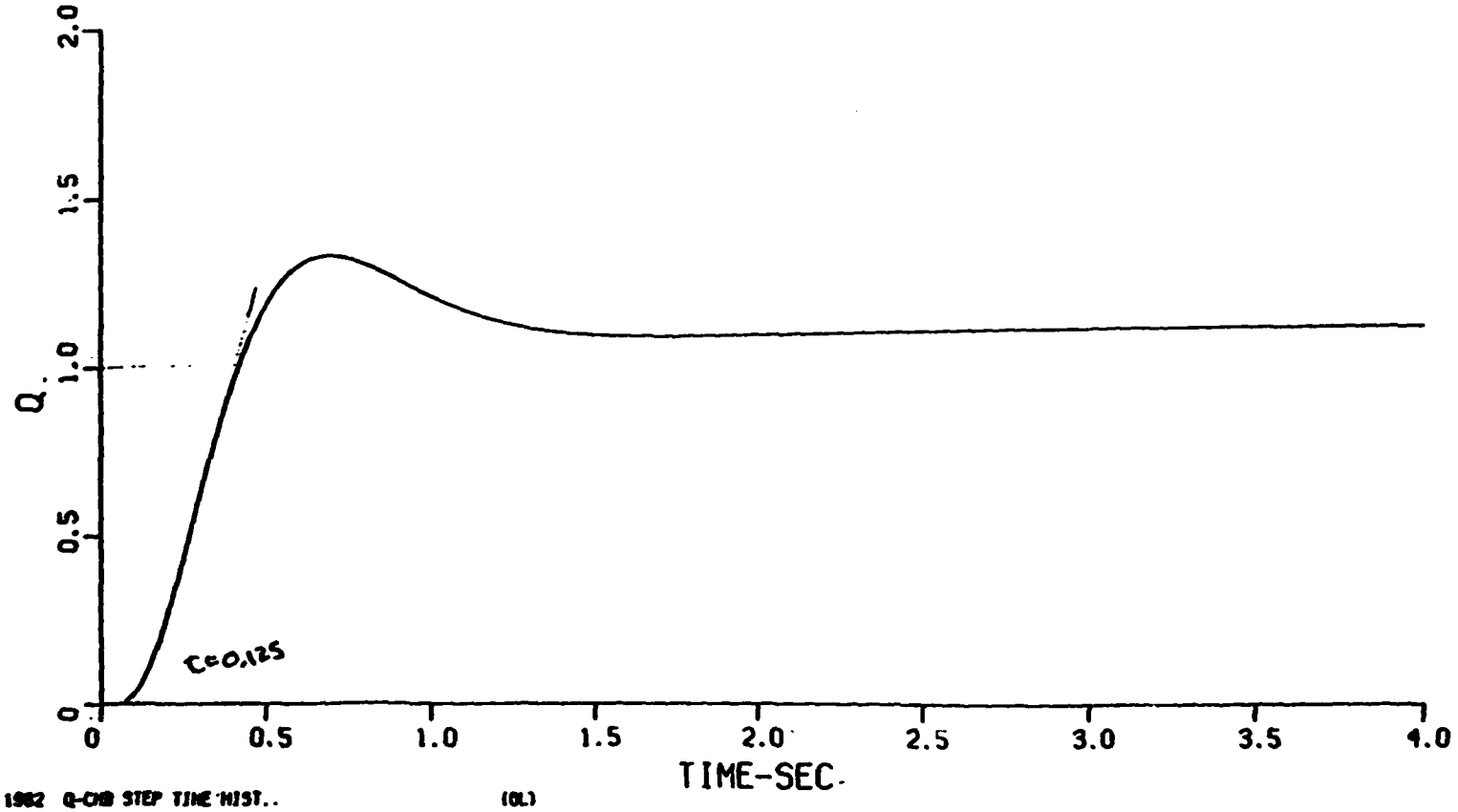


FIGURE 6
ALTERNATIVE CORRELATIONS OF "SLUGGISH" DYNAMICS WITH MIL-F-87858 CAT. C REQUIREMENT

(q/q_c) – unit step response



Equivalent Systems

$\frac{1}{T_{\theta_2}}$ ~ Fixed

$$\frac{\theta}{F_{ES}} = \frac{K(s+.55)\,e^{-.20s}}{s(s+.7)(s+5.9)}$$

$$\frac{\gamma}{F_{ES}} = \frac{\theta}{F_{ES}}\,\frac{\gamma}{\theta}$$

where: $\left.\frac{\gamma}{\theta}\right|_{V=C} = \frac{1/T_{\theta_2}}{s+1/T_{\theta_2}}$ Aerodynamic or Actual Value of $\frac{1}{T_{\theta_2}}$

$$= \frac{K\,\frac{1}{T_{\theta_2}}}{s(s+.7)}\,\frac{e^{-.20s}}{(s+5.9)}$$

$\frac{1}{T_{\theta_2}}$ ~ Free

$$\frac{\theta}{F_{ES}} = \frac{K(s+10.5)\,e^{-.13s}}{s\left[s^2+2(.52)5.3\,s+5.3^2\right]}$$

$$\frac{\gamma}{F_{ES}} = \frac{K\,\frac{1}{T_{\theta_2}}}{s(s+.55)}\,\frac{(s+10.5)\,e^{-.13s}}{\left[s^2+2(.52)5.3\,s+5.3^2\right]}$$

Classical Transfer Function

$$\frac{\gamma}{F_{ES}} = \frac{K}{s\left[s^2+2\zeta_{sp}\omega_n s+\omega_n^2\right]}$$

Pitch Rate Demand Systems

$$\frac{\gamma}{F_{ES}} \approx \frac{K}{s(s+\frac{1}{T_{\theta_2}})}$$ Bandwidth Restricted

PITCH RATE DEMAND SYSTEMS

- TEND TO BALLOON FOLLOWING FLARE & LAND LONG
- REQUIRE MORE COMPLEX CONTROL INPUTS BY PILOT TO LAND
- REQUIRE PILOT TO PUSH NOSE DOWN TO REDUCE ANGLE OF ATTACK WHILE NEAR GROUND
- CAUSE LARGE EFFECTIVE TIME DELAY
- REDUCES FEELING OF POSITIVE CONTROL
- HIGHLY SUSEPTIBLE TO PIO NEAR GROUND
- PRIMARY FACTOR IS POLE NEAR $1/T_{\theta_2}$

COMMENTS AND QUESTIONS

Ed Rynaski, Calspan: Could you use α or $\dot{\gamma}$ instead of $\dot{\theta}$ in the time history envelopes?

Answer: A requirement could be added for flight path response.

Duane McRuer, STI: The importance of time delay is true. The Space Shuttle is a good example. However, the Flight Control System for this vehicle did not follow a standardized design procedure. The Shuttle has an effective time delay of approximately 0.25. Effective $\dot{\theta}/\delta$ (1st order) has time response of 1/3.5 (.286) rather than the $1/T_{\theta_2}$ value. The major parts of the effective time delay, τ_e, is a composite of components of the FCS: stick filter, low ω and phase lag effects of anti-bending filters, aliasing filters, and mini-effects of computational lags. You could possible eliminate some of these effects or reduce their influence by changing location of some of these filters or by making the system gain-stabilized rather than phase-stabilized.

GUIDANCE FOR THE USE OF EQUIVALENT SYSTEMS WITH MIL-F-8785C

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Flight Dynamics Laboratory
Wright-Patterson Air Force Base, Ohio

Abstract

The increased use of augmentation in aircraft flight control systems has made comparison of these aircraft with MIL-F-8785C increasingly difficult. One solution is by using a lower-order equivalent system (LOS) of the complete aircraft high-order system (HOS). Guidance in the use of longitudinal and lateral-directional equivalent systems with MIL-F-8785C is presented. Topics discussed include fixed versus free-L_α matching, simultaneous matching, the frequency range for LOS matching, the equivalent system effects of forward-loop integration, prefilters, actuators, feel systems and structural filters, the effect of the phugoid mode on the longitudinal LOS parameters, and digital control systems. The special importance of the equivalent time delay which is produced by high-frequency control system elements is also stressed.

I. Introduction

Handling qualities requirements for military conventional aircraft (excluding V/STOL aircraft) are specified in MIL-F-8785C, "Military Specification - Flying Qualities of Piloted Airplanes". This specification does not concern itself directly with the actual design of an aircraft system, but rather places requirements on the characteristics of the overall aircraft system as perceived by the pilot during piloted control. Conventional aircraft have typically had fairly simple characteristics for which the specification could rather easily and confidently be applied. Now, however, with more complex flight control systems, application of the specification to check for good handling qualities must be done carefully.

*Aerospace Engineer

Highly augmented aircraft can have many characteristic response modes. Some aircraft designers have examined longitudinal characteristic equations of order as high as 50th, 60th, even 70th. How can such characteristics be checked for compliance with the specification? To answer this question it must be remembered that a pilot will not be able to distinguish each individual mode but will instead perceive the system response as an interaction of all of the modes simultaneously. It is believed that pilots have a simple mental model of aircraft response to control inputs. Furthermore, both upper and lower bounds have been found to exist in pilots' frequency response for closed-loop control. Good results have been obtained by considering the frequency range or time span for short-term control as nominally 0.3 to 10 rad/sec or 0 to 10 sec. Longer motions have not been much of a problem with higher-order control systems, and anyway, pilots tend to control them open-loop. Frequencies much beyond 10 rad/sec are generally beyond pilots' control capability. Control theory indicates a need for good system representation in the frequency range around the closed-loop bandwidth frequency.

II. Equivalent System Approach

Equivalent System Matching

In order to compare future augmented aircraft systems to MIL-F-8785C the equivalent system approach has been suggested (Reference 1) and much work in this area has been performed by John Hodgkinson (References 8, 9, 10, 11) and Dave Bischoff (References 12, 13). Simply stated, this approach attempts to approximate the actual characteristics of an augmented aircraft by the use of perceived characteristics which are important to the pilot, as specified in MIL-F-8785C. First use has been in the area of longitudinal dynamic analysis. This paper presents guidance in the application of the equivalent system approach to augmented aircraft longitudinal dynamics and similar application to lateral-directional dynamics where appropriate.

The equivalent of an augmented system is actually produced by matching the actual high-order system (HOS) with an equivalent low-order system

(LOS). We choose to do the fitting in the frequency domain. First we choose an appropriate form of transfer function for the LOS and then we match the HOS Bode plot within a predetermined frequency range. Such matching is very easily accomplished on a digital computer. The program currently being used at the Flight Dynamics Laboratory is one developed by John Hodgkinson and Jim Buckley of the McDonnell Douglas Corporation and is now available from McDonnell Douglas on request. For longitudinal dynamics the program input is the transfer function of pitch rate to stick force, the form of the low-order system, and the frequency values at which to match. The program output is the LOS transfer-function coefficients and the COST function. Since the LOS cannot be an exact match of the HOS, the program attempts to minimize the mismatch by varying the LOS coefficients in an organized manner until the COST function is minimized. Its final value is then an indication of the actual mismatch between the LOS and HOS.

The COST function used in this program is:

$$\text{COST} = (20/n)\Sigma_{\omega_1}^{\omega_n}[(\text{gain}_{HOS}-\text{gain}_{LOS})^2+.01745(\text{phase}_{HOS}-\text{phase}_{LOS})^2]$$

where: gain is in dB
phase is in degrees
ω denotes the input frequency
n is the number of discrete frequencies

The relative weighting of phase and amplitude can be changed if desired. The user may specify the frequency values for the match or input a minimum value, maximum value, and the number of discrete frequencies, n, letting the program calculate the required frequency values for equal spacing on a logarithmic scale. A good visual match on a Bode diagram is normally obtained for a COST value of 10 or less.

A multivariable search routine is used to vary the LOS transfer-function coefficients (user-defined form) to minimize the COST function. The user has the option to fix any of the LOS coefficients at the initial-guess

values. Another option allows the inhibition of sign changes in any of the variable parameters. The program iterates through the search routine until either the user-specified number of iterations is reached or the variation of each LOS coefficient remains within a very small percentage change (.001 percent). The program will output the LOS coefficients, the value of the COST function and, at the user's request, the amplitude ratio and phase angle of the HOS and LOS at the matched frequency values and the roots of the LOS transfer function numerator and denominator polynomials.

Because the program is searching for a local minimum of the COST function, the initial guess is very important. If an arbitrary initial guess is given to the program it may converge to a totally meaningless final match, wasting user and computer time.

HOS Model Accuracy

Since all of the equivalent system analysis relies on the HOS characteristics, it is imperative that the HOS characteristics be an accurate, complete description of the aircraft response dynamics. This point cannot be stressed enough. It is especially important to include the lower-frequency effects of high-frequency dynamics from structural filters, servo-actuators, etc., which individually would not appear to be significant to pilot control but when taken together with the airframe dynamics and the rest of the control system have the potential to significantly impact aircraft controllability. Every effort should be made to ensure the accuracy of the complete HOS model amplitude and phase within the matching frequency band before the equivalent system analysis is performed.

Frequency Range of the Match

As stated previously, a nominal frequency range of 0.3 to 10 rad/sec is typically used for equivalent system matching. A maximum range of 0.1 to 10 rad/sec should be the largest normally required. The upper limit is based on the maximum frequency that human pilots have been seen to generate in high-gain manual control situations (Reference 14). The lower limit is

an estimate of the frequency below which pilots tend to control the aircraft open-loop, i.e., make an input and check later on the resultant response. One investigation of augmented CTOL aircraft (Reference 3) suggests that pilots are most sensitive to frequency response characteristics within the range of approximately 1 to 5 rad/sec. Another investigation of V/STOL aircraft (Reference 4) suggests that pilots are most sensitive in the range of approximately 0.5 to 4 rad/sec. The two ranges are different because of the different tasks and types of aircraft involved. These restricted ranges are useful as an indication of the frequency range in which a good match is most important. However, by no means should only the restricted ranges be used. In closed-loop piloting tasks, bandwidths as low as 1 rad/sec have been found for single-loop attitude control on approach, 0.5 rad/sec for a second path-loop closure. One might arbitrarily raise the lower bound from 0.1 to 0.3 rad/sec to eliminate the distortion of a lightly damped phugoid mode, since the pilot's attitude-loop closure will tend to suppress that mode anyway. At the high-frequency end, closely matching a greatly attenuated response may not be warranted. However, any contraction of the matching range should first get careful consideration of its possible effects.

Number of Frequency Values

An absolute minimum of 20 frequency values equally spaced on a logarithmic scale is recommended. For the range from 0.1 to 10 rad/sec this ensures 10 frequency values per decade. Normally 25 or 30 values have been used to provide closer spacing. If a particular match requires more values, the computer program previously discussed will handle up to 50; but this also adds to computer cost and required capacity.

Mismatch Criteria

Throughout the following discussions the value of the COST function is given as an indication of the goodness of fit of the respective matches, but without indicating whether any COST criterion is exceeded. Mismatch criteria for equivalent system matching are not well defined yet. Although,

as we have said a COST value less than 10 represents a good match, for higher COST more research is needed - especially for matches with COST values in the hundreds and thousands (example Reference 15). One common observation so far is that aircraft configurations for which a "good" equivalent system match cannot be obtained are generally not rated well by pilots. That is, aircraft which deviate too far from the assumed classical form with added time delay will need special attention. A good example is the YF-16 (Reference 6). The initial value of the breakpoint frequency for the pitch-axis stick prefilter was 4 rad/sec, well within the pilot's frequency range of interest. During final approach the pilots noticed a mild PIO tendency. Only after the prefilter breakpoint frequency was raised to 8 rad/sec late in the testing was this tendency lessened to the point of pilot acceptance.

III. Longitudinal Equivalent System

Longitudinal LOS Form

For comparison with MIL-F-8785C the short-term dynamics of pitch rate to control stick force are required. The general LOS form of this transfer function is

$$\frac{q}{F_s} = \frac{KT_{\theta_{1e}}T_{\theta_{2e}}\omega_{ph_e}^2\omega_{sp_e}^2(0)(1/T_{\theta_{1e}})(1/T_{\theta_{2e}})e^{-\tau_e s}}{[\zeta_{ph_e},\omega_{ph_e}][\zeta_{sp_e},\omega_{sp_e}]} \quad \frac{\text{rad/sec}}{\text{lb}}$$

where: $(1/T) = s + 1/T$

$[\zeta,\omega] = s^2 + 2\zeta\omega s + \omega^2$

q = aircraft pitch rate, rad/sec

F_s = control stick force, lb

K = steady-state gain, (rad/sec)/lb

$T_{\theta_{1e}}, T_{\theta_{2e}}$ = equivalent numerator time constants, sec

τ_e = equivalent time delay, sec

ω_{ph_e} = equivalent phugoid natural frequency, rad/sec

ζ_{ph_e} = equivalent phugoid damping ratio, dimensionless

ω_{sp_e} = equivalent short-period natural frequency, rad/sec

and ζ_{sp_e} = equivalent short-period damping ratio, dimensionless.

This is the most general LOS form for comparison with the longitudinal modal and time-delay requirements of MIL-F-8785C. Because the phugoid mode may have a natural frequency below .1 rad/sec an expanded frequency range for matching from .01 to 10 rad/sec should normally suffice for this 4th-order match. The phugoid mode has been included because its damping ratio is specified in MIL-F-8785C and in principle should be matched with an equivalent mode.

In practice, though, inspection of a few 4th-order matches will probably justify reducing the LOS order to a first over second-order form with added time delay. Normally the actual phugoid mode essentially "stands alone" in the low frequency range of the match (.01 to .2 rad/sec) and so will be matched almost exactly with the corresponding equivalent-system mode. The normally very light damping of this mode will produce very high levels of mismatch if the actual mode is not matched almost exactly. Once the presence of a unique, lightly damped phugoid mode has been established in actual matches, the investigator may thereafter use the damping ratio of the actual phugoid mode for camparison with this requirement in MIL-F-8785C. Further order reduction of the LOS will normally be allowed to the first over second-order (short-period) form of

$$\frac{q}{F_s} = \frac{KT_{\theta_e}\omega_{sp_e}^2(1/T_{\theta_e})e^{-\tau_e s}}{[\zeta_{sp_e}, \omega_{sp_e}]}$$

where, in order to simplify the nomenclature, $T_{\theta_{2e}}$ has been replaced by T_{θ_e}.

If augmentation does provide greater than normal damping, then the phugoid requirement would certainly be met. The preceding arguments may not apply and order reduction to the short-period form would need other justification.

On the Bode diagram of the reduced-order LOS the low-frequency amplitude ratio and phase angle asymptotes are 20 log K dB and 0 degrees, respectively. Breakpoint frequencies are at $1/T_{\theta_e}$ and ω_{sp_e}, with the value of ζ_{sp_e} controlling the amount of resonance near ω_{sp_e}. The equivalent time delay contributes only phase lag of an angle equal to $\omega\tau_e$.

This transfer function has the conventional approximate short-period dynamics with a time delay term added in order to match the phase-angle effects of the high-frequency dynamics of actuators, filters, compensators, etc. which the pilot perceives as a time delay. MIL-F-8785C places limits on ζ_{sp_e} and τ_e directly and on ω_{sp_e} versus n/α. Limits on T_{θ_e} are not specified. At the writing of this paper, discussion is centering on whether to fix the value of T_{θ_e} at the actual value of T_{θ_2}. A more detailed explanation of this discussion follows.

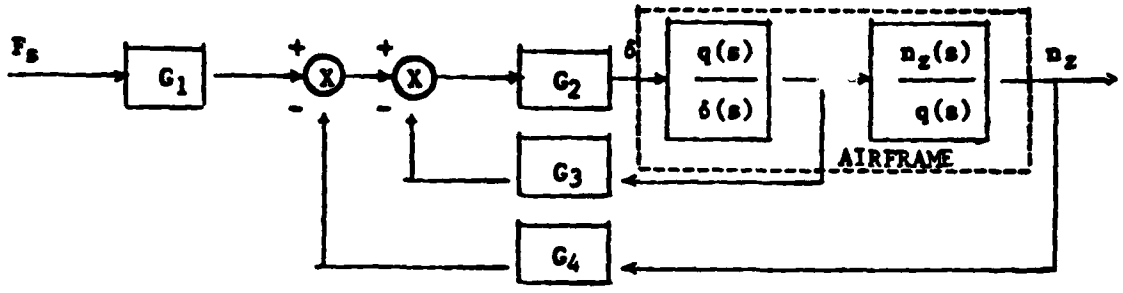
Feedbacks of angle of attack, pitch rate and normal acceleration change the frequency and damping, but generally do not add new modes. Some recent designs, however, by incorporating forward-loop integration or proportional-plus-integral feedback do create new modes. Even then it has often been possible to get a good match with this LOS. One might think to improve the match by increasing the order of the LOS, but unfortunately the data base for our requirements does not include such dynamics. There is no purpose, then, in adding more elements to the LOS.

IV. Guidance For Use With MIL-F-8785C

Fixed vs Free - $1/T_{\theta_e}$ (L_α) Match

Probably the most discussed and most investigated aspect of the longitudinal equivalent system approach so far has been the question of whether to fix or free the value of the LOS numerator zero at the value of $1/T_{\theta_2}$. For a given configuration and flight condition, according to the short-period approximation n_z/α has a steady-state value of $-Z_w V_o/g$, which is independent of any flight control system which, longitudinally, involves

only the pitch controller. This static sensitivity is one flying qualities parameter. Classically, $n_z/\alpha \approx (1/T_\theta)V_o/g$ - but since the ratio is independent of the flight control system, here $1/T_{\theta_e}$ should be fixed when matching the HOS. But consider the block diagram

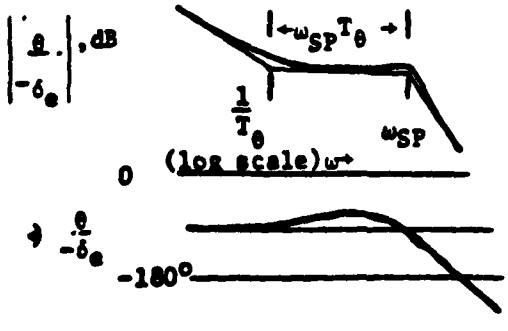


It is apparent that, using the short-period approximation and taking normal acceleration at the instantaneous center of rotation for pitch control,

$$\frac{n_z(s)}{q(s)} = \frac{n_z(s)/\delta(s)}{q(s)/\delta(s)} \approx \frac{-V_o M_{\dot{\alpha}} Z_w e^{-\tau s}}{g(s^2 + 2\zeta_{SP}\omega_{SP}s + \omega_{SP}^2)} \cdot \frac{(s^2 + 2\zeta_{SP}\omega_{SP}s + \omega_{SP}^2)}{M_\delta(s + 1/T_\theta)e^{-\tau s}}$$

$$\approx \frac{-V_o Z_w}{g(s + 1/T_\theta)}$$

but since the time constant here belongs to the airframe and has nothing to do with the flight control system (the elevator wiggles and the airframe responds) again $1/T_{\theta_e}$ should be fixed when matching the HOS. Still, control of pitch attitude is itself a major factor in flying qualities. On that basis, the product $\omega_{sp}T_\theta$, which is the frequency separation (on a logarithmic scale) between ω_{sp} and $1/T_\theta$, is an important flying qualities parameter. It governs the slope of the amplitude vs frequency curve near the



bandwidth frequency; large values can result in low gain margin and large pitch-rate overshoot. Mooij (Reference 16) has shown pilot ratings to deteriorate with decreasing $1/T_{\theta_2}$ at constant ω_{sp} and n_z/α. Also STI has shown that the available data correlate about as well (they claim better) with $\omega_{sp}T_{\theta_2}$ as with the MIL-F-8785C parameter $\omega_{sp}^2/(n/\alpha)$, for a lower boundary. Thus, depending upon one's point of view, either fixed or free $1/T_{\theta_e}$ can be justified. Investigation is continuing. Note that the value of Z_w is generally available with good accuracy, even when maneuvering flaps must be accounted for.

Simultaneous q/F_s and n_z/F_s Matching

A fixed $1/T_{\theta_e}$ match utilizes a theoretically derived relationship between q and n_z as previously stated, while a free $1/T_{\theta_e}$ match essentially ignores the q to n_z relationship. Again, certain tasks essentially involve pitch attitude control only, with the n_z response not a critical factor. But a recent large-aircraft simulation program (Reference 2) by Arvin/Calspan using the USAF Total In-Flight Simulator (TIFS) demonstrated an additional complication.

In this program one set of approach and landing simulations was performed for different simulated pilot positions along the fuselage, keeping all other parameters fixed. What this variation produced in terms of the q/F_s and n_z/F_s responses was a fixed q/F_s response with a variation in the numerator zeros of the transfer function of the n_z/F_s response sensed by the pilot. The simulated pilot positions produced a range of s-plane locations of the n_z/F_s numerator zeros. One pilot location was 10 feet behind the instantaneous center of rotation of the simulated aircraft, which caused one of these zeros to become nonminimum-phase. For this position the initial pilot normal acceleration for pitch commands then was in the opposite direction to that of the steady-state n_z. The other pilot locations were 10 feet and 50 feet in front of the instantaneous center of rotation which produced all minimum-phase n_z/F_s zeros. For these positions the initial pilot normal acceleration was in the same direction as the steady-state normal acceleration. At 50 feet the initial pilot normal acceleration

was more abrupt than that for 10 feet in front of the instantaneous center of rotation (see Figure 1). For a more detailed discussion of the effect of position on the numerator zeros see Reference 20.

The pilot ratings and comments for these three simulated pilot positions were different, with further aft pilot positions rated progressively worse, even though the simulated pitch attitude responses were maintained identical. This means that at least for certain tasks, here approach and landing, the normal acceleration at the pilot's seat should be considered in the analysis of an aircraft's flying qualities along with the pitch rate response characteristics.

For such cases where both pitch rate and pilot normal acceleration responses need to be considered, simultaneous matching of the q/F_s HOS and the n_{zp}/F_s HOS is suggested. The required form of the n_{zp}/F_s LOS is:

$$\frac{n_{z_p}}{F_s} = \frac{K_{h_e}\omega_{sp_e}^2[\zeta_{h_e},\omega_{h_e}]e^{-\tau_{h_e}s}}{\omega_{h_e}^2[\zeta_{sp_e},\omega_{sp_e}]} \quad \frac{g}{lb}$$

where n_{z_p} = normal acceleration at pilot seat, g
F_s = control stick force, lb
K_{h_e} = steady-state gain, g/lb
ζ_{h_e} = equivalent numerator "damping ratio", dimensionless
ω_{h_e} = equivalent numerator "natural frequency", rad/sec
ζ_{sp_e} = equivalent short-period damping ratio, dimensionless
ω_{sp_e} = equivalent short-period natural frequency, rad/sec
and τ_e = equivalent n_{z_p} time delay, sec

Of course the n_{zp}/F_s LOS has the same characteristic mode as the q/F_s LOS. Also the value of ζ_{h_e} may be greater than one and $\omega_{h_e}^2$ can be negative. For a pilot position aft of the instantaneous center of rotation the numerator should factor to two real-valued zeros, one negative and one positive, indicating the expected nonminimum-phase effect for this position. For reasonable matches the value of τ_{h_e} should be close to the value of τ_e.

Currently no requirements exist on the allowable range of ζ_{h_e} and ω_{h_e} simply because pilot position effects had not been a real problem until fairly recently with the space shuttle. The importance of the pilot's normal acceleration characteristics on longitudinal PIO tendencies has been investigated by Ralph Smith (Reference 7). In qualitative terms of flying qualities a pilot position behind the instantaneous center of rotation needs to be checked for its capability to produce poor flying qualities. It is also possible that a pilot position too far forward as could occur in an extremely large aircraft, will be rated poor because of severe normal-acceleration abruptness to pitch control.

STI has proposed for the conversion of MIL-F-8785C to a Standard and Handbook to recommend simultaneously matching the normal acceleration at the instantaneous center of rotation with the $1/T_{\theta_e}$-free q/F_s LOS. The resulting pure-gain n_z/δ numerator precludes concern about matching parameters ζ_{h_e}, ω_{h_e} which do not appear in the requirements. This proposal is still being evaluated and may not be adopted. As already discussed, simultaneous matching preserves the relationship between pitch and flight path response. There may be tasks, however, for which only the pitch response affects pilot rating. Such a match also cannot predict pilot rating differences caused by different pilot positions on the same aircraft, as produced by the large aircraft TIFS program. Additional research is needed to determine the proper form of requirements to handle this question.

Influence of the Phugoid Mode on Short-Term Response

Conventional aircraft typically have well separated phugoid and short-period modes. MIL-F-8785C assumes this separation by not putting any quantitative requirements on the natural frequency of the phugoid mode. The phugoid is generally at a low enough frequency that the pilot controls it open-loop. The short-period mode then is the only longitudinal response mode that the pilot has to control closed-loop for good task performance. The British specification AvP 970 even warns that problems may occur if the phugoid natural frequency is greater than one-tenth of the short-period natural frequency. This separation of modes helps keep pilot workload at

a minimum. The form of the longitudinal equivalent system transfer function also assumes enough modal frequency separation so that the first over second-order LOS form will adequately match the HOS short-term characteristics.

When the phugoid mode affects the response within the frequency range of the match, the values of the first over second-order LOS parameters will be different than when the phugoid effects are absent. A simple example will demonstrate the varied effects that will occur. In this example the HOS is

$$\frac{\theta}{F_s} = \frac{K(.0607)(.526)}{[.0965,\omega_{ph}][.774,.787][.7,15](19.9)}$$

with a variable phugoid natural frequency. The HOS also includes a 15 rad/sec feel system and a 19.9 rad/sec actuator which contribute equivalent time delay. This HOS was matched with the equivalent first over second-order transfer function with time delay, using the previously mentioned computer program, over a frequency range of .2 to 10 rad/sec for 30 equally spaced frequency values on a logarithmic scale. Following are the results (ω_{ph} = phugoid natural frequency).

$1/T_{\theta_e}$-FIXED

ω_{ph} (r/s)	ω_{sp_e} (r/s)	ζ_{sp_e}	$1/T_{\theta_e}$ (1/s)	τ_e (s)	COST
.0524	.730	.830	.526	.149	6.66
.0787	.723	.828	.526	.148	5.90
.157	.665	.835	.526	.142	43.4
.210	.623	.739	.526	.132	314.

$1/T_{\theta_e}$-FREE

ω_{ph} (r/s)	ω_{sp_e} (r/s)	ζ_{sp_e}	$1/T_{\theta_e}$ (1/s)	τ_e (s)	COST
.0524	1.068	.796	1.256	.143	3.58
.0787	1.070	.800	1.289	.142	2.97
.157	1.321	.947	2.471	.131	40.6
.210	.316	.823	0.00	.137	180.

Substantial variations in the values of the LOS parameters are produced by the varying degrees of influence of the respective phugoid modes. For the $1/T_{\theta_e}$-fixed matches some definite trends can be noted: the equivalent natural frequency tends to become lower as the phugoid natural frequency is raised, while the damping ratio and time delay are not greatly changed. For the $1/T_{\theta_e}$-free matches, as ω_{ph} increases, ω_{sp_e}, ζ_{sp_e} and $1/T_{\theta_e}$ first increase then decrease. In fact, for the match with ω_{ph} = .210 rad/sec, the computer program would have made $1/T_{\theta_e}$ a negative value if it had not been prevented from doing so by the user, hence the zero value for $1/T_{\theta_e}$ for this match.

This sensitivity of the short-period LOS parameters to the influence of the phugoid mode is not a desirable feature, since not enough is known yet in this area to clearly determine that such effects are discernible and of concern to the pilot. Because the phugoid mode is so lightly damped (ζ < .1 normally), the phugoid mode's frequency response characteristics are very nearly equal to its high-frequency asymptotes (magnitude and phase angle) at a frequency just twice its natural frequency (see Figure 2). Therefore to effectively eliminate the influence of the phugoid mode all that need be done is to make sure that the lower frequency limit of the match is at least twice the phugoid natural frequency. In some instances this lower frequency limit may be higher than the previously suggested lower limit of 0.3 rad/sec; however, twice the phugoid natural frequency will normally not be much higher than 0.3 rad/sec, so the slight loss in frequency range will be outweighed by the increase in the quality of the match.

A good example is the equivalent system matches given in the Appendix of Reference 2. For these matches the lower frequency limit of the matches was set at .25 rad/sec. Angle-of-attack feedback was used to alter the aircraft characteristics, which also varied the phugoid natural frequency to as high as .16 rad/sec. The value of .25 rad/sec was chosen for convenience at the beginning of the matching process. Based on the highest phugoid natural frequency the lower limit could have been set at .3 rad/sec and there would have been no need to change it thereafter. Though .25 rad/sec is not always twice the phugoid natural frequency for all of the configurations, even for the matches where it is not, the quality of these matches is still good as indicated by a relatively low COST value, meaning that the effect of the phugoid had been effectively eliminated. For comparison the fixed and free-$1/T_{\theta_e}$ matches for the configuration with the highest phugoid natural frequency of .16 rad/sec were rerun over a frequency range of .3 to 10 rad/sec with the same number of frequency values (25). These two matches showed no substantial change in equivalent modal parameters (ζ_{sp_e}, ω_{sp_e}) or equivalent time delay when compared to the same respective parameters for the matches down to .25 rad/sec and for both matches to .3 rad/sec the COST values were approximately one-half the respective COST values for the matches to .25 rad/sec. The only substantial change in parameters occurred for $1/T_{\theta_e}$ in the free-$1/T_{\theta_e}$ match, which changed from .873 for the .25-10 rad/sec match to .770 for the .3-10 rad/sec match. The actual lower limit of .25 rad/sec was adequate because the configurations with the higher phugoid natural frequencies also had very low values of phugoid damping ratio ($\zeta \approx .04$).

Unstable Airframes

To reap the performance benefits attributed to unstable airframes has called for augmentation to provide stability of the aircraft. Although unstable airframes might not seem amenable to the use of MIL-F-8785C and equivalent systems for analysis, such is not the case. Reference 2 presents such configurations in which unstable airframes are augmented with either angle-of-attack feedback or pitch-rate feedback with a forward-loop integrator. The latter combination produces an attitude-hold/rate-command system. All of the configurations were matched with simple first over

second-order equivalent systems with time delays; even unaugmented, unstable configurations were well matched. In fact the worst match of all had a COST value of 35.4, so actually none of the matches could be considered poor and many were actually very good. We see that just because an unstable airframe is used does not mean the aircraft characteristics cannot be matched with an equivalent system. In fact equivalent system matching is encouraged since such matching extracts those aircraft characteristics important to the pilot that may be hidden within the complete aircraft characteristics.

V. Lateral-Directional Equivalent Systems

Lateral-Directional LOS Forms

For comparison with MIL-F-8785C, the short-term dynamics of bank angle to roll control stick force (typically aileron control) and sideslip to yaw control stick force (typically rudder control) are required. The respective LOS forms of these two transfer functions are

$$\frac{\phi}{F_A} = \frac{K_\phi \omega_{De}^2 [\zeta_{\phi e}, \omega_{\phi e}] e^{-\tau_{\phi e} s}}{\omega_{\phi e}^2 T_{Se} T_{Re} (1/T_{Se})(1/T_{Re})[\zeta_{De}, \omega_{De}]} \quad \frac{\text{rad}}{\text{lb}}$$

and

$$\frac{\beta}{F_R} = \frac{K_\beta T_{\beta 1e} T_{\beta 2e} T_{\beta 3e} \omega_{De}^2 (1/T_{\beta 1e})(1/T_{\beta 2e})(1/T_{\beta 3e}) e^{-\tau_{\beta e} s}}{T_{Se} T_{Re} (1/T_{Se})(1/T_{Re})[\zeta_{De}, \omega_{De}]} \quad \frac{\text{rad}}{\text{lb}}$$

where ϕ = aircraft bank angle, rad
F_A = lateral control stick force, lb
β = aircraft sideslip angle, rad
F_R = directional control stick force, lb
K_ϕ = roll steady-state gain, rad/lb
K_β = directional steady-state gain, rad/lb
$\zeta_{\phi e}$ = equivalent roll numerator "damping ratio", dimensionless
$\omega_{\phi e}$ = equivalent roll numerator "natural frequency", rad/sec
T_{Se} = equivalent spiral mode time constant, sec
T_{Re} = equivalent roll mode time constant, sec

ζ_{D_e} = equivalent Dutch-roll damping ratio, dimensionless

ω_{D_e} = equivalent Dutch-roll natural frequency, rad/sec

$T_{\beta_{1e}}, T_{\beta_{2e}}, T_{\beta_{3e}}$ = equivalent directional numerator "time constants", sec (there may instead be a complex conjugate root pair)

τ_{ϕ_e} = roll equivalent time delay, sec

and τ_{β_e} = directional equivalent time delay, sec.

In the case of a coupled roll-spiral the roll mode and spiral mode would combine to a second-order factor with appropriate damping ratio and natural frequency.

Although the yaw-rate and lateral-acceleration responses can also be significant, presently there are no requirements on them. The roll and sideslip transfer functions have the conventional lateral and directional dynamics with the addition of respective equivalent time delay terms in order to match the phase angle effects of the high-frequency dynamics of actuators, filters, etc. just as for the longitudinal equivalent system. Simultaneous matching of both transfer functions should give the "best" match ' general, one that is physically meaningful. This means that both LOS transfer functions should have the exact same denominator or characteristic modes as shown in the given forms. MIL-F-8785C places direct limits on the characteristics of the roll, spiral, and Dutch-roll characteristic modes. Indirect requirements are placed on the numerator dynamics with requirements on the time-response parameters p_{osc}/p_{av} and $\Delta\beta/K$, respectively.

VI. Guidance For Use With MIL-F-8785C

Very little work in the area of lateral-directional equivalent systems has been performed so far. This will be reflected in the limited discussions presented here. This is not to be misinterpreted to mean that lateral-directional flying qualities-equivalent system analyses are less important than longitudinal flying qualities analyses. It is just that work in the

area of equivalent systems is still relatively new and investigators are first dealing with the somewhat less complicated longitudinal dynamics before attempting to deal with the more complicated lateral-directional dynamics.

General Guidance

The complexity of both transfer functions requires an involved matching procedure but the coupling between ϕ and β also produces some advantages. Three modes (or for coupled roll-spiral, 2 second-order modes) must be matched, making the matching routine more involved and generally requiring more time than the longitudinal routine. A computer program to perform the simultaneous match is also available from the McDonnell Douglas Corporation. This program is very similar to the previously described program. Simultaneous matching is encouraged because of problems that can occur when only matching one transfer function. A good example is the case where the ζ_ϕ-ω_ϕ second-order numerator happens to cancel the Dutch-roll mode in the HOS ϕ/F_A transfer function. This cancellation prevents the equivalent Dutch-roll parameters ζ_{De} and ω_{De} from being determined from a match of only ϕ/F_A. Likewise a match of only the β/F_R characteristics could have similar difficulties for the equivalent spiral or roll mode time constants. Simultaneously matching the two responses effectively prevents such problems because of the different ϕ/F_A and β/F_R numerator characteristics. The equivalent characteristic modes so obtained are then to be compared with the lateral-directional modal requirements in MIL-F-8785C.

Spiral Mode Simplification

In many instances the spiral mode time constant is such a large value that the factor associated with this mode in the transfer functions may be simplified to a free s (an integrator). This would allow the matching of $\dot{\phi}/F_A$ and $\dot{\beta}/F_R$ with third-order denominator LOS forms. Justification for this technique would be shown by a spiral mode breakpoint frequency below 0.1 rad/sec (preferably well below) with preliminary full fourth-order lateral-directional matches which consistently yield an equivalent spiral

mode time constant essentially equal to the HOS spiral mode time constant. The first condition is usually met, while the second condition will be met if no other low frequency modes are introduced by the aircraft flight control system; i.e. the spiral mode essentially "stands alone" in the low frequency lateral-directional characteristics. When these conditions are met, the actual spiral mode time constant can be compared with MIL-F-8785C and the resulting third-order modal parameters would be compared to the MIL-F-8785C roll and Dutch-roll modal requirements and the roll-yaw coupling requirements.

Alternatively, the existence of a coupled roll-spiral mode will be obvious in the actual HOS. The two appropriate LOS transfer functions would then be matched in that form for comparison with MIL-F-8785C where a coupled roll-spiral is allowed.

VII. Design Guidance

Particular Element Effects

Among the flight control system elements which have become popular for use in augmented aircraft are five particular types: (1) forward-loop integration, (2) stick prefilters, (3) actuators, (4) feel systems, and (5) structural filters. It is worth investigating the effects each one can have on an aircraft from a flying qualities equivalent-system viewpoint. The effects of the first three can be demonstrated well with a YF-16 example. The last two will be discussed separately.

This example is a simplified representation of the YF-16 CCV aircraft used by Systems Technology, Incorporated (STI) in Reference 5; Figure 3 is the block diagram for the longitudinal flight control system in the conventional flight mode. The transfer functions for angle of attack (α), pitch rate (q) and normal acceleration (a_z) response to control surface deflection (δ_e) are

$$\frac{\alpha}{\delta_e} = \frac{-.1534[.1503,.05473](138.6)}{\Delta} \quad \frac{\text{rad}}{\text{rad}}$$

$$\frac{q}{\delta_e} = \frac{-21.13(0)(.02598)(1.082)}{\Delta} \quad \frac{rad/sec}{rad}$$

$$\frac{a_z}{\delta_e} = \frac{139.1(.02298)[.05438, 11.73]}{\Delta} \quad \frac{ft/sec^2}{rad}$$

where $\Delta = [.1426, .05702](4.496)(-2.372)$ is the bare airframe characteristic polynomial. It is interesting to note that the bare airframe has a very unstable root at $s = +2.372$, corresponding to $C_{M_\alpha}/C_{L_\alpha} = 0.10$ - a negative 10% static margin. The acceleration a_z is taken at the feedback accelerometer, which is located forward in the aircraft at a position near the pilot's seat.

In order to get the LOS for this configuration it is necessary to obtain the transfer function of pitch rate to stick force (q/F_s). Two transfer functions will actually be matched. The first will be the transfer function for the ratio of the pitch rate to the signal F_1 shown on the system block diagram (Figure 3). The other transfer function will be the final desired one of q/F_s. The difference between these two will show the effect of the stick prefilter on the LOS match.

Inserting the required bare airframe transfer functions into the block diagram and solving for q/F_1 yields

$$\frac{q}{F_1} = \frac{3.868(1.074)(1.007)(.02598)(10)(15)(5)(15)}{(.8433)(1.468)(.02285)[.6205, 4.449][.999, 11.53][.6504, 19.40]} \quad \frac{rad/sec}{lb}$$

This transfer function has been cleared of common factors in the numerator and denominator. The numerator factor for $1/T_{\theta_2}$ of $(s + 1.082)$ does not appear because it has been cancelled exactly by a factor in the denominator. Note that the system now exhibits all stable roots.

From the system block diagram, the transfer function q/F_s is easily determined to be

$$\frac{q}{F_s} = \frac{1.328}{(8.3)} \cdot \frac{q}{F_1} \quad \frac{rad/sec}{lb}$$

The prefilter and stick gain change the system gain and introduce an additional real root at s = -8.3.

Next these two transfer functions are matched with the LOS equivalent, a first over second-order transfer function with exponential time delay. A quick check of the q/F_1 HOS transfer function shows that three zeros at s = -1.074, -1.007 and -.02598 roughly cancel three poles at s = -.8433, -1.468 and -.02285 leaving high-frequency modes at and beyond 10 rad/sec, one complex pair of poles having a natural frequency of 4.449 rad/sec and a damping ratio of .6205, and one zero at s = -5. Because this rough cancellation technique leaves the proper form, a good match is expected.

When the two HOS transfer functions are matched with the best-fit LOS the following transfer functions result:

		COST
$1/T_{\theta_e}$ fixed	$\frac{q}{F_1} = \frac{.2979(1.082)e^{-.0572s}}{[1.11,2.96]}$	8.76
$1/T_{\theta_e}$ free	$\frac{q}{F_1} = \frac{.2193(3.094)e^{-.0337s}}{[.653,4.20]}$	.16
$1/T_{\theta_e}$ fixed	$\frac{q}{F_s} = \frac{.03329(1.082)e^{-.1286s}}{[.987,2.49]}$	17.81
$1/T_{\theta_e}$ free	$\frac{q}{F_s} = \frac{.02025(5.648)e^{-.089s}}{[.544,4.30]}$	.63

All of the matches are good, with the matches for $1/T_{\theta_e}$ free being excellent. This is expected, since the $1/T_{\theta_2}$ factor was cancelled out and the nearest numerator factor not cancelled out is (s + 5) (This factor actually is produced by the gain on the forward-loop integrator in the flight control system). The effect of the stick prefilter can also be seen mainly as an increase in the equivalent time delay. The effect of the high-frequency modes is reflected mainly in the value of the equivalent time delay.

From this example some design guides can be inferred. First, the placement of the numerator zero produced by the forward-loop integrator can be

very important. In this case, because the numerator factor for $1/T_{\theta_2}$ is exactly cancelled out, the value of $1/T_{\theta_e}$ for the $1/T_{\theta_e}$-free fits is strongly influenced by the value of this numerator zero. For the $1/T_{\theta_e}$-fixed fits this cancellation causes relatively poorer matches because actually the "effective" short-period value of $1/T_{\theta_2}$ has been "moved" to 5. Second, a stick prefilter will produce one or two effects depending upon the value of its breakpoint frequency (for a simple first-order prefilter). For a prefilter with a breakpoint frequency above 10 rad/sec the main effect will be an increase in the equivalent time delay, with increasing additional time delay for decreasing prefilter breakpoint frequency. For a prefilter with a breakpoint frequency at or below 10 rad/sec, besides the equivalent time delay effect, the presence of the prefilter will also lower the equivalent system natural frequency. This double effect can be seen in a comparison of the YF-16 $1/T_{\theta_e}$-fixed fits with and without the 8.3 rad/sec prefilter. Without the prefilter the equivalent time delay is .0572 sec and the equivalent natural frequency is 2.96 rad/sec. With the prefilter the equivalent time delay increases to .1286 sec (an increase of .0714 sec) and the natural frequency lowers to 2.49 rad/sec. It is interesting to note that the Level 1 requirement in MIL-F-8785C is that there be no more than .1 second of equivalent time delay. In view of the substantial increase in equivalent time delay it is important that designers carefully weigh the benefit of input smoothing against a prefilter's capability to produce a significant system time delay.

Last, a universally common source of equivalent time delay is the control surface actuator. Obviously, a slow actuator will produce more equivalent time delay than a faster actuator. Of course, as in the YF-16 example, the actuator is one part of the complete closed-loop flight control system and augmentation in the flight control system can increase the effective actuator natural frequency. However, only so much augmentation can be used before the demands on a relatively slow actuator exceed its mechanical capabilities, indicating the need for a faster actuator all along. One good approximation technique is to match the actuator model with only a time delay. The value of time delay obtained is then the equivalent time delay contribution produced by the unaugmented actuator. For example, the YF-16 actuator model of $13/(s + 13)$ can be approximated by an equivalent time

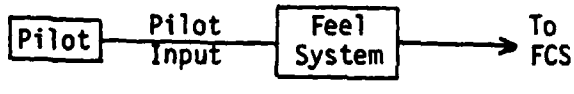
delay of .07 seconds for piloted control. A common actuator model is 20/(s + 20), which could be approximated by a time delay of .048 seconds. This approximation technique can be compared to equating the phase lag of the first-order model to the phase lag of its equivalent time delay at a frequency of 7 rad/sec. Solving for the time delay yields

$$T_D = .002493 \tan^{-1}(7/\omega_B) \quad \omega_B \geq 10 \text{ rad/sec}$$

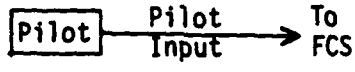
where T_D = equivalent time delay contribution, sec
and ω_B = breakpoint frequency of first-order actuator model, rad/sec.

It is not recommended that this equation be used for $\omega_B < 10$ rad/sec.

Feel systems, another very common element of manual control systems, can be in series or in parallel in the flight control system. In terms of equivalent system analysis the distinction between series and parallel is an important one. A simple block diagram for each will help show the difference.



Series



Parallel

In the series configuration the output of the feel system is the input to the flight control system, while in the parallel configuration the pilot input is sent directly to the flight control system. Therefore, in terms of aircraft response to pilot input, the series configuration would need to have the feel system included while the parallel configuration would not.

This distinction becomes important because of the contribution series feel can make to equivalent time delay.

Two typical examples for investigation are second-order feel systems with natural frequencies of 15 and 25 rad/sec. Generally the damping ratio is .7 so this value will be used for both. A match of these two feel systems with an equivalent time delay yields the following results

15 rad/sec feel system ≈ .100 sec time delay

25 rad/sec feel system ≈ .058 sec time delay

Just like prefilters and actuators, a series feel system will cause a substantial increase in the equivalent time delay of a system even though the natural frequency of the feel system may appear high enough that the feel system dynamics would not be important. Because pilots use both force and deflection cues, feel systems, whether series or parallel need to be carefully considered in aircraft design, development and testing.

Figures 4 and 5 summarize the significant effects of prefilters, actuators and feel systems. Figure 4 gives the approximate time delay equivalents for varying values of the breakpoint frequency of these elements (feel system damping ratio of .7). Figure 5 shows the effect of a prefilter on the equivalent short-period natural frequency for a LOS match of the higher-order system

$$\frac{q}{F_s} = \frac{18(.5)}{[.7,3]} \cdot \frac{a}{(a)}$$

for breakpoint frequencies a = 5,6,7,8,9,10 rad/sec. This figure shows the very pronounced effect of the prefilter element on the value of ω_{sp_e} for the lower values of the breakpoint frequency. The value of ζ_{sp_e} ranged from .653 (a = 10) to .614 (a = 5) and τ_e ranged from .070 sec (a = 10) to .0977 sec (a = 5). This means that for the lower values of the prefilter breakpoint frequency the q response to pilot commands will appear to be slower and with somewhat less damping than the actual HOS mode would

indicate, and will also have a substantial apparent time delay.

Figures 6 and 7 show that an equivalent time delay is a good model for the effects of these elements. Figure 6 compares the phase shift produced by a 15 rad/sec prefilter (or actuator) with that produced by its .062 second time delay equivalent. Figure 7 shows a similar comparison for a 25 rad/sec feel system (ζ = .7) and its time delay equivalent of .058 seconds. Both figures show very close agreement between the particular element and its respective time delay equivalent within the pilot's frequency range of interest. Thus these elements, when combined with the airframe dynamics and the rest of the flight control system, essentially appear to the pilot as time delays in the aircraft response to pilot commands.

The last common control system element which merits some discussion is the structural filter. Even a structural filter with a relatively high cutout frequency may affect piloted control. For example Reference 6 shows a 55 rad/sec structural filter in the roll axis of the flight control system functional block diagram. The equivalent time delay for this filter is .036 seconds. Even a 147 rad/sec structural filter shown in the yaw axis equates to a .014 second equivalent time delay. Although the intended function, to sharply attenuate the amplitude at the cutout frequency is realized, even .01 second time delay may be a significant contribution, considering the 0.1 second limit for Level 1 flying qualities.

As can be seen in many of these examples, equivalent time delay becomes more and more important as more augmentation is added to aircraft. Very few of the previously cited elements can be used together without the accompanying time delay effects accumulating beyond the maximum level required to assure good handling qualities. It should also be painfully obvious that flying qualities can only be assessed correctly by analysing the cumulative effect of components which may appear innocuous individually.

Digital Control Systems

In spite of the well-advertised benefits of digital computation, the single most important flying qualities aspect of digital flight control systems may well be time delay. Digital control systems cannot avoid it. Conventional zero-order hold digital controls will take an average ½ sampling increment for commanded changes to be input, and at least 1 sampling increment for computation. For a 20 Hz system an average .075 sec will therefore elapse before any commanded changes can occur. This time delay is three-fourths of the allowable Level 1 value of .1 second and does not include equivalent time delay effects of the actuators, sensors, smoothing filters and anti-aliasing filters that would add to the digital time delay. Digital systems can avoid a significant delay if they stick to doing the "old job better". This has not been done, so that time delay has become a problem.

Since equivalent system matching is performed in the frequency domain an equivalent system match of an aircraft with a digital flight control system would require that frequency response data (amplitude ratio and phase angle) of the aircraft be obtained. Since digital systems normally use the z-transform the frequency response would have to be derived from the z-domain characteristics (References 17, 18) or obtained by actual frequency response testing of the aircraft model. In some cases, such as with prototype aircraft, the actual aircraft can be tested to obtain the frequency response data for validation of the model and equivalent system of the aircraft.

VIII. Conclusions

The current flying qualities specification, MIL-F-8785C, requires the contractor to define equivalent system matches to represent the high-order dynamics typical of highly augmented aircraft. These equivalent matches are formulated in classical terms so that the equivalent modal parameters can be compared with the requirements directly. It has also been necessary to add a new term, equivalent time delay, for which new requirements were

formulated. This paper has presented some guidance in determination and application of equivalent systems. The cumulative effect on equivalent time delay, from seemingly harmless individual components, has been highlighted.

It is also admitted that much more work is needed, especially for lateral and directional axes, and also for digital systems. A generic simulation model based on the equivalent system concept (Reference 19) is currently being verified. This will be a major tool in our continuing research into equivalent systems.

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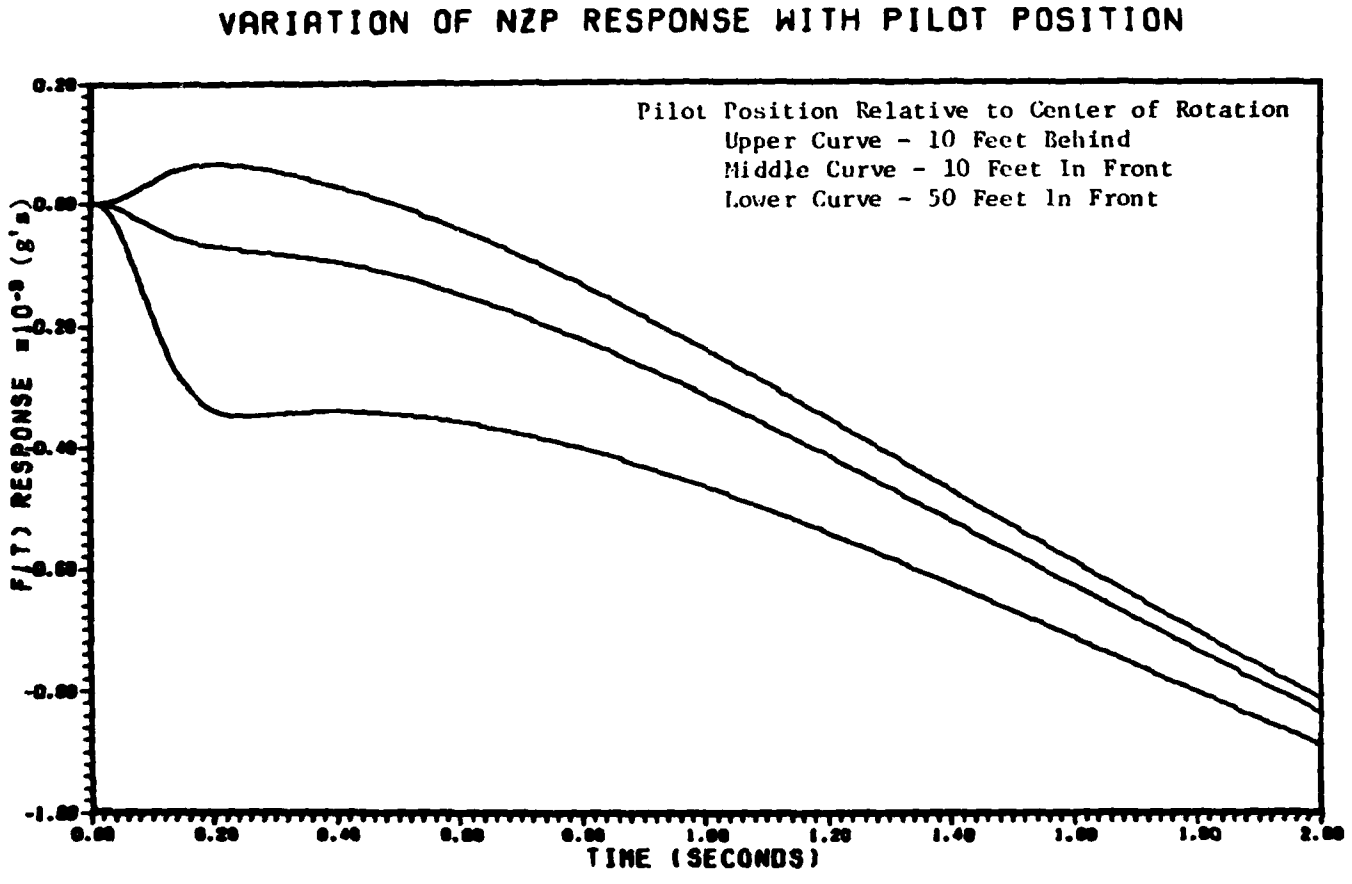
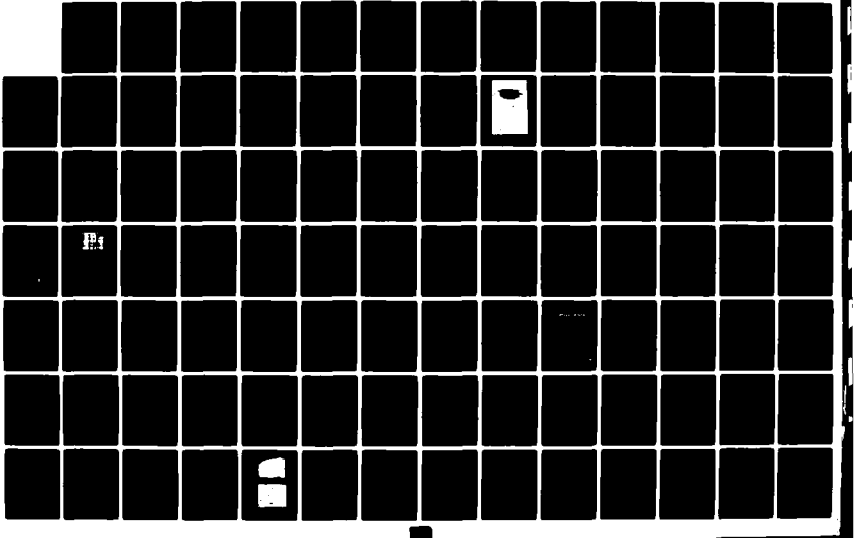


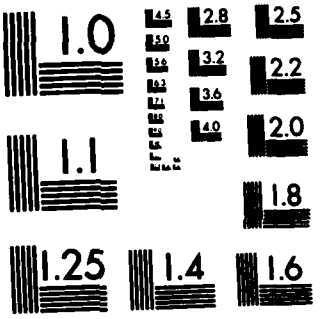
Figure 1. Pilot Normal Acceleration Step Response at Three Pilot Positions

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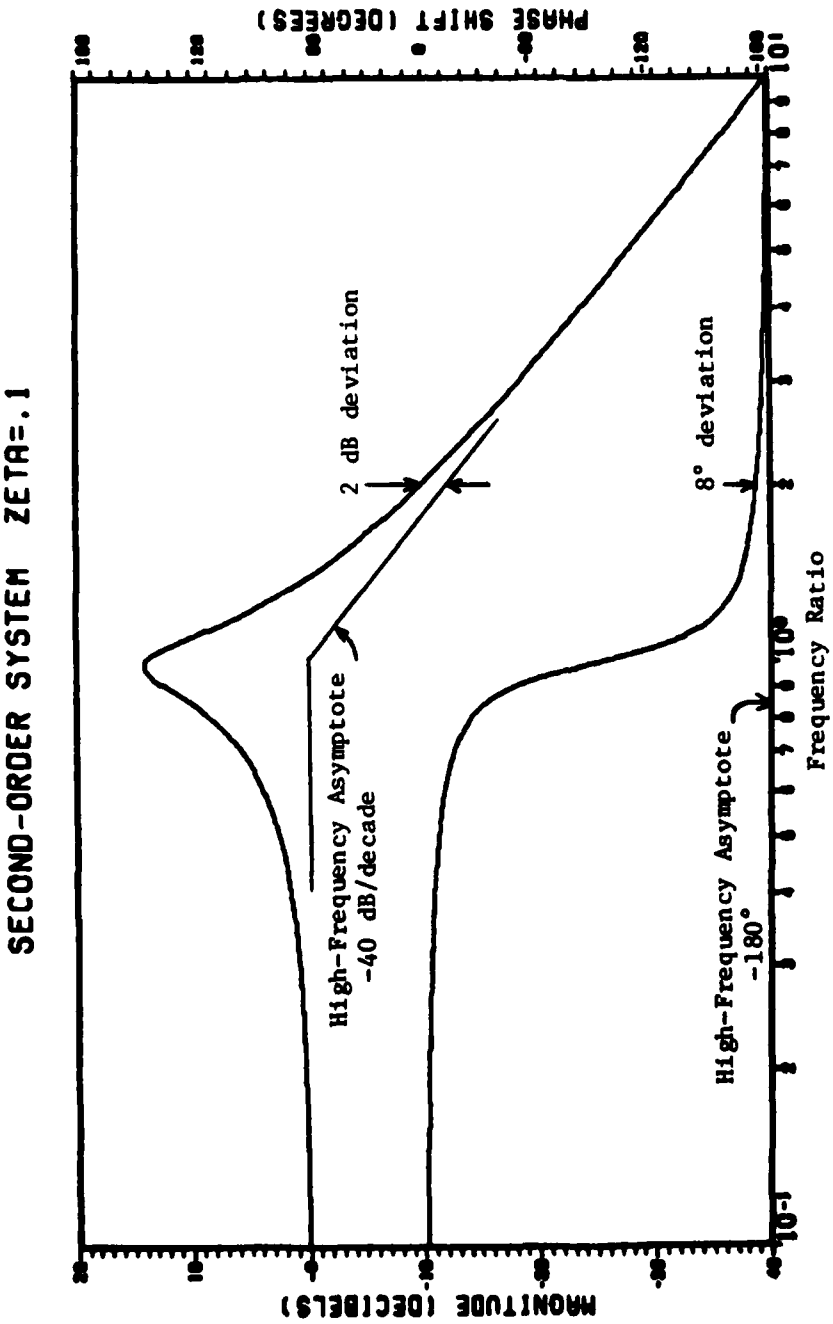


Figure 2. Frequency Response of Lightly Damped Phugoid Mode (ζ=.1)

(5) = s+5, (15) = s+15, etc.

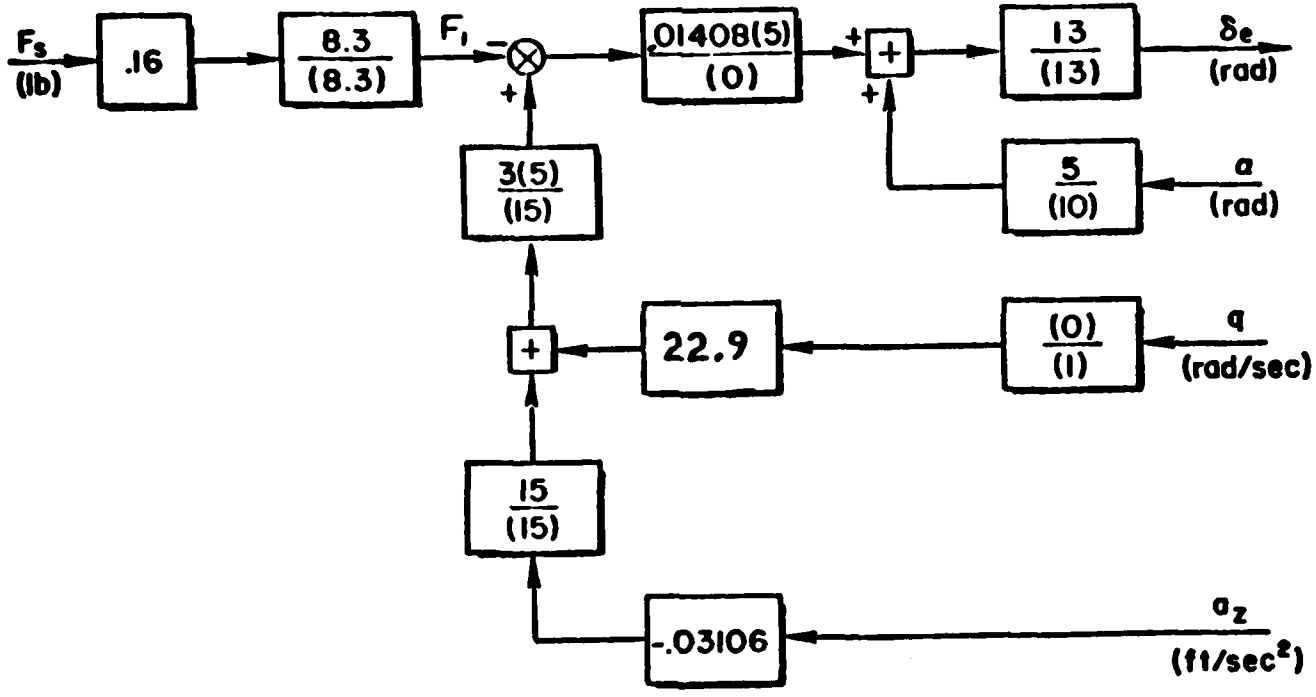


Figure 3. Longitudinal Flight Control System, Conventional Flight Mode

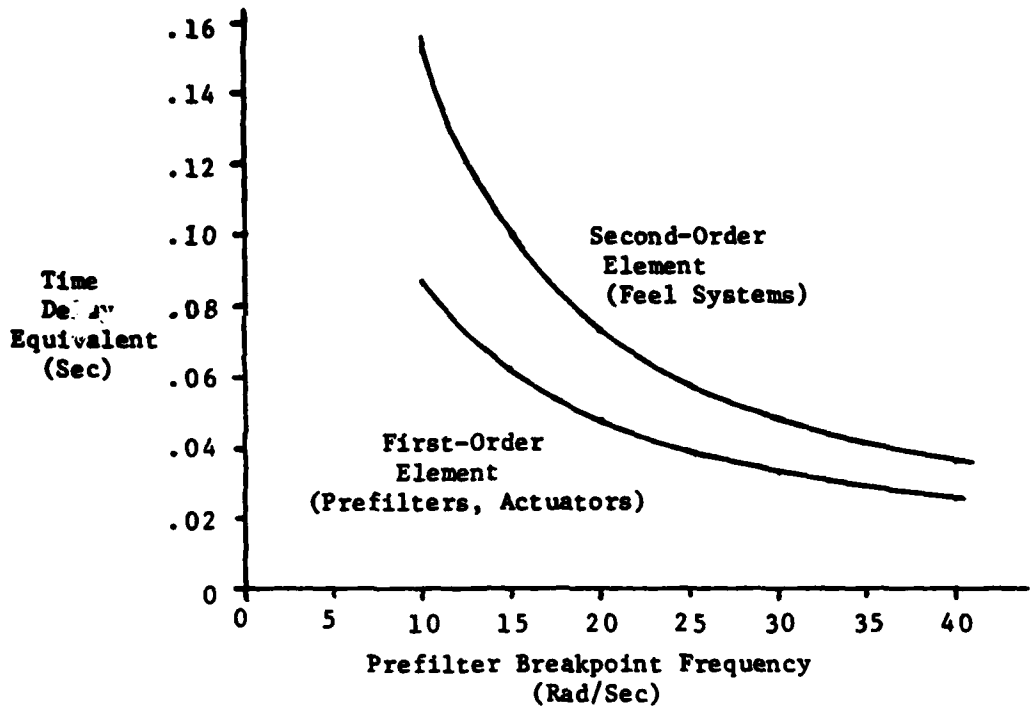


Figure 4. Approximate Time Delay Equivalents of First- and Second-Order Elements

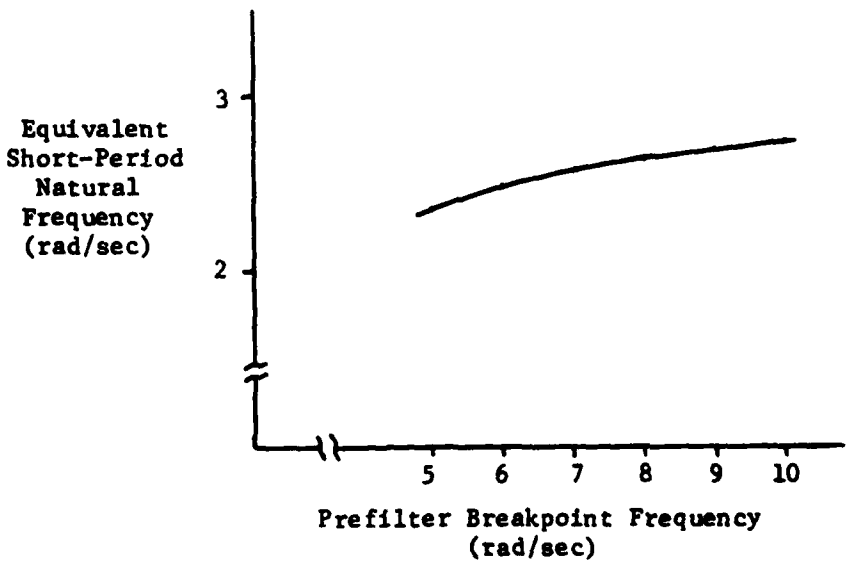


Figure 5. Prefilter Effect on Equivalent Short-Period Natural Frequency

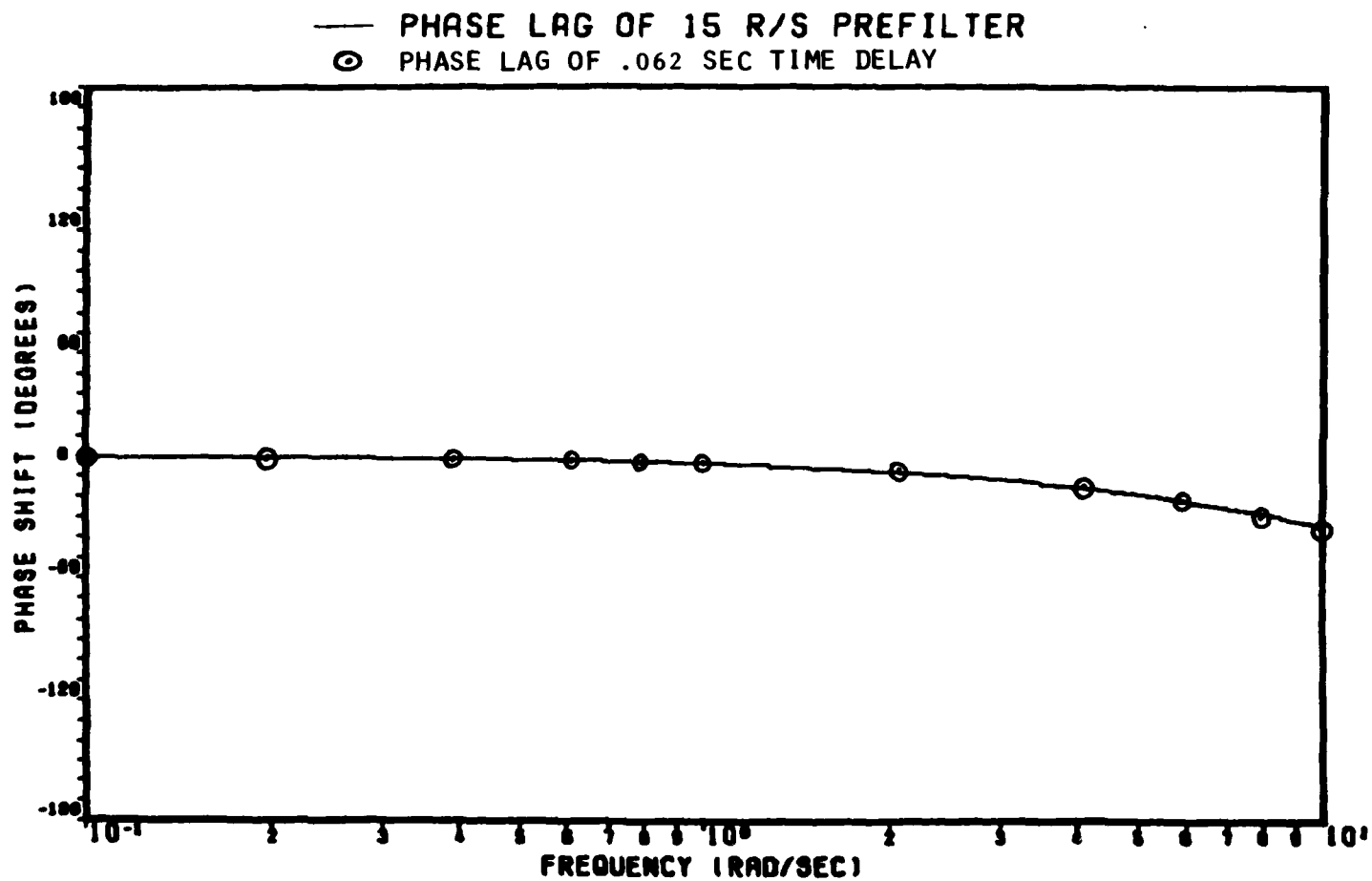


Figure 6. Comparison of Phase Lag of 15 Rad/Sec Prefilter With It's .062 Second Time Delay Equivalent

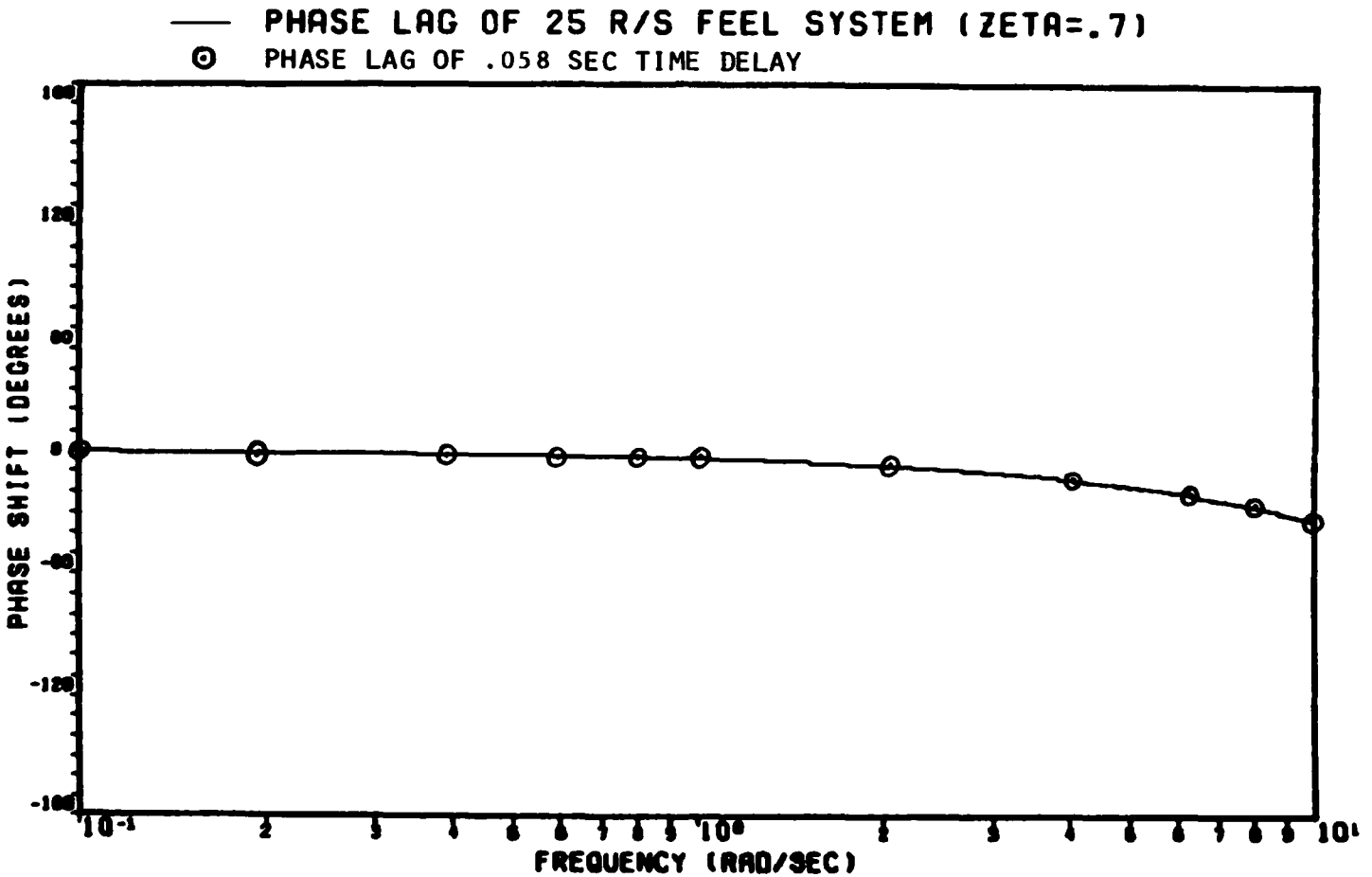


Figure 7. Comparison of Phase Lag of 25 Rad/Sec Feel System With It's .058 Second Time Delay Equivalent

COMMENTS AND QUESTIONS

Roger Hoh, STI: Concerning fixing or freeing L_α. Freeing L_α gives a better match - however only pitch attitude is investigated and not γ. You can't use L_α on $\omega_{n_{sp}}$ vs n_z/α figures of the specification since n_z/α is really flight path. Simultaneous match is the only proper way to do it if you're going to compare to the n_z/α figure in the specification. You can free L_α for pitch response but you will need another criterion for path.

Concerning digital systems, and the Space Shuttle, only 50 ms of time delay came from digital portions; the rest came from the high-gain/high-authority FCS.

Ed Rynaski, Calspan: You're using n_z as a state to be identified which is a function of the center of rotation. An alternate would be to use α response. In low-speed flight, phugoid and short period are not very separated. Then you have to worry about $1/T_{\theta_1}$.

Lateral-directional matching - you only showed ϕ/F_{AS} and β/F_{RP}. You should also look at ϕ/δ_{RP} and β/δ_A.

Answer: The current specification only matches ϕ/F_{AS} and β/F_{RP} and that was the scope of my investigation.

NEW FLYING QUALITIES CRITERIA FOR RELAXED STATIC STABILITY

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Abstract

New criteria are developed for airplanes with relaxed static longitudinal stability based on a fixed base ground simulator investigation of approach and landing, and the available flight test data. It is shown that a criterion based on just time-to-double amplitude is invalid, and other elements of the pitch attitude transfer function (θ/F_s) must be included to adequately define flying qualities. Criteria based on both airplane parameters (open loop) and closed loop frequency response are developed. The results were obtained from Boeing IR&D studies and from Air Force Contract No. F33615-78-C-3603, one of a series of contracts to update MIL-F-8785, Flying Qualities of Piloted Airplanes. This paper summarizes only some of the results of the two studies. The full results are presented in Reference 1.

Introduction

Substantial performance benefits may be realized by relaxing the requirements for aerodynamic stability (e.g., by placing the c.g. aft of the range normally required). To allow this option, special alternate requirements are formulated applicable to the deliberate use of relaxed static stability (RSS). The alternate requirements are formulated on the basis that stablity augmentation will be used to provide normal-state flying qualities.

This paper is concerned only with the requirements for stability and the response of pitch attitude to pitch control. These are central to RSS. Furthermore, the existing requirements (time-to-double amplitude greater than 6 seconds) are neither sufficient nor necessary. The results summarized in this paper provide new and more valid criteria for stability and pitch attitude response.

[illegible]

The investigation of flying qualities requirements for RSS concentrated on the approach and landing task as this is likely to be critical for the design of any airplane with RSS. This criticality is in part due to the low Mach no., low dynamic pressure, high lift coefficient, and high probability of encountering turbulence. The landing is a demanding task requiring precise attitude and flight path control, is the primary task pertinent to flight safety, and is the one most likely to have to be accomplished with failed augmentation. Furthermore, there is no way to avoid this critical task - the airplane must be landed.

Existing Flight Data on RSS Flying Qualities

Criteria developed in past investigations for the minimum levels of allowable stability (maximum instability) for safe operation have mostly been in terms of the time to double amplitude of the airplanes response, usually calculated from the unstable root (λ_1) of the three degree of freedom characteristic equation as follows:

$$T_2 = 1\ 2/\lambda_1 = .693/\lambda_1$$

Alternatively, boundaries have been drawn in the ω_n v.s. $2\zeta\omega_n$ plane where ω_n^2 and $2\zeta\omega_n$ are the coefficients in the quadratic defining the short period mode as follows:

$$s^2 + bs + a = 0$$
$$a = \omega_{n_{sp}}^2$$
$$b = 2\zeta_{sp}\omega_{n_{sp}}$$

The advantage of the ω_n^2 v.s. $2\zeta\omega_n$ coordinates is that they allow plotting of all possible values of short period roots, stable or unstable, oscillatory or real. Also the MIl-F-8785C short period requirements can be plotted on these coordinates.

Since the approach and landing data from the three variable-stability airplane flight test programs of References 2, 3, and 4 comprise the bulk of the flight data on minimum stability levels applicable to RSS, they are analyzed in some detail. Acronyms (LAHOS, SST, B-26) are defined for each for

ready reference, and a synopsis of the characteristics, limitation and procedures for each investigation follows.

LAHOS	Smith (Ref. 2)
SST	Wasserman and Mitchel (Ref. 3)
B-26	Bull (Ref. 4)

Bull's investigation predated the Cooper-Harper scale, and the pilot ratings are given with adjectives: acceptable, acceptable poor, and unacceptable. These were considered to apply to making a landing in the emergency case with failed augmentation system. Based on the wording used in the Cooper-Harper Scale (Ref. 5) and MIL-F-8785C, the following equivalents are believed appropriate.

Adjective	Pilot Rating	Level
Acceptable	5-7 (or better)	2,3(1)
Acceptable Poor	8-9	3
Unacceptable	10	>3

To provide an overview of the flight data and various criteria, selected data points from the LAHOS, SST (TIFS), and B-26 flight test investigations have been plotted on the ω_n^2 v.s. $2\zeta\omega_n$ plane in Figure 1, together with the B-26 rough air and smooth air boundaries, appropriate Level 1, 2, and 3 boundaries from MIL-F-8785C, and lines of constant time to double amplitude (T_2 = 2 and 6 sec).

The SST stable configurations (1,13,20) support the Level 1 boundary, but SST configurations 14 and 15, and all three LAHOS configurations (7-1, -2, -3) indicate that the Level 2 boundary should be well below the $\omega_n^2 = 0$ axis, going somewhere between the T_2 = 6 sec. and 2 sec. lines for $2\zeta\omega_n$ larger than 1.0. SST configurations 2, 3, 4, 10, and 11 all have PR$\leq$9 with the exception of a flare and touchdown ratings of 10 for each of configurations 2 and 3. This suggests that near $\omega_n^2 = 0$, the B-26 rough air boundary (which goes through all these points) is about on the Level 3 boundary,. However SST configurations 5 and 12 (also on the B-26 rough air boundary) with T_2 = 2 sec have PR = 10, indicating the boundary should be above and to the right of these points.

If we except SST configuration 16 (PR =10), there are three bands of data running parallel to the B-26 boundaries, (1) the B-26 rough air boundary with PR $\approx$ 9.5, (2) a line intercepting the ω_n^2 axis through $2\zeta\omega_n$ = 1.1 with PR $\approx$ 6.5, and (3) a line intercepting the ω_n^2 axis at $2\ \zeta\omega_n$ = 1.9 with PR>6. Clearly, there is a strong gradient of PR along lines of constant T_2, with PR improving as $2\zeta\omega_n$ increases. In summary, the specification Level 2 boundary should be lower and the Level 3 boundary much lower than they currently are, allowing negative ω_n^2 for large amounts of damping ($2\zeta\omega_n$). Clearly, T_2 does not define the flying qualities for statically unstable aircraft as there is a strong gradient of pilot rating along lines of constant T_2.

Proposed Criteria for RSS

A piloted flight simulator was the primary tool for establishing criteria. A fixed-base simulation, including a visual scene of a runway during approach and landing, was used for the experiments. The pilot's task included glide path acquisition, instrument approach, breakout, visual approach, and flare and touchdown. The C-X cab was used for the cockpit to take advantage of its high-quality center stick which has adjustable, well-controlled, well-defined, static and dynamic characteristics. High-quality flight instruments were also included. For fighter simulation, the right seat with its left-hand throttles was used and a screen was installed to create the illusion of a single-place cockpit.

The various elements of the landing simulation are shown schematically in Figure 2. The cockpit arrangement of pilot controls and instruments is shown in Figure 3. The actual field-of-view is larger than shown since the photo was taken well aft of the pilot's eye position. Controls are stick, rudder pedals, throttles, flap handle, wing-sweep handle, and gear handle. The instruments on the main panel are the ADI with (raw) ILS localizer and glide-slope on the needles, HSI, RMI, airspeed indicator with digital Mach number readout, altimeter, radar altimeter, VSI, digital DME with ground speed readout, control position indicators, and thrust indicator. Gear lights, marker beacon lights, and augmentation system failure lights are provided. Stall warning is audible and tire screech indicates touchdown. Rollout is not simulated, but to maintain a semblance of realism the airplane

is automatically stabilized in ground attitude and decelerated to a stop once touchdown occurs.

The simulator was used to perform piloted evaluations of different augmentation systems, with CG locations reflecting relaxed static stability, in both normal and failed conditions. The evaluations were performed for three different pitch augmentation systems, various levels of stability, various values of actuator rate and position limits, and with both normal and failed pitch augmentation systems. Each evaluation consisted of three landings. The first was in still air, started five miles out on instruments with level flight for two miles to glide-slope acquisition, during which the pilot was asked to feel out the airplane. Then an ILS approach was made with breakout at 200 feet altitude, followed by a flare and tuchdown. The second landing was started from three miles out, on glide slope, with moderate turbulence. A lateral offset of the localizer was included, randomly to left or right, so that the pilot had to perform a rapid lateral maneuver before landing. The third landing was from three miles out, in heavy turbulence, without any lateral offset. Desirable lateral-directional characteristics were maintained constant throughout.

Parameters must be found upon which to base flying qualities prediction and criteria. Since attitude response is considered to be of primary concern to the pilot during approach and landing, we look to the attitude transfer function for the needed parameters.

Airplane

$$\frac{\theta}{\delta_h}(s) = \frac{A_\theta (s - Z_{\theta_2})(s - Z_{\theta_1})}{(s - \lambda_{sp_1})(s - \lambda_{sp_2})(s^2 + 2\zeta_p \omega_{n_p} s + \omega_{n_p}{}^2)}$$

Control System

$$\frac{\delta_h}{F_s}(s) = \left[\frac{\delta_{es}}{F_s}(s)\right]_{\substack{\text{Feel} \\ \text{system}}} \left[\frac{\delta_h}{\delta_{es}}(s)\right]_{\text{Actuators}}$$

Gain

$$\frac{\theta}{F_s} = \frac{\delta_{es}}{F_s} \frac{\delta_h}{\delta_{es}} A_\theta \quad , \quad A_\theta \cong M_{\delta_h}$$

$$M_{\delta_{es}} = \frac{\delta_h}{\delta_{es}} M_{\delta_h} \quad \text{- pitch control sensitivity, rad/sec}^2\text{/in}$$

The above transfer functions are in the form for the unaugmented airplane. However, most augmented airplane transfer functions can be recast into the above form by one of two techniques: 1) equivalent stability derivative approach, or 2) equivalent system approach. The first is suitable when simple response feedbacks are used (e.g., $\alpha, n_z, q...$), without significant low frequency compensation or feedback dynamics, so the feedback can be represented as the weighted sum of the airplane state variables. The second is suitable when significant compensation or control system dynamic elements are included so that the closed loop airplane response is of higher order than normal in the frequency range of interest (0.1 to 10 rad/sec). Thus by specifying response characteristics in the normal unaugmented form for an RSS airplane, criteria for two different conditions are developed:

1) Unaugmented RSS airplane, following failure of normal FCS,
2) RSS airplane augmented with backup FCS, following failure of normal FCS.

The specific parameters in the θ/F_s transfer function selected for study were λsp_1, λsp_2, and $Z\theta_2$ on the assumption that variations in ω_{n_p}, ζ_p, and $Z\theta_1$ would not be as important. Some investigation was also made of the control sensitivity $M_{\delta_{ES}}$. In addition to the linear response characteristics defining minimum stability levels, the minimum requirements for control system rate and authority were investigated for both the augmented and unaugmented RSS airplane.

Criteria for relaxed static stability are based on the following equivalence between Level and pilot rating (PR):

Level 1	$1 < PR < 3.5$
Level 2	$3.5 < PR < 6.5$
Level 3	$6.5 < PR < 8.5$

The Level 3 boundary, conventionally considered equivalent to PR = 9.5, has been chosen at PR = 8.5 as being more consistent with the definition of Level 3 for the landing task.

Criteria for the short-period roots (λsp_1,λsp_2) are presented in Figure 4 for a restricted range of $Z_{\theta_2} = -1/T\theta_2$ (large zero of the θ/F_s transfer function) and desirable levels of control sensitivity, defined as follows:

$$.25 < M_\delta < .55 \text{ rad/sec}^2/\text{in}$$
$$2 < M_F < 4.5 \quad \text{deg/sec}^2/\text{lb - stick controller}$$
$$4 < M_F < 9 \quad \text{deg/sec}^2/\text{lb - wheel controller}$$

The dashed line labeled "critical" in Figure 4 separates the λsp_1, λsp_2 plane into two regions. Above the critical line, PR does not vary as the magnitude of λsp_2 increases at constant λsp_1. Below the line, PR decreases sharply with the magnitude of λsp_2. Apparently, pilots find airplane dynamics in the upper region uniformly mediocre, but a boundary exists past which flying quality deteriorates rapidly.

The criteria in Figure 4 are specified at three different levels of turbulence. These correspond closely to the three levels specified in MIL-F-8785C. The specification was released in November 1980, after all of the simulation was completed. The differences are probably undetectable by the pilots.

Turbulence Level (Simulation)	σ_w ft/sec	Turbulence Level (MIL-F-8785C)	σ_w ft/sec	Exceedence Probability
Negligible	2.5	Light	2.5	10^{-1}
Moderate	5.2	Moderate	5.1	10^{-3}
Heavy	7.2	Severe	7.6	10^{-5}

The right hand boundary in Figure 4 at $\lambda sp_1 = .35$ ($T_2 = 2$ sec) is not based on specific data. Rather, it reflects the lack of any data for larger values of λsp_1, the rapidity of a two second divergence, and the certainty that such a boundary does exist for some λsp_1 larger than .35.

Figure 5 compares the actual pilot ratings obtained from the simulator to the proposed criteria. Agreement is quite good. Corrections to the pilot ratings for aircraft with Z_{θ_2} or $M_{\delta_{ES}}$ outside the nominal values have been developed, but are not given here due to space limitations. The corrections appear in Reference 1, and some of the data upon which they are based is presented in Figures 8 and 9. The effect of Z_{θ_2} is profound. The effect of low sensitivity ($M_{\delta_{ES}}$) can be quite deleterious.

RSS Neal-Smith Criterion

An alternative approach employing the closed-loop frequency-response analysis techniques of Neal and Smith (Ref. 6) has been developed which does not depend on the specific form of the transfer functions. It may be presumed that if criteria for RSS airplanes can be developed using the normal form of the θ/F_s transfer function, then these criteria will apply to higher order systems as well. Of course, the assumption must be tested and proved valid. The beauty of the Neal-Smith approach is that is should be able to handle simultaneously the low frequency problems attributable to RSS and the high frequency problems associated with higher order responses and excessive control system lags.

The criterion of Neal and Smith (Ref. 6) has been modified to make it applicable to the assessment of flying qualities for airplanes with relaxed static stability. The data presented here are based directly on the fixed-base ground simulator investigation of approach and landing, with some extrapolation made to broaden the applicability of the criterion. The criterion, as modified for application to conditions of relaxed static stability, is called the RSS Neal-Smith Criterion. It is based upon a closed-loop analysis of a pitch attitude system consisting of a pilot model and the airplane pitch attitude transfer function.

A modified pilot model is used for application to RSS or cases with low static stability where pilot lead above 85 deg is needed to achieve the higher bandwidths.

$$Y_p(s) = K_p e^{-0.3s} \frac{(\tau_{p_1} s + 1)(\tau_{p_3} s + 1)}{(\tau_{p_2} s + 1)}$$

$1/\tau_{p_3}$ = BW
BW = 1 and 3 rad/sec
Droop = 0 db

Changes from the standard Neal-Smith criteria are 1) the added lead term, 2) minimization of pilot lead (ϕ_{PL}) instead of resonant amplitude (RA), and 3) the simultaneous application at two specific bandwidth frequencies (BW) instead of one. The selecion of zero droop follows directly from the thesis that minimization of pilot lead is the primary adjustment criterion. The selection of $1/\tau_{p_3}$ = BW, and criterion based on two bandwidths, 1 and 3 rad/sec, were arrived at from extensive analysis and correlation of the pilot rating data as described in Reference 1.

To represent flying qualities for a given aircraft, K_p and the τ's in the pilot model are adjusted. For stable aircraft, they are adjusted to minimize the amplitude ratio (AR) of the closed loop response; for unstable aircraft to minimize the phase lead of the pilot transfer function (ϕ_{PL}). Bandwidth (BW) is defined as the frequency at which -90^0 phase response occurs for the closed-loop system. An additional criterion dealing with "droop" is invoked. Droop is defined as the minimum AR measured between .1 rad/sec and the BW frequency. Droop must be between 0 and -3 db at some frequency between .1 rad/sec and the BW frequency.

With the above criteria, the relationship between flying qualities and the parameters Φ_{PL} and resonant amplitude of the closed-loop transfer function (RA) have been developed from the simulation data base, and are shown on Figure 6.

The Neal-Smith PR = 6.5 boundary has been somewhat arbitrarily used as a cut-off of resonant amplitude for the Level 2 boundaries at bandwidth (BW) = 1 rad/sec. The Neal-Smith Level 1 boundary is used to indicate potential approach to Level 1 flying qualities for relaxed static stability, though caution should certainly be used in allowing any airplane with marginal, neutral, or a lack of longitudinal static stability to be considered Level 1.

For BW = 3 rad/sec, the boundaries have been extended from 80^0 to 125^0 of pilot lead. The Level 2, heavy turbulence boundary is reasonably well established by the simulator data. The remaining boundaries involve substantial extrapolation, especially the Level 3 boundary. This Level 3 boundary passes through the PR = 8.5 data for moderate turbulence at $\Phi_{PL} = 110^0$, with a slope judged consistent with the rest of the data. The PR = 8.5 data for heavy turbulence has almost the same iso-rating as that for moderate turbulence, and extrapolation indicates the same for negligible turbulence. The boundaries are drawn to $\Phi_{PL} = 80^0$ to indicate that this is an appropriate value at which to shift from the standard Neal-Smith approach to the RSS approach with its additional pilot lead term. However, with the RSS approach, a pilot lead of less than 80^0 is readily obtainable. The boundaries are extended to 125^0, with a cut-off indicated.

The analysis of the simulator pilot rating data with the proposed RSS Neal-Smith approach using a resonant amplitude vs. pilot lead criterion provides excellent correlation of the data for a bandwidth of 1 rad/sec. The results appear to provide a good basis for developing a criterion for flying qualities of airplanes with relaxed static stability. Figure 7 shows a portion of the pilot rating data from which the proposed criterion was developed. Establishment of the new criterion for BW=1 is relatively clear; however, the results of the analysis for a bandwidth of 3 rad/sec are not as satisfactory. Some modification to the approach seems indicated.

From the experimental data it is clearly apparent that the pilot varies bandwidth during the course of an approach and landing, and criteria for both high and low bandwidths are necessary. However, the high bandwidth criteria for BW = 3 rad/sec is based on data which did not severely excercise

high frequency problems. These are normally associated with sluggish control system dynamics and too much lag or time delay in the control system. Both feel system and actuators had reasonably high natural frequencies and good rapid response for the data on which the criteria are based. It would be very desirable to combine slower control system dynamics with relaxed static stability to further test and establish the boundaries for the high bandwidth criteria.

Conclusions and Recommendations

1. The long held criteria for the amount of static instability in pitch allowable, a time-to-double amplitude of less than 6 seconds, is essentially an invalid criteria. Other parameters in the θ/F_s transfer function are found equally, if not more, important.

2. The results of fixed-base ground simulation of approach and landing show that criteria for relaxed static stability can be based on four primary parameters, the value of the short period roots (λ_{sp_1} and λ_{sp_2}, the small positive root and the large negative root), the large zero in the θ/F_s transfer function (Z_{θ_2}), and the control sensitivity ($M_{\delta_{Fs}}$ or M_{F_s}). For the criteria to hold, the phugoid roots must be small.

3. Alternate frequency domain criterion, based on the closed-loop characteristics of θ/F_s developed by Neal and Smith (Ref. 6), can satisfactorily handle all the above parameters with the exception of control sensitivity. This frequency response approach looks promising as the criteria are able to account for phugoid as well as control system and higher-order characteristics.

4. Ground simulator investigations should be performed to extend the results to larger values and more combinations of parameters for approach and landing, and to other flight conditions.

5. The frequency domain approach to criteria for relaxed static stability should be further developed as it appears to offer more promise than other approaches (parametric, or equivalent system). The following specifics are recomended.

   a. Improve pilot model by adding lag to go with lead added for RSS.

   b. Apply technique to additional existing data.

   c. Develop BW = 3 rad/sec RSS criteria by applying to RSS cases with degraded actuators and feel systems.

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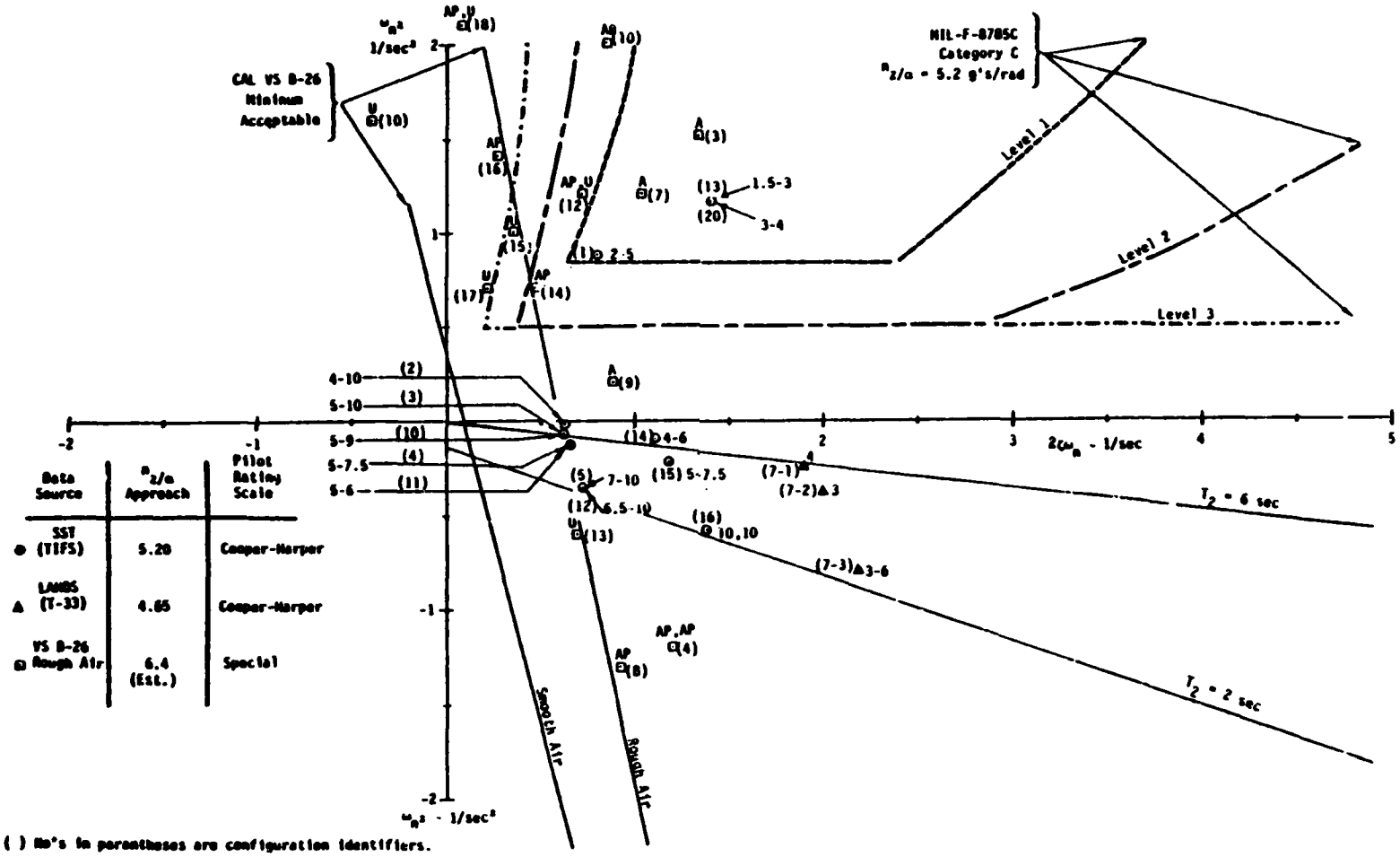
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( ) No's in parentheses are configuration identifiers.

Numbers beside points are Cooper-Harper pilot ratings. B-26: A = Acceptable; AP = Acceptable Poor; U = Unacceptable. Two repeats separated by commas. Range is shown (e.g.,6.5-10) for multiple ratings or repeats.

Figure 1. Flight Data on Minimum Longitudinal Stability, ω_{n2} vs $2\zeta\omega_n$

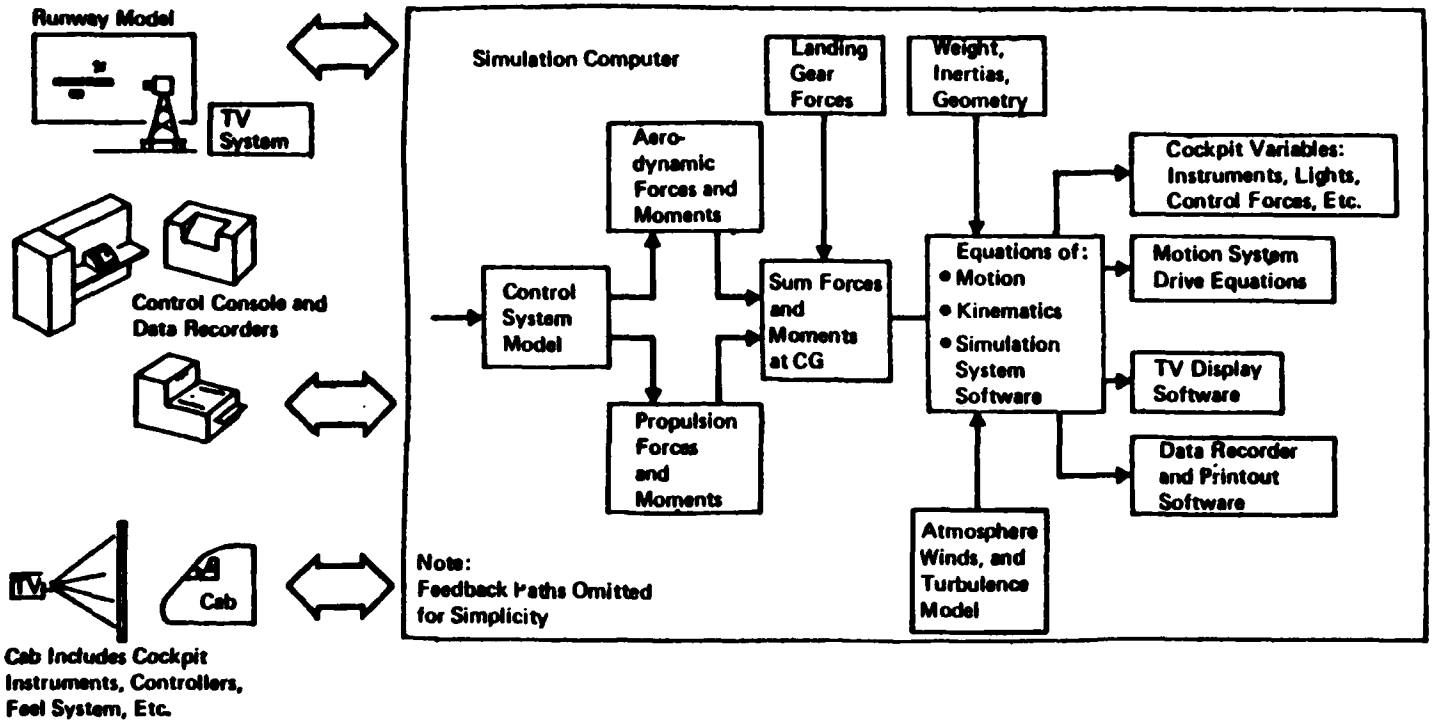


FIGURE 2. SIMULATOR SCHEMATIC

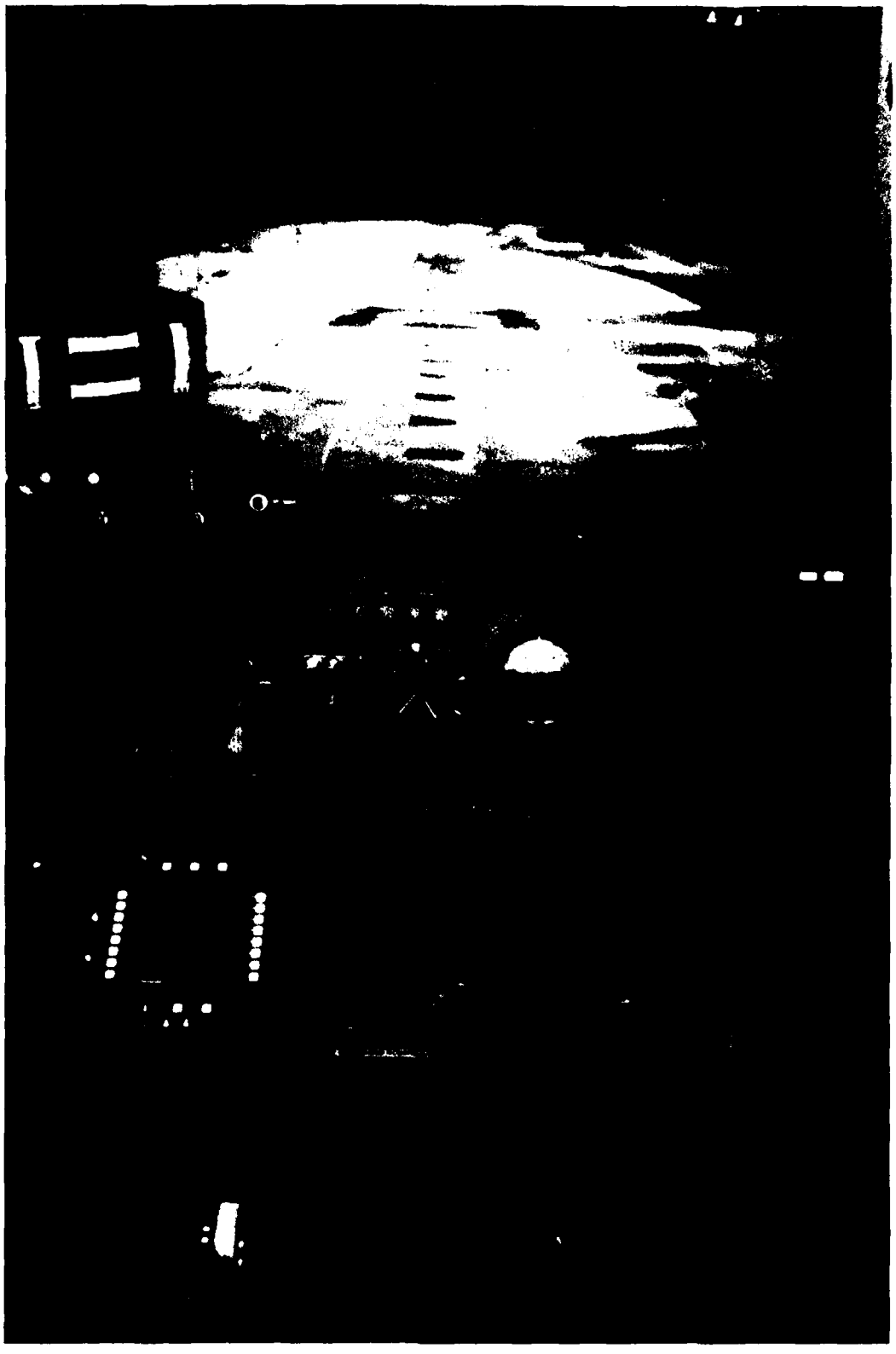


FIGURE 3. COCKPIT CONTROLS, INSTRUMENTS, AND LANDING VISUAL SCENE

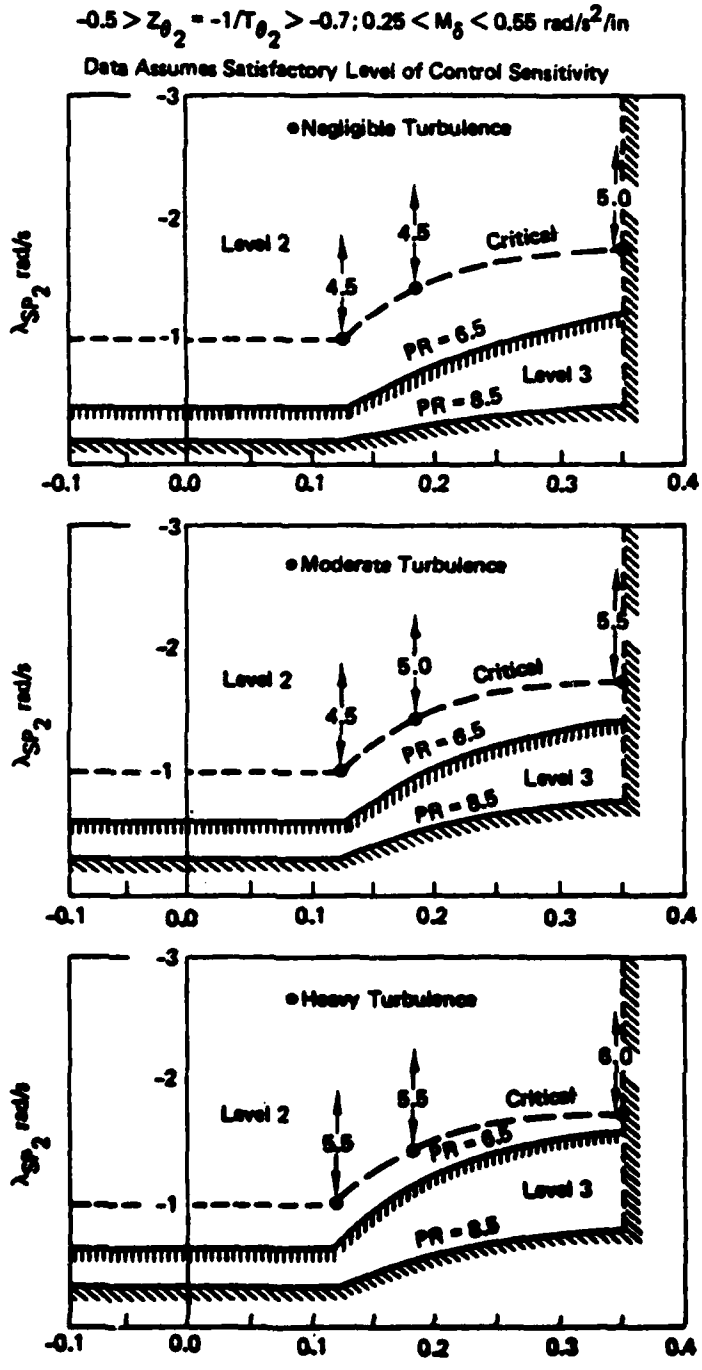


FIGURE 4. RELAXED STATIC STABILITY (RSS) CRITERIA FOR SHORT-PERIOD ROOTS $\lambda_{SP_1}, \lambda_{SP_2}$ IN APPROACH AND LANDING

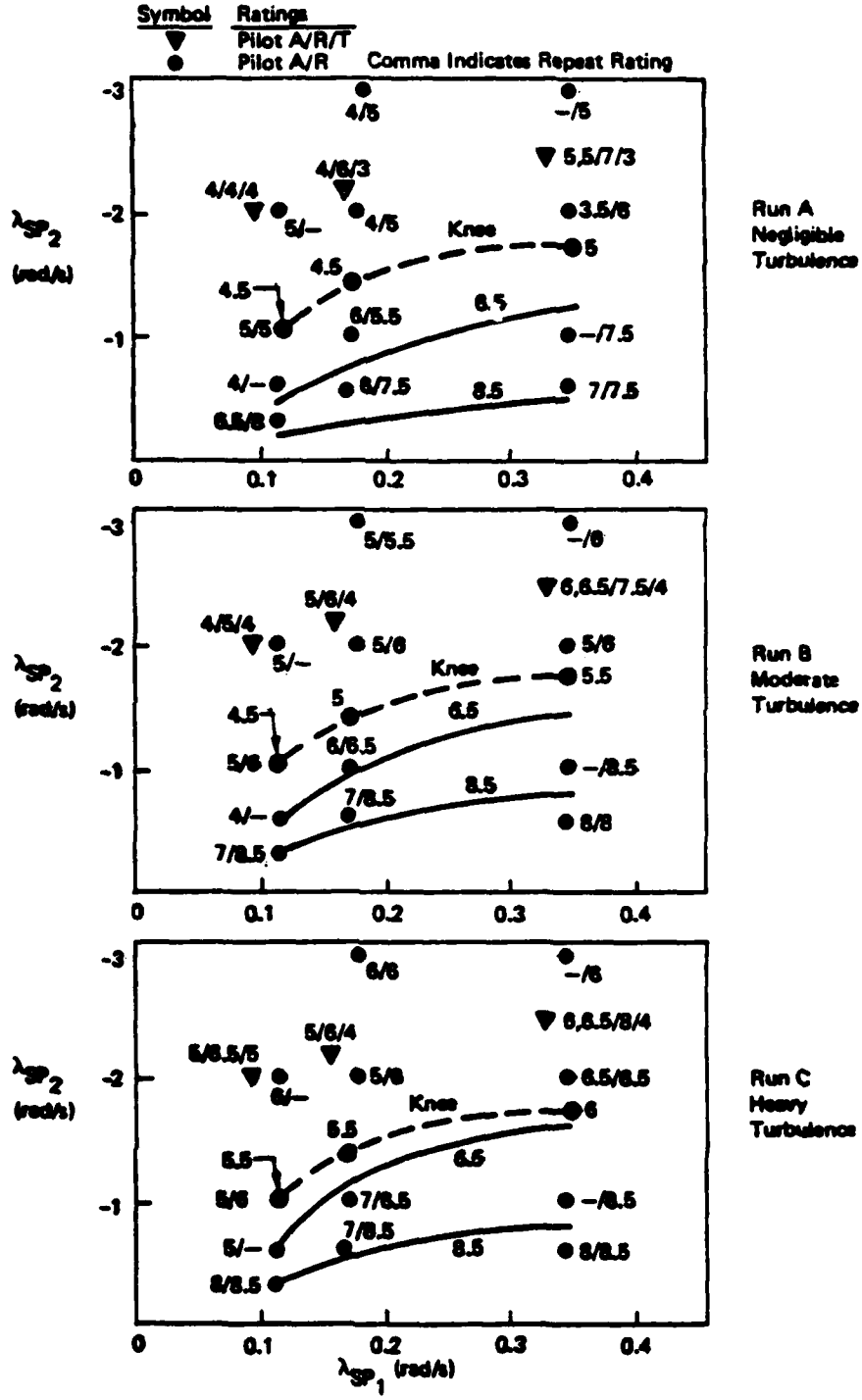


FIGURE 5 PILOT RATING AS FUNCTION OF REAL ROOTS (λ_{sp_1}, λ_{sp_2})

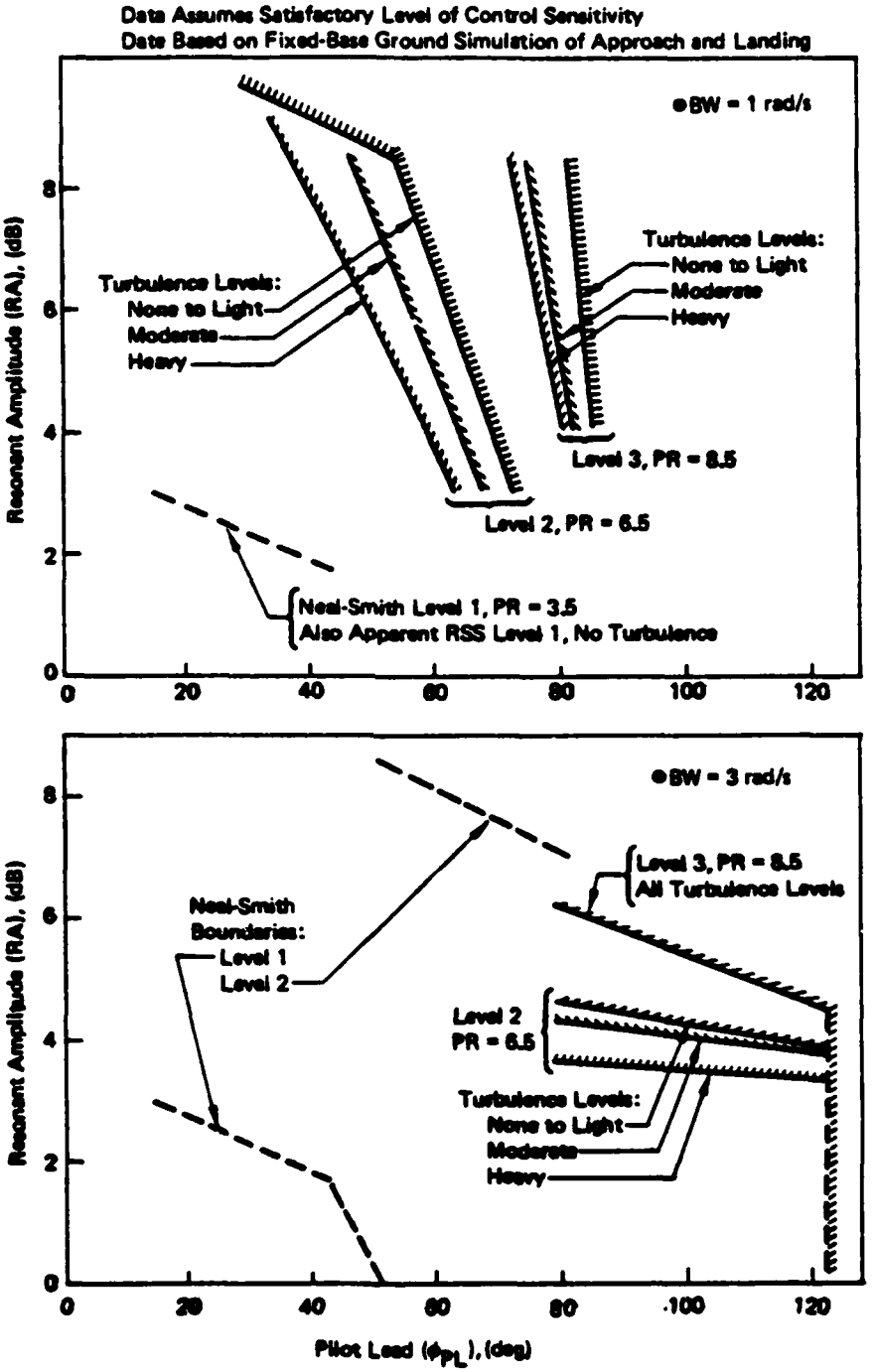


FIGURE 6 CRITERION FOR PITCH ATTITUDE DYNAMICS OF RELAXED STATIC STABILITY (RSS) AIRPLANE

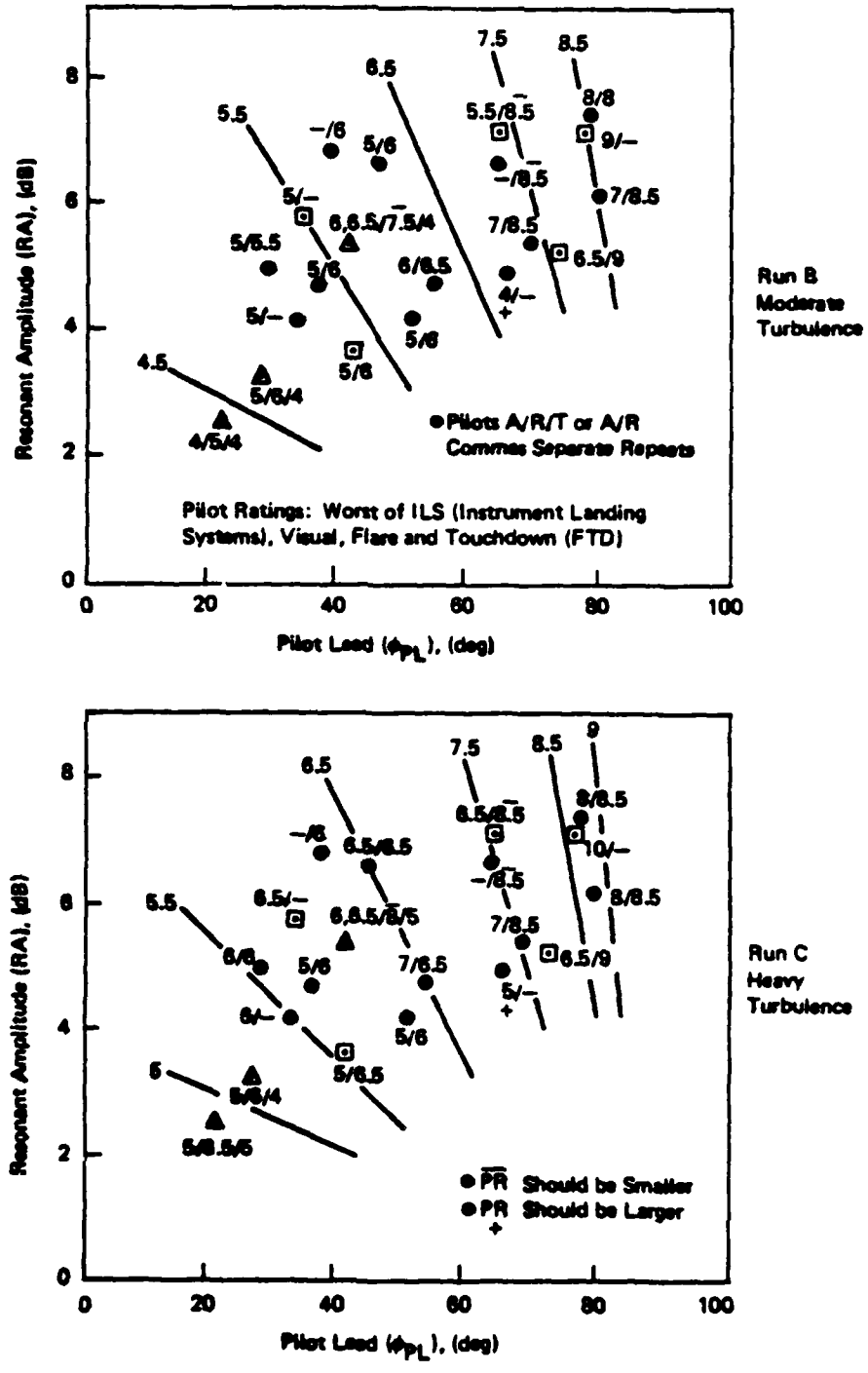


FIGURE 7. PILOT RATING AS A FUNCTION OF RESONANT AMPLITUDE AND PILOT LEAD

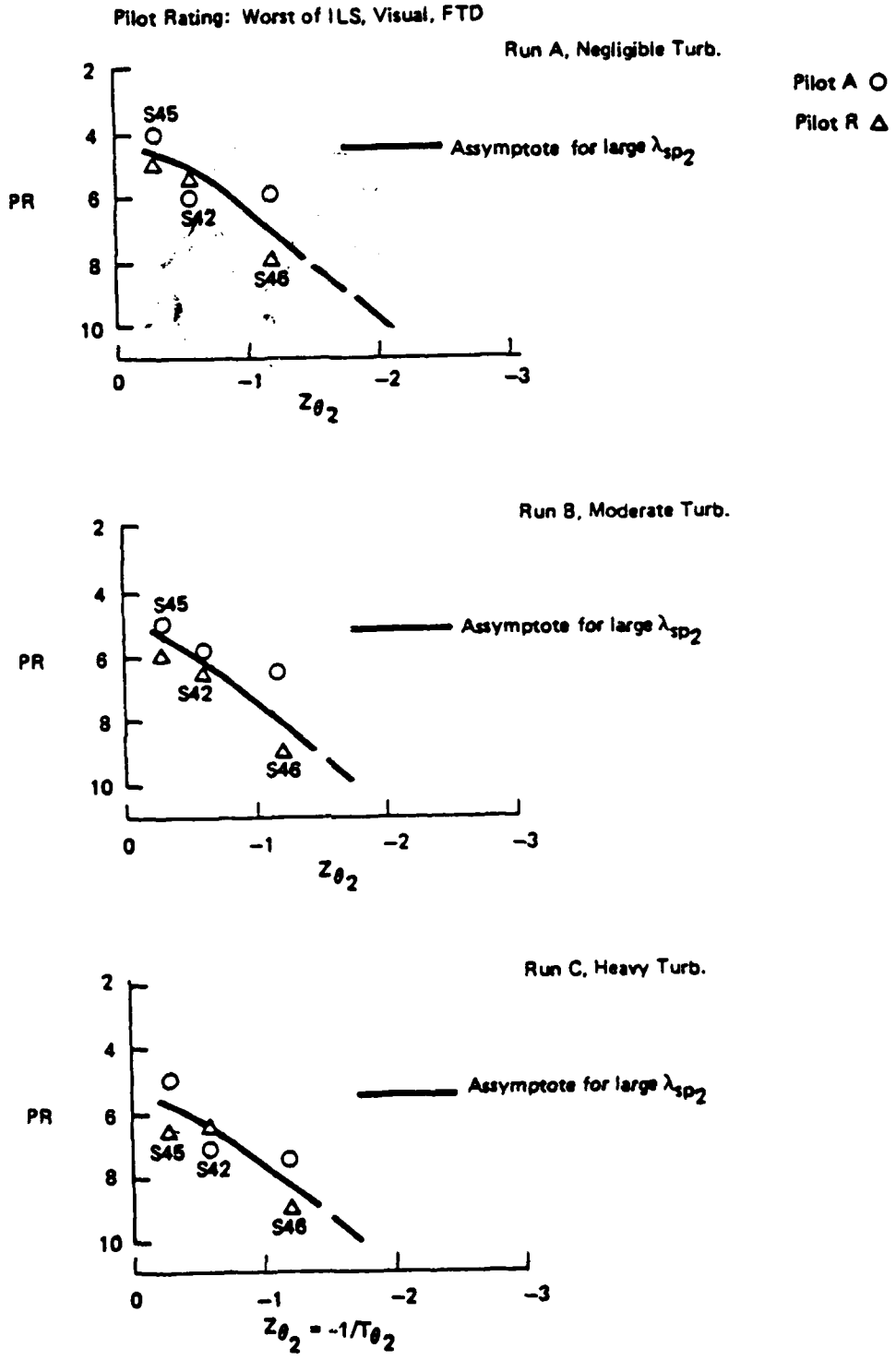


Figure 8. Pilot Rating vs. Zero of θ/F_s Transfer Function

$\lambda_{sp_2} = -1, T_2 = 4$ sec ($\lambda_{sp_1} = +.173$)

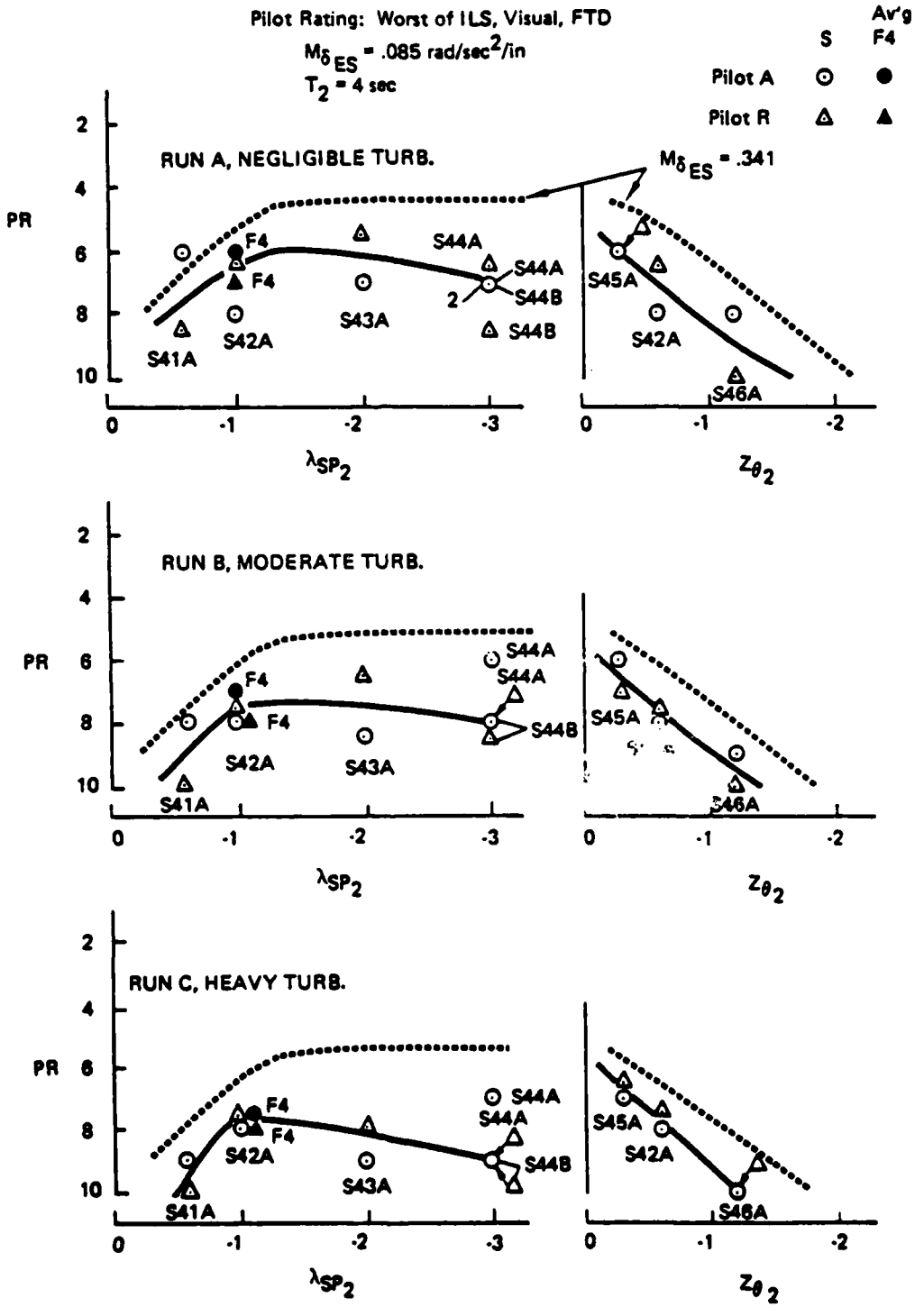


Figure 9 Effect of Control Sensitivity ($M_{\delta_{ES}}$) on Pilot Rating

A COMPARISON OF
PROPOSED MIL-HANDBOOK
DYNAMIC LONGITUDINAL FLYING QUALITIES CRITERIA

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ABSTRACT

Three alternative criteria described in the proposed MIL Handbook - Flying Qualities of Piloted Airplanes, are applied to the pitch response of the F-14A airplane. Shortcomings in the definition of each criteria are addressed and suggestions provided for corrections which will improve the correlation between alternative criteria. Among the criteria under consideration, the requirements of the current specification, MIL-F-8785C, with proper interpretation of the boundary conditions, should be retained as the primary method for describing dynamic pitch response characteristics.

NOMENCLATURE

SYMBOLS

g	-	Acceleration due to gravity - ft/sec^2
K	-	Gain
n/α	-	Acceleration sensitivity parameter - g's/rad
s	-	LaPlace operator
V	-	Velocity - ft/sec
α	-	Angle of attack - rad
δ	-	Control deflection - deg
θ	-	Pitch angle - rad
τ	-	Time delay - sec
ζ	-	Damping ratio
ω	-	Natural frequency - rad/sec
T_{θ_2}	-	Pitch numerator time constant - sec

ABBREVIATIONS

CAP	-	Control Anticipation Parameter
CAP'	-	Attenuated Control Anticipation Parameter
HOS	-	High Order System
LOES	-	Low Order Equivalent System

SUBSCRIPTS

BW	-	Bandwidth
e	-	Equivalent
nd	-	Non-dimensional
p	-	Phase response estimated parameter
sp	-	Short period
ss	-	Steady state

INTRODUCTION

The proposed MIL Standard - Handling Qualities of Pilot Airplanes, reference 1, will provide the military procuring activity with the freedom to specify the requirements it feels are necessary to develop an airplane with satisfactory handling qualities. General areas of concern are identified, with the detailed requirements to be specified for the design of each particular aircraft. With this approach, the procuring activity's engineers must decide the criteria format that is applicable to the aircraft being designed, as well as the appropriate numerical requirements. In order to assist them in this task, a Handbook, reference 2, is being prepared which provides recommended, as well as alternative, criteria for various applications. The procuring activity, then, will be required to become familiar with these requirements and their applicability to the particular design situation confronting them.

In the case of the pitch attitude response to pitch controller requirement, three alternative criteria are presented in the Handbook: 1) the equivalent systems approach, 2) a closed-loop bandwidth criterion, and 3) a time response criterion. Two boundaries are presented for the equivalent system approach - one correlated via the acceleration sensitivity parameter (n/α) and one via the pitch numerator time constant (T_{θ_2}). There are currently no time response criteria in the Handbook.

In this paper, the criteria presented in the Handbook were applied to the F-14A airplane and the results (in terms of levels of flying qualities) compared; both to gain an understanding of the methodologies required and the criteria's applicability.

SUMMARY OF CRITERIA

Equivalent Systems Criterion

The application of equivalent systems to high order system (HOS) aircraft responses has been widely discussed in the literature (references 3 - 5, for example). Briefly, the method consists of matching the high order frequency response, via the aid of a digital computer, with a low order equivalent system (LOES) defined by

$$\frac{\delta(s)}{\delta(s)} = \frac{K_\theta(s + 1/T_{\theta_2})e^{-\tau_e s}}{s^2 + 2\zeta_e \omega_e s + \omega_e^2} \qquad (1)$$

The match is conducted by individually varying the parameters of

...e LOES until the variance between the high and low order systems is minimized. This match is typically conducted in the frequency domain over a range of .1 to 10 rad/sec. (The frequency range may need to be modified to avoid phugoid contamination of the match). The modal parameters obtained from the LOES are then compared to the requirements of figure 1. It should be noted that this method is the one presented in the current specification, MIL-F-8785C, reference 6. The major problem associated with this procedure has been the question of whether $1/T_{\theta_2}$ should be restricted to the known aircraft value or allowed to be selected by the computer algorithm in the matching process.

The frequency, damping ratio and n/α requirements of figure 1 were developed from unaugmented aircraft analyses. The time delay requirements resulted from recent high order system aircraft flight tests. The frequency and n/α requirements of figure 1 can be correlated with pilot opinion ratings via the control anticipation parameter (CAP) which is a measure of the initial pitch acceleration to steady state normal acceleration response:

$$CAP = \frac{\ddot{\theta}(t=0^+)}{n_{z_{ss}}} = \frac{\omega_{sp}^2}{n/\alpha} \qquad (2)$$

An alternative correlating parameter ($1/T_{\theta_2}$) is proposed in the Handbook. The basis for this parameter arises from the fact that

$$\frac{n}{\alpha} = \frac{\Delta n/\delta}{\Delta \alpha/\delta} = \frac{V}{g} \frac{1}{T_{\theta_2}} \qquad (3)$$

and the assumption that data which correlate with n/α will also correlate with $1/T_{\theta_2}$. The controversy over whether the experimental data correlates better with n/α or $1/T_{\theta_2}$ has raged for a long time. The inclusion of the T_{θ_2} derived boundary in the Handbook is an attempt to allow the procuring activity to choose the criteria it feels is most appropriate. The T_{θ_2} boundary requirements are presented in figure 2.

Bandwidth Criterion

The bandwidth criterion attempts to measure an aircraft's response characteristics when operated in a closed-loop compensatory tracking task. The bandwidth is measured from the open loop frequency response as that frequency for which closed loop tracking can occur without threatening stability, as defined in figure 3. The phase margin choice of 45 deg is based on the condition that minimum acceptable closed loop damping ratio (ζ = .35) corresponds to an open loop phase margin of approximately 45 deg (reference 7). The 6 db gain margin results from the requirement that the magnitude of the response at the bandwidth frequency be at least twice that at the

condition for instability (Φ = -180 deg). The bandwidth criteria resulting from an analysis of the reference 8 flight test data is presented in figure 4.

CRITERIA APPLICATION

The criteria of figures 1, 2 and 4 were applied to the F-14A airplane in cruise configuration at 15,000 ft altitude. The F-14A airplane's pitch response to cockpit control position inputs was modelled from the wind tunnel and flight control system information of reference 9. The aircraft system description consisted of the bare airframe, a first order power actuator and compensated, washed-out pitch rate feedback, as outlined in figure 5. The cockpit control feel system was not included in this analysis.

RESULTS AND DISCUSSION

EQUIVALENT SYSTEM RESULTS

n/α Correlation

Equivalent system models for the F-14A airplane were developed in reference 5. The resulting modal parameters are plotted against the n/α criterion in figure 6. In all cases, the data indicate level I flying qualities.

The slowest speed data points (.5M) in figure 6 can be used to illustrate the $1/T_{\theta_2}$ fixed versus free controversy mentioned above. The frequencies plotted represent the values obtained from: a) the oscillatory root pair of the high order system, b) fixing $1/T_{\theta_2}$ at the known aircraft value, and c) allowing $1/T_{\theta_2}$ to be free in the search process. Each of the resulting frequencies lie within the acceptable level 1 region. However, the identified $1/T_{\theta_2}$ value, when freed in the search process, has nearly doubled, resulting in a very unrealistic value. In addition, calculation of the respective control anticipation parameters yields widely varying values as indicated on figure 6. Equivalent system models have been developed for other aircraft configurations (references 4 and 5) which indicate significant variations in identified flying qualities levels as $1/T_{\theta_2}$ is freed. Proponents of this procedure have argued that freeing $1/T_{\theta_2}$ yields a control anticipation parameter which more nearly approximates that measured from the time history responses as

$$CAP' = \frac{\ddot{\theta}_{max}}{n_{z_{ss}}} \qquad (4)$$

and more readily correlates with pilot opinion ratings (reference 4).

In utilizing this procedure, however, it must be recognized that the maximum pitch acceleration measured from actual aircraft responses is not the same as the initial pitch acceleration obtained from the short period approximation. Rather, it is generally a smaller value, having been attenuated from the short period approximate response by the interaction of the control system dynamics. In general, CAP and CAP' can be related by

$$CAP' = \frac{\omega_{sp}^2}{n/\alpha} \ddot{\theta}_{nd} \tag{5}$$

where $\ddot{\theta}_{nd}$ is a non-dimensional pitch acceleration attenuation factor. It equals the ratio of the maximum pitch acceleration, including control system dynamics, to the initial pitch acceleration, excluding such dynamics. Similar relationships are seen to exist between the high and low order equivalent system time responses. Therefore, an equivalent CAP' can be defined as

$$CAP'_e = \frac{\omega_e^2 \ddot{\theta}_{max\ HOS}}{n/\alpha\ \ddot{\theta}_{max\ LOS}} = \frac{\omega_e^2 \ddot{\theta}_{max\ HOS}}{n/\alpha\ K_\theta} \tag{6}$$

Applying these concepts to the example aircraft, the results presented in Table I are obtained. The correlation between the high and low order systems is seen to be improved for the attenuated control anticipation parameter and defines a consistent level of response. This procedure has been applied to various Navy aircraft with similar results (reference 5).

Table I

CONTROL ANTICIPATION PARAMETER COMPARISONS

F-14A Airplane - 0.5 Mach, 15,000 ft Altitude

Parameter	HOS	LOS	
		T_{θ_2} FIXED	T_{θ_2} FREE
ω_{sp}	2.78	2.36	2.74
n/α	12.7	12.7	21.9
$\ddot{\theta}(0^+)$	0.0	.277	.245
$\ddot{\theta}_{max}$	.200	.277	.245
$n_{z_{ss}}$	.701	.630	.714
$\omega_{sp}^2/n/\alpha$	.61	.44	.34
$CAP = \ddot{\theta}(0^+)/n_{z_{ss}}$	0.0	.44	.34
CAP'	.29	.32	.28

In order to be useful in the definition of levels of flying qualities, boundaries based on CAP' must be developed which will in general be different from those for CAP. The unaugmented aircraft data utilized to develop the specification boundaries of figure 1 were originally developed in support of the CAP' concept (reference 10). Assuming the CAP' values developed in reference 10 to be applicable, the parameter plane presented in figure 7 results, where the abscissa is defined as

$$\omega_{EFF} = \omega_{sp}\sqrt{\theta_{nd}} = \sqrt{(CAP')(n/\alpha)} \qquad (7)$$

When viewed in this manner, similar results are obtained for the high order system, and both the $1/T_{\theta_2}$ fixed and free low order equivalent systems.

ωT_{θ_2} Correlation

The equivalent system results for the F-14A airplane are presented against the ωT_{θ_2} requirements in figure 8. The data again indicate level 1 flying qualities for all conditions investigated. However, further examination of the data reveals discrepancies when comparing the minimum frequency requirements obtained from the ωT_{θ_2} requirement versus those obtained from the n/α requirement.

For any particular flight condition (i.e. - velocity and T_{θ_2} known), it should be possible to calculate minimum frequency requirements from the minimum CAP and ωT_{θ_2} requirements. For example, at a flight condition of .7M, 15,000 ft altitude, the minimum frequency requirements of Table II are obtained for the F-14A airplane.

Table II

F-14A Airplane Minimum Frequency Requirements

0.7 Mach, 15,000 feet altitude

$1/T_{\theta_2}$ = .962 /sec n/α = 21.9 g's/rad

Specification Requirement	Minimum Frequency
CAP = 0.28 (rad/sec) /g	ω_{sp} = 2.48 rad/sec
ωT_{θ_2} = 1.6 rad	ω_{sp} = 1.54 rad/sec

The ωT_{θ_2} boundary, when viewed in this manner is found to be more lenient than the CAP boundary. These same discrepancies are noted for other aircraft and flight conditions in figure 9, where the ωT_{θ_2} boundaries for a constant value of CAP (.28) are presented. From this figure, it can be seen that constant

.alues of ωT_{θ_2} can be determined which approximate the CAP requirements of figure 1. However, that value of ωT_{θ_2} is peculiar to each aircraft and altitude. It is not the purpose of this analysis to debate the merits of correlating short period frequency with n/α vice $1/T_{\theta_2}$ for any particular aircraft. That question has received considerable attention in the literature, with various conclusions being stated. It is important, however, to realize the limitations of establishing universal requirements based on such correlations.

BANDWIDTH RESULTS

Bandwidth results for the F-14A airplane at 15,000 ft altitude are plotted against the proposed criteria in figure 10. Only one of the flight conditions analyzed (Mach number = 1.2) lies within the level 1 boundary. These results are in contradiction to the results presented above.

The acceleration sensitivity and bandwidth criteria are both developed from the classical pitch attitude response to control input transfer function:

$$\frac{\theta(s)}{\delta(s)} = \frac{K_\theta(s + 1/T_{\theta_2})e^{-\tau s}}{(s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2)\, s} \qquad (8)$$

The n/α criteria reflect the pilot's desire for increased frequency response as speed and/or $1/T_{\theta_2}$ increase (i.e. as n/α increases). In addition, limits are placed on the acceptability of damping ratio and time delay. In this manner, short period requirements are defined by a minimum of 4 parameters, ω_{sp} , ζ_{sp} , n/α and τ , with the overall level being defined as that of the worst parameter. The bandwidth criteria proposes to reduce the problem to the specification of 2 parameters - bandwidth frequency and time delay. The bandwidth frequency is put forth as a measure of the frequency response which accounts for $1/T_{\theta_2}$, ω_{sp} , ζ_{sp} and τ . Further, it is hypothesized that pilot opinion ratings, and therefore, flying qualities levels can be correlaed via the two parameters; bandwidth frequency and time delay.

Based on the augmented aircraft flight test data of reference 8, the bandwidth boundary between level 1 and level 2 flying qualities is established at a frequency of 6.5 rad/sec (for low values of time delay). Attempts to correlate the unaugmented aircraft of reference 10 via the bandwidth criterion results in a lower level 1 boundary (ω_{BW} = 4 rad/sec) as shown in the Handbook. This disagreement is left unresolved, with the inference that the evaluation tasks for the unaugmented aircraft may not have been demanding enough to promote pilot objections to aircraft characteristics. Although this may be a possible explanation, it should give rise to objections to the quality of the unaugmented aircraft criteria. However, the Handbook acknowledges that the unaugmented aircraft criteria are well

established and documented by the reference 10 data.

Further discrepancies are noted when the unaugmented configurations of the Neal-Smith data are analyzed with the reference 10 data as shown in figure 11. Those configurations which have level 1 damping ratios correlate well with the unaugmented data. (The reference 10 configurations all have level 1 damping ratios.) However, configurations 4A and 5A, which have low damping ratios, only correlate via a high bandwidth requirement (6.5 rad/sec), whereas configurations with level 1 damping ratios result in lower acceptable bandwidths. Based on these observations, closer analysis of the bandwidth hypothesis was undertaken.

Frequency responses for equation (8) with ω_{sp} = 5 rad/sec, $1/T_{\theta_2}$ = 1.25, and various damping ratios and time delays were developed. The resulting gain and phase characteristics are presented in figure 12. Using the definitions of figure 3, bandwidth is seen to be a function of damping ratio as well as time delay at any particular value of $1/T_{\theta_2}$ and ω_{sp}. Similar curves can be developed for variations in $1/T_{\theta_2}$ and/or ω_{sp}, resulting in the complex parameter maps of figure 13. Restricting the discussion to values of $1/T_{\theta_2}$ = 1.25/sec, ω_{sp} = 5 rad/sec (i.e. Neal-Smith configurations 2, 4A and 5A) the bandwidth parameter plane appears as shown in figure 14. Defining acceptable bandwidth as being greater than 6.5 rad/sec, eliminates a large number of configurations which are acceptable by the current damping ratio ($.35 \leq \zeta_{sp} \leq 1.3$) and time delay ($\tau \leq .07$) criteria. Neal-Smith configurations 4A and 5A, which were driving factors in establishing the acceptable bandwidth range, are seen to correlate with the revised boundaries. Generation of bandwidth contours for configurations with limiting values of the control anticipation parameter (CAP = .28, 3.6) compare favorably with Neal-Smith configurations 1- and 3- as shown in figure 15.

This analysis indicates that while the bandwidth parameter provides a measure of the important parameters in an aircraft's pitch attitude response, it is also highly sensitive to those parameters.

Utilizing the acceptable regions for the classically defined short period values, differing regions of acceptable bandwidth can be defined for each aircraft flight condition. In order to determine the proper acceptable region for each flight condition, the basic $1/T_{\theta_2}$ and ω_{sp} parameters, to which the high order system can be related, must be determined. One way of accomplishing this is to utilize the equivalent system response as the starting point for determining acceptable bandwidths.

The F-14A airplane was analyzed in this manner. First, equivalent frequency and $1/T_{\theta_2}$ (fixed) values were obtained for each flight condition. Using these values as starting points, regions of acceptable bandwidths were defined with

$.35 \leq \zeta_{sp} \leq 1.3$, $\tau \leq .07$. The bandwidths of the complete high order system responses were then plotted versus these criteria boundaries. The results are presented in figure 16. The F-14A airplane's response to control position inputs (as measured by bandwidth) is now seen to exhibit level 1 flying qualities at each of the flight conditions analyzed; in agreement with the results of the n/α criteria.

In this manner, the bandwidth parameter serves as a measure of the acceptability of the equivalent system match and provides little information beyond that obtained from the equivalent system results.

The bandwidth parameter is an effective means of obtaining information concerning the overall frequency response of an arbitrary system. However, in the form in which it has been presented, its use appears to be limited to those applications which require a fixed speed of response, regardless of operating condition - such as in the decoupled force modes for which it was originally developed.

CONCLUSIONS AND RECOMMENDATIONS

Based on an analysis of the F-14A airplane, the proposed MIL-Handbook ωT_{θ_2} and bandwidth criteria for pitch response to pitch controller inputs are inconsistent with the ω vs n/α requirements. The minimum ωT_{θ_2} boundary results in minimum frequency requirements which are less than those obtained from the minimum CAP boundary. The bandwidth parameter, while encompassing the frequency, damping ratio, time delay and numerator time constant parameters in evaluating the characteristics of a particular frequency response, fails to allow for acceptable variations in these same parameters when specifying boundary conditions.

The equivalent systems criteria, correlated with n/α, should be retained as the primary method of evaluating pitch response to pitch controller input dynamic characteristics. The problems associated with fixing or freeing $1/T_{\theta_2}$ in the equivalent system search routines can be resolved through correlation with the attenuated control anticipation parameter (CAP'). Additional work is necessary to determine the influence of various control system configurations on the determination of CAP' boundaries.

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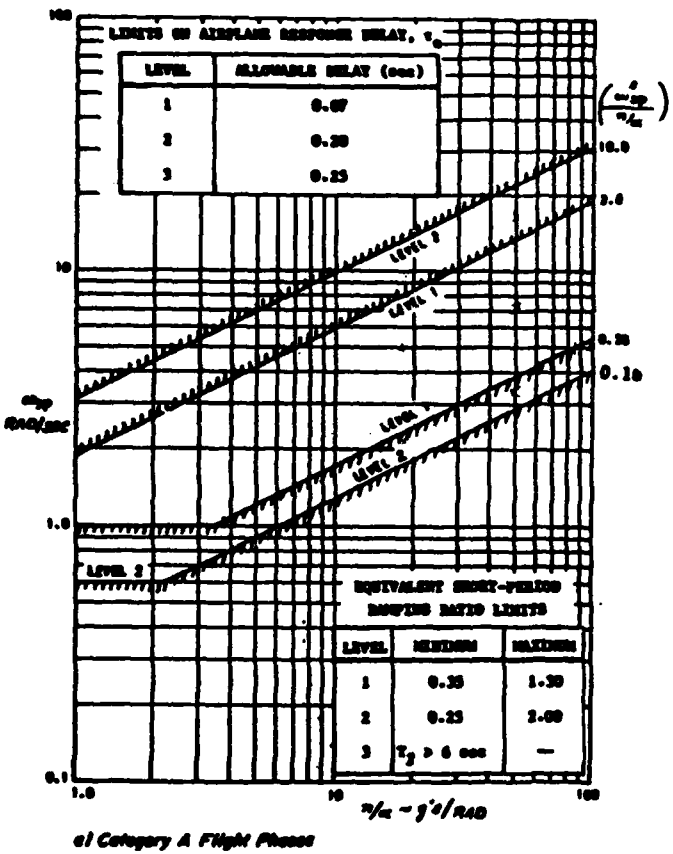
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a/ Category A Flight Phase

Figure 1: Short Term Pitch Response Requirements
n/α Correlation

EQUIVALENT SHORT PERIOD
FREQUENCY LIMITS - (rad/sec)

LEVEL	MINIMUM
1	1.0
2	0.6
3	-

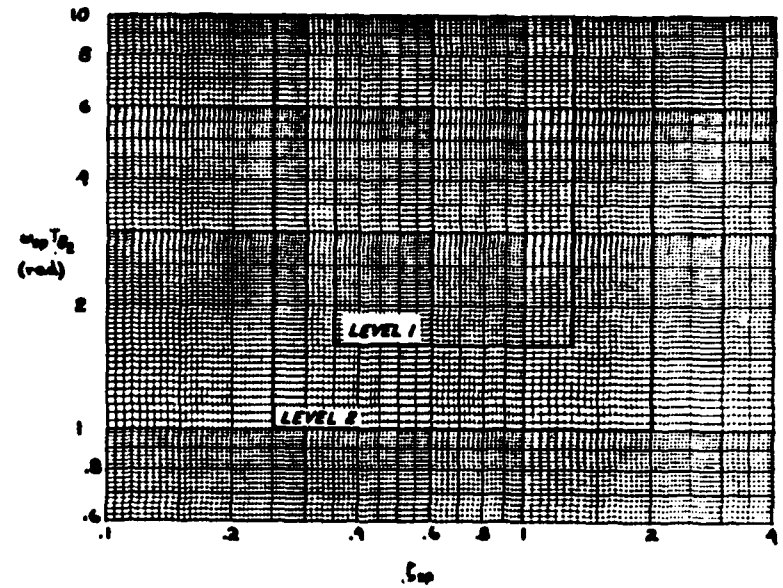


Figure 2: Short Term Pitch Response Requirements
ωT_{θ_2} Correlation

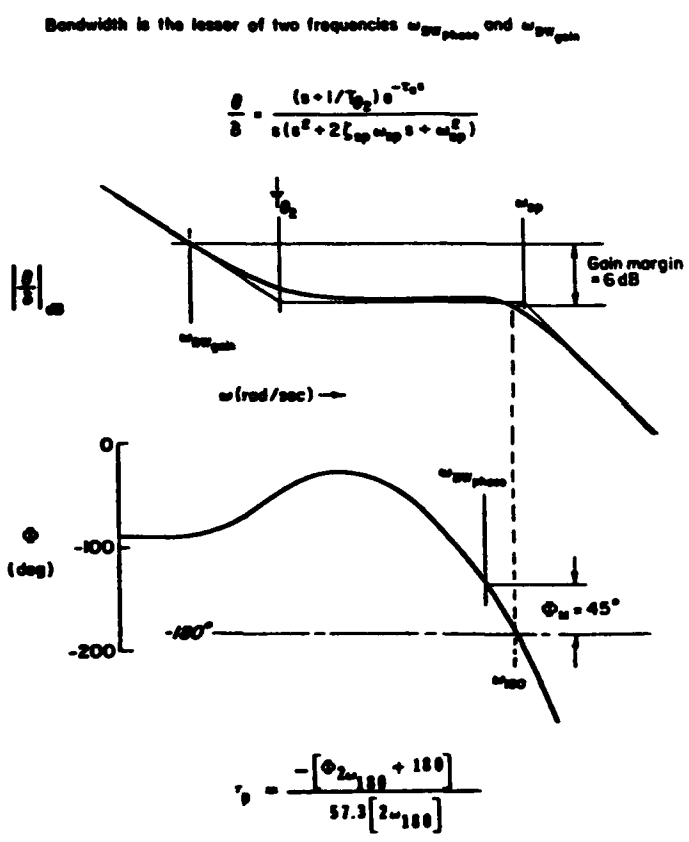
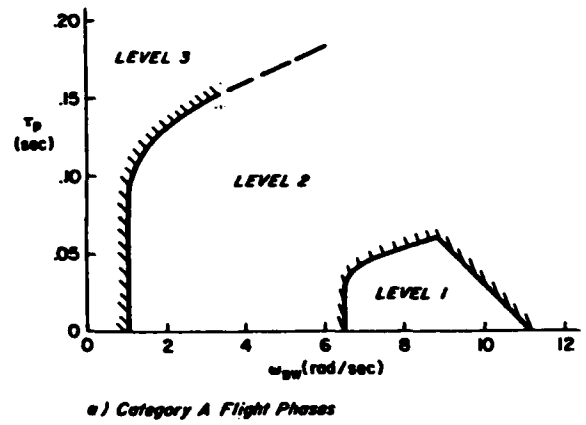


Figure 3: Bandwidth Frequency Definition



a) Category A Flight Phases

Figure 4: Short Term Pitch Response Bandwidth Requirements

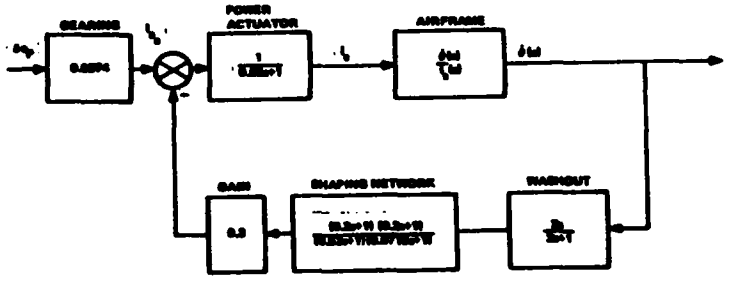


Figure 5: F-14A Airplane Block Diagram - Longitudinal Axis

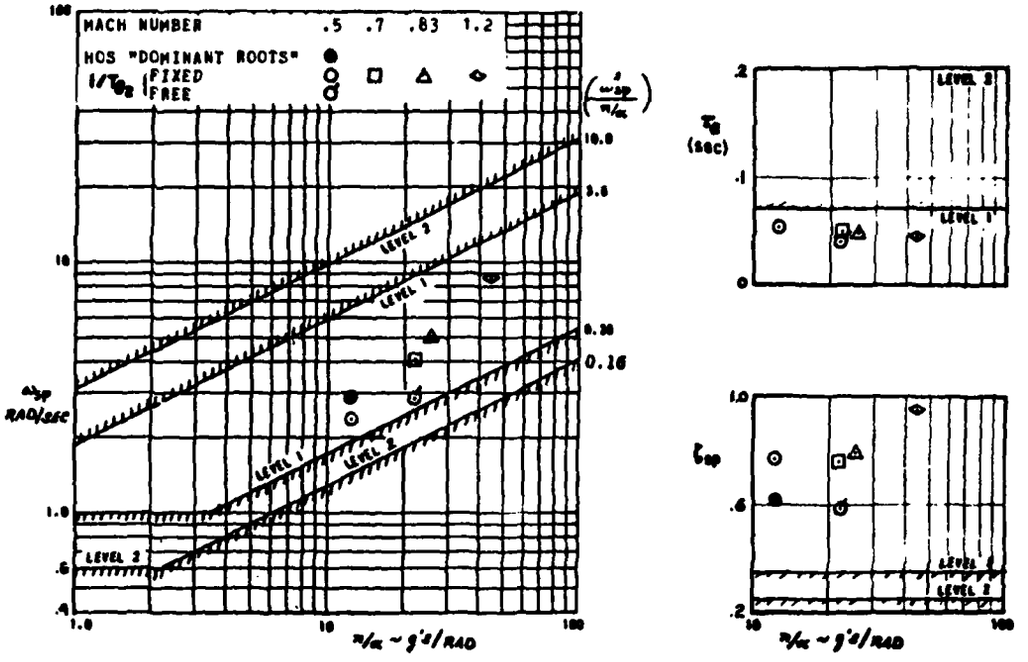


Figure 6: F-14A Airplane Short Term Pitch Response Results
n/α Correlation

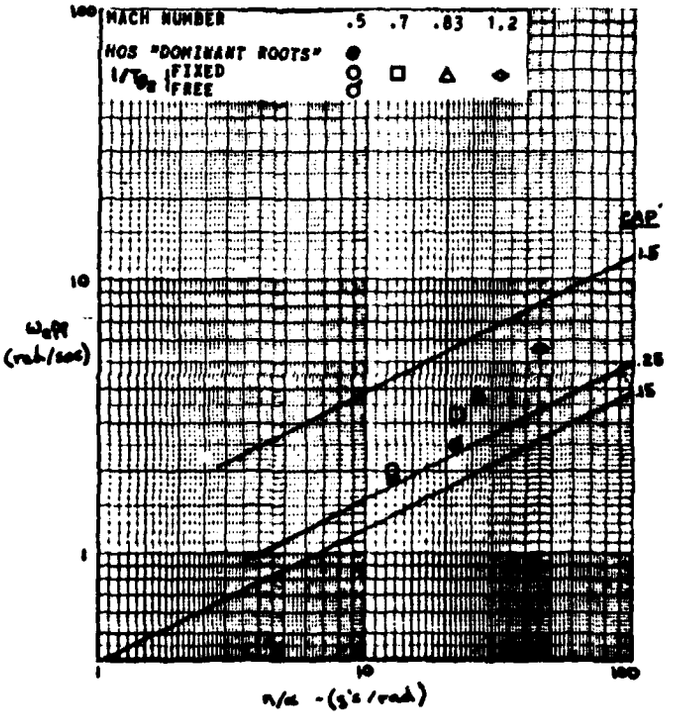


Figure 7: F-14A Airplane Short Term Pitch Response Results
CAP' Correlation

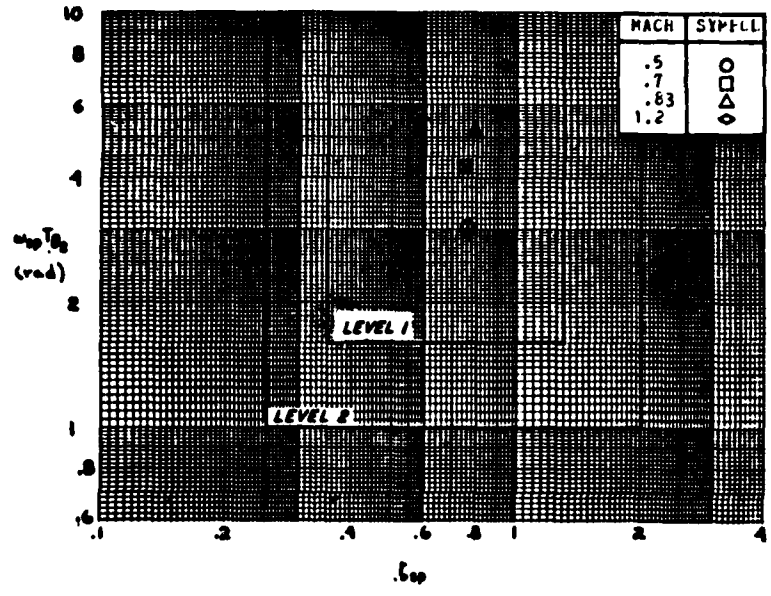


Figure 8: F-14A Airplane Short Term Pitch Response Results ωT_{θ_2} Correlation

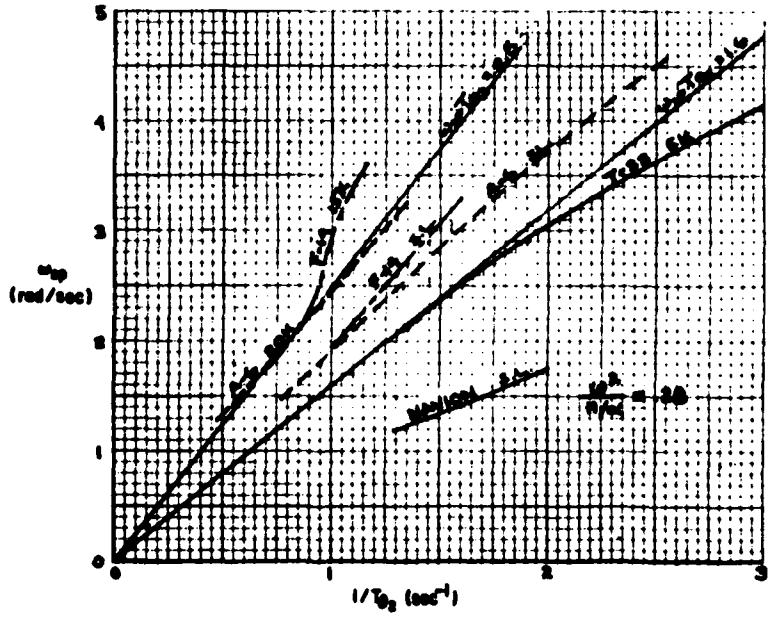


Figure 9: Comparison of ωT_{θ_2} Boundaries for Minimum Level 1 CAP

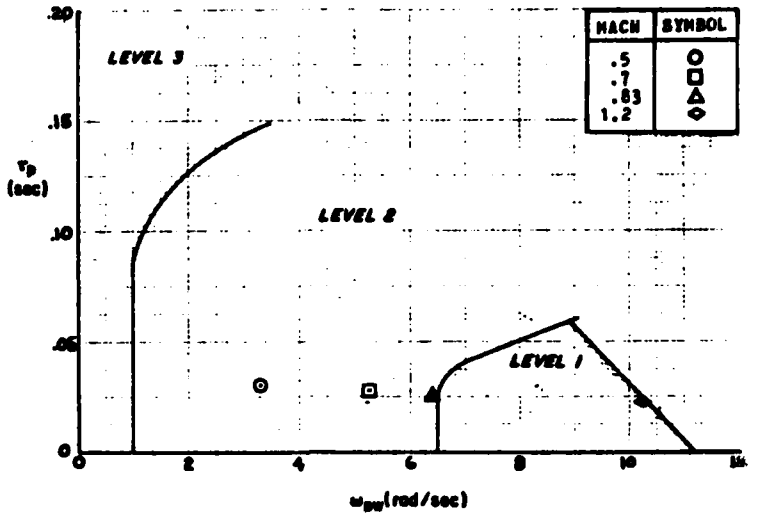


Figure 10: F-14A Airplane Short Term Pitch Response Results Bandwidth Correlation

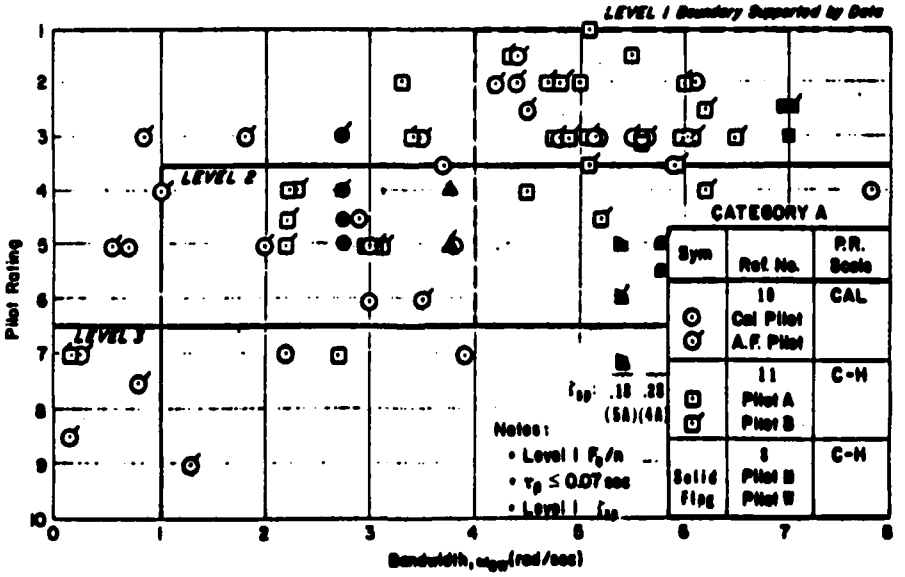


Figure 11: Comparison of Short Term Pitch Response Pilot Ratings with Bandwidth - Unaugmented Airplanes

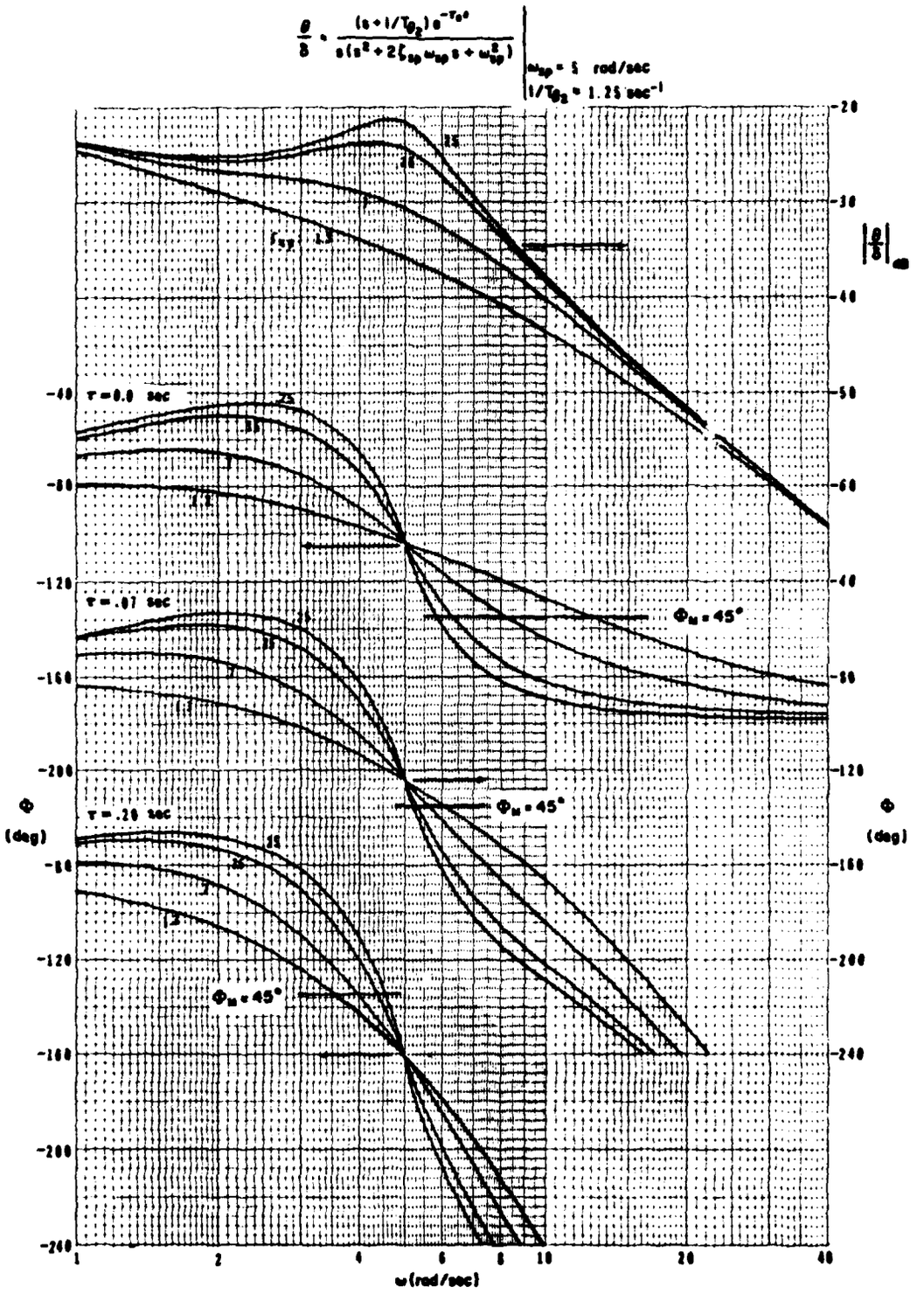


Figure 12: Pitch Attitude to Control Input Frequency Response Characteristics
ω_{sp} = 5 rad/sec, $1/T_{\theta_2}$ = 1.25 /sec

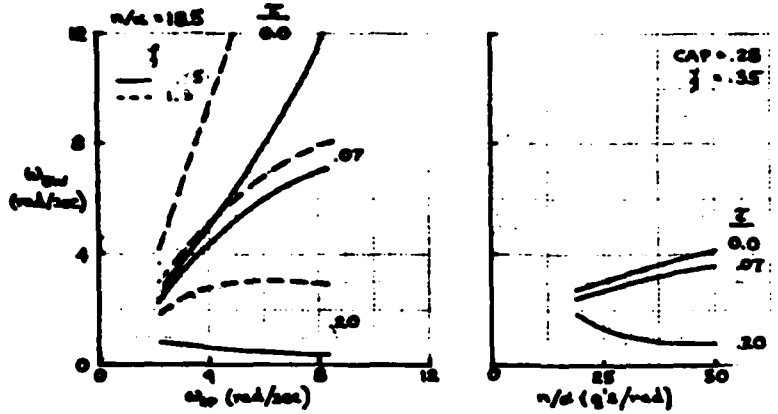


Figure 13: Variation of Bandwidth with Classical Short Period Parameters

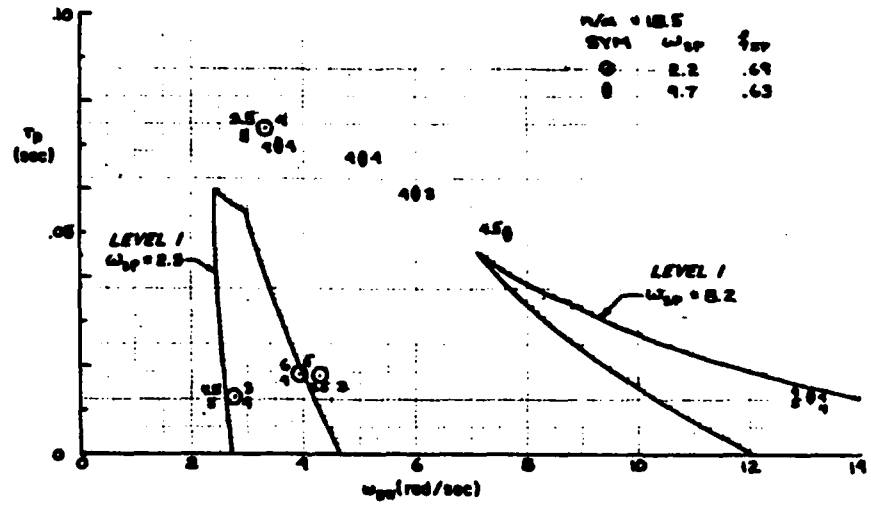


Figure 15: Revised Bandwidth Correlation of Neal-Smith Data Configurations 1- and 3-

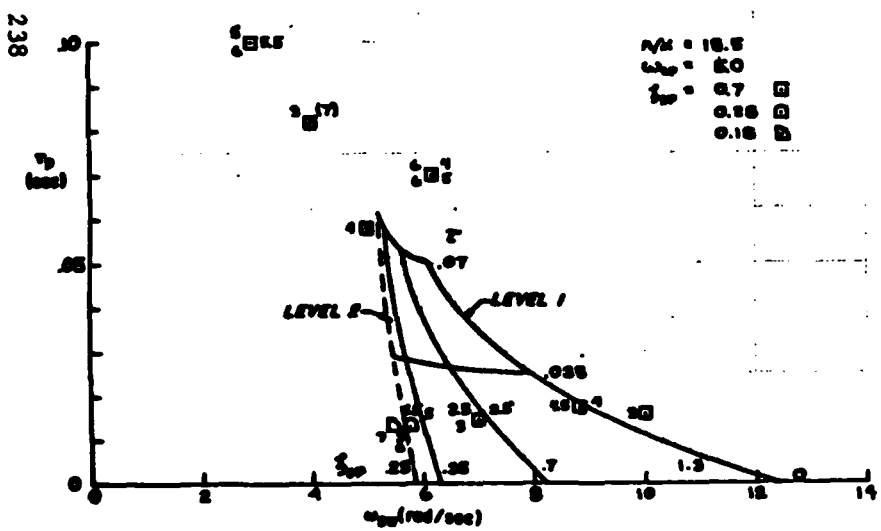


Figure 14: Revised Bandwidth Correlation of Neal-Smith Data Configurations 2-, 4A and 5A

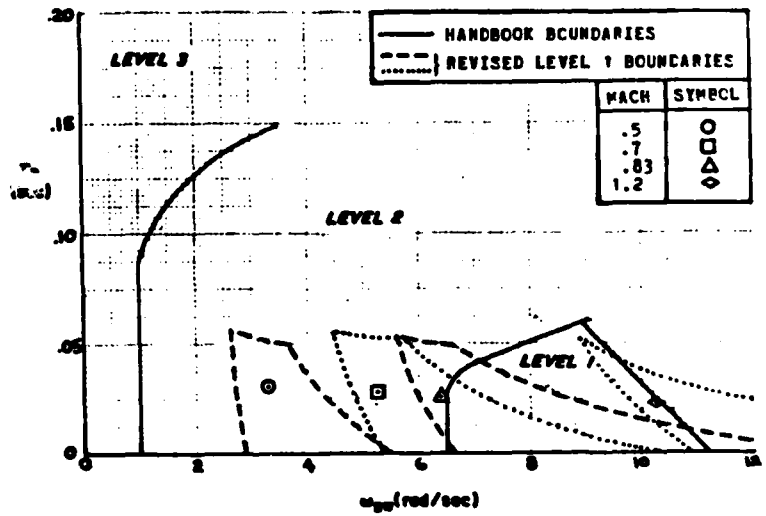


Figure 16: F-14A Airplane Short Term Pitch Response Results Revised Pandwidth Criteria.

COMMENTS AND QUESTIONS

Roger Hoh, STI: We need to know operating conditions. Neal-Smith data was trying to correlate task. Bandwidth minimum value is intended to be based on task and therefore shouldn't vary with Mach. Also, all criteria should be used as design guidance since each is supposed to highlight something.

EXPERIENCE IN DETERMINING LATERAL-DIRECTIONAL EQUIVALENT SYSTEM MODELS

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ABSTRACT

Lateral-directional equivalent system models were developed for three Navy aircraft using the classical roll mode and Dutch roll approximate and full three degree of freedom transfer function representations. Examples of applying the methods are shown for the A-6 airplane. Acceptable models were generally obtained for the classical approximate forms. Matching of the full three degree of freedom forms required simultaneous matching of bank angle and sideslip response transfer functions. Additional study is necessary to determine methods of evaluating high order systems with prefilter components and to verify the equivalency of high and low order responses via piloted tasks.

LIST OF SYMBOLS

Symbol	Definition	Units
CO	Air-to-air combat	-
GA	Ground attack	-
K	Numerator gain	-
L_p	Rolling moment due to roll rate	$1/sec_2$
L_{δ_a}	Roll equivalent system gain	$1/sec^2$
N_{δ_r}	Sideslip equivalent system gain	$1/sec^2$
q	Dynamic pressure	lb/ft^2
s	Laplace operator	1/sec
t	Time	sec
τ_β	Sideslip numerator time constant	sec
τ_r	Roll mode time constant	sec
τ_s	Spiral mode time constant	sec
β	Sideslip angle	deg
δ	Control deflection	deg
ψ	Yaw angle	deg
ϕ	Roll angle	deg
ζ	Damping ratio	-
ω	Frequency	rad/sec

Subscripts	
DR	Dutch roll
f	Flaperon
PED	Pedal
r	Rudder
(·)	Derivative with respect to time

INTRODUCTION

The determination of lateral-directional flying qualities of piloted aircraft as described by MIL-F-8785C and the proposed MIL- Standard (references (a) and (b)) requires the definition of equivalent classical systems whose responses most closely match those of the actual aircraft. For these equivalent systems the numerical requirements of linear system parameters such as frequency, damping ratio, and modal phase angles are to be applied. However, no guidance is given as to how these systems shall be defined nor with what criteria their adequacy will be judged. In the longitudinal case, reference(c) presents an effort to determine equivalent system descriptions of current tactical Navy aircraft. For the more complex lateral directional case, these frequency response matching techniques have experienced limited application to date.

This paper will discuss an ongoing effort at the Naval Air Development Center to generate equivalent system descriptions for the lateral- directional modes of current tactical Navy aircraft. Results will only be presented for the A-6 aircraft although similar analyses have been completed for the S-3 and A-7 aircraft. These preliminary results indicate that within the scope of the completed work, the equivalent systems closely match the higher order augmented systems. Problem areas and limitations which have been encountered during these analyses will also be discussed.

APPROACH

The frequency response matching techniques used in this analysis are described in references(d) and (e). These methods match, in the frequency domain, a high order phi(roll angle) to pilot command transfer function, beta(sideslip angle) to pilot command transfer function, or both with equivalent low order systems. The forms of these equivalent systems are shown as equations (1) and (2). These are the standard lateral directional transfer functions (reference (f)) which have been augmented by a time delay (t_ϕ or t_β) to account for the phase characteristics of high frequency roots in the frequency range of interest.

$$\frac{\phi}{\delta_a} = \frac{L_{\delta_a}\,(s^2 + 2\zeta_\phi\omega_\phi s + \omega_\phi{}^2)\,e^{-t_\phi s}}{(s+1/\tau_r)(s+1/\tau_s)(s^2 + 2\zeta_{DR}\omega_{DR}s + \omega_{DR}{}^2)} \qquad (1)$$

$$\frac{\beta}{\delta_r} = \frac{N_{\delta_r}(s+1/\tau_{\beta_1})(s+1/\tau_{\beta_2})(s+1/\tau_{\beta_3})\,e^{-t_\beta s}}{(s+1/\tau_r)(s+1/\tau_s)(s^2 + 2\zeta_{DR}\omega_{DR}s + \omega_{DR}{}^2)} \qquad (2)$$

In addition to the above equations, a rolling approximation and a Dutch roll approximation were developed.

By assuming the rolling motion to involve only the ϕ degree of freedom in the equations of motion, the equivalent transfer function becomes,

$$\phi/\delta_a = \frac{L_{\delta_a} e^{-t_\phi s}}{s(s-L_p)} \tag{3}$$

For steady state roll rate, $L_p = -1/\tau_r$ and equation (3) yields the rolling approximation,

$$\phi/\delta_a = \frac{K_\phi e^{-t_\phi s}}{s(s+1/\tau_r)} \tag{4}$$

The same result could have been obtained from equation (1) by assuming $\zeta_\phi = \zeta_{DR}$, $\omega_\phi = \omega_{DR}$ and neutral spiral stability($1/\tau_s = 0$).

In the case of the Dutch roll approximation the rolling degree of freedom is eliminated from the equations of motion. After accounting for the time delay, t_β , the equivalent system form of the Dutch roll approximation becomes,

$$\beta/\delta_r = \frac{K_\beta e^{-t_\beta s}}{(s^2 + 2\zeta_{DR}\omega_{DR}s + \omega_{DR}^2)} \tag{5}$$

This result could also be obtained from the standard lateral-directional form (Equation (2)) by assuming $\tau_{\beta_1} \sim \tau_{\beta_r}$, and that $\tau_{\beta_2} \sim \tau_s$ and $1/\tau_{\beta_3} \gg 10$.

The standard lateral-directional equivalent system equations ((1) and (2)) along with these approximations ((4) and (5)) were used to obtain equivalent system representations of the higher order systems. The accuracy of these matches in the frequency domain was measured by the following cost function (reference (d)),

$$\text{COST} = \frac{20}{n} \sum_{\omega_1}^{\omega_n} \left[(\text{gain}_{HOS} - \text{gain}_{LOS})^2 + .01745(\text{phase}_{HOS} - \text{phase}_{LOS})^2 \right]$$

where:

gain is in decibels
phase is in degrees
ω - denotes input frequency
n - number of discrete frequencies

Although no quantitative measure of the cost function has been conclusively established to determine a good match, preliminary tests of high and equivalent low order responses with mismatches as high as 190 have yielded equivalent pilot ratings (reference (g)). The frequency, damping ratio, and time constants identified by these lower order equivalent systems were then compared to the requirements of MIL-F-8785C. The A-6 lateral and directional flight control systems are presented in Figure 1, along with the ϕ/δ_a and β/δ_r transfer functions analyzed. The Stability Augmentation System (SAS) OFF transfer functions were constructed from the stability and control information of reference (h). The SAS ON transfer functions were obtained from a state space representation of the coupled system using the computer program TOTAL (reference (k)). The conditions at which these transfer functions were calculated are Mach number equal to 0.4, altitude equals 20000 ft., and a clean flexible airplane.

RESULTS AND DISCUSSION

GENERAL

The results presented in the following sections were obtained via three procedures of determining lower order equivalent system matches for each higher order system (ϕ/δ_a or β/δ_r). The first procedure utilized the NAVFIT (reference (e)) computer program to obtain the approximate equivalent system described by equation (4) or (5), depending upon the parameter response being matched. For the second procedure, the program LATFIT (reference (d)) was used which assumes the lower order system to be one of the standard lateral-directional transfer functions (equations (1) or (2)). The last of the three procedures also assumed the form of the standard equations, with both ϕ/δ_a and β/δ_r being matched simultaneously while constraining the identified denominators to be identical. Simultaneous matching of the standard equations was found to be necessary since ζ_ϕ, ω_ϕ and ζ_{DR}, ω_{DR} as well as τ_{β_1} and τ_r fall relatively close together and are masked in the higher order response. As a result, LATFIT identifies erroneous values for ζ_{DR} and ω_{DR} when matching only the ϕ/δ_a transfer function unless ζ_ϕ and ω_ϕ are constrained at known values. Similarly, erroneous values for τ_r are identified when only matching the β/δ transfer function unless τ_{β_1} is constrained at a known value. Matching both generally allows ζ_{DR}, ω_{DR}, and τ_r to be determined without constraining these other parameters in the frequency range of interest.

STABILITY AUGMENTATION OFF

Each of the three matching procedures discussed above was applied to the higher order systems with the stability augmentation off in order to gain familiarity with and confidence in the fitting routines. Table I summarizes these

results for the A-6 airplane at Mach number equal to 0.4 and an altitude of 20000 ft. The values of ζ_{DR}, ω_{DR} , and τ_r identified by NAVFIT, using the rolling and Dutch roll approximations, show good correlation with the high order system. When the standard equations for ϕ/δ_a and β/δ_r were used individually to match the higher order system (LATFIT) two significant results were obtained. First, in order to generate a good match, ζ_ϕ and ω_ϕ had to be fixed to known values for the ϕ/δ_a transfer function. Second, in the case of the β/δ_r transfer function, the parameter τ_{β_1} had to be fixed to identify good values of ζ_{DR} and ω_{DR} as well as having a low cost function. By using the standard equations to simultaneously match ϕ/δ_a and β/δ_r , none of the parameters had to be fixed and a match consistent with the high order system was obtained.

STABILITY AUGMENTATION ON

Table II summarizes the results obtained by applying the three matching procedures to the ϕ/δ_a and β/δ_r transfer functions with the stability augmentation system on. A typical lateral frequency response obtained from the matching process is shown in Figure 2. Roll rate time histories obtained for each of the matching procedures are shown in Figure 3. The cost functions associated with these matches indicate a significant increase as compared to the case with no stability augmentation. This is due to the additional control roots in the frequency range of interest which were not present in the SAS off case. These results also show that the rolling approximation and the simultaneous matches of ϕ/δ_a and β/δ_r yield similar results. However, for the simultaneous matching technique the parameters ζ_ϕ and ω_ϕ had to be fixed at a known value in order to obtain an acceptable match. The lowest mismatch obtained resulted from independently matching ϕ/δ_a with the standard form of the ϕ/δ_a transfer function (equation (1)). However, in this case the match yields a separation in ω_ϕ and ω_{DR} along with an increase in τ_r , none of which are desirable effects. As indicated in Figure 3, this match produces an oscillatory response up to 3.0 seconds which may be disturbing to the pilot.

The directional responses of these equivalent systems are shown in Figures 4 and 5. The typical frequency response (Figure 4) shows good agreement between the high order system and the low order equivalent system. In the time domain (Figure 5) all the responses appear similar with the only discernable difference being a higher damped equivalent system due to the simultaneous matching technique. Based on these results, it would be desirable in the directional case to use the equivalent system generated by the Dutch roll approximation to model the high order system.

The matching techniques described above for the A-6 airplane produced similar results when appiled to the A-7 and S-3. However, in the case of the A-7, forward loop prefilters are present in the control system descripton. As a result, the equivalent systems models expressed above are not sufficient to

adequately define the resulting ϕ/δ_a response as shown in Figure 6. Additional work is necessary to evaluate acceptable equivalent systems responses for these types of control systems.

COMPARISON WITH MIL-F-8785C REQUIREMENTS

The lateral-directional oscillation, roll mode, and time delay paragraphs of MIL-F-8785C include the following requirements for Class IV, Category A level 1 flying qualities:

$$\tau_r \leq 1.0 \text{ sec}$$
$$\omega_{DR} \geq 1.0 \text{ rad/sec}$$
$$\zeta_{DR} \geq 0.4 \text{ (configurations CO and GA)}$$
$$\zeta_{DR} \geq 0.19 \text{ (all other configurations)}$$
$$\zeta_{DR}\omega_{DR} \geq 0.35 \text{ (configurations other than CO and GA)}$$
$$t \leq 0.1 \text{ sec}$$

The equivalent values for τ_r , ω_{DR} , and t resulting from acceptable matching procedures all meet these requirements. However, the equivalent damping ratio, while meeting the requirement for configurations such as cruise, formation flying, etc., falls short of the requirements for combat and ground attack configurations.

CONCLUSIONS AND RECOMMENDATIONS

Lateral-directional equivalent system descriptions have been determined for three tactical Navy aircraft using the frequency response matching techniques of references (d) and (e). These techniques are relatively straightforward and easy to apply. As a result of applying these techniques to the A-6,A-7, and S-3 aircraft, the following conclusions can be made:

1.) The rolling and Dutch roll approximation equivalent system forms identify values of τ_r , ζ_{DR} , and ω_{DR} similar to both the unaugmented and augmented high order systems.

2.) Independently matching ϕ/δ_a or β/δ_r with the standard forms of the equivalent systems requires ζ_ϕ , ω_ϕ , and τ_{β_1} to be fixed to known values in order to generate acceptable matches with the high order systems.

3.) Simultaneous matching of ϕ/δ_a and β/δ_r with the standard equivalent systems generated acceptable matches. However, ζ_ϕ and ω_ϕ had to be fixed in the augmented case.

4.) Comparisons of τ_r , ζ_{DR} , and ω_{DR} identified by these equivalent systems procedures with the requirements of MIL-F-8785C indicate level 1 flying qualities for the A-6 in all but configurations CO and GA where $\zeta_{DR} \leq 0.4$.

The following items are recommended for further study in the development of the lateral-directional equivalent system methodology:

1.) Methods of defining acceptable equivalent responses for high order control systems incorporating prefilters in the frequency range of interest.

2.) More extensive comparison of equivalent system modal parameters with specification requirements.

3.) Verification of equivalent system models of high order system responses via piloted evaluation tasks.

REFERENCES

a) Anonymous,"Military Specification-Flying Qualities of Piloted Airplanes,MIL-F-8785C",November 1980.

b) Hoh,R.,et.al.,"Proposed MIL Standard-Handling Qualities of Piloted Airplanes",Report No. AFWAL-TR-82- ,Draft Report, December,1981.

c) Bischoff,D.E.,"Development of Longitudinal Equivalent System Models for Selected U.S.Navy Tactical Aircraft",Report No. NADC-81069-60,August 1981.

d) Givan,M.E.,et.al.,"LATFIT User's Guide",McDonnell Aircraft Company,October 1978.

e) Hodgkinson,J.,and Buckley,J.,"NAVFIT User's Guide",McDonnell Aircraft Company,October 1978.

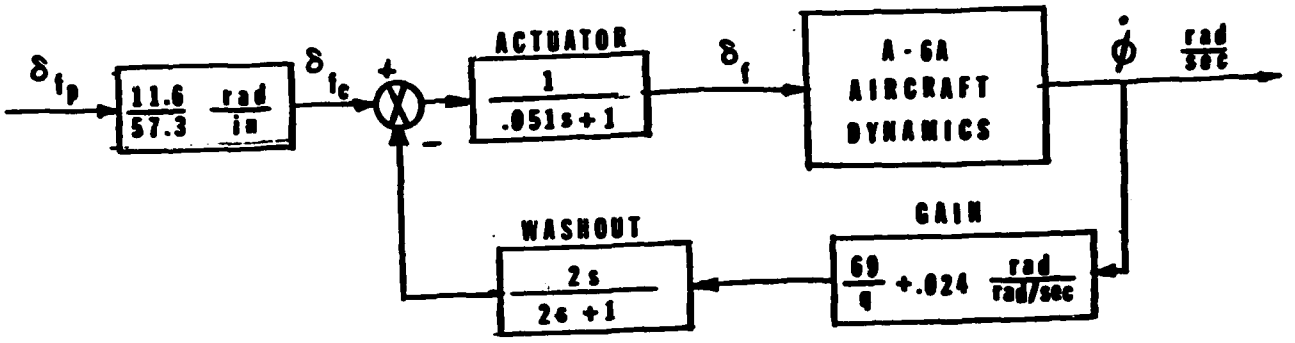
f) Roskam,J.,"Flight Dynamics of Rigid and Elastic Airplanes", Roskam Aviation and Engineering Corporation,1976.

g) Smith,R.E.,"Equivalent System Verification and Evaluation of Augmentation Effects on Fighter Approach and Landing Flying Qualities",Calspan Report No. 6241-F-3,August 1979.

h) Scheutz,A.,"An Aerodynamic and Stability and Control Data Summary for Selected Military Aircraft,Vol.1:Conventional Aircraft",Report No. NADC AM-7106,Sept 1971.

k) Larimer,S.J.,"User's Manual for TOTAL",Air Force Institue of Technology,March 1978.

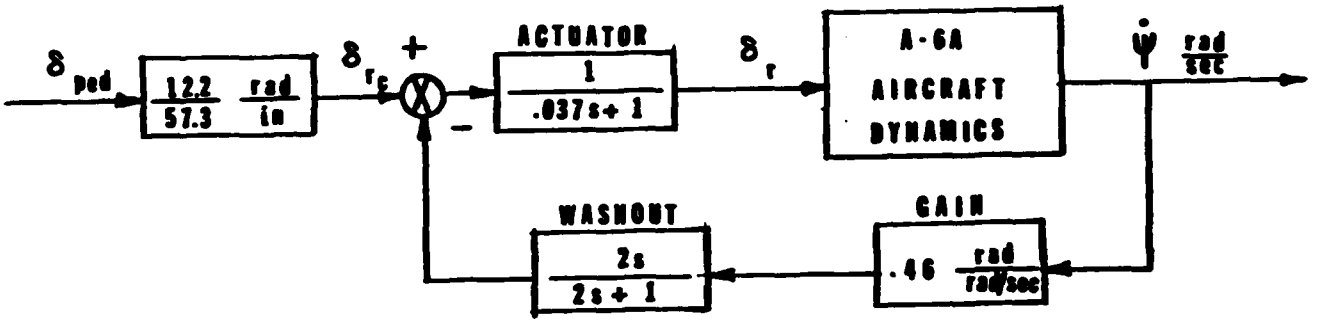
LATERAL



SAS OFF $\quad \phi/\delta = \dfrac{17.098\ [.097, 1.879]}{(19.61)(.0095)(1.685)[.182, 1.839]}$

SAS ON $\quad \phi/\delta = \dfrac{17.06\ (.50)(.556)(26.27)[.293, 1.817]}{(.177)(.009)(15.25)(6.64)(.559)(26.24)[.32, 1.752]}$

DIRECTIONAL



SAS OFF $\quad \beta/\delta = \dfrac{.084\ (-.008)(110.0)(1.752)}{(27.03)(.0095)(1.658)[.182, 1.839]}$

SAS ON $\quad \beta/\delta = \dfrac{.082\ (.187)(-.008)(.50)(6.012)(15.66)(110.6)}{(.177)(.009)(15.25)(6.64)(.559)(26.24)[.32, 1.752]}$

Figure 1. A-6 Lateral Directional Flight Control System

TABLE I

A-6 Airplane .40M 20000 ft Altitude

Stability Augmentation OFF

	HOS	NAVFIT		LATFIT		LATFIT
		ϕ/δ	β/δ	ϕ/δ	β/δ	$\phi/\delta + \beta/\delta$
ζ_ϕ	.097	-	-	FIX	-	.096
ω_ϕ	1.89	-	-	FIX	-	1.88
ζ_{DR}	.182	-	.180	.176	.178	.177
ω_{DR}	1.84	-	1.82	1.85	1.84	1.84
τ_{β_1}	.57	-	-	-	FIX	.58
τ_r	.59	.72	-	.63	.61	.63
t	-	.033	.027	.045	.034	.046/.034
COST	-	34.3	4.7	.65	.20	.65/.21

NAVFIT- ϕ/δ, β/δ K/2nd order denominator (Eqs.(5),(6))

LATFIT- ϕ/δ 2nd order num./4th order denom. (Eq.(1))

β/δ 3rd order num./4th order denom. (Eq.(2))

TABLE II

A-6 Airplane .40M 20000 ft Altitude

Stability Augmentation ON

	HOS*	NAVFIT		LATFIT		LATFIT
		ϕ/δ	β/δ	ϕ/δ	β/δ	ϕ/δ + β/δ
ζ_ϕ	.30	-	-	FIX	-	FIX
ω_ϕ	1.80	-	-	FIX	-	FIX
ζ_{DR}	.32	-	.30	.53	.30	.43
ω_{DR}	1.75	-	1.79	2.34	1.77	1.89
τ_{β_1}	.17	-	-	-	FIX	.49
τ_r	.15	.48	-	.87	.17	.53
t	-	.002	.019	.020	.035	.012/.041
COST	-	164.0	5.6	86.0	0.6	118.0/25.0

* ζ, ω from oscillatory root pair, τ from root tracking

NAVFIT- ϕ/δ β/δ K/2nd order denominator (Eqs.(5),(6)

LATFIT- ϕ/δ 2nd order num./4th order denom. (Eq.(1))

β/δ 3rd order num./4th order denom. (Eq.(2))

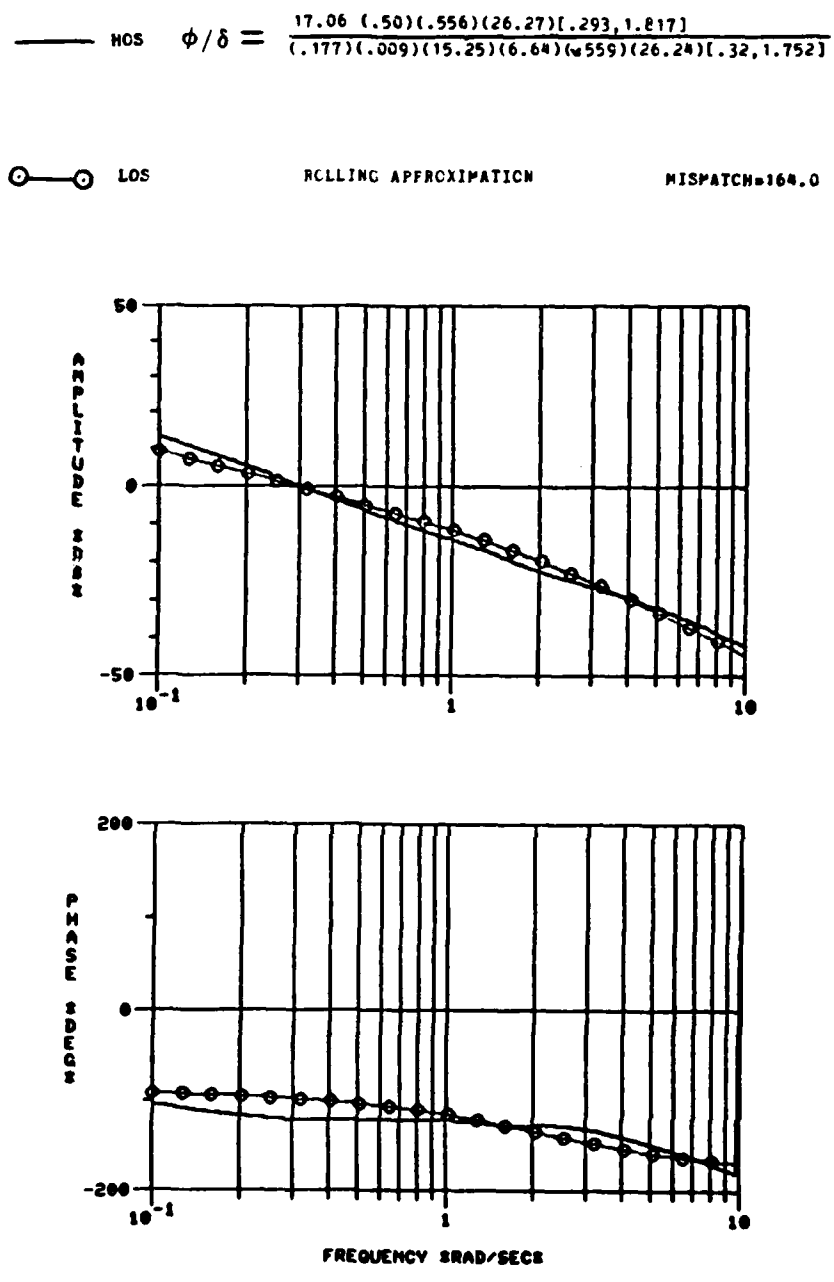
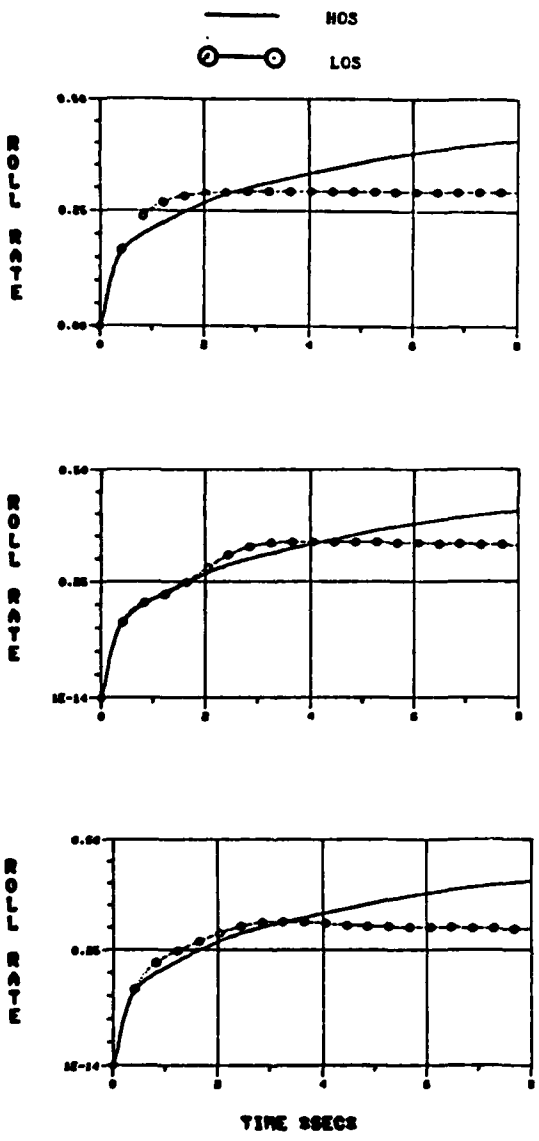


Figure 2. Typical A-6 Lateral Equivalent Frequency Response Match



ROLLING APPROXIMATION

$$\phi/\delta = \frac{.61e^{-.0017s}}{(0)(2.09)}$$

MISMATCH=164.0

STANDARD FORM

$$\phi/\delta = \frac{.68\ [.30,1.80]e^{-.020s}}{(1.15)(.009)[.53,2.34]}$$

MISMATCH=86.0

SIMULTANEOUS MATCH

$$\phi/\delta = \frac{.65\ [.30,1.80]e^{-.012s}}{(1.87)(.009)[.43,1.89]}$$

MISMATCH=118.0

Figure 3. A-6 Equivalent Roll Rate Time Response

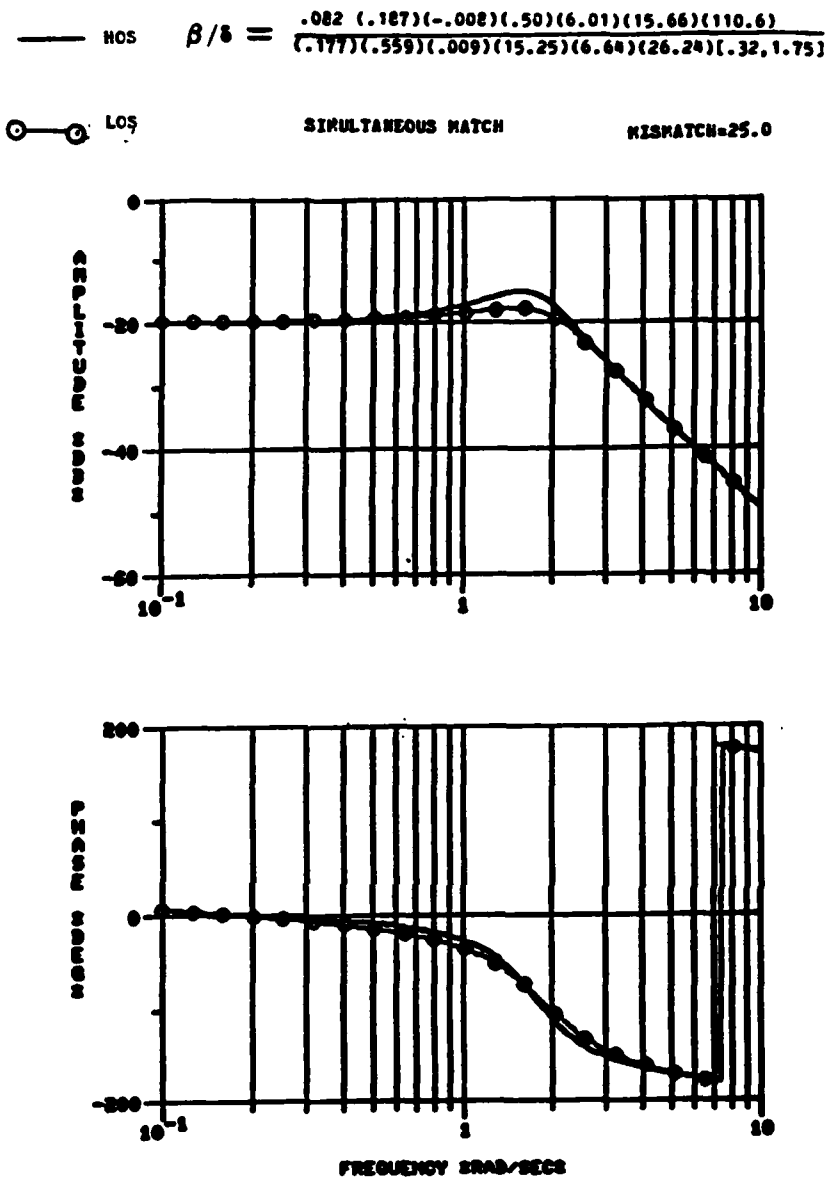
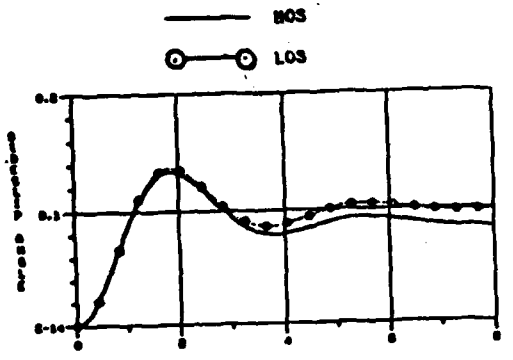


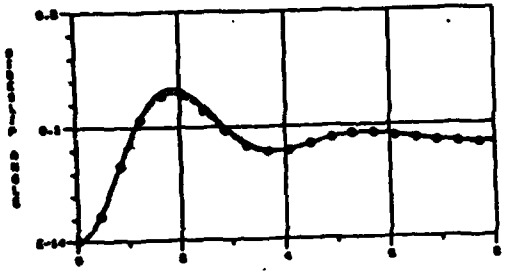
Figure 4. Typical A-6 Directional Equivalent Frequency Response Match



DUTCH ROLL APPROXIMATION

$$\beta/\delta = \frac{.32e^{-.019s}}{[.302, 1.79]}$$

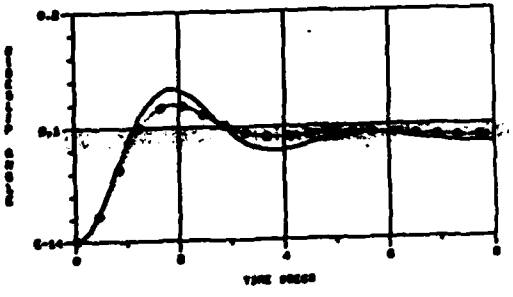
MISMATCH=5.6



STANDARD FORM

$$\beta/\delta = \frac{.003\ (-.008)(6.01)(110.6)e^{-.035s}}{(6.01)(.009)[.304, 1.77]}$$

MISMATCH=0.6



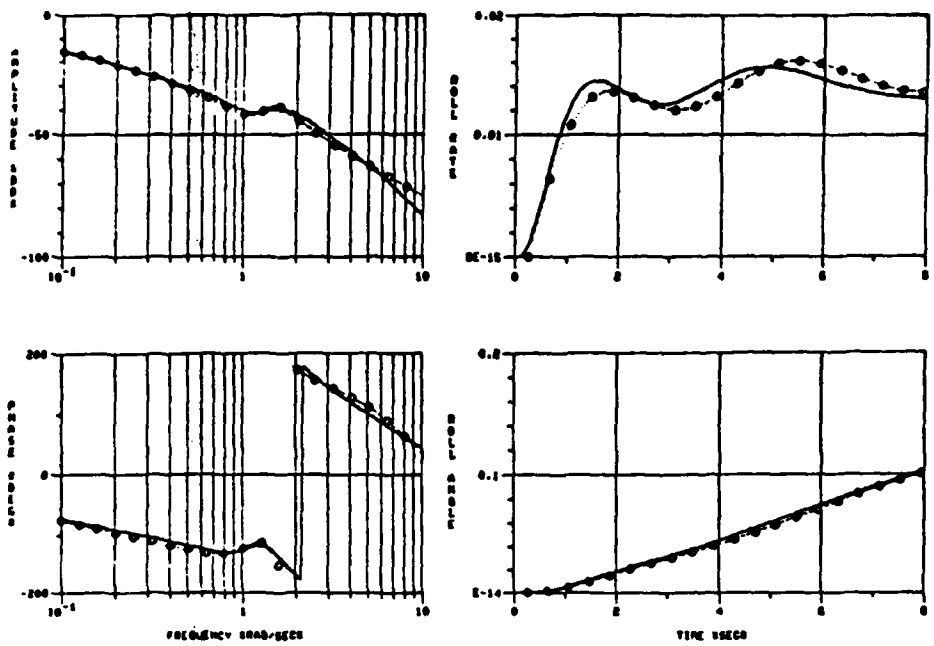
SIMULTANEOUS MATCH

$$\beta/\delta = \frac{.003\ (-.008)(2.04)(110.6)e^{-.041s}}{(1.81)(.009)[.43, 1.89]}$$

MISMATCH=26.0

Figure 5. A-6 Equivalent Sideslip Angle Time Response

A-7 .30 M 15000 ft



HOS ——— $\phi/\delta = \dfrac{23.63\ (1.246)(19.58)[.292, 1.163]}{(1.013)(1.513)(.045)(3)(10)[1.0, 19.57][.335, 1.578]}$

LOS ⓪——⓪ $\phi/\delta = \dfrac{.018\ [.29, 1.16]e^{-.26s}}{(.562)(.045)[.188, 1.51]}$ MISMATCH=141.5

Figure 6. A-7 Lateral Equivalent System Roll Response

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AN IN-FLIGHT INVESTIGATION OF HIGHER ORDER CONTROL SYSTEM EFFECTS ON THE LATERAL FLYING QUALITIES OF FIGHTER AIRPLANES

by

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AN IN-FLIGHT INVESTIGATION OF HIGHER ORDER CONTROL SYSTEM EFFECTS ON THE LATERAL-DIRECTIONAL FLYING QUALITIES OF FIGHTER AIRPLANES

Abstract

This in-flight simulation experiment, using the USAF NT-33 variable stability aircraft operated by Calspan, was undertaken to generate lateral-directional flying qualities data applicable to highly augmented fighter aircraft. In particular, the effects of time delay and prefilter lag in the lateral flight control system were studied for representative Flight Phase Category A and C tasks. Included were actual target tracking, air refueling and precision landing tasks as well as special Head-Up Display (HUD) tracking tasks. Results indicate that a HUD bank angle tracking task is a valid flying qualities evaluation task. Data show that lateral flying qualities are very sensitive to control system time delay and that very short values of roll mode time constant typically result in poor lateral flying qualities. Excellent separation of the data into flying qualities levels is achieved for the Category A task data using equivalent time delay and roll mode time constant parameters. An optimum equivalent time constant value of 0.6 sec is indicated by the data.

Acknowledgements

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1. Introduction and Objectives

Modern fighter flight control systems use digital or analog computation techniques in combination with their advanced "fly-by-wire" technology to gain potential advantages such as improved mission performance and weight/cost reduction. Examples of modern fighter aircraft which incorporate such advanced flight control system designs are the F-16, YF-17, F-18 and Tornado. Unfortunately, the potential of this expanded flight control technology has not been realized. In fact, new flying qualities problems have often been created in the process of solving the old ones.

With the operational acceptance of full-authority electronic augmentation systems, the designer literally has the capability to tailor the flying qualities of the aircraft as desired for each mission task. Typically, these advanced design efforts have produced overly complex designs characterized by "higher order" responses to the pilot's inputs. The additional control system dynamics, or higher order effects, can potentially cause serious flying qualities problems for modern fighter aircraft while performing precision tasks.

These new flying qualities problems are most often related to the time delays which are introduced into the control system by the advanced flight control design. The source of these time delays, which can cause dramatic degradation in flying qualities for precision tasks, can be from the higher order complexity of the flight control system design or, in the case of digital systems, inherent time delays. Digital flight control systems tend to be the worse offenders since the power of the computer unfortunately encourages the design of very complex systems.

Criteria based on classical aircraft characteristics, such as those presented in MIL-F-8785B (Reference 1) are not applicable to the design of modern aircraft with highly augmented flight control systems; they are also not adequate to evaluate the flying qualities of aircraft equipped with such systems. A series of research programs have been conducted using the USAF/Calspan NT-33A variable stability aircraft (References 3 to 10) to acquire a flying qualities data base which is applicable to aircraft with highly augmented flight control systems. The new military flying qualities specification, MIL-F-8785C (Reference 2), utilized these data to produce new requirements which are directed at today's complex fighter aircraft.

Most of these previous flying qualities research efforts have centered on fighter aircraft longitudinal flying qualities. However, aircraft with modern, highly-augmented flight control systems have exhibited equally serious lateral flying qualities problems. A suitable lateral flying qualities data base applicable to modern, complex fighter aircraft did not exist. Without such a data base the designer cannot avoid a potentially very expensive trial and error development process with the real aircraft. The genesis of the research experiment described in this paper comes from a clear need for a lateral higher order system flying qualities data base for fighter aircraft.

This paper describes a research program intended to collect basic lateral-directional flying qualities data applicable to aircraft with higher order lateral flight control systems. The major portion of this experiment was devoted to the lateral axis because 1) the directional axis is not yet a primary control axis, 2) experience to date with higher order flight control systems has not shown significant directional flying qualities problems, and 3) modern flight control systems allow the isolation of the lateral and directional axes. Future flight control systems may use the directional axis as a primary control axis (e.g. wings level turn, fire control-flight control coupling) and will require extensive directional flying qualities research.

The specific objectives of the flying qualities research program described in this paper were to:

- Gather lateral-directional flying qualities data applicable to fighter aircraft with complex higher order lateral flight control systems in the context of precision maneuvering, tracking, and refueling tasks, and terminal approach and landing tasks (Class IV aircraft, Category A and C Flight Phases), as a function of important lateral control system parameters.

- Continue the development of suitable control system design and evaluation criteria which are applicable to highly augmented fighter aircraft.

- Compare various Flight Phase A and C lateral evaluation tasks with head-up display based evaluation tasks. Determine which evaluation tasks are most sensitive to lateral control system parameter changes and evaluate the validity of head-up display evaluation tasks.

The research program on which this paper is reported in some detail in Reference 18; this paper is intended to be a summary of the main features of the experiment and the primary results.

2. Experiment Design

2.1 NT-33 Aircraft

The test aircraft for this program was the USAF NT-33A research aircraft operated by Calspan. This aircraft is equipped with a Variable Stability System (VSS) which utilizes an analog response feedback technique to generate the desired augmented basic aircraft dynamic response. A variable feel system, suitable control system dynamics, in the form of prefilters and an adjustable time delay circuit, allow simulation of various flight control parameters. For this program, a center stick was used. A detailed description of the NT-33A VSS is included in Reference 11.

A potential limitation in the experiment was the NT-33A maximum achievable steady state roll rate of approximately 100 deg/sec at 280 KIAS. An examination of the flight records showed that the maximum roll rate commanded during the evaluation tasks was less than 100 deg/sec. Therefore, the NT-33A roll rate limit did not affect the results of this experiment.

For the refueling task evaluations, an air-to-air refueling boom was attached to the lower right forward portion of the NT-33A nose (Fig. 1) The boom latched into the tanker drogue but did not transfer fuel.

2.2 DEFT System

The NT-33A is also equipped with a Display Evaluation Flight Test (DEFT) system which includes a fully programmable Head-Up Display (HUD) system. For this program the HUD was used as the primary instrument reference by the evaluation pilot (Fig. 2). A fixed HUD symbol, depressed approximately 1 degree below the horizon in level flight, was used as the air-to-air tracking index or "pipper". The HUD and associated digital computers were also used to produce the bank angle and heading tracking tasks used during the evaluations in this program.

2.3 Lateral-Directional Flight Control System

For this experiment the evaluation configurations were mechanized using the NT-33A variable stability system, special electronic circuits, and a special digital time delay circuit. A block diagram of the lateral-directional flight control system is presented in Fig. 3.

The lateral-directional flight control system was designed to allow investigation of several primary characteristics typically found in highly augmented fighter aircraft.

Experiment Controlled Variables

- τ_R, $L'_{F_{AS}}$

  - high roll damping (short τ_R) in combination with the necessary high command gains (high $L'_{F_{AS}}$) to achieve satisfactory steady-state roll performance is the typical modern fighter situation and was of particular interest.

- $e^{-\tau s}$

  - transport time delay to represent the equivalent delay effects of high frequency higher order control system elements and pure digital time delays found in typical modern flight control system designs.

- $\frac{\tau_1 s + 1}{\tau_2 s + 1}$

  - first order lag or lead/lag representative of typical command path prefilters.

Mini-experiments were performed during the program to investigate the effects of non-linear command gain and high values of Dutch roll damping ratio (~0.7). The results of these experiments are contained in the full report, Reference 18.

The selected evaluation configurations were specific combinations of these primary experiment parameters and the other fixed simulation characteristics. The experiment controlled variables and the range of values tested for each flight phase are summarized in Table 1. A complete summary of the configuration characteristics is contained in Reference 18. Values for the fixed characteristics and the ranges for the variable elements of the lateral directional control system were selected as appropriate for modern high performance fighter aircraft engaged in Flight Phase A and C tasks.

TABLE 2-1

LATERAL-DIRECTIONAL EXPERIMENT VARIABLES			
VARIABLE	FLIGHT PHASE CATEGORY	NOMINAL VALUES TESTED	COMMENTS
τ_R (Roll Damping)	A	• .15, .25, .45, .8 sec.	- Simulation minimum τ_R is .15 sec. - MIL-F-8785B Level 1 maximum τ_R is 1.0 sec.
	C	• .2, .25, .45, .8 sec.	
p_{ss}/F_{AS} (Related to Command Gain $L'_{F_{AS}}$)	A	• 10, 18, 25 deg/sec/lb	- Spans approximate MIL-8785B Level 1 limits.
	C	• 5, 10, deg/sec/lb	- Spans approximate MIL-8785B Level 1 limits.
$e^{-\tau s}$ (Equivalent Time Delay)	A,C	• 55,75,105,125,225 milli sec (ms) (T0 to T4)	- See Reference 18 for details.
$\frac{\tau_1 s+1}{\tau_2 s+1}$ (Prefilter)	A,C	• Lag ($\tau_1=0$): τ_2 = .025, .10, .17, .33, .5, 1.0 sec (F1 to F5) • Lead/Lag: τ_1 = .05, (F7) τ_2 = .025 • Lag/Lead: τ_1 = .15 (F6) τ_2 = .4	- Nominal configurations all included .025 sec. (40 rps) prefilter. - Used with τ_R = 0.45 τ_R=0.80 cases. - Used with τ_R = 0.15 cases.

2.4 Experiment Configurations

Experiment configurations were formed by choosing combinations of:

- τ_R and $L'_{F_{AS}}$
- τ_1, τ_2 (lateral prefilter characteristics)
- τ (lateral transport time delay)

The complete lateral-directional characteristics for an evaluation configuration consists of a combination of these elements as illustrated in Fig. 3.

Baseline Lateral-Directional Configurations

The first step before the effects of the major control system elements of interest — time delay and prefilter lag — could be properly evaluated was to evaluate a baseline set of configurations with different combinations of τ_R and $L'_{F_{AS}}$. These baseline configurations were all flown with a 40 rad/sec lag prefilter because of VSS lateral noise considerations with force commands. In effect, these configurations can be considered to be without significant control system dynamics.

The baseline configurations are presented in Fig. 4 on a plot of τ_R versus $L'_{F_{AS}}$. Configurations were selected to lie along 3 lines of constant p_{ss}/F_{AS}: 10, 18 and 25 deg/sec/lb as shown.

Other Lateral-Directional Configurations

During the remainder of the experiment the effects of time delay and prefilter dynamics on the baseline $\tau_R/L'_{F_{AS}}$ combinations were evaluated. The primary emphasis in the experiment was the investigation of the effects of time delay and prefilter lag for the various Flight Phase Category A and C tasks. First, the effects of the experiment variables were evaluated individually and then, to the extent possible in the context of this experiment, in combination.

Each configuration represents a particular combination of the experiment variables as previously discussed and illustrated in Fig. 2. For example, a configuration identified as "Configuration 5-2T1F1" has $\tau_R = .15$ *sec*, $p_{ss}/F_{AS} = 10$ *deg/sec/lb*, $\tau_E = 75$ *millisec*, *prefilter* $\tau_2 = 0.1$ *sec*.

The nominal Dutch roll damping ratio was $\zeta \doteq 0.35$ and the roll rate response to lateral input was essentially first order (no Dutch roll excitation) for the evaluation configurations discussed in this paper.

2.5 Evaluation Tasks

Flying qualities evaluations are dependent on configuration characteristics and the task being performed. It has been shown that evaluations of highly augmented aircraft with significant control system dynamics are particularly sensitive to task. For example, the flying qualities of aircraft with large time delays in the longitudinal flight control system can degrade dramatically during the last 50 ft prior to landing when a precision landing is the task (see Reference 8). This "flying qualities cliff" may not be exposed if the task constraints are relaxed. If for example, no landing is required or the precision landing goal is removed. Also, if the visual environment cues are sufficiently inhibited (as in a ground-based simulation) such that the pilot is not properly stressed and his "gain" does not approach real task values, the serious flying qualities deficiencies may not be observed.

For this experiment, which is primarily concerned with the effects of representative higher order lateral control system elements on lateral-directional fighter flying qualities, it was therefore imperative that realistic tasks be used for the evaluations. Since the tests were performed in the NT-33A aircraft, the visual environment was the real world and no compromises existed in that area. Within the constraints of flight safety, every effort was therefore made to make the tasks realistic. Tracking was done using a real target; refueling included all the ingredients of the real task except the actual transfer of fuel. Close formation maneuvers were on the wing of the target aircraft; finally, the approach and landing tasks included precision actual touchdowns. In addition, realistic HUD tracking tasks were included to evaluate the validity of HUD evaluation tasks. In every case, tasks were intended to direct the pilot's attention to the evaluation of lateral flying qualities.

1) Flight Phase Category A Tasks

- Close Formation Flying
- Air-to-Air Gun Tracking
- Air-to-Air Refueling
- HUD Bank Angle Tracking
- HUD Heading Tracking

2) Flight Phase Category C Tasks

- Instrument Landing System Approach and Visual Landing
- Visual Landing
- HUD Bank Angle and Heading Tracking

Evaluation of lateral flying qualities was primary. Use of rudder was allowed if necessary, or if rudder significantly improved task performance/reduced pilot compensation. Otherwise use of rudder should be kept to a minimum.

3. Conduct of the Experiment

3.1 Simulation Situation

For this program, the simulated aircraft was defined as a typical modern, single seat, fighter aircraft (Class IV). Where appropriate, such as during simulated instrument tasks, the pilot was required to extrapolate to this fighter aircraft environment which would include realistic additional cockpit duties.

Since inclusion of wind and turbulence as controlled variables was beyond the scope of the program, flights were conducted in a wide range of wind and turbulence; conditions encountered are considered normal for typical fighter operations. The pilots were asked to evaluate the aircraft in the condition of the day, but to comment, if appropriate, on the projected effects of different representative wind and turbulence conditions.

3.2 Experiment Data

The primary data from the experiment take these forms:

- Pilot Ratings
  - At the completion of each evaluation, the pilot was asked to assign a pilot rating using the Cooper-Harper Rating Scale (Reference 12)
  - These ratings were assigned immediately after the completion of the evaluation tasks before making any detailed pilot comments; a review of the initial rating was a part of the comment card
  - In addition to the evaluation pilot rating, the safety pilot assigned a pilot rating before the evaluation pilot gave his rating. This additional rating can be used to increase the credibility of the evaluation pilot's rating and potentially as an aid to understanding any rating discrepancies.
- Pilot Comments
  - After the initial rating, the pilot was asked to make recorded comments on specific items listed on the Pilot Comment Card.
- Task Performance Records
  - Complete records were taken of task performance during each evaluation using the NT-33A 28 channel digital magnetic tape recorder.
  - These records included complete records of the HUD tracking task performance; both the input commands to the pilot, the error signal created and his response were recorded.

3.3 Evaluation Summary

The three evaluation pilots performed a total of 214 evaluations of 118 different configurations during the program; 42 evaluation flights of approximately 1.3 hours each were flown. There was approximately 20% overlap in configurations and each pilot repeated approximately 20% of his evaluations.

4. Task Comparisons and Baseline Configuration Results

The purpose of this section is to present the pilot rating results of the experiment which, along with the pilot comment data, form the data base for the more detailed discussion and analysis of the results presented in Section 5.

The major thrust of this experiment was to gather a lateral flying qualities data base applicable to highly augmented fighter aircraft with significant control system dynamics in the form of time delays and lags. A few evaluations to investigate the effects of special filtering (lead/lag, lag/lead) were also performed. The presentation of the results of this multi-dimensional experiment in an orderly fashion is not easy. To assist in this effort the results of the gun tracking (TR) and air refueling task (AR) are combined and the HUD only evaluations are not included directly in the data base. The justification for this step is given in the next two subsections.

4.1 Comparison of Tracking (TR) and Air Refueling (AR) Results

The averaged pilot ratings for the two tasks are compared in Figure 5. Use of averaged pilot ratings is the only way in which the trends of the data can be seen clearly. In addition, the fact that the evaluation pilots were fortuitously representative of a wide, but realistic, range of pilot task aggressiveness makes the averaging process more credible. In the context of the typical inter and intra pilot ratings scatter in the experiment (see Section 5 for details), the results for the two tasks are similar. The TR and AR pilot rating results are therefore considered together in this report.

4.2 Comparison of Tracking and Refueling (TR + AR) Results With HUD-Only Results

The averaged pilot ratings for these tasks are compared in Figure 6. HUD only results are for the evaluations in which only HUD tracking tasks were evaluated. HUD tracking tasks were generally included in the tracking (TR).

Although the scatter in the data is larger than for the other task comparisons, in the context of the inter and intra pilot rating variability shown in this experiment, the results for the HUD-only evaluations are representative of those given for the actual tasks. Further support for this generalization can be found in the pilot comments for the actual

tracking tasks when HUD tasks were also included. In the majority of cases the pilots indicated that the observations from the HUD task were similar to those for the real tracking task.

These HUD only data are not used as part of the experiment data base except for guidance when no other data exist

4.3 Baseline Pilot Rating Data

The results for the combined TR and AR tasks are presented in Figure 7 in the form of averaged pilot ratings. Estimated PR = 3.5 and 6.5 boundaries are included on the figure.

Baseline configuration averaged pilot rating data for the approach and landing tasks (LA) are presented in Figure 8. No estimated pilot rating boundaries could realistically be estimated with the limited data set.

Presentation of the complete results on the effects of time delay and lag on the flying qualities of the baseline lateral configurations is beyond the scope of this paper; the results are documented in Reference 18 and discussed in the next section.

5. Discussion of the Results

5.1 Baseline Configuration Data, TR + AR Tasks

The approximate PR = 3.5 (Level 1) and the PR = 6.5 (Level 2) boundaries drawn on Figure 7 show that the data from this experiment indicate limits on roll damping (τ_R) and command gain ($L'_{F_{AS}}$). The values of steady-state performance, p_{ss}/F_{AS} used in this experiment appear to be satisfactory provided satisfactory values of τ_R and $L'_{F_{AS}}$ are selected.

The data suggest minimum values of τ_R of:

Level 1 (PR $\leq$ 3.5) $\sim$ 0.3 secs

Level 2 (PR $\leq$ 6.5) $\sim$ 0.17 secs

and maximum values of $L'_{F_{AS}}$ of:

Level 1 $\sim$ 55 deg/sec^2/lb

Level 2 $\sim$ 110 deg/sec^2/lb

Assuming that the Dutch roll is effectively cancelled in the ϕ/F_{AS} transfer function and the spiral is neutral, which are valid assumptions for this experiment.

$$\frac{\phi}{F_{AS}} = \frac{L'_{F_{AS}}}{s(s + 1/\tau_R)} ; \quad \frac{p_{ss}}{F_{AS}} = L'_{F_{AS}} \tau_R$$

Without significant control system dynamics, as in the baseline configurations,

- $L'_{F_{AS}}$ is a measure of the initial acceleration
- τ_R is the dominant factor in the predictability of the final response
- p_{ss}/F_{AS} is a measure of the steady-state roll performance

p_{ss}/F_{AS} is related to the gross roll maneuvering performance and is of course, a function of $L'_{F_{AS}}$ and τ_R. $L'_{F_{AS}}$ and τ_R are of direct importance to the fine tracking performance of the aircraft. All of these parameters are interrelated and the discussion of the data can therefore be made from several different viewpoints. From the pilot's viewpoint, for a given task he desires good initial response ($\dot{p}_{MAX}/F_{AS}$ *or* $L'_{F_{AS}}$ for the baseline configurations), predictable final response (good value of τ_R) and satisfactory roll performance (p_{ss}/F_{AS}).

Correlation of all the Category A data including the baseline configurations as well as those with added time delay and prefilter lag is discussed in Section 6.

Of primary interest is the observed trend from the pilot rating data which indicates a degradation in pilot rating as τ_R is decreased at essentially constant $L'_{F_{AS}}$ and satisfactory values of p_{ss}/F_{AS}. The data suggests that there are lower (τ_R *too short*) limits as well as upper (τ_R *too large*) limits limits on roll mode time constant.

Baseline configurations 2-4, 3-3 and 5-2 are obvious candidates for discussion; they are configurations with approximately constant initial acceleration to a pilot input ($L'_{F_{AS}}$) yet the averaged pilot ratings degrade from 3.5 to 7 as τ_R decreases from 0.45 to 0.15 sec for otherwise satisfactory values of p_{ss}/F_{AS} (25 to 10 deg/sec/lb).

5.2 "Roll Ratcheting", Baseline Configurations 2-2, 3-3, 5-2

As shown on Figure 7, the pilot ratings degrade as τ_R is decreased in moving from 2-4 (PR = 3.5) to 3-3 (PR = 5) to 5-2 (PR = 7). Typical pilot comments were:

Config.	Pilot	Comments
2-4	B	"Precision/accuracy good even when aggressive"
3-3	P	"Desired performance obtained but jumpy response"
	B	"Definite ratcheting - small corrections during fine tracking were a problem"
5-2	B	"Wing rocking, roll oscillations, quick, sharp, ratcheting - certainly did bother fine tracking (rudders didn't help)

The conundrum presented by this data is centered on the fact that as τ_R is decreased the ϕ/F_{AS} transfer function becomes more *"K/s like"*. Since the general assumption is that pilot's prefer *K/s* type systems, the pilot ratings should improve with increased roll damping (τ_R *decreasing*), not degrade. The data, both pilot ratings and comments, however do not appear to support this position.

Although the scope of this present effort precludes a very extensive exploration into this apparent dilemma, it is logical to look into the experiment data more carefully and to review outside data sources for suitable information.

HUD Tracking Task Data

A review of sample HUD tracking task data for baseline Configurations 2-4, 3-3 and 5-2 indicates that:

- The tracking performance in terms of the ϕ_{ERROR} is essentially the same for each configuration in that no overshoots or oscillations are present.
- Small amplitude oscillations are evident in roll rate for Configuration 3-3 (Pilot B) and strongly present for Configuration 5-2. Frequency of the "ratcheting" is = 16 rad/sec.

- These oscillations are pilot induced.
- Nulling of the tracking error is done less crisply for Configurations 3-3 and 5-2 in that a long "tail" exists on the ϕ_{ERROR} trace.
- The roll rate and lateral stick force traces for 5-2 are less sharp than for 2-4 indicating that the pilot is perhaps intentionally flying smoothly (applying lag compensation) or backing out of the closed loop in the presence of the ratcheting potential of the configuration.
- The sideslip excursions during the task are about the same for all configurations.

The tracking records indicate that the ratcheting problems certainly were real. It is interesting to note that the deterioration in performance as measured by bank angle errors in the HUD task or pipper motion in the gun tracking task is not significant; in fact, desired performance can often be achieved yet the overall aircraft is judge to require improvement, i.e. "ratcheting is not acceptable," and gets a PR = 7 for Configuration 5.2. This situation often led to a "rating/comment anomaly".

The problem of ratcheting is almost a ride qualities concern in that the angular accelerations or lateral accelerations at the pilot's head are the major problem; the aircraft doesn't move far but the ride is unacceptable in the fighter task. A simulation that did not include very accurate accelerations at the pilot station would not therefore expose the "ratcheting" difficulties observed in this experiment. Perhaps the experiments which verified the "goodness" of K/s systems did not properly reflect these attendant real-life acceleration factors.

Open-Loop Considerations

As previously mentioned, there are several vantage points from which to view the interaction of the primary variables in this discussion (τ_R, $L'_{F_{AS}}$ *and* p_{ss}/F_{AS}) in the context of the pilot's lateral task.

For a step input, the configurations exhibit nearly identical maximum values of $\dot{p}$ and $\ddot{p}$ ("jerk") although the shapes of the responses are different. The p_{ss} achieved varies from 25 deg/sec/lb for 2-4 to 10 deg/sec/lb for 5-2.

If the pilot is assumed to desire a specific roll rate then his input must be 2.5 times greater for 5-2 than for 2-4; the attendant $\dot{p}$ maxima would be proportionately greater.

The response of 2-4, 3-3 and 5-2 to the same unit pulse show that the maximum values of p, $\dot{p}$ and $\ddot{p}$ are essentially the same for all the configurations but the bank angle achieved is reduced as τ_R decreases (going

from 2-4 to 5-2). Again if one assumes that the pilot has some standard of performance during tracking such as requiring a given bank angle the lateral accelerations would be much higher for 5-2 than for 2-4.

The high lateral accelerations associated with 5-2 are apparently the basis for the roll ratcheting problem. These high accelerations would be generated if the same bank angle performance achieved for 2-4 was attempted in 5-2. In any event the catalyst for the phenomenon would appear to be excessive roll damping (τ_R *too short*).

It appears from the HUD tracking performance records that the pilot attempts to compensate with 5-2 by using similar sized inputs as in 2-4 but holds the pulse for a longer time to achieve the desired bank angle change. He, in effect, attempts to slow down his inputs; however, he typically reverts inadvertently to abrupt commands which lead to the small amplitude "ratcheting" oscillation.

Closed-Loop Considerations

A recent analysis centered on analytically investigating the roll ratcheting question (Reference 13) indicates that the ingredients of the observed ratcheting problem can be reproduced in a reasonable fashion if the following scenario is followed.

- A simple pilot model consisting of a gain, a first-order lag compensator and 0.3 transport delay is adjusted to achieve a satisfactory closed-loop bank angle tracking bandwidth (using the Neal-Smith definitions in Reference 5) of approximately 2 rad/sec for a K/s like aircraft (very short roll mode time constant).

- This compensation and bandwidth would allow satisfactory bank angle control and avoid abrupt inputs which produce unwanted high accelerations.

- Suppose the pilot reverts to an abrupt input technique to demand the desired response more rapidly, creates high angular accelerations and then switches his closure to angular acceleration error instead of bank angle error. Then, with sufficient pilot gain a ratcheting type oscillation of ≈ 16 rad/sec results. The study concludes the roll angular acceleration and the lateral linear accelerations at the pilot station are important considerations in flying qualities.

  Roll ratchet is best explained by a model that assumes the pilot is closing the lateral loop on angular acceleration response cues.

Clearly, more analysis is required in this area; fortunately, the HUD tracking task performance data which contains all the necessary input and output data present a unique opportunity for pilot modelling studies.

Other Data

Recent modern fighter aircraft have exhibited roll ratcheting problems similar to the problems noted for Configuration 5-2. In each case the aircraft was highly augmented with particularly high levels of roll damping. This evidence adds further substance to the credibility of the data set from this experiment.

A previous NT-33 experiment (Reference 14) conducted to investigate lateral-directional flying qualities of lifting body entry vehicles noted similar ratcheting problems when τ_R became small (around 0.1 secs).

Finally, the V/STOL flying qualities specification background data (Reference 15) contains examples from hovering experiments which substantiate the trends shown in the data from this experiment. The hover data indicates a degradation in pilot rating, for constant control sensitivity (L_δ or M_δ), as the damping (L_p or M_q) is increased.

These data represent further evidence that there is a real-world upper limit to the levels of roll damping (lower limit on τ_R) for each level of flying qualities. The K/s criterion for good flying qualities does not apparently directly apply to real aircraft in high gain tasks.

5.3 Time Delay and Lag Effects, TR + AR Tasks

Time Delay

Although the data are hardly sufficient to define the rating trends with time delay completely the following estimates are made. Configurations 2-2, 2-3 and 2-4 are the basis for these estimates which are clearly "best guesses".

- Additional Time Delay Threshold: ≈ 75 ms (millisec) (Equivalent time delay added with no effect on PR)
- Total Time Delay Threshold: ≈ 125 ms (millisec) (Includes actuator and nominal prefilter effects)
- Slope After Threshold: ≈ 1 PR/15 ms (millisec)

Prefilter

For good basic configurations such as the "2-" series the effect of the prefilter is not apparant until values of τ_2 of about .17 sec (6 rad/sec prefilter). For the more sensitive configurations, 3-4 and 5-3, the prefilter lag is clearly beneficial and lags of $\tau_2 = 0.3$ can be tolerated before degradation due to lag begins.

Combination

In each case, the rating with the time delay added to a given prefilter configuration is worse than the rating with the prefilter alone; in most cases the combined rating is worse than the time delay alone case.

The most startling result is that the beneficial effects of the prefilter lag are totally eliminated when even small time delays are included in combination.

5.4 LA Tasks

Baseline Configurations

The data, although limited in coverage, suggests a minimum value of τ_R of 0.2 to 0.25 sec for Level 1 (PR $\leq$ 3.5) flying qualities. As in the Category A data, when τ_R is reduced at a constant value of $L'_{F_{AS}}$ flying qualities begin to deteriorate for small τ_R *($\approx$ 0.2 sec)* when the roll ratcheting problem surfaces (Configuration L4-1).

Time Delay Effects

As for the Category A case, estimates which qualify as "best guesses" can be made using the better Configurations (L1-2 and L2-1) for guidance:

- Additional Time Delay Threshold ≈ 75 ms
  (Equivalent time delay added with no effect on PR)
- Total Time Delay Threshold ≈ 125 ms
  (Includes actuator and normal prefilter effects)
- Slope After Threshold: ≈] PR/30 ms

Prefilter

Again the trends are similar to those shown in the Category A task data.

For a good Configuration (L2-2), a .17 sec prefilter lag (6 rad/sec prefilter) can be tolerated before significant degradation in pilot rating occurs. Prefilter lag is beneficial to "sensitive" configurations like L4-1 which exhibits the beginnings of roll ratcheting.

6. Correlation of the Data Using Equivalent Time History Parameters

6.1 Equivalent Parameters

The search for a suitable criterion with which all of the data could be viewed finally centered on a time history criteria analogous to that used by Chalk for pitch axis correlations in Reference 16. This approach is similar in concept but different in some details to that used by Van Gool in Reference 17 to correlate large aircraft lateral flying qualities.

The criterion is in effect an equivalent system approach in the time domain. As shown in Figure 9, the time history of the p response to a step force input is utilized to make the necessary measurements of the equivalent parameters.

τ_{Eff} - Effective Time Delay (Sec)

$\tau_{R_{Eff}}$ - Effective Roll Mode Time Constant (Sec)

The τ_{Eff} is not included in the measurement of $\tau_{R_{Eff}}$ and is measured as shown by back plotting the slope of the response to the axis.

6.2 Application to Category A Task Data (TR + AR)

After calculation of the equivalent parameters, the next step in the correlation process was to assume that for each set of configurations with the same τ_{R_E} value there exists an optimum command gain. Assuming that the command gain can be optimized, the best pilot rating from among the set of configurations was used as the representative pilot rating data point.

Consider, for example, Configurations 3-2, 3-3 and 3-4 which all have the same $\tau_{R_{Eff}} = 0.25$ and $\tau_{Eff} = 0.05$ sec. Pilot rating varies from 3.5 to 6 as command gain increases; the $PR = 3.5$ data point was therefore used.

The selection procedure outline above was used in reviewing the Category A task (TR + AR) pilot rating data; the results are plotted in Figure 10 with τ_{Eff} versus $\tau_{R_{Eff}}$.

Considering the very wide range of configuration characteristics included in the data base, the separation of the rating data into flying qualities levels is really excellent.

Observations are:

- A value of $\tau_{R_{Eff}}$ of approximately 0.5 sec is optimum; sensitivity to τ_{Eff} is at a minimum at this value.
- Maximum tolerable τ_{Eff} for Level 1 flying qualities is 0.1 sec.
- The increment in τ_{Eff} between Level 1 and Level 2 pilot rating boundaries is approximately .04 sec; lateral fighter flying qualities are apparently very sensitive to time delay.
- Lower limits on τ_{Eff} are evident.

6.3 Application to Category C Task Data (LA)

The equivalent parameter correlation process was employed for the Category C approach and landing data. All the Category C data are plotted on the equivalent parameter plane (τ_{Eff} versus $\tau_{R_{Eff}}$) in Figure 11. The data base for this portion of the experiment is considerably smaller than for the Category A tasks and the variation in pilot ratings is somewhat higher.

Considering the wide variety of characteristics, the separation of the data into flying qualities levels is reasonable and similar to the results for the Category A tasks data. The Level 1 boundary is similar to that estimated for the Category A data with a slightly greater tolerance to larger τ_{Eff} values suggested. A level 2 boundary cannot be completely defined but appears also to indicate greater tolerance to larger τ_{Eff} values than for the Category A tasks. This increased tolerance to effective time delays would seem to be reasonable for the less demanding landing task.

The separation of the data into well defined flying qualities regions is clearly not as good as shown for the Category A task data. In most cases the anomalies are the result of somewhat inconsistent pilot ratings; with the limited data set these anomolies cannot be clarified properly.

Observations are:

- A value of $\tau_{R_{Eff}}$ of approximately 0.5 sec is optimum; sensitivity to τ_{Eff} is at a minimum at this value.
- Maximum tolerable τ_{Eff} for Level 1 flying qualities is about 0.14 sec.
- The increment in τ_{Eff} between Level 1 and Level 2 pilot rating boundaries cannot be accurately defined but is approximately the same as that for the Category A task data.
- A lower limit on $\tau_{R_{Eff}}$ is suggested but not clearly defined.

7. Concluding Remarks

This experiment which employed the NT-33 variable stability in-flight simulator was directed at the lateral-directional flying qualities of advanced fighter aircraft. In particular, the effects on fighter lateral flying qualities of control system elements, such as time delay and prefilter lag, were of interest. Although further analysis is clearly in order, the following conclusions may be drawn.

- Air-to-air gun tracking and air refueling (probe and drogue style) are equally demanding lateral flying qualities tasks; precision formation flying is not a critical task.
- A properly designed HUD bank angle tracking task is a valid lateral flying qualities evaluation task.
- Short roll mode time constant (high roll damping) can lead to serious lateral flying qualities problems in the form of "roll ratcheting" during precision tasks. This experiment defined bounds on roll mode time constant for satisfactory flying qualities.
- Fighter lateral flying qualities are very sensitive to time delay in the lateral control system.
- Excellent correlation of pilot rating data with the lower order equivalent system parameters, time delay and roll mode time constant, was obtained. The equivalent system parameters were derived from the augmented roll rate step response time history.

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Fig. 1 NT-33 Variable Stability Research Aircraft

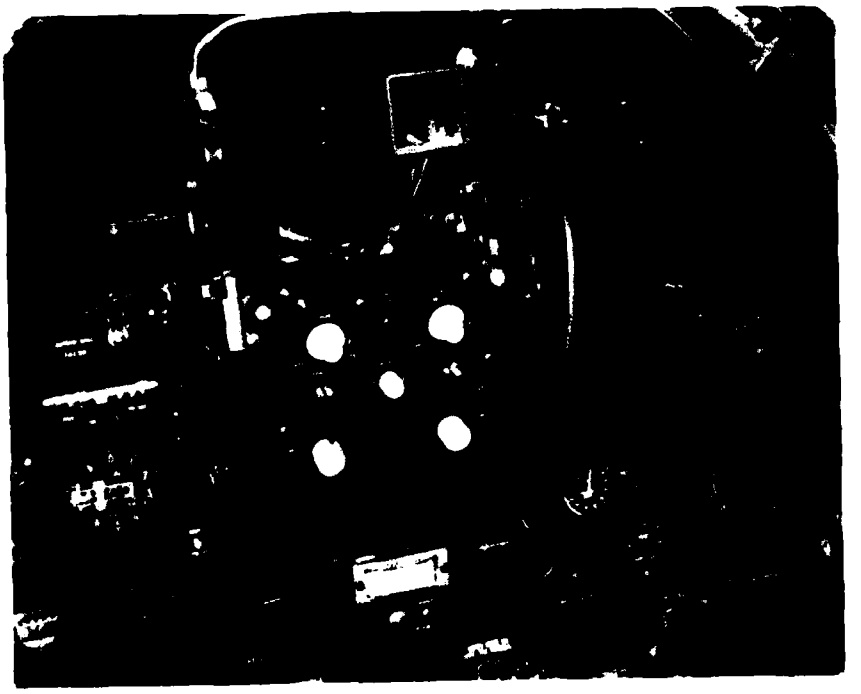


Fig. 2 Evaluation Pilot Cockpit in NT-33 Aircraft

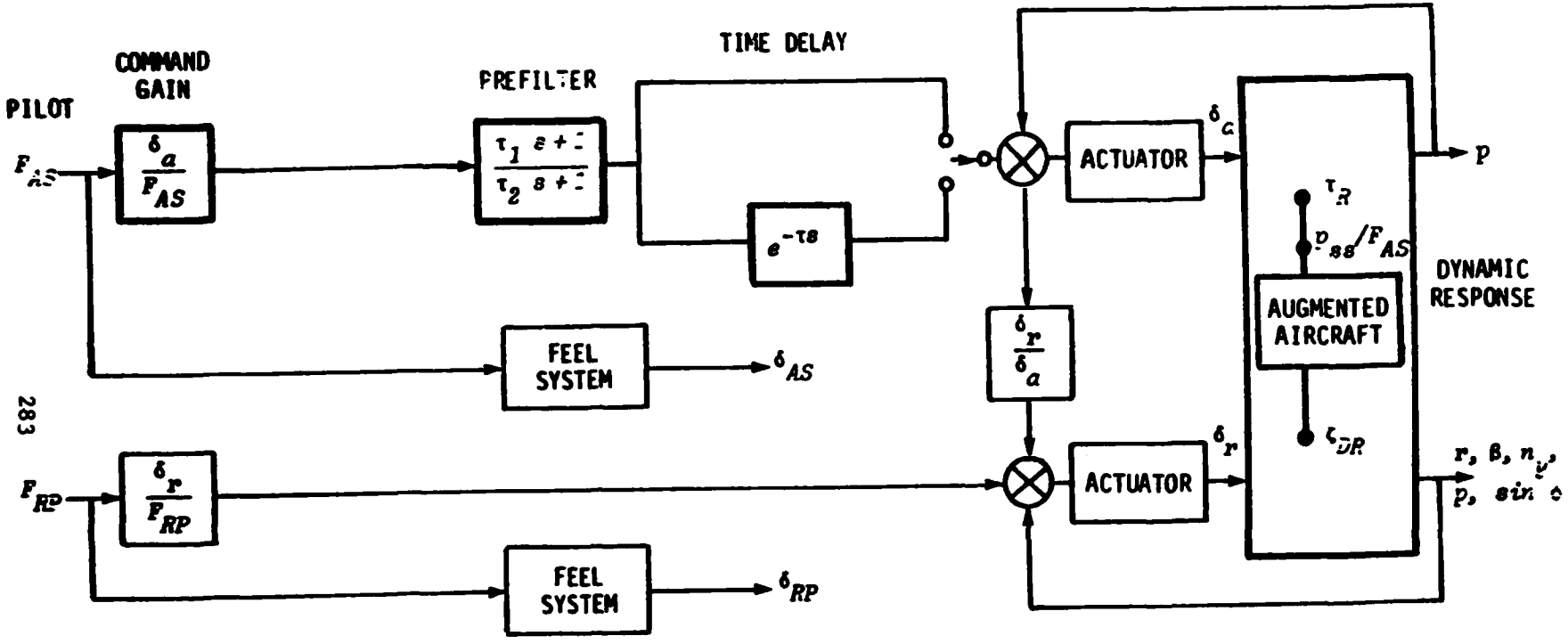


Fig. 3 Lateral-Directional Flight Control System Block Diagram

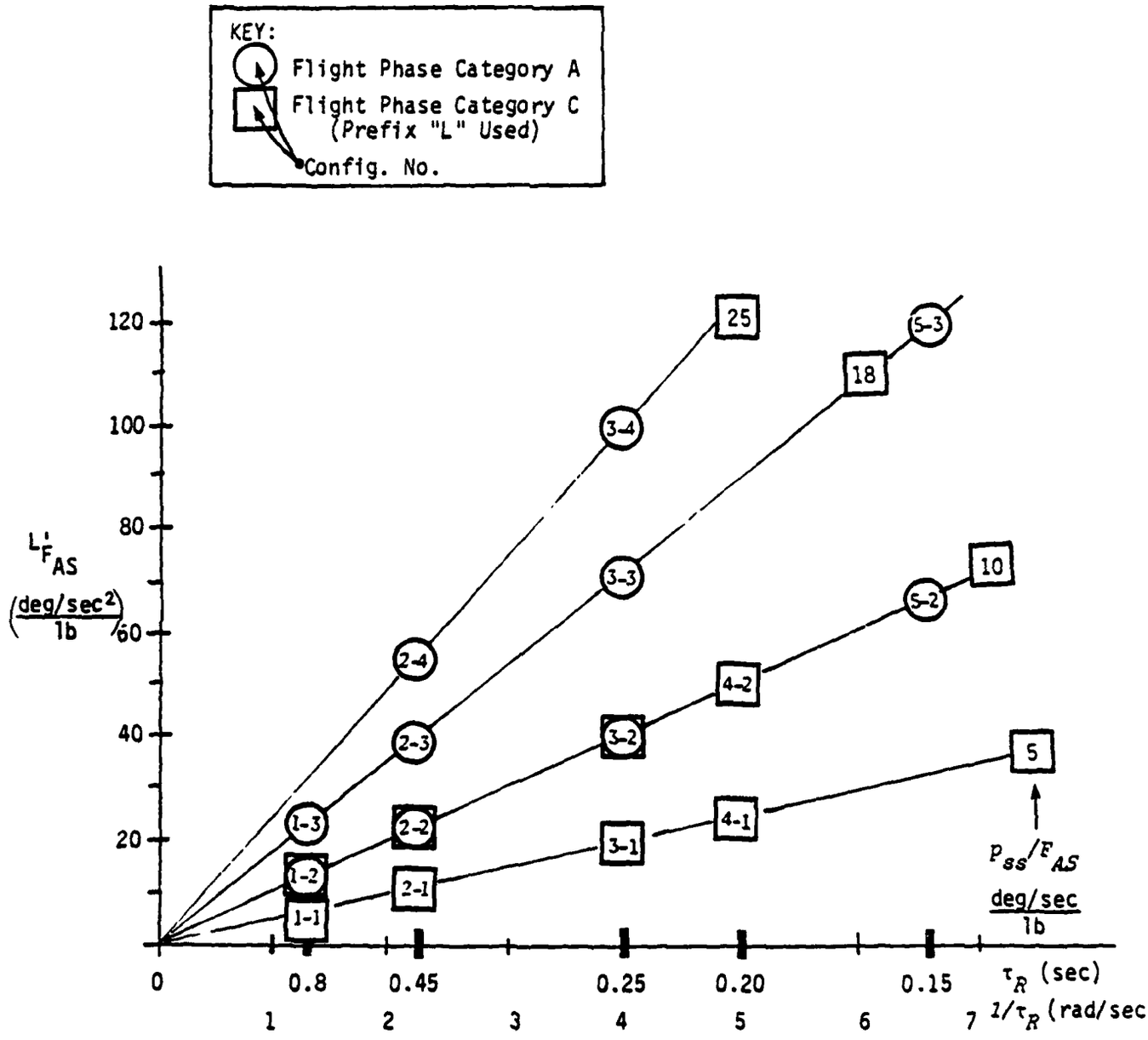


Fig. 4 Baseline Configurations (All Include an Actuator and Prefilter, τ_2 = .025 Sec)

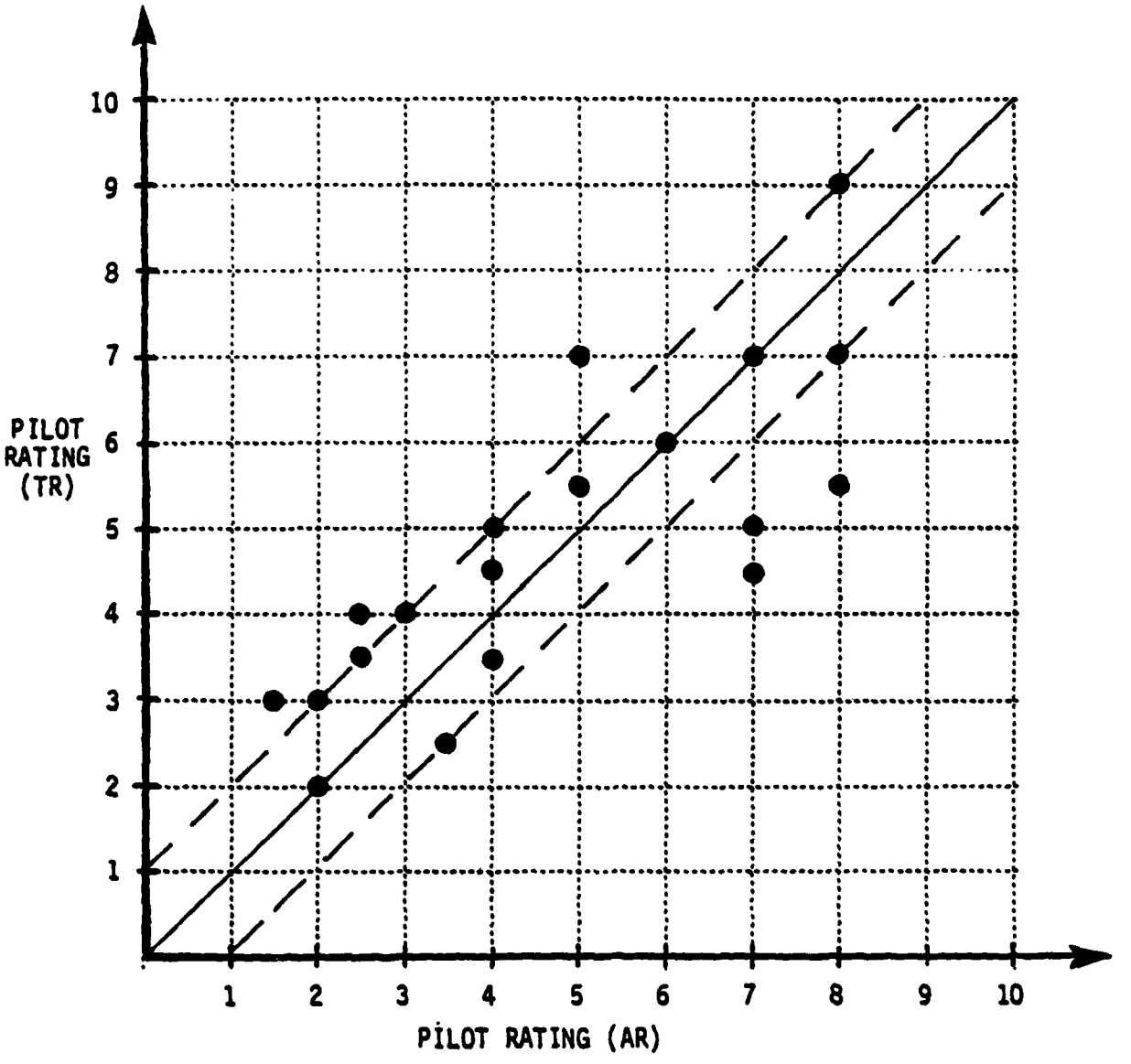


Fig. 5 Comparison of Averaged Pilot Ratings for Gun Tracking (TR) and Air Refueling (AR) Tasks

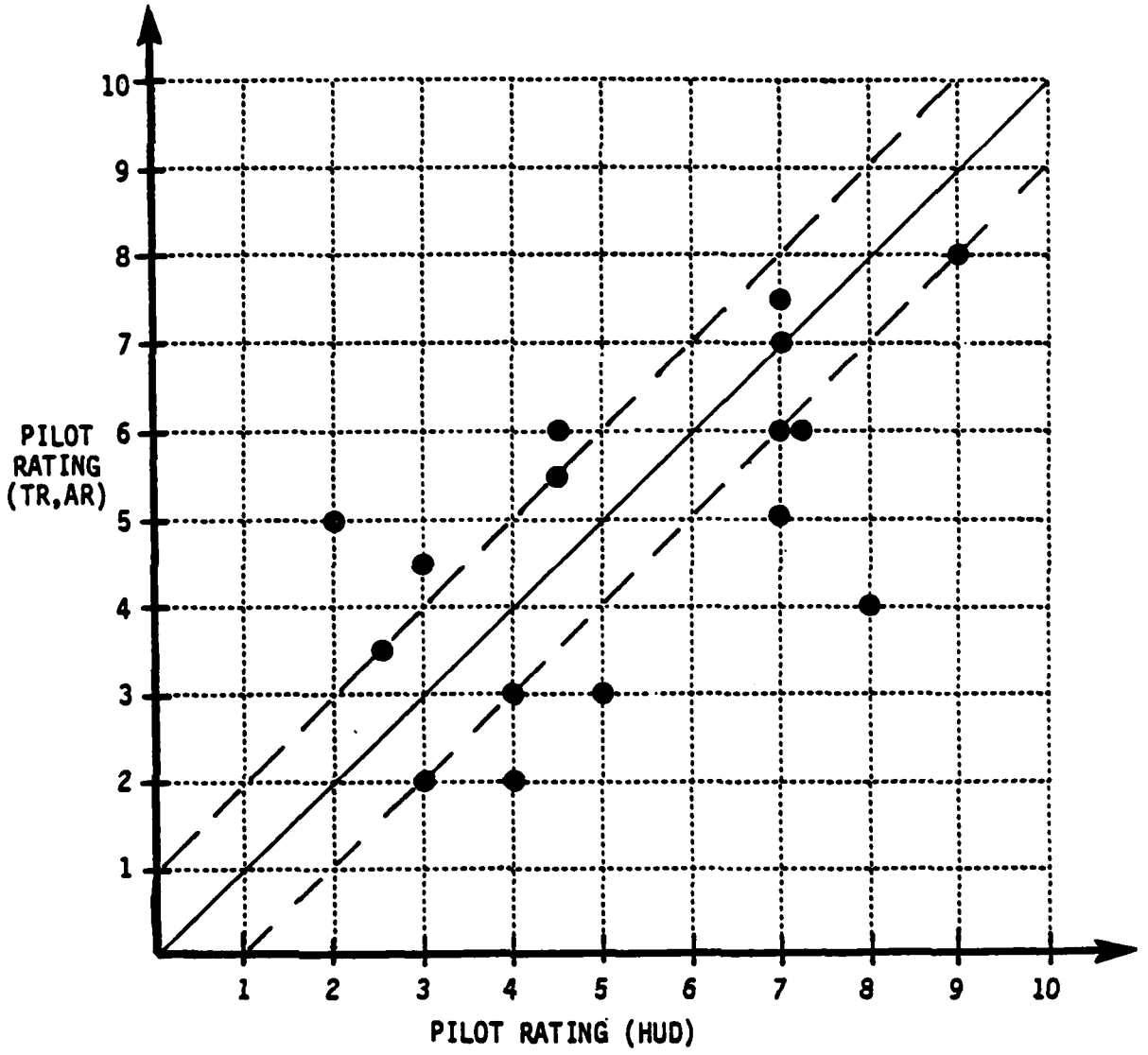


Fig. 6 Comparison of Averaged Pilot Ratings for Gun Tracking (TR) and Air Refueling (AR) Tasks with HUD Tracking Task Data

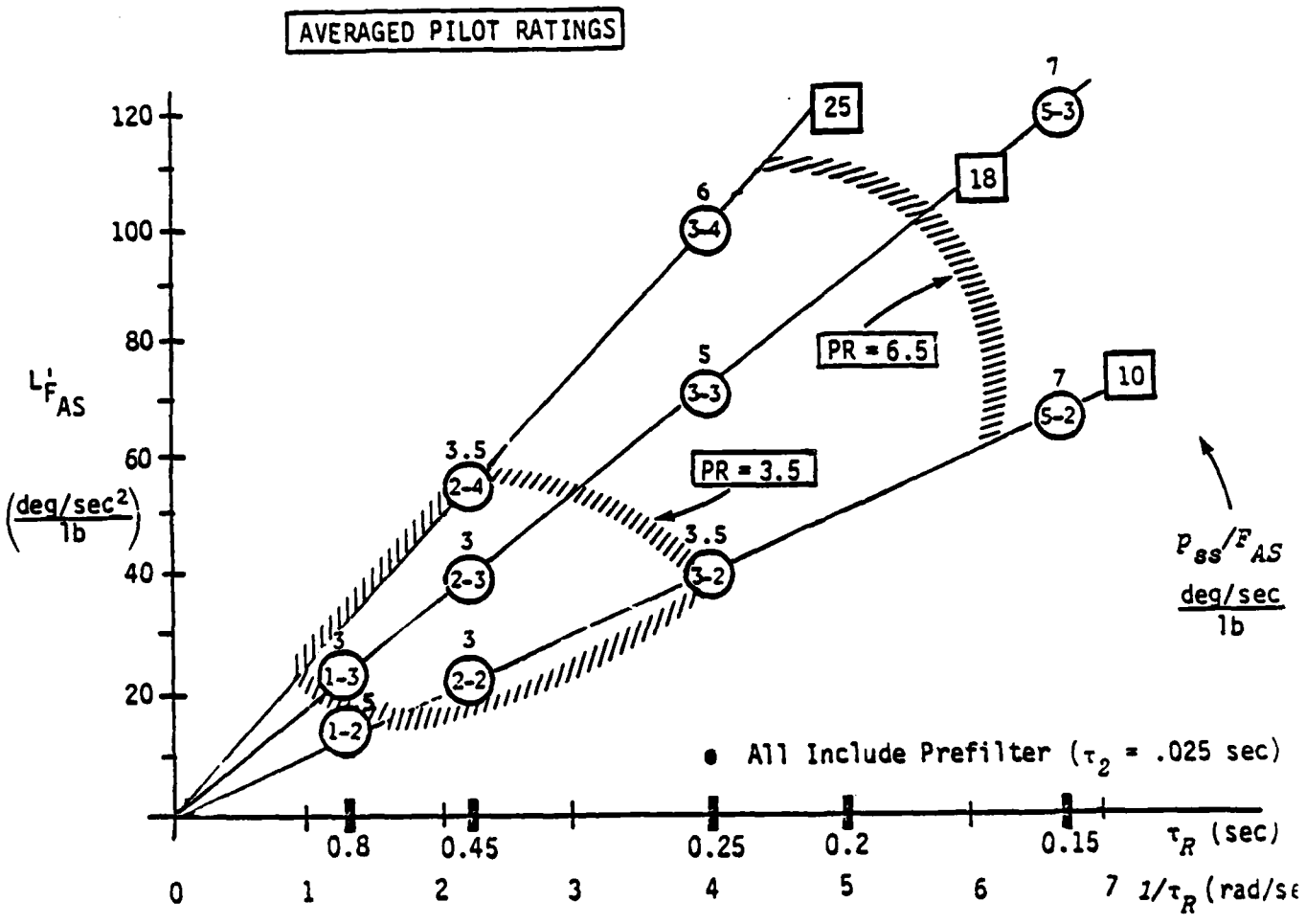


Fig. 7 Pilot Rating Data, Baseline Configurations, Gun Tracking (TR) and Air Refueling Tasks (AR), Flight Phase Category A

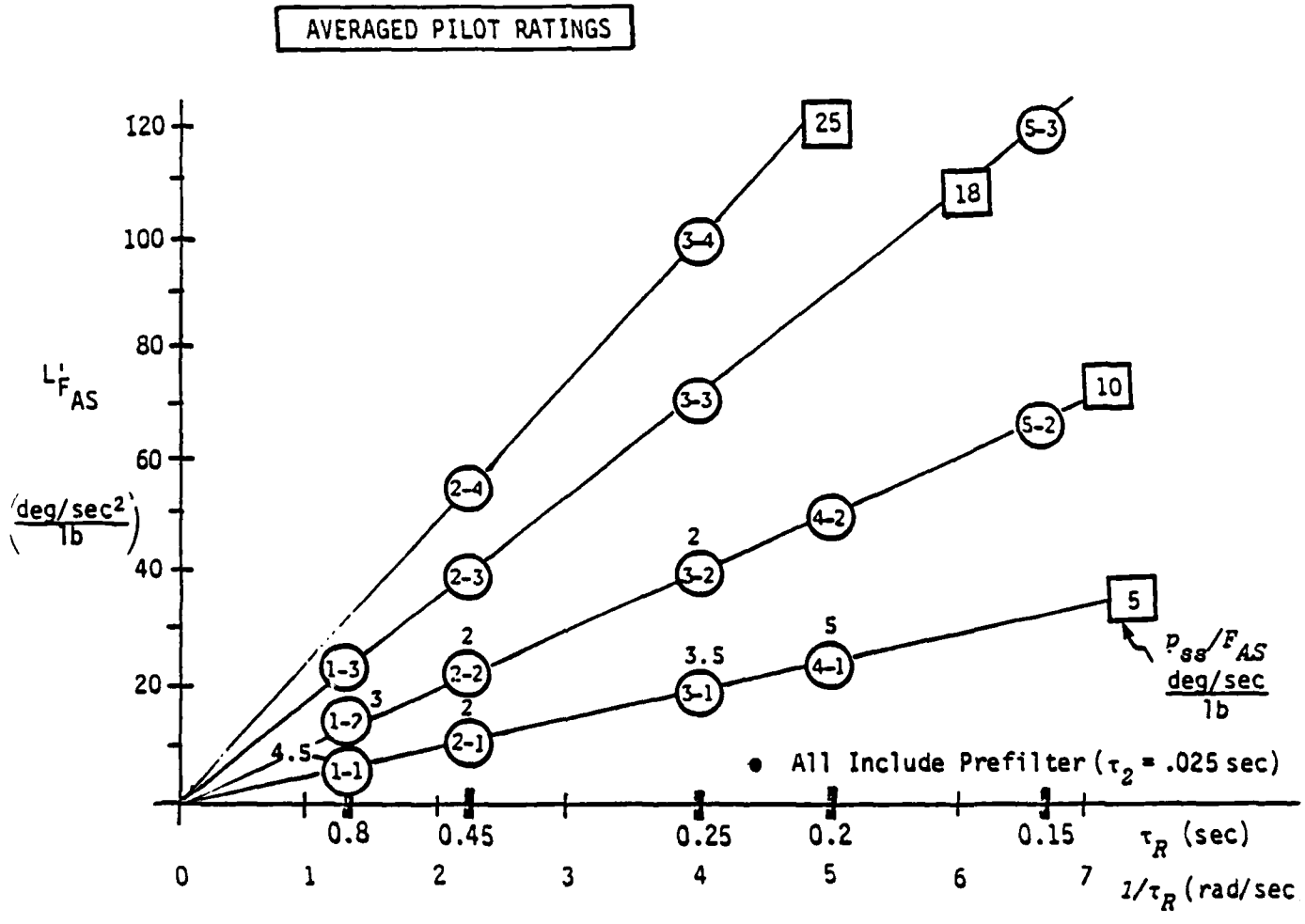


Fig. 8 Pilot Rating Data, Baseline Configurations, Landing Task (LA), Flight Phase Category C

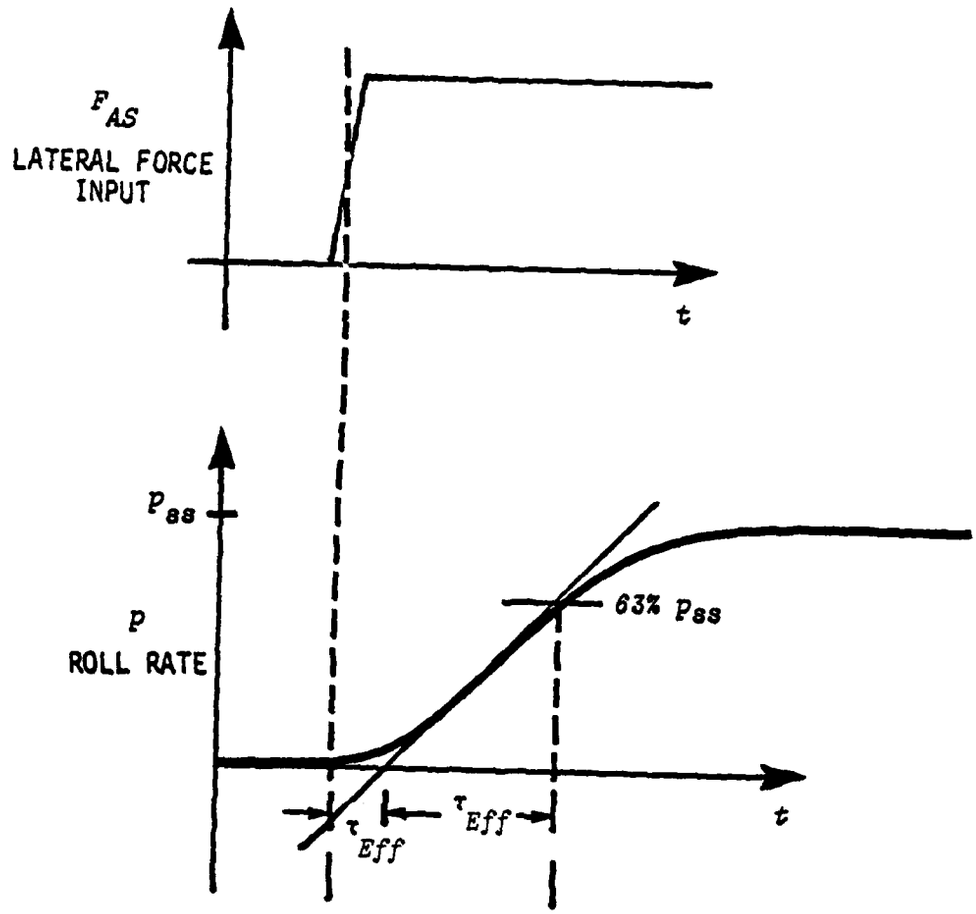


Fig. 9 Calculation of Equivalent Parameters: Time Delay (τ_{Eff}) and Roll Mode Time Constant ($\tau_{T_{Eff}}$)

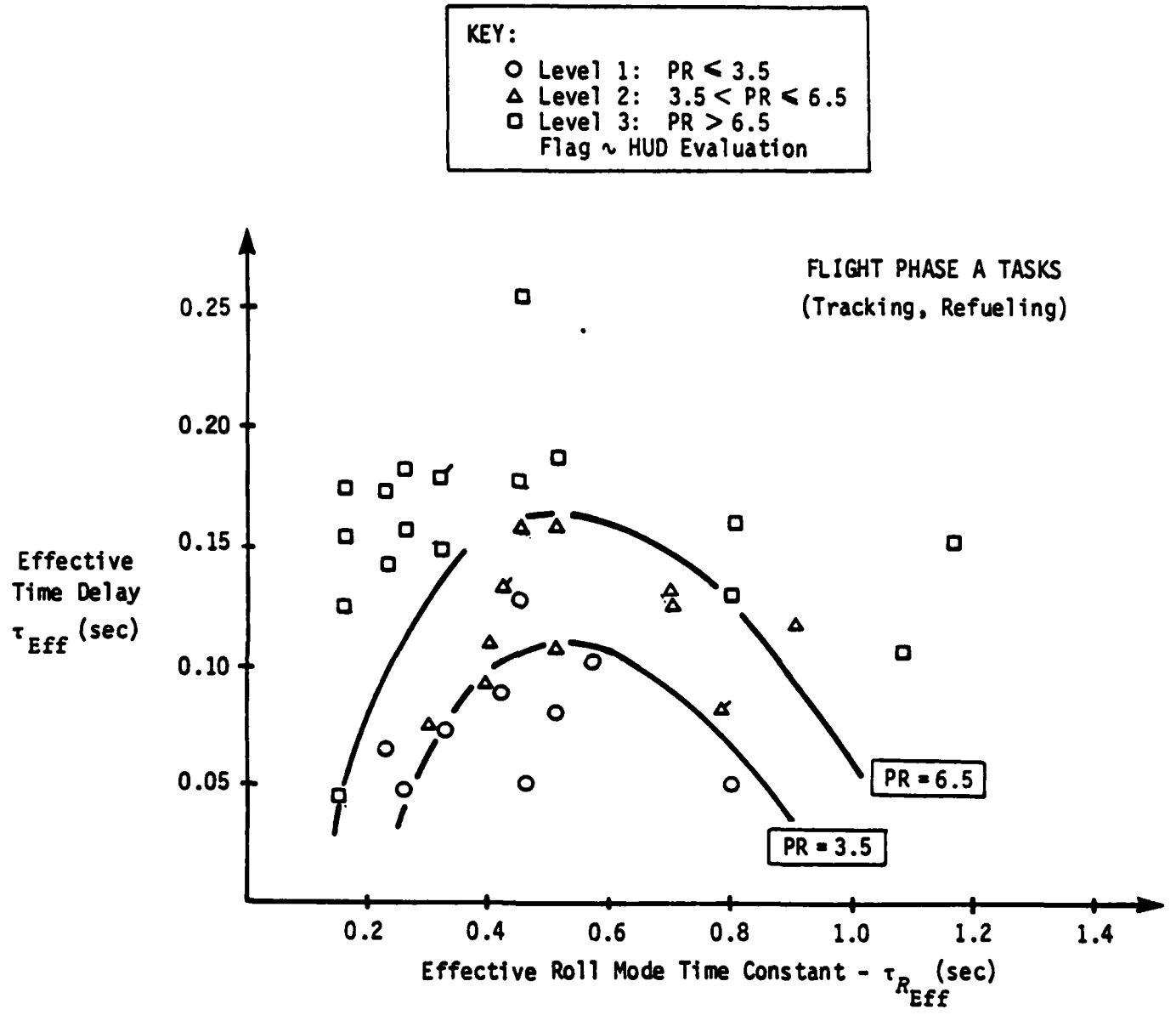


Fig. 10: Correlation of Category A Task (TR + AR) Data with τ_{Eff} and $\tau_{R_{Eff}}$

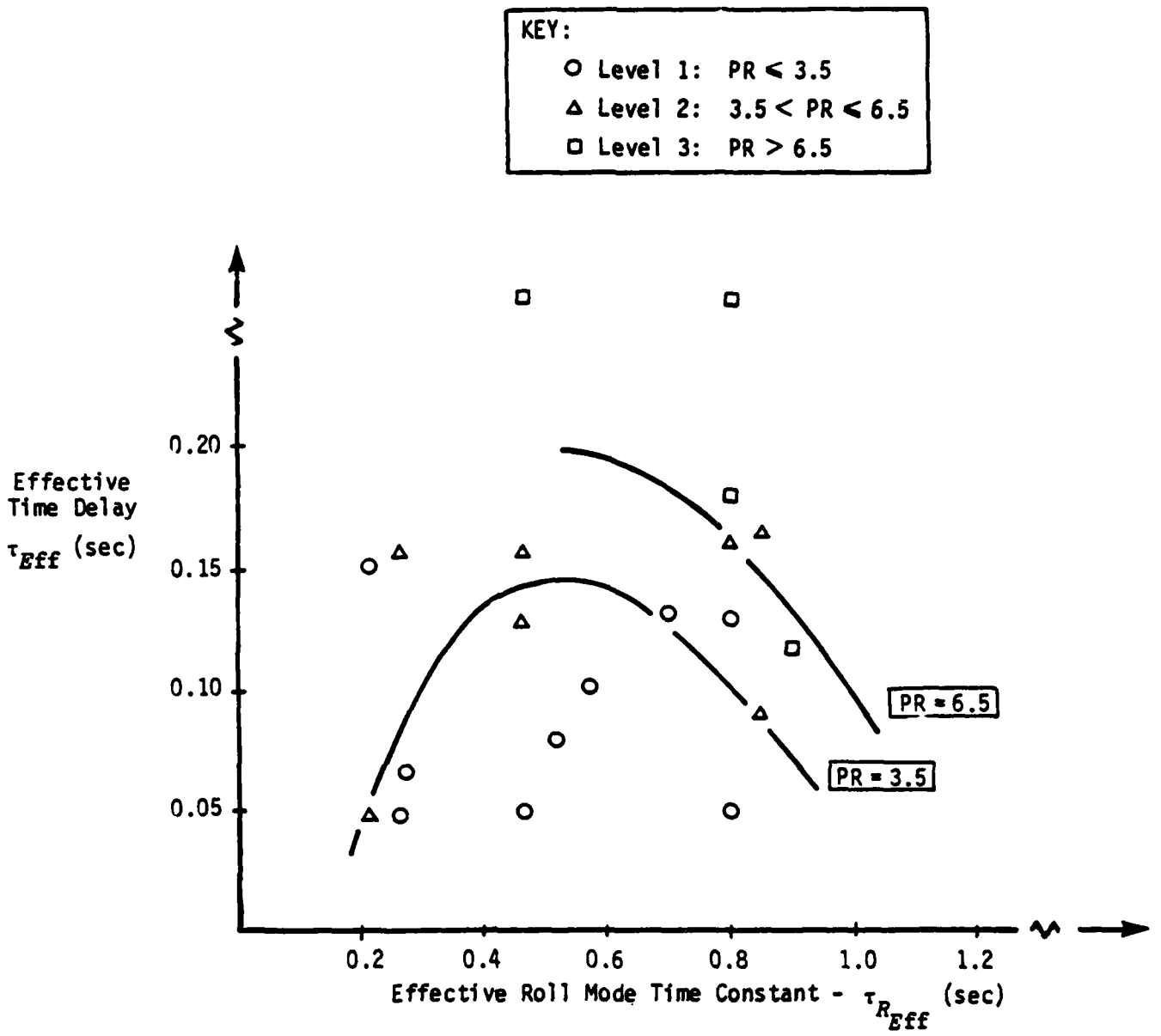
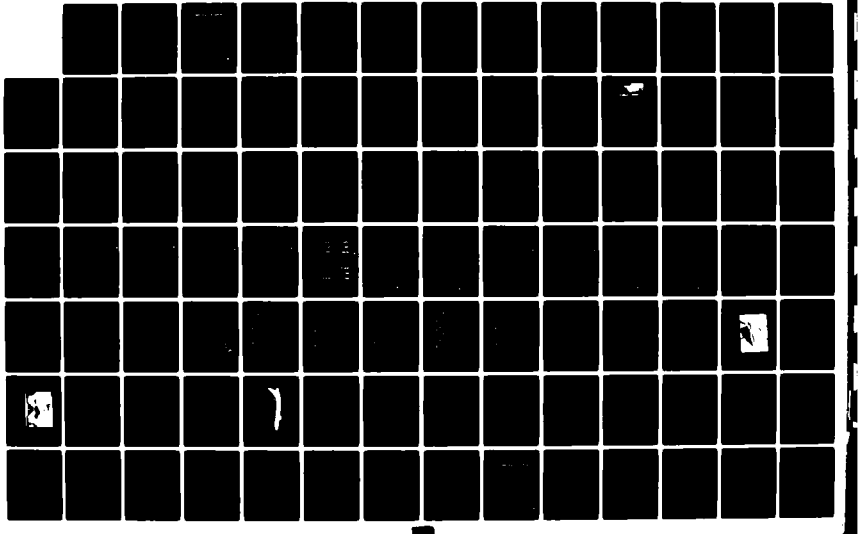


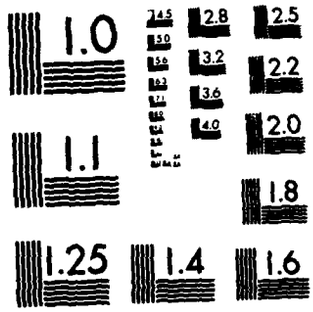
Fig. 11: Correlation of Category C Task (LA) Data with τ_{Eff} and $\tau_{R_{Eff}}$

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MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

COMMENTS AND QUESTIONS

Jerry Lockenour, Northrop: There is a potential problem with all the different definitions of time delay.

Sam Craig: Was a force stick used?

Answer: It was a center stick with motion.

Dick Quinlivan, GE: A difference of one on the Cooper-Harper scale (7 to 8) is the difference between doing the job and pilot comfort. This was based on the film of NT-33 experiments. This is not compatable with a mission-oriented specification.

Answer: Good point.

ARVIN/CALSPAN

IN-FLIGHT INVESTIGATION OF LARGE AIRPLANE FLYING QUALITIES FOR APPROACH AND LANDING

Norman C. Weingarten and Charles R. Chalk

Prepared For:

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on Design Criteria for the Future of Flight Controls

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Wright-Patterson Air Force Base
Dayton, Ohio 45433

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Introduction

The objective of this in-flight research program, utilizing the Air Force Wright Aeronautical Laboratory/Calspan Total In-Flight Simulator (TIFS), was to obtain data applicable to Flight Phase Category C operation of Class III airplanes, i.e., approach and landing task for very large (one million pound), low-load factor airplanes. The experiment was to provide data on the following factors:

- Minimum short period dynamics
- The need for absolute n/α limits
- Effect of normal acceleration cues
- Augmentation system bandwidth
- Control system time delay and phase shift limits
- Multi-loop control in landing
- Lateral acceleration tolerable to pilot
- Demonstration of lateral-directional augmentation concept

Three different aircraft designs were generated to evaluate pilot position versus instantaneous center of pitch rotation. The aerodynamics and control systems of all of these configurations were essentially the same except for the value of Z_{δ_e}, or lift due to elevator deflection, which was used to shift the center of rotation. The three basic configurations were: (Also see Figure 1).

Long Aft Tail - a generic conventionally designed aircraft.

Canard - pitching moment controller forward, shifting the center of rotation aft, similar to a slender arrow-wing supersonic cruise design with a canard.

Short Aft Tail - a generic delta wing design with elevons for pitch and roll control, shifting the center of rotation forward of the pilot, similar to the space shuttle orbiter design.

The location of the cockpit relative to the center of gravity was also varied to cover an extreme range of pilot locations relative to the center of rotation.

Combined with the three basic configurations were two different types of pitch augmentation systems: an angle of attack feedback system (Figure 2) and a pitch rate feedback system (Figure 3). Control system gains were varied to augment the statically unstable basic airframe toward Level 1 handling qualities.

Included in the command paths were different levels of extra transport delays (representative of digital control systems) and first order prefilters (representative of structural filters).

Low-maneuverability configurations (low n_z/α) were evaluated by reducing the lift curve slope for the Long Aft Tail configuration with the angle of attack augmentation system.

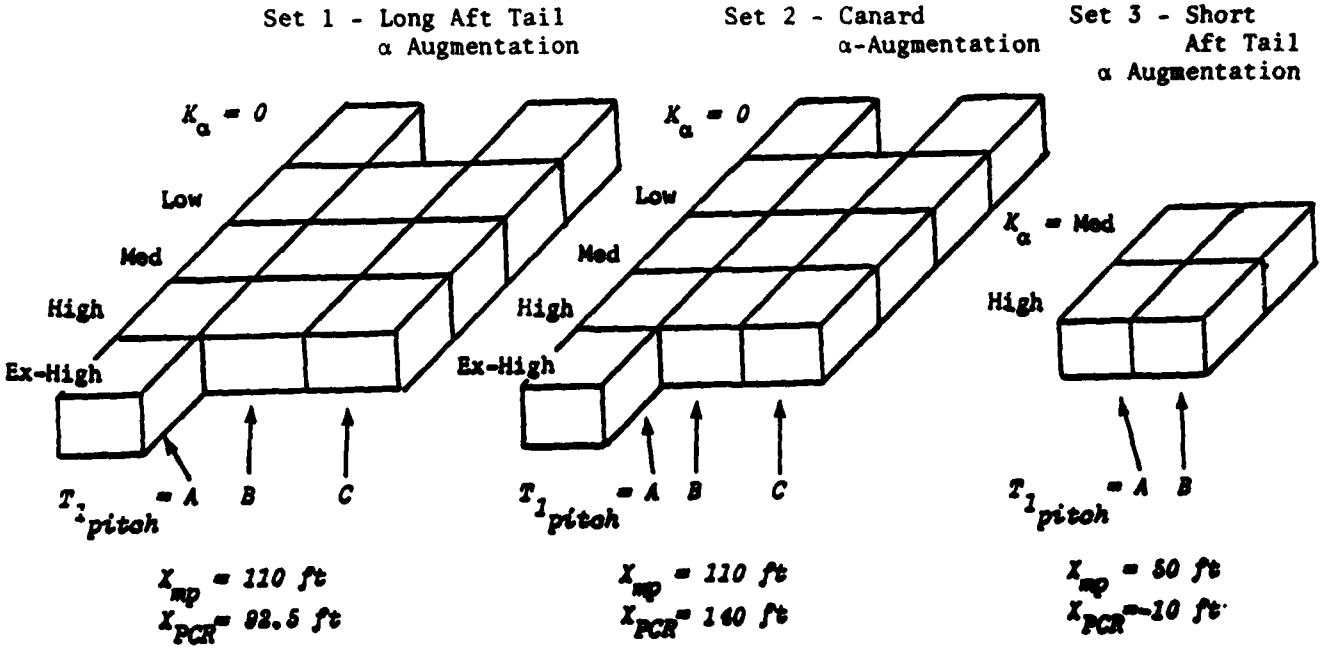
In the lateral-directional evaluations, two values of roll-mode time constants were combined with various levels of roll command path delays and prefilters as in the pitch axis. In addition, different vertical pilot positions were evaluated to investigate lateral acceleration effects.

A more detailed description of the configurations which were evaluated are outlined and illustrated in the following section along with other details of the experiment design. The mechanization of the experiment including the description of the TIFS setup follows that. The results of the program are presented along with the conclusions. The entire experiment is documented in Reference 1, AFWAL TR-81-3118. This technical paper will discuss only the longitudinal portions of the experiment.

Experiment Design

Configuration Description

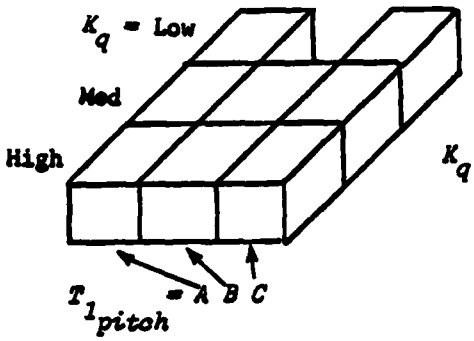
This flight research program consisted of seven sets of longitudinal configurations which are outlined and illustrated by the following discussion and diagrams. Configuration sets 1, 2, and 3 were intended to explore the interactions of basic configuration factors together with an angle of attack augmentation loop only. The α augmentation system is shown in Figure 3. The α signal used was an inertial quantity which eliminated direct turbulence effects on the feedback signal. The α feedback gain was varied, along with the effective time delays in the pilot's command path to the elevator. These configuration sets are illustrated by the following diagrams.



$T_{1_{pitch}}$ is the nominal effective time delay (A = .06, B = .13, C = .2 sec). X_{mp} and X_{PCR} refer to the pilot position with respect to the center of gravity and center of rotation, respectively.

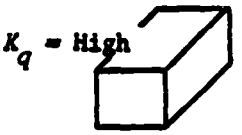
The q augmentation configuration sets are illustrated by the following diagrams:

Set 4 - Long Aft Tail q Augmentation



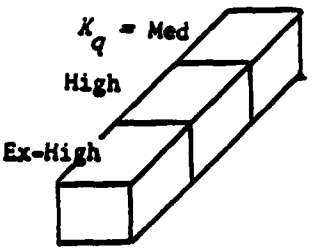
X_{mp} = 110 ft.
X_{PCR} = 97.5 ft.

Set 5 - Canard q Augmentation



X_{mp} = 110 ft.
X_{PCR} = 140 ft.

Set 6 - Short Aft Tail q Augmentation



X_{mp} = 50 ft.
X_{PCR} = -10 ft.

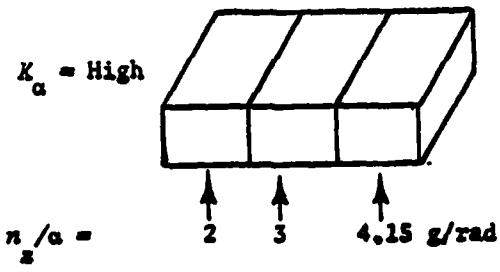
The q augmentation parameters (K_q and T_q) on Figure 3 were selected to give augmented dynamics analogous in an "equivalent system" sense to the short period dynamics of the α augmented configurations of sets 1, 2, and 3. The K_q gain was inversely proportional to dynamic pressure, $\bar{q}$, to keep the dynamics constant when speed changed. Actually the gain calculations were done before formal equivalent system parameters were obtained. Specifically, the value for T_q was arbitrarily set at 1 second and the K_q gain varied until the pitch rate time history from a step input reached a maximum at the same time as that for the equivalent α augmented configuration. Figure 4 shows where these configurations appear on the MIL-F-8785C short period requirements. Equivalent system analyses of these configurations are presented in Reference 1.

In addition to the above configurations, which were flown at their respective nominal pilot positions, a few extra evaluations were flown with the pilot position shifted. This was done to gather data on the effect of initial normal acceleration and altitude cues on the pilot. These were all run with $T_{1_{pitch}}$ = A:

Long Aft Tail, High q , X_{mp} = 50', X_{PCR} = 32.5'
Canard Aft Tail, High q, X_{mp} = 50', X_{PCR} = 80'
Short Aft Tail, High q , X_{mp} = 70', X_{PCR} = 10'
Short Aft Tail, High q , X_{mp} = 110', X_{PCR} = 50'

Configuration set 7 was intended to test the validity of the requirements for minimum n_z/α limits in the MIL-F-8785C requirements. These configurations were achieved by rotating the C_L versus α curve about the trim and by revising the C_D versus α curve such that the C_D versus C_L curve was common for all three configurations. This avoided complications relating to extreme backside of the power required curve operations that might have otherwise occurred.

Set 7 - Long Aft Tail, High α Augmentation
$T_{1_{pitch}}$ = A, n_z/α variation



Experiment Mechanization

Equipment

The USAF/Calspan Total In-Flight Simulator (TIFS) was used as the test vehicle in this experiment. TIFS is a highly modified C-131 (Convair 580) configured as a six degree-of-freedom simulator (Figure 5). It has a separate evaluation cockpit forward and below the normal C-131 cockpit. When flown from the evaluation cockpit in the simulation or fly-by-wire mode, the pilot control commands are fed as inputs to the model computer which calculates the aircraft response to be reproduced. These responses, along with TIFS motion sensor signals, are used to generate feedforward and response error signals which drive the six controllers on the TIFS. The result is a high fidelity reproduction of the motion and visual cues at the pilot position of the model aircraft. A detailed description of the TIFS can be found in Reference 2.

Simulation Geometry

The TIFS motion system was configured to reproduce the model's motion at the evaluation pilot's eye point as if the TIFS were positioned as shown in Figure 6. In this sketch, the model is shown in its approximate attitude at touchdown. Despite qualms about the possible effect on pilot rating of not actually touching down, it was decided to preserve the proper geometric relationship between the pilot and main gear at touchdown.

Approaches were made to a simulated touchdown with the evaluation pilot at his proper eye height. The TIFS wheels at this altitude were approximately 29 feet above the ground. Altitude was measured by a radar altimeter mounted on the underside of the TIFS fuselage.

Evaluation Cockpit Configuration

The evaluation cockpit was configured with the evaluation pilot in the left seat with wheel-column and rudder pedals. The four throttle levers were active and commanded the total thrust of all four engines on the model without any yawing moment effects, i.e., each throttle lever controlled one fourth of the input to the total thrust computation. This provided a large-airplane feel without added computational complexity.

The following cockpit instruments were included in this program: ADI, HSI, horizontal meter between the ADI and the HSI displaying sideslip angle and a vertical meter to the right of the HSI displaying angle of attack. Raw glide slope error was displayed as a vertical bug motion on the left side of the ADI. Raw localizer was shown on the localizer needle on the HSI. Rate of climb and radar altitude were displayed on the tape instrument to the right of the ADI. Pitch and roll trim controls were combined in a wheel-mounted thumb switch. The rudder trim control was a switch on the center console. A Collins flight director, installed in the TIFS, was used during the IFR portion of the evaluation task and drove the command bars on the ADI.

Evaluation Procedure and Task Description

The subject aircraft in these evaluations was a very large Class III military transport which was evaluated in the terminal area flight phase.

The evaluation tasks consisted of the following elements:

- Up-and-away airwork (Specific evaluations of up-and-away tasks were eliminated after the second evaluation flight to allow more time for approaches. Thereafter, the pilot was allowed to briefly sample the up-and-away characteristics of the configuration before the first approach and on the downwind leg between approaches).
  - Trimmability
  - Maneuvering about level flight
  - Airspeed changes
  - Altitude changes
- Specific landing approaches aided by flight director information:
  - Localizer offset, randomly right or left
  - Crosswind, randomly right or left
  - Turbulence, α_g and β_g
  - Precise touchdown parameters

The approach and landing evaluation task, following the brief airwork, consisted of the following:

Precision tracking of the ILS beam, preceded by a "capture" segment beginning beyond the outer marker and at an angle between 30^{o} and 45^{o} to the beam. The evaluation pilot was "under a hood" during the simulated IFR approaches until the final portion starting from the middle marker at an altitude of approximately 300 feet down to the completion of the task. This latter portion of the approach including flare and a simulated touchdown at proper model eye height of 43 feet was to be completed visually. Precise simulated touchdowns were to be attempted. Acceptable landings were defined to be within a 1000 feet zone centered 1000 ft from the threshold of the runway with a low sink rate (<5 ft/sec). Touchdown was signaled by a tone over the intercom and a signal light.

The task was made more difficult with the addition of localizer offsets and artificial or natural atmospheric disturbances of crosswinds and turbulence.

The localizer offset was a constant 1.5 degrees or 1.2 dot angular offset that translated to a 400 ft lateral error at the breakout altitude of 300 feet. This forced the pilot to make lateral-directional corrections, so all of his attention was not kept on the longitudinal task.

The crosswind was added or canceled out with the TIFS sideslip mismatch capability. This capability is limited to a β of .1 radian, equivalent to a 15 knot change in the apparent crosswind at an airspeed of 150 knots.

Turbulence was also added to disturb the model's response. It was desired to have a light to moderate level of turbulence during each evaluation. When the natural level of turbulence was at this level, it was measured and introduced into the model's aerodynamic equations through α_g and β_g components added to the inertial α_I and β_I signals to form the total signals α_T and β_T. When the natural level of turbulence was less than this, artificially generated turbulence was introduced into the model. The turbulence signals recorded on an FM recorder are filtered Gaussian white noise. The filtered noise approximates a Dryden model of turbulence at one specific altitude and speed. The filter characteristics were chosen to duplicate the power spectrum of turbulence at 330 feet and 150 KIAS.

Pilots and Evaluation Summary

Two evaluation pilots participated in this flying qualities investigation. Both of them are Calspan research pilots with very extensive experience as flying qualities evaluation pilots. They are also flying qualities instructors at the Air Force and Navy Test Pilot Schools, demonstrating stability and control characteristics with Calspan's variable stability aircraft. Pilot A's flight experience of 7500 hours includes 750 hours in Class III aircraft. He was also an evaluation pilot in Calspan's space shuttle orbiter simulations. Pilot B's flight experience of 5500 hours has been in a wide variety of aircraft.

Results of the Experiment

The primary variables in the Large Airplane longitudinal experiments were:

- Pilot location with respect to pitch center of rotation presented as three different aircraft design configurations - Long Aft Tail, Canard, and Short Aft Tail.
- Augmentation schemes - α-feedback and q-feedback with proportional plus integral command to yield attitude hold.
- Level of augmentation - from statically unstable to Level 1 stability.

Time delay - produced by model-following lags and inserted pre-filters and pure time delays.

The results of the experiment are extensively analyzed and reported in Reference 1. This paper will briefly discuss airspeed control problems and the effects of pilot location relative to the center of rotation. The effects of augmentation and time delay are treated through closed-loop analysis.

Airspeed Control

The pilots noted problems with airspeed control on about two thirds of the evaluations. Airspeed problems occurred a little less often with q-augmentation than with α-augmentation and the problems were less severe for the higher augmentation gains than for the lowest gain configurations and the unaugmented airplane. For the latter cases, pitch control required so much attention that airspeed simply could not be given enough attention. There were very few cases, however, where pilot ratings of better than 3 were received even when there were no problems with pitch control. There may have been a one-to-two-point degradation in pilot rating due to the speed control problem. A number of factors can be identified which contributed to the airspeed control problems. The configurations were slightly on the backside thus requiring active control of airspeed and thrust management in turns. The lag in thrust buildup following throttle inputs was long (a 3-second time constant) and the throttle position for trim was difficult to find. Together with turbulence, these factors caused airspeed to wander and made the response to throttle difficult to predict. Although low thrust-to-weight was not mentioned, the longitudinal acceleration/deceleration limit on the order of 0.1 g may also have contributed to speed control problems.

Pilot Location Effects

Figure 7 shows how pilot ratings were affected by the variation of pilot position with respect to pitch center of rotation. The pilot position was varied from ten feet aft of the center of rotation in the Short Aft Tail configuration to 140 feet forward in the Canard. The data presented in Figure 7 is only the high level of augmentation cases with the low time delay level, $T_1 = A$. There is a definite trend towards better ratings as the pilot is positioned further forward of the center of rotation. The differences in pilot ratings between the Long Aft and Short Aft Tail configurations are generally three to five.

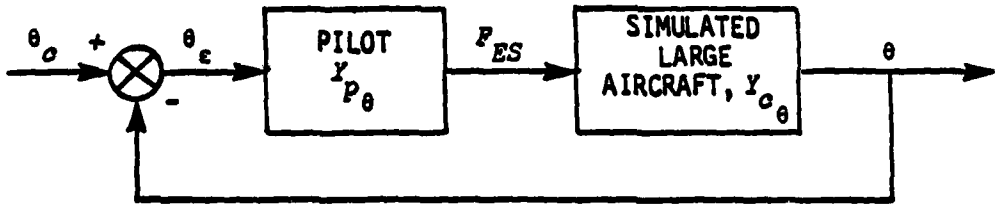
This large variation in pilot ratings for configurations that were essentially the same except for pilot position is partly the effect of visual perception of rate of climb and altitude at the pilot position when near the ground and partly the effect of normal acceleration felt by the pilot. These cues are the normal acceleration at the pilot station and essentially the integrations of it. Normal acceleration at the pilot station is defined by:

$$n_{z_p} = n_{z_{c.g.}} + \frac{X_{MP}\dot{q}}{g}$$

Figure 8 presents the normal acceleration and altitude step responses for the three configuration designs (Long Aft Tail, Canard, Short Aft Tail), each for the High α augmentation level. The distances from the center of rotation to pilot position are +92.5, +140., -10. feet, respectively for these configurations. It can be seen that the Canard configuration has a 50% larger initial N_{z_p} kick than the Long Aft Tail configuration. The Short Aft Tail design produces a nonminimum-phase shape with the response initially going slightly negative before going positive and matching the other responses near three seconds into the time history. It is near one and one-half seconds into the response before the pilot can actually see his altitude change. The pilot comments clearly indicate that the pilots perceived this. With the Canard configuration, the pilots found they could fly the airplane more "naturally," the response felt more crisp and fine corrections in sink rate near touchdown were easily made. These comparisons are with respect to the Long Aft Tail configuration. The better perceived control over rate of sink, especially in the flare, overcame some of the problems related to the low short period frequency, sometimes described as ponderous, with the Long Aft Tail. The Short Aft Tail design was described as "very sluggish and delayed" even with the high augmentation levels and no extra lags or delays added. The ILS and VFR tracking away from the ground was described as "all right" but as soon as the pilot acquired outside cues for references in flare and touchdown, the control deteriorated. Many times, PIO's resulted. Comments indicated precise control of sink rate near touchdown was very poor or impossible. All of the pilot's attention was devoted to the altitude and rate of sink task with the touchdown point and lateral-directional task ignored many times.

Pitch Attitude Pilot/Airplane Control Loop Analysis

The effects of time delay, augmentation type and level of augmentation were treated through closed-loop analysis. The pitch attitude control loop structure used in the analysis is illustrated by the following block diagram:



The analysis is derived from the work by Neal and Smith reported in Reference 3. The basic approach is to model the pilot-airplane pitch attitude control loop as a unity feedback system with a pilot model of an assumed form in the forward loop. The form of the assumed pilot model permits accounting for the following characteristics exhibited by pilots when controlling dynamic systems:

- Adjustable gain.
- Time delay.
- Ability to develop lead or to operate on derivative or rate information.

- Ability to develop lag or to "smooth" inputs. (Lag was not used for the configurations investigated because it would not improve the closed-loop dynamics).
- Ability to provide low frequency integration.

The form of the pilot model defined below accounts for the observed capabilities and limitations of the pilot with sufficient accuracy to permit approximate analysis of the dynamics of the closed-loop, pilot-airplane system in pitch. It should be emphasized that it is not necessary for the pilot model to be an exact analog of the human pilot for it to be useful in the context of design criteria. The design criteria are based on the hypothesis that if good closed-loop dynamic performance can be achieved with an autopilot of the form described by the assumed pilot model, then the human pilot will also be able to achieve good closed-loop dynamic performance.

The pilot model used is:

$$Y_{P_\theta} = K_{P_\theta} e^{-.25s} \left(\frac{5s+1}{s}\right)(\tau_L s+1)$$

The gain, K_{P_θ}, is in the units of pounds/rad.

The $e^{-.25s}$ term accounts for time delay in the pilot's neuromuscular system. The value of 0.25 sec. is based on delays observed in records for the discrete tracking task performed in References 3 and 4. These records exhibit delays ranging from 0.20 to 0.40 seconds. The value of 0.25, selected on the basis of cut and try data correlation, is interrelated with the bandwidth frequency that is specified for a given flight phase or task.

The $\frac{5s+1}{s}$ term provides low frequency integration capability. A form of the pilot model <u>without</u> this term can be used when <u>constant speed</u> or <u>two degree-of-freedom</u> equations are used to represent the airplane. In that case, the airplane transfer function should have a free s in the denominator and low-frequency integration by the pilot will not be necessary. When three degree-of-freedom equations are used, as is the case in the present analysis, or when the flight control system uses high gain attitude stabilization, it may be necessary for the pilot model to perform low frequency integration to avoid droop at frequencies less than ω_{BW}. The 5 sec. lead term permits using integration to avoid the droop limit at low frequency but will not significantly affect the short term dynamics of primary interest.

The $(\tau_L s+1)$ term accounts for the lead that the pilot provides to achieve desired closed-loop performance and is a measure of his workload.

Because the closed-loop, pilot-airplane dynamic system has been modeled as a negative feedback system with unity gain in the feedback path, it is possible to relate the dynamic characteristics of the elements in the forward loop, $\theta/\theta_\varepsilon = Y_{p_\theta} Y_{c_\theta}$, to the dynamic characteristics of the closed-loop system, $\theta/\theta_c = Y_{p_\theta} Y_{c_\theta} / 1+Y_{p_\theta} Y_{c_\theta}$, through use of a Nichols diagram, (Figure 9). This diagram consists of the superposition of two grid systems. The rectangular grid is the magnitude and phase of the forward loop dynamic elements,

$Y_{p_\theta} Y_{c_\theta}$, and the curved grid system represents the magnitude and phase of the closed-loop system $\theta/\theta_c = Y_{p_\theta} Y_{c_\theta} / 1+Y_{p_\theta} Y_{c_\theta}$. Therefore, one can determine the closed-loop dynamic characteristics by plotting the magnitude and phase data of $Y_{p_\theta} Y_{c_\theta}$ for a range of frequency on the rectangular grid.

It is hypothesized that a given Flight Phase or task performed in a typical environment will require certain *minimum* dynamic characteristics of the closed-loop, pilot-airplane system. The parameters used to define the closed-loop dynamic performance are bandwidth, droop at frequencies below the bandwidth, and resonance magnitude. These closed-loop system parameters are defined by the curved lines on Figure 9. The maximum droop permitted for $\omega < \omega_{BW}$ is -3.0 db. This value has been defined somewhat arbitrarily but can be justified from examination of discrete tracking task records in References 3 and 4 and by interpretation of pilot comments in these references (ω is a parameter which varies as shown along the amplitude-phase curve).

The closed-loop system resonance limits for Level 1 and Level 2 have been determined from empirical data correlation.

The bandwidth frequency is dependent upon the task.

In application of these design criteria, the designer must succeed in finding a combination of K_{p_θ} and τ_L which will cause the amplitude and phase data for $Y_{p_\theta} Y_{c_\theta}$ to plot in the Level 1 or Level 2 regions of Figure 9. It is necessary, therefore, to perform a parameter search. This search procedure is not difficult; it can be performed graphically using graphical aids described in Reference 3 or the process can be mechanized on a digital computer. Because the calculations involved in evaluating the magnitude and phase of $Y_p Y_c$ as a function of frequency are simple to perform, it is feasible to use a simple trial and error approach to test whether or not a proposed airplane design meets the design criteria for closed-loop performance.

Pilot Compensation (Neal-Smith) Analysis

In this analysis, pilot lead compensation ($\tau_L s+1$) was obtained that would make the open-loop compensated pilot plus aircraft transfer function ($\theta/\theta_\varepsilon$) drawn on a Nichols diagram pass through the acceptable closed-loop criteria region (see Figure 9). That is, find the appropriate gain and lead to keep closed-loop resonance less than +3 dB and closed-loop droop less than -3 dB for $\omega < \omega_{BW_\theta}$. The bandwidth frequency is defined as the frequency which results in a closed-loop phase of -90 degrees. The bandwidth chosen for this set of data was 1.5 rad/sec. This value of bandwidth resulted from correlation of the PR = 3.5 data with pilot lead compensation of approximately 45^o or less. This value of bandwidth appears appropriate for the task of landing a very large transport in a manner which does not require high agility of the closed-loop pilot-airplane system.

To obtain the pilot compensation, lead was added to force the 1.5 rad/sec point through the -90 deg closed-loop phase line with the θ/θ_ϵ plot just skimming the +3 dB closed-loop resonance boundary. The resulting closed-loop droop was much less than -3 dB (near 0 dB) for most configurations. Lower resonance could have been obtained with the droop still not dropping below -3 dB by using more lead compensation. The solutions chosen, therefore, usually represent minimum pilot lead required to meet the performance standard. The maximum lead time constant used was approximately 7 seconds. This results in lead of: $\tan^{-1}(\tau_L \omega_{BW_\theta}) = 85$ degrees at the 1.5 rad/sec bandwidth. This limit is arbitrary but represents the situation of diminishing returns that occurs in the closed-loop system, i.e., extreme increases in pilot lead do little to improve closed-loop performance. For a few cases, the performance criterion of less than 3 dB resonance could not be achieved with this maximum lead.

The aircraft (with the 25 rad/sec feel system) plus compensated-pilot, open-loop θ/θ_ϵ transfer functions for each configuration evaluated are presented in Reference 1. Plots of pilot rating versus the pilot compensation, $\not{P}C$, are presented in Figures 10 through 12. All of pilot B's ratings are included although many were performed using the 15 rad/sec feel system.

There is a definite trend towards worse pilot ratings as more pilot compensation is required. From the Long Aft Tail and Canard configurations data, it appears that the phase compensation must be less than 55 degrees for Level 1 ratings and less than 75 degrees for Level 2 ratings. The points with large pilot compensation correspond to the configurations with low augmentation levels and extra time delays and lags added. The correlation of pilot rating and pilot compensation generally agrees with data from Reference 3 and 5. This means that the amount of phase compensation at the bandwidth frequency required to meet the closed-loop performance criteria is a good measure of pilot acceptance of the configuration. The same values appear to be valid for fighter tasks as well as transport approach tasks as long as the appropriate bandwidth is chosen.

The Short Aft Tail configurations do not appear to correlate well with these criteria. Pilot ratings up to 10 were received for configurations which required only 55 degrees of phase compensation. The Extra-High q-augmented configuration required only 17 degrees of compensation but still received a pilot rating of 4. This points out the fact that the pilot uses more than just pitch attitude in his control scheme. Normal acceleration, altitude rate, and altitude responses at the pilot position must also be important.

For both the Long Aft and Short Aft Tail configurations, the q-augmented configurations consistently received better ratings than the α-augmented ones even though the required pilot compensation was nearly the same. This again shows that characteristics other than closed-loop attitude control are affecting pilot ratings. The q-augmented configurations exhibited reduced response to turbulence (see Figure 13) and did not require control force in turns. These features definitely improved these ratings over the comparable α-augmented configurations. The operation of the aircraft on the

backside of the power required curve in conjunction with the slow thrust response also appears to put a limit on the best pilot ratings of approximately 3. Only rarely were pilot ratings of 2 or 1 received. The pilots downgraded otherwise good configurations due to the speed control problems.

Effect of Bandwidth on Allowable Time Delay

From previous experiments dealing with higher-order systems and their effective time delays, there appears to be a general increase in the level of time delay acceptable as the task presented the pilot becomes less difficult. Reference 6 compiles much of this data and, in particular, shows the effect of time delay on pilot ratings for three degrees of task difficulty. Data from Reference 3 was obtained from air-to-air combat evaluations. Data from Reference 4 was obtained from fighter landing approach and actual touchdown evaluations. Data from Reference 7 was obtained from "up-and-away" and low-altitude waveoff approach evaluations. The closed-loop pitch attitude bandwidths which the pilots were generally believed to be requiring in these experiments were 3.5 rad/sec, 2.5 rad/sec, and 1.5 rad/sec, respectively as the task became less critical and the pilot did not have to be as aggressive. Shown in Figure 14 are the bands of effective time delay t_1, calculated from the maximum slope intercept method, associated with the boundaries of flying qualities levels (pilot rating of 10, 6.5, 3.5) versus the bandwidth for the evaluation task. The data from which these bands were obtained are from configurations that were rated Level 1 with minimal time delay. It can easily be seen that the pilot becomes much more tolerant of, or less sensitive to, time delays as the tasks become less critical. The landing approach and simulated touchdown task of the present experiment with a large, slow-responding aircraft can be considered as having the same bandwidth requirements (1.5 rad/sec) as the "up-and-away" and low altitude waveoff task of Reference 7. When the present experimental data for the Long Aft Tail and Canard High α and q-augmented configurations are pointed out on Figure 14, it agrees with the trend shown, i.e. large time delays become acceptable at low bandwidth and relatively little degradation in pilot rating results from the large variation of time delay used in the present experiment, compared to higher bandwidth tasks.

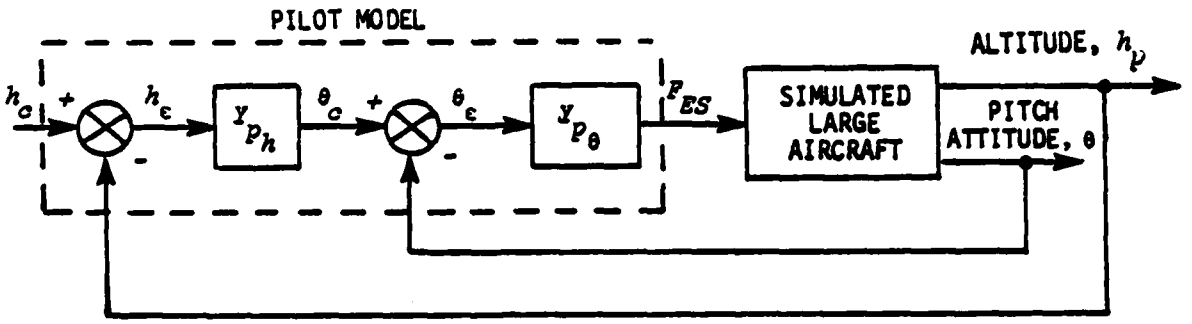
A functional relationship was determined between the average tolerable effective time delay and bandwidth for the task for pilot ratings of 10, 6.5, and 3.5. In the relationships derived, the allowable effective time delay, t_1, was inversely proportional to the bandwidth of the task for the various flying qualities levels:

$$\text{@ PR = 10} \quad t_1 = \frac{.65}{\omega_{BW}} \; ; \; \text{@ PR = 6.5} \; t_1 = \frac{.4}{\omega_{BW}} \; ; \; \text{@ PR = 3.5} \; t_1 = \frac{.3}{\omega_{BW}}$$

These relationships are plotted on Figure 14, along with the data from the Long Aft Tail and Canard, High α and q-augmented configurations. For the data from the present experiment, the average pilot ratings increased from approximately 3.5 to 6 as the effective time delay increased from .14 to .3. This tends to support the relationships shown at ω_{BW} = 1.5 rad/sec.

Multi-Loop Analysis

In order to better understand the evaluations of configurations with varying pilot position versus instantaneous pitch center of rotation with all other characteristics constant, a multi-loop analysis was performed. The model of the control structure is shown below. There is an inner pitch attitude con-



$$Y_{p_\theta} = K_{p_\theta} e^{-.25s}\left(\frac{5s+1}{s}\right)(\tau_L s + 1), \text{ pound/rad}$$

$$Y_{p_h} = K_{p_h}, \text{ rad/ft}$$

trol loop with an outer altitude control loop in series. In the outer loop, the pilot is controlling the altitude he sees at the pilot station. The inner-loop pilot gain (K_{P_θ}) and lead (τ_L) were fixed at the values obtained in the pitch attitude closed-loop analysis where a bandwidth of 1.5 rad/sec was achieved. The pilot model for the outer loop was a pure gain, K_{p_h}, regulating the perceived altitude error, h_ε, at the pilot's position. The lead term in the inner loop ($\tau_L s+1$) effectively gives some lead in the altitude loop also.

Configurations analyzed included the Short Aft Tail, High q-augmented, delay $T_1 = A$, with pilot positoin X_{MP} = 50, 70, 110 feet or pilot position with respect to the center of rotation (X_{PCR}) of 10 feet aft, 10 feet forward, and 50 feet forward, respectively. Added to these configurations were the Long Aft Tail and Canard, High q-augmented configurations which have similar dynamics as the Short Aft Tail configurations. The pilot positions of these extra configurations were X_{PCR} = 92.5 feet forward and 140 feet forward of the center of rotation. In addition, the Short Aft Tail, High q-augmented configuration with extra delay, T_1 = .35 (equivalent to the shuttle's lag/delay) and the Extra-High q-augmented configuration were analyzed.

The analysis is based on the transfer functions in Reference 1 which are evaluated at the nominal trim speed. Complete transfer functions were used without simplification or approximation. The time delays were treated in $e^{-\tau s}$ form. The computer program developed in Reference 8 was used to calculate root loci and Nichols diagrams were used to determine closed-loop bandwidth. It should be noted that all of the configurations have a low-frequency factor in the numerator of the altitude-elevator transfer function that is in the right

half plane as a result of being on the "backside." The analysis performed considered multiple feedback to a single controller, the elevator. This loop closure results in a low-frequency pole of the closed-loop system being driven toward the low-frequency zero of the altitude-elevator transfer function, and in all of these configurations this root was unstable.

Configuration	Zero Location	Closed Loop Pole
Short Aft	+.0037	+.0036 for K_{P_h} = .010
Long Aft	+.0030	+.0030 for K_{P_h} = .014
Canard	+.0023	+.0022 for K_{P_h} = .014

In order to stabilize this closed-loop pole, it would be necessary to close a low gain feedback loop of airspeed to the throttle. This loop closure was not included in the analysis, and the results described in the following paragraphs must be viewed with that fact in mind.

Although the closed-loop system transfer function was 11th order over 15th order and included time delay, the results of the analysis will be discussed in terms of the dominant set of complex roots of the closed-loop altitude-stick force dynamic system.

The root locus analysis for the Short Aft Tail configurations show that the altitude mode goes unstable at increasingly higher gain and higher frequency as the pilot position is moved forward. The potential closed-loop bandwidth is thus higher at the more forward pilot locations. Low bandwidth of the altitude loop correlates highly with the occurrence of PIO's near touchdown. The Long Aft Tail and Canard configurations do not go unstable with increased altitude loop gain.

The Nichols analysis for these configurations show that the highest achievable bandwidth for the altitude control loop increased from .43 rad/sec to 2.30 rad/sec as the pilot position was moved from 10 feet aft to 140 feet forward of the center of rotation. A large increase in bandwidth was obtained when going from the Long Aft Tail to Canard configuration. It should also be noted that the pilot lead used for the inner loop (τ_L) has a significant effect on the bandwidth of the altitude loop. The effect of pilot lead in the outer altitude loop on the altitude loop bandwidth was also shown to be significant (see Figure 15).

Pilot rating and pilot-induced oscillation rating are correlated with the calculated altitude loop bandwidth in Figures 15, 16 and 17; the trend towards better ratings with high bandwidth can be seen. Though not enough samples were taken to absolutely define flying qualities boundaries, it appears that a bandwidth of greater than .5 rad/sec may be necessary for Level 1 ratings. This correlates well with data obtained by the Dutch in an NLR study (Reference 9). They used the same altitude control loop pilot model in a medium transport landing approach experiment, and proposed a .55 rad/sec altitude bandwidth as necessary for Level 1 flying qualities.

Conclusions

1. The pilot rating and comment data obtained in this experiment for a million-pound airplane exhibit significant effects of the following experiment variables:

   - Augmentation type and level of loop gain, i.e., angle of attack feedback or pitch rate feedback with proportional plus integral in forward path and automatic elevator for turns.
   - Pilot location relative to the center of rotation for elevator commands.
   - Lag and time delay in the command path for both pitch and roll.
   - Slow thrust response coupled with backside aerodynamic characteristics.
   - Direct lift control.
   - Lateral acceleration at the pilot location.

   Neither the MIL-F-8785C requirements nor any of several proposed requirements for pitch and control system dynamics were capable of correlating the experiment results without significant modification or extension.

2. The pitch rate augmentation system was generally preferred over the angle of attack augmentation. This was especially true for the Short Aft Tail configurations with the pilot behind the center of rotation. This was due to the lower turbulence response, attitude-hold feature, and level turn capability without pitch inputs with the q-augmented configurations.

3. The pilot ratings were degraded for the cases where the pilot was located near or behind the center of rotation.

4. The evaluation pilots tended to apply a less demanding standard of maneuverability than for previous landing approach studies because the configurations were defined to be very large, one-million pound, Class III aircraft. The closed-loop pitch attitude bandwidth requirement for the landing approach task with this Class of aircraft appears to be 1.5 rad/sec.

5. The degradation caused by time delay was less severe than in previous landing approach studies in both pitch and roll. This is primarily a result of the decreased bandwidth demanded by the pilots for this class airplane. The present equivalent time delay requirements of MIL-F-8785C appear to be conservative for this class of airplane and flight phase. Data is presented which suggests that the amount of time delay that can be tolerated in the command path is inversely related to the dynamic bandwidth required to perform the task.

6. When the pilot position is forward of the center of rotation, the pitch acceleration response to control provides an earlier linear acceleration cue at the pilot position that is easily perceived by the pilot and serves to confirm to the pilot that the airplane is responding to his command. When the pilot is located far ahead of the center of rotation, the linear acceleration cue is amplified immediately following the transmission delay through the control system but before the lag associated with the short-period mode. This effect may contribute to the higher tolerance to control system time delay observed in this experiment.

7. A multi-loop analysis which modeled an outer altitude control loop in series around the inner pitch attitude loop provided insight into the effects of pilot location relative to the center of rotation. A low-frequency closed-loop pole goes unstable at relatively low gain and frequency with the pilot aft of the center of rotation. As the pilot moves further forward of the center of rotation, this complex mode remains stable and closed-loop bandwidth of the altitude control loop increases. A closed-loop altitude bandwidth of .5 rad/sec appears necessary for Level 1 ratings. For the Short Aft Tail configurations, it was shown that increasing the level of q-augmentation had a similar effect on altitude bandwidth as moving the pilot forward.

8. Evaluation of the shuttle-like Short Aft Tail configuration with the pilot located ten feet behind the center of rotation indicated acceptable flying qualities could be achieved when the command path time delay was low and the Extra-High pitch rate augmentation was used. This aircraft design was unacceptable when time lag and delay equal to that of the shuttle was introduced into the pitch command path and the High pitch rate augmentation was used.

9. The effect of turbulence on the unaugmented configurations was relatively low except for long-term speed control due to its negative static stability. As the α-augmentation level was increased, a pitching and airspeed response to turbulence became greater at frequencies below 1 rad/sec. At the highest levels of augmentation, the response to turbulence at low frequency seriously hindered control. The effect of the pilot being very far from the center of rotation also added to the motion felt by the pilot in turbulence. As the q-augmentation level was increased, these turbulence effects became less. This was due to the low static stability of the base airplane and the long-term attitude hold of the q-feedback configurations.

10. The slow thrust response (three second time constant) to throttle caused difficulty in thrust management and forced open-loop manipulation of the throttles, i.e., set and wait to see if further adjustment is required. This complicated airspeed control and degraded the pilot ratings, especially for the α-augmented configurations. The slow thrust response compounded airspeed control for these configurations since they were also slightly on the "backside" at the trim speed.

11. Reduction in n_z/α from 4.2 to 2.0 g/rad caused pilot ratings to degrade by PR = 2-3 points. The degradation, however, was more related to the pitch control force and thrust required in turns than to pitch dynamics.

12. Direct lift control, commanded by a thumb wheel, mounted on the throttle lever, improved control of sink rate during flare and touchdown for the Short Aft Tail configuration. More pilot experience and a force/feel system with the direct lift control would be necessary for a thorough evaluation.

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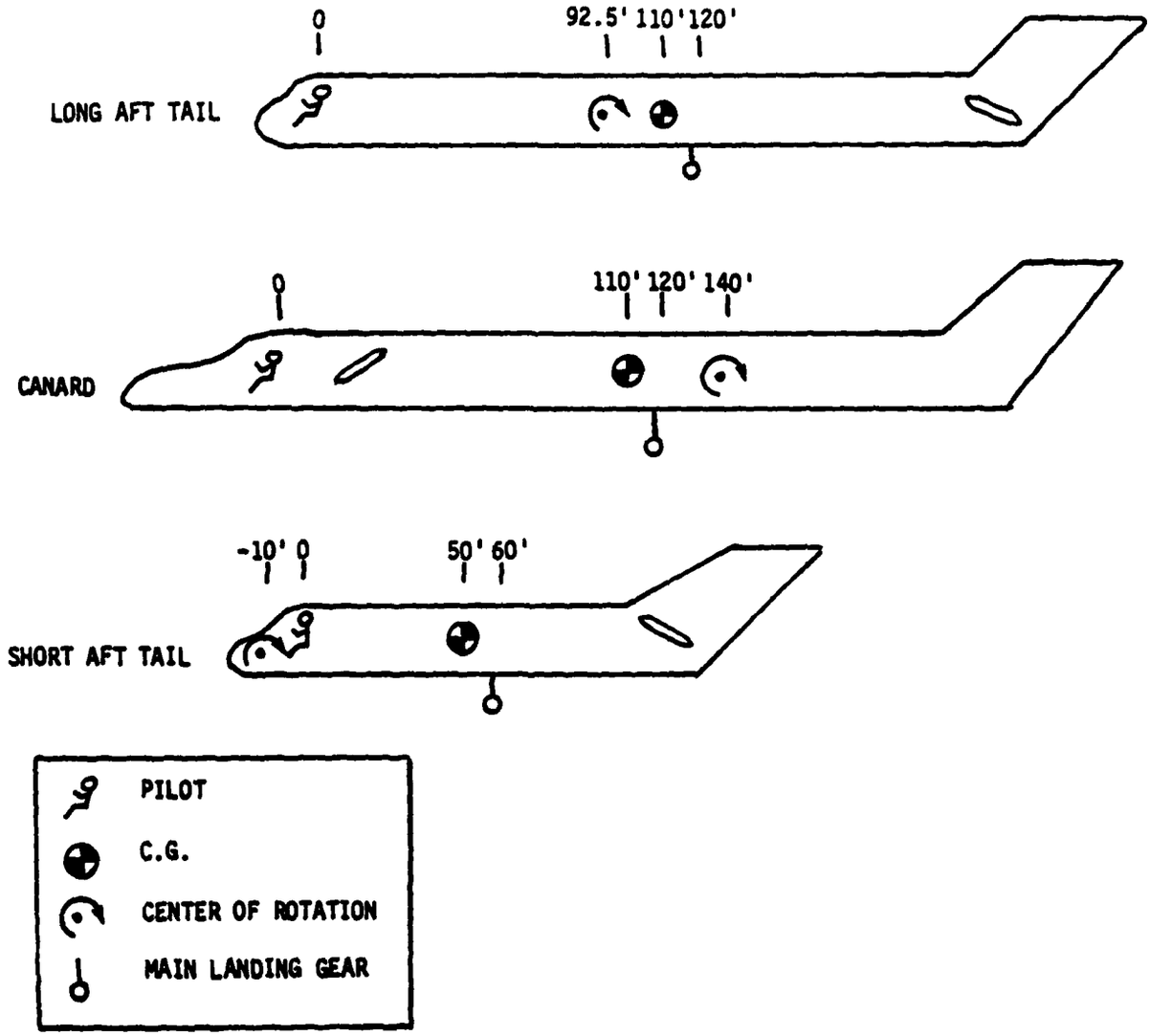


Figure 1. RELATIVE LOCATIONS OF PILOT, C.G., CENTER OF ROTATION, AND MAIN LANDING GEAR OF VARIOUS BASE CONFIGURATIONS

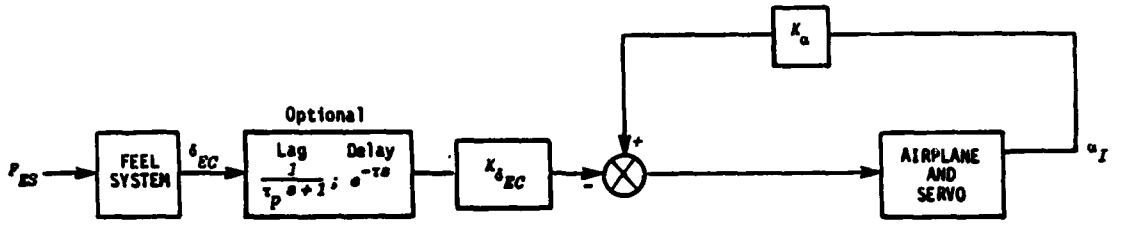
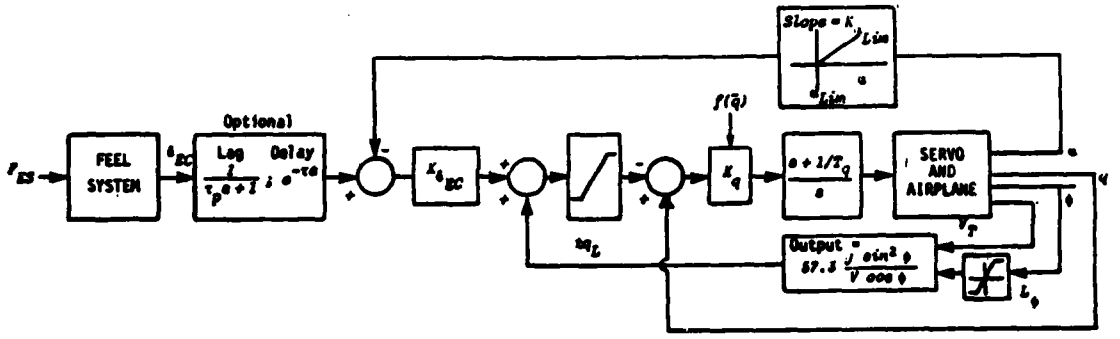


Figure 2. ANGLE OF ATTACK AUGMENTATION



$tq_L = -\frac{g}{V_T}[\pm n_L + \cos\theta \cos\phi]$, n_L set at $1.3g$ just to check operation in tests, not used in evaluations

L_ϕ ~ Limit bank angle for which elevator is compensated for level turn (±45 deg)

K_q ~ Loop gain establishes dynamics, function of $\bar{q}$

$K_{\delta_{e_c}}$ ~ Command gain, set by pilot

$\frac{1}{T_q}$ ~ Integral/Proportional Ratio Influence Augmented Dynamics

Figure 3. PITCH RATE AUGMENTATION SYSTEM

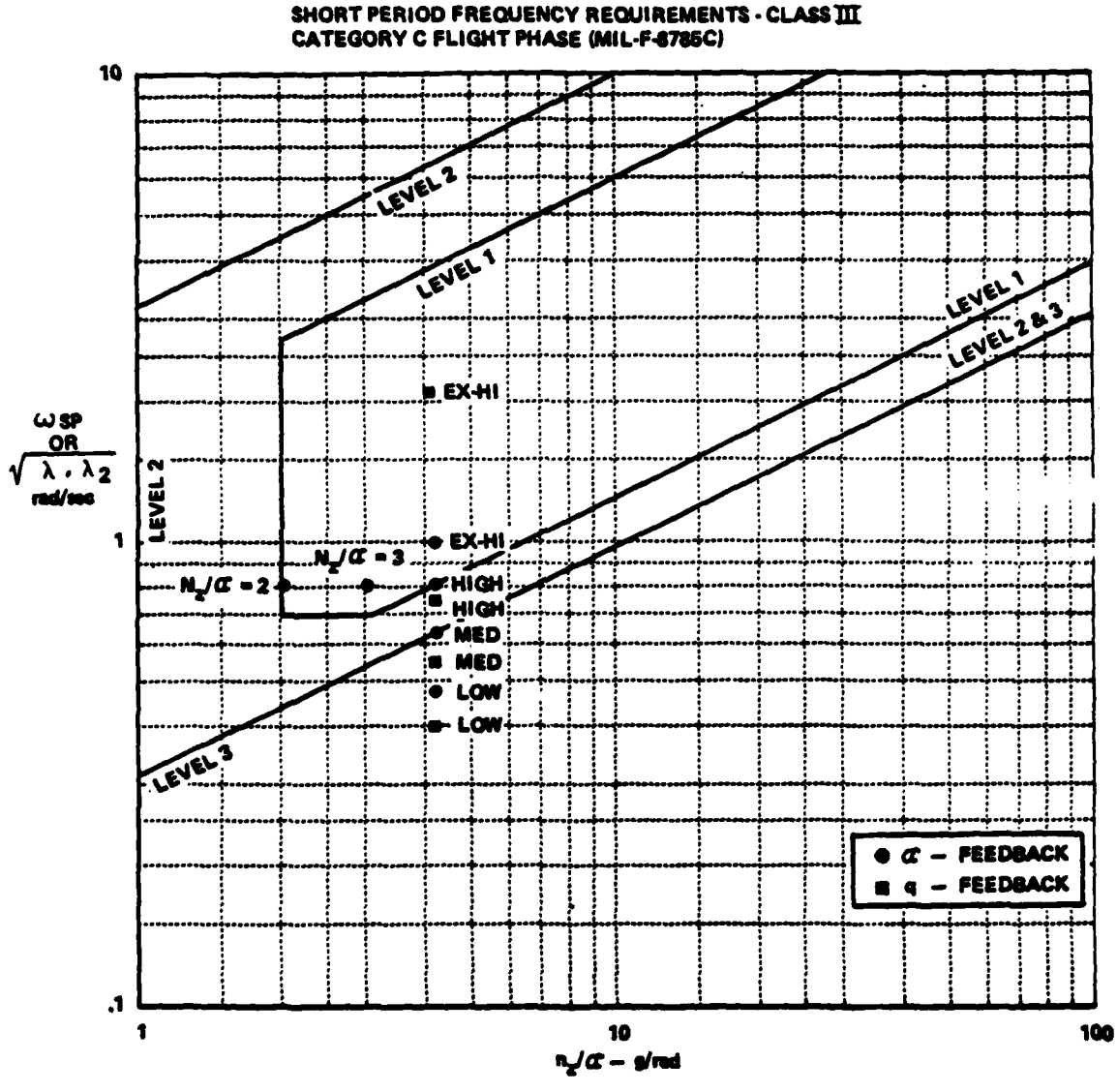
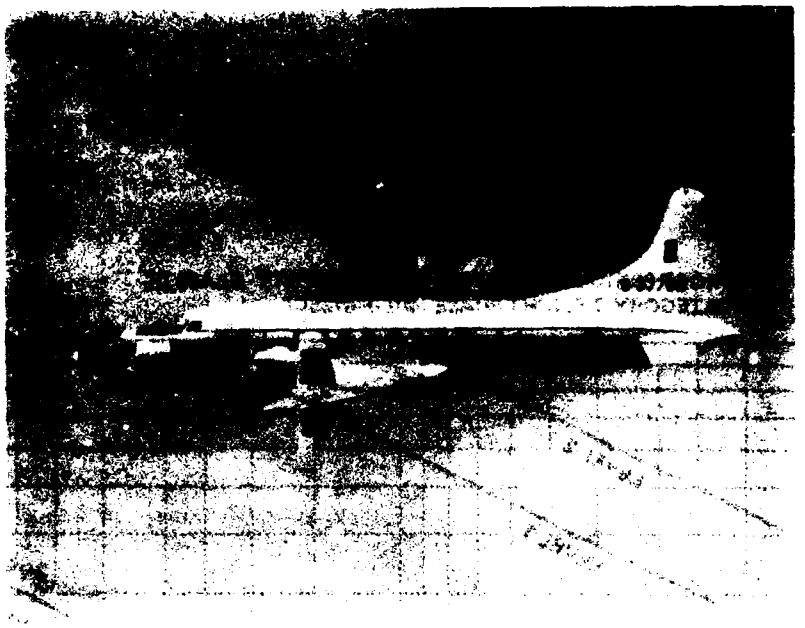


Figure 4. AUGMENTATION LEVELS VS ω_{SP} REQUIREMENTS



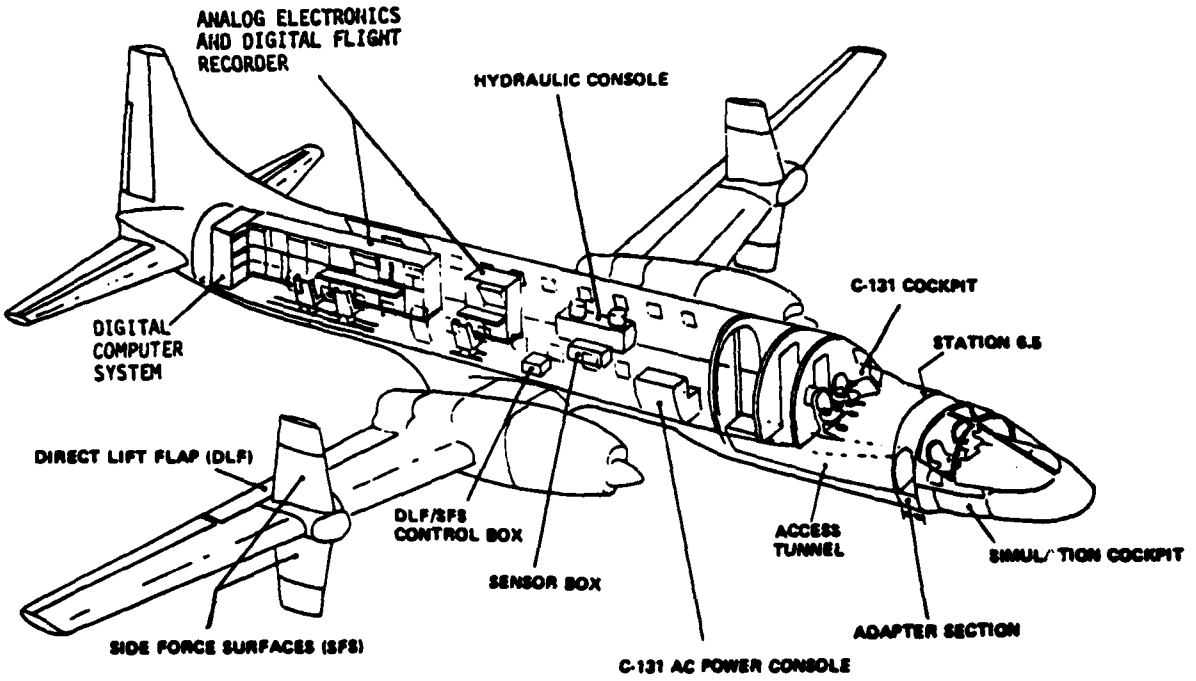


Figure 5. USAF/CALSPAN TOTAL IN-FLIGHT SIMULATOR (TIFS)

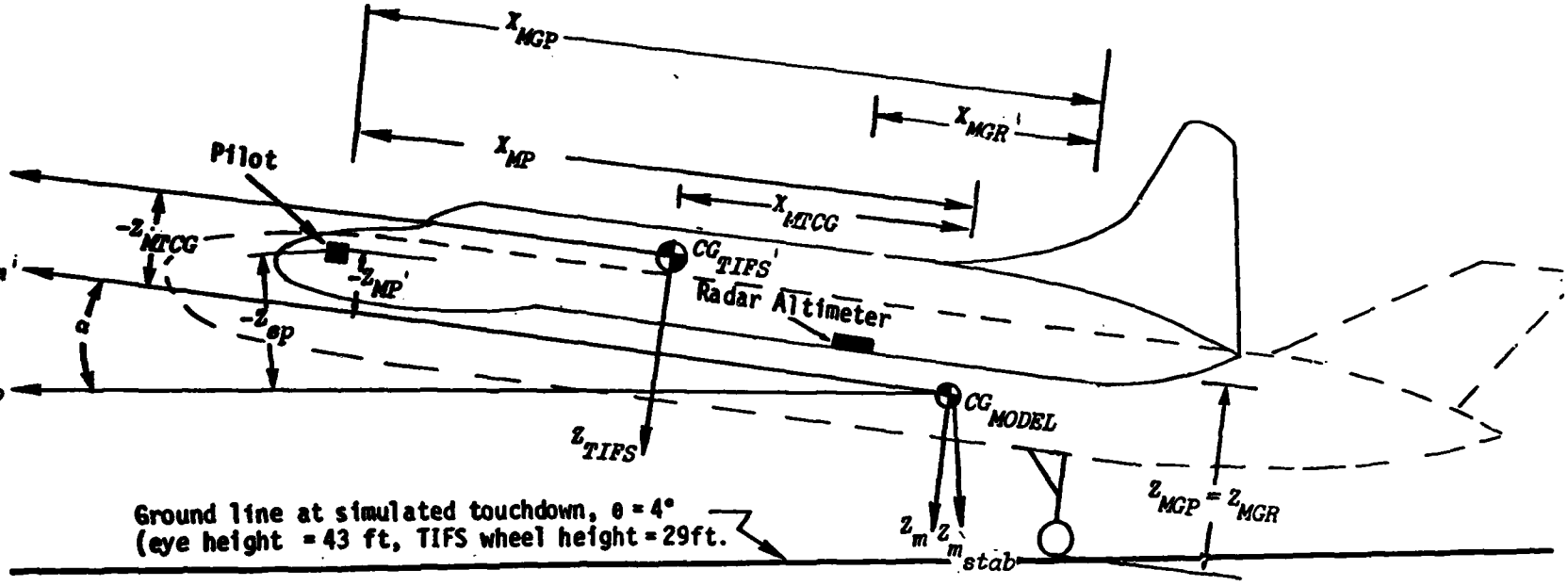


Figure 6. GEOMETRY OF TIFS SUPERIMPOSED ON MODEL

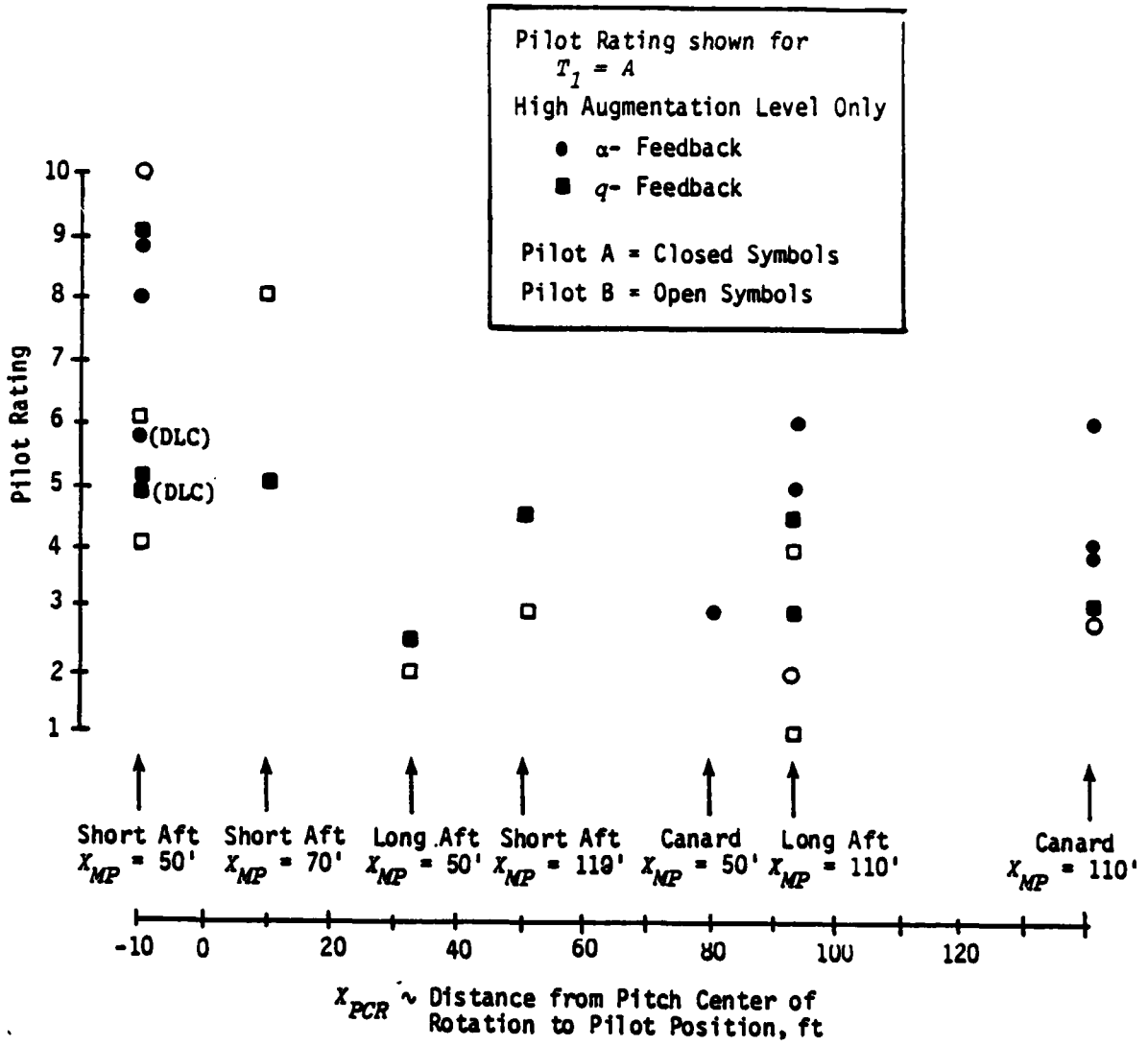


Figure 7. PILOT RATING VS PILOT POSITION - CENTER OF ROTATION (X_{PCR})

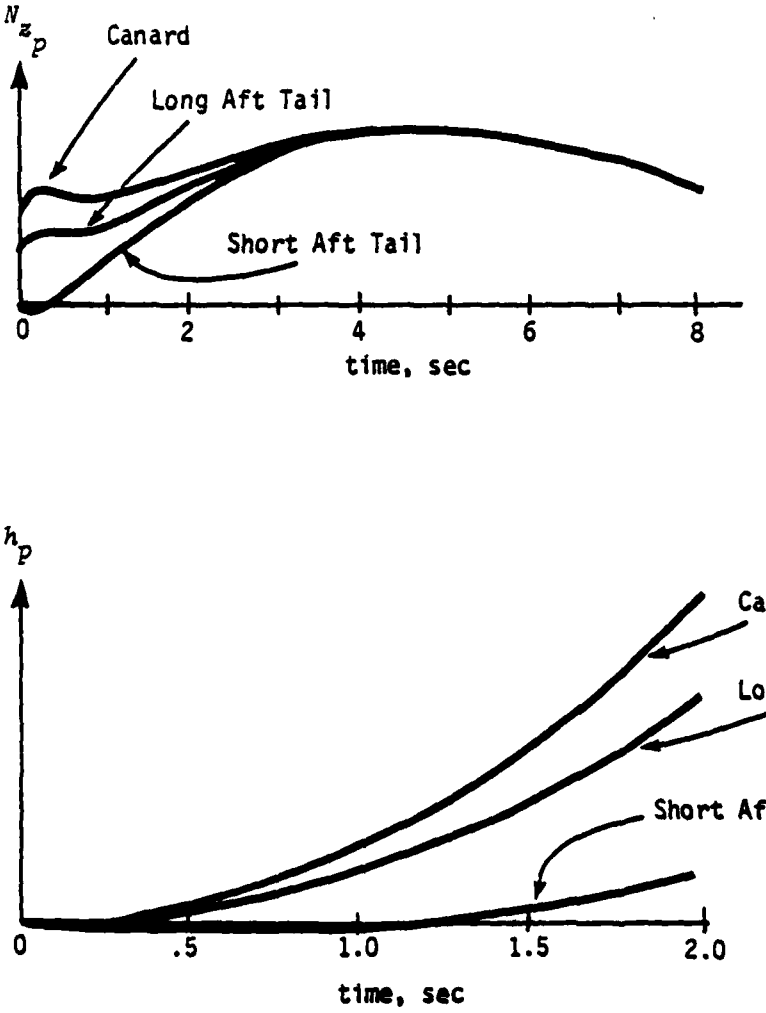


Figure 8. NORMAL ACCELERATION AND ALTITUDE AT PILOT STATION RESPONSES TO STEP INPUT, HIGH α AUGMENTATION, $T_1 = A$

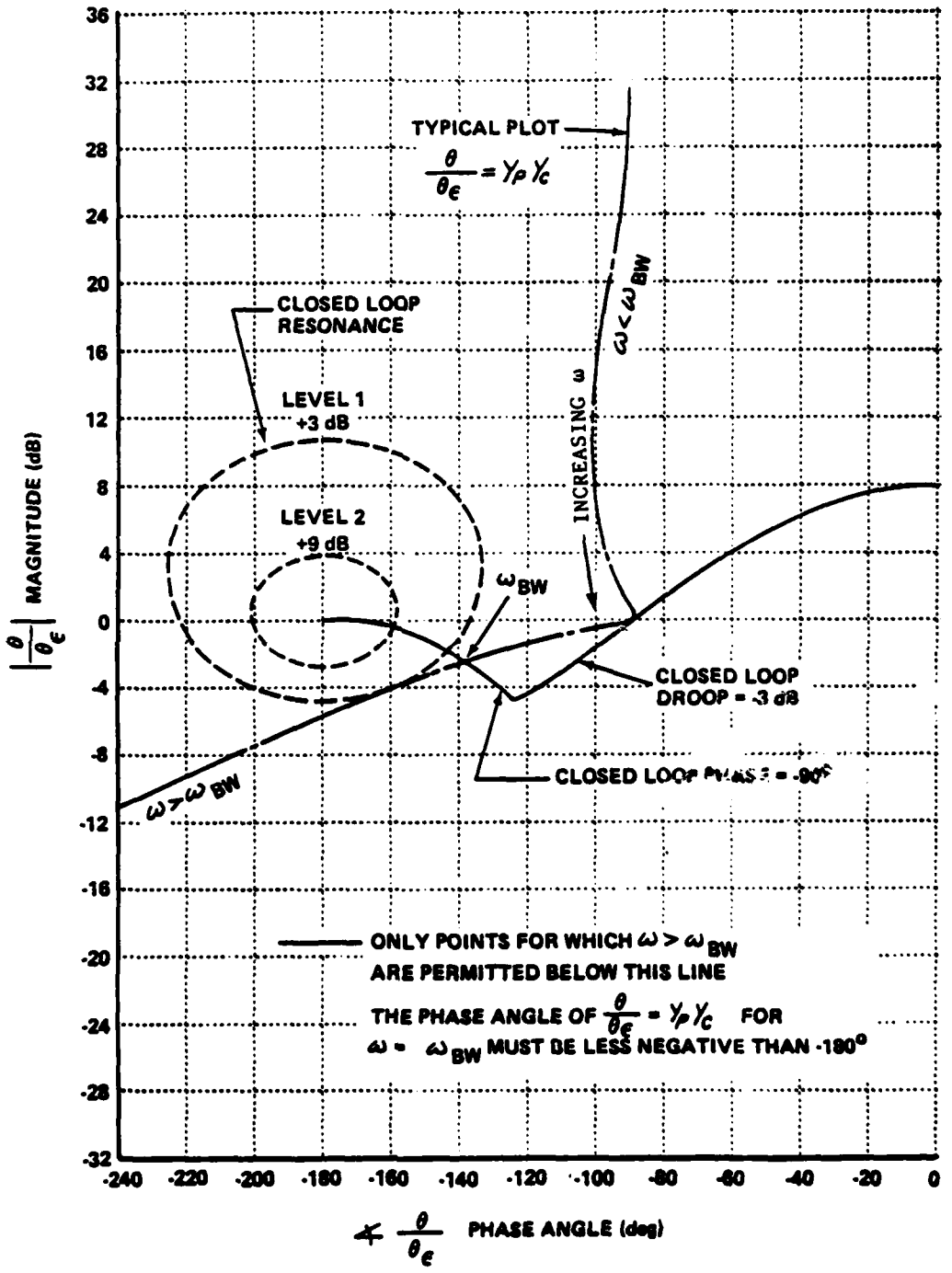


Figure 9. DESIGN CRITERIA FOR PITCH DYNAMICS WITH THE PILOT IN THE LOOP

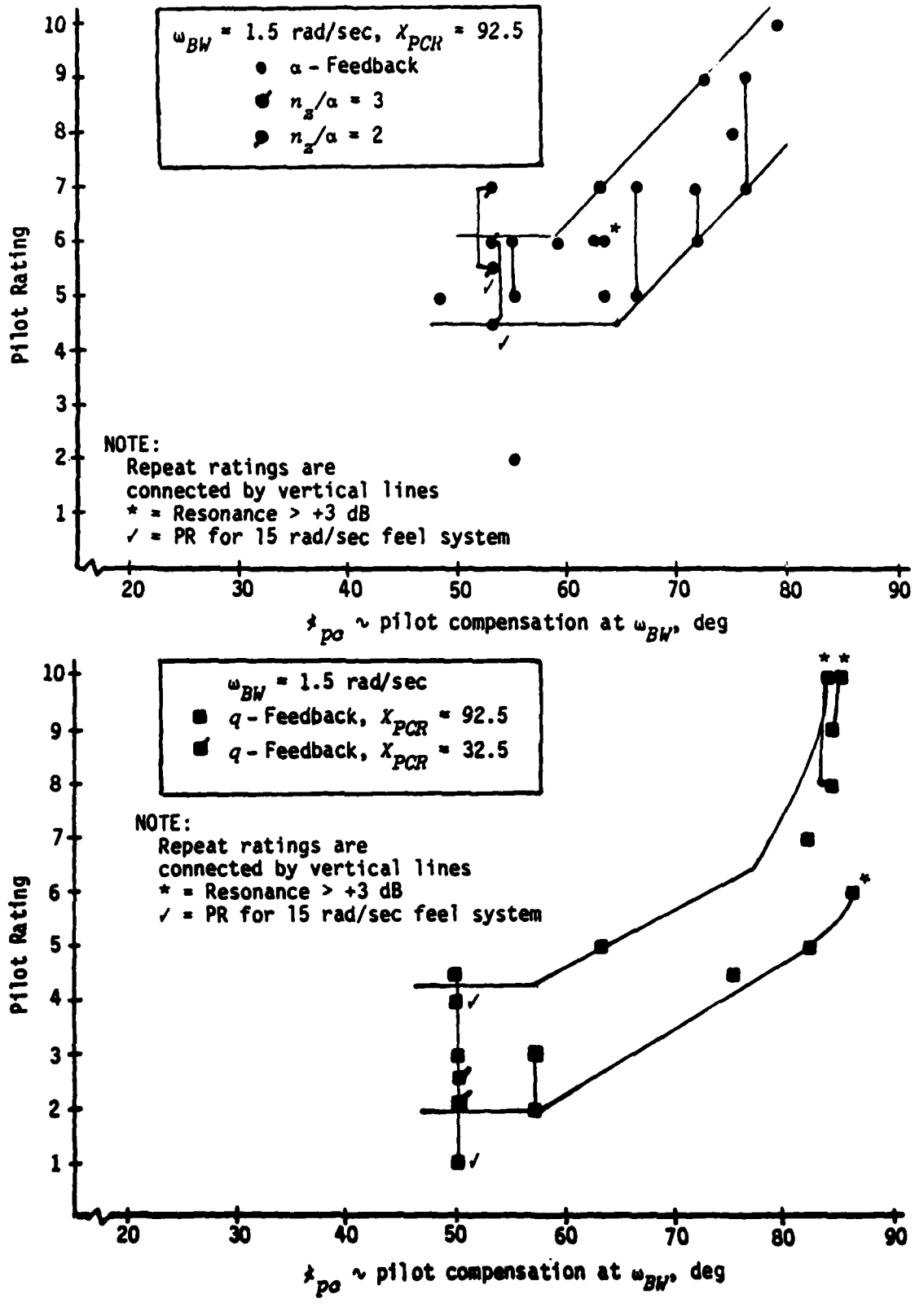


Figure 10. LONG AFT TAIL PILOT RATINGS VS PILOT LEAD COMPENSATION

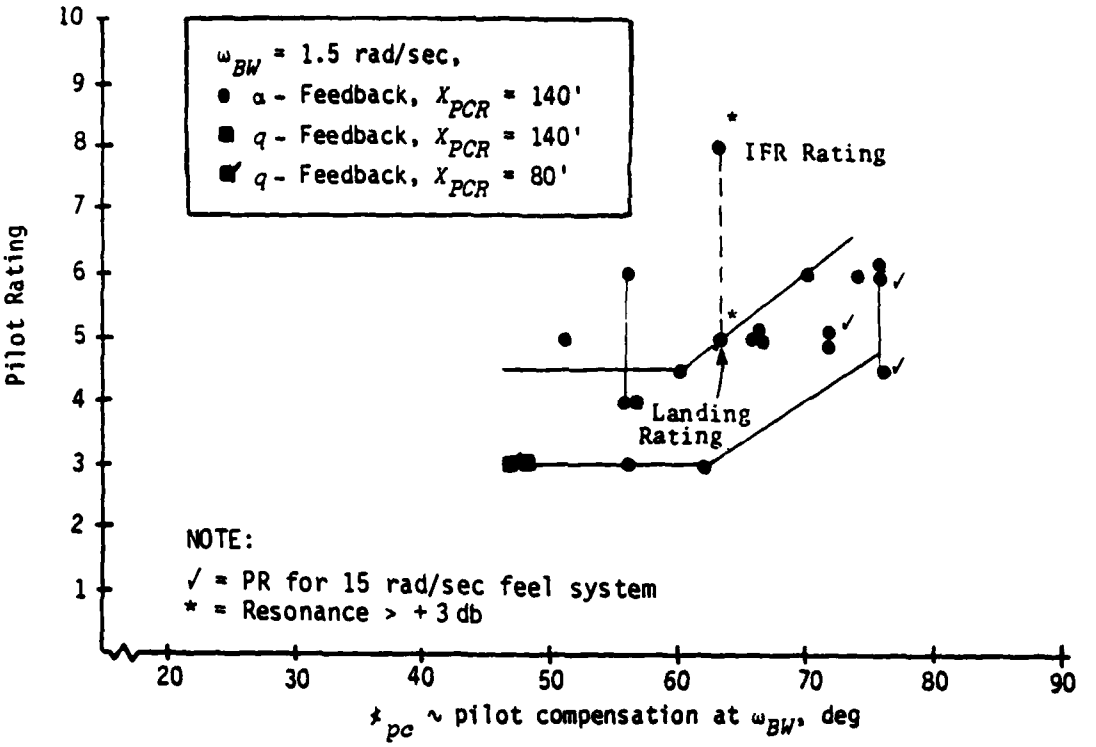


Figure 11. CANARD PILOT RATINGS VS PILOT LEAD COMPENSATION

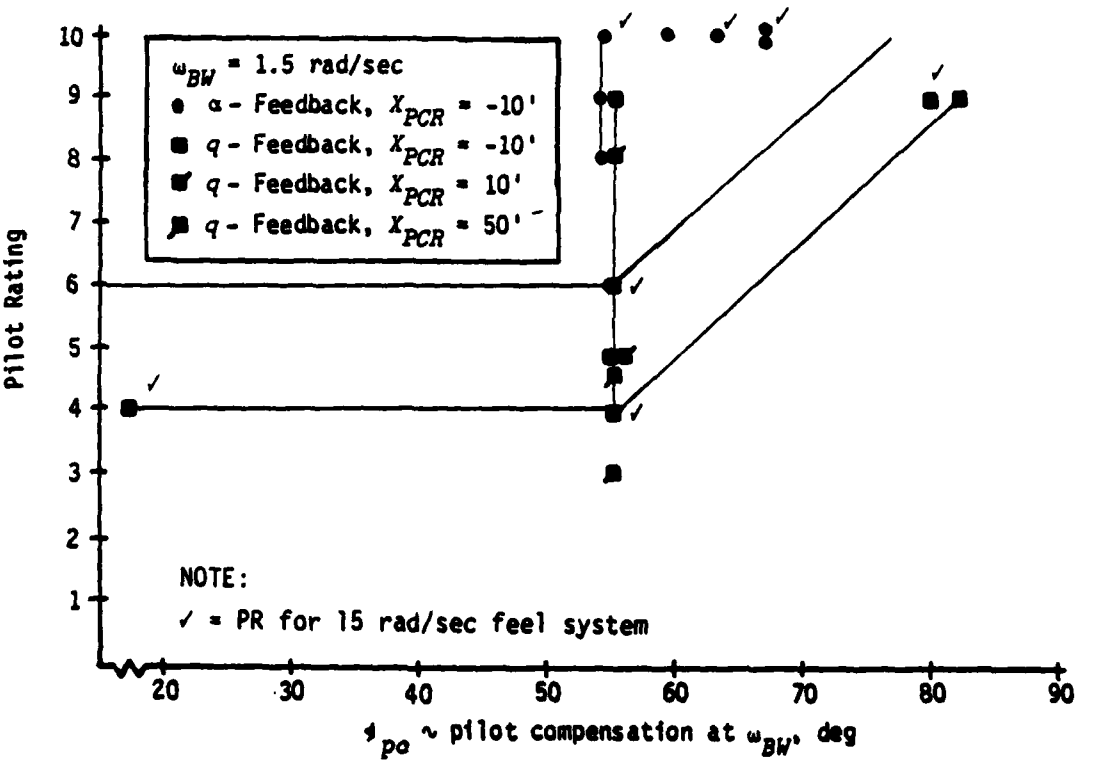


Figure 12. SHORT AFT TAIL PILOT RATINGS VS PILOT LEAD COMPENSATION

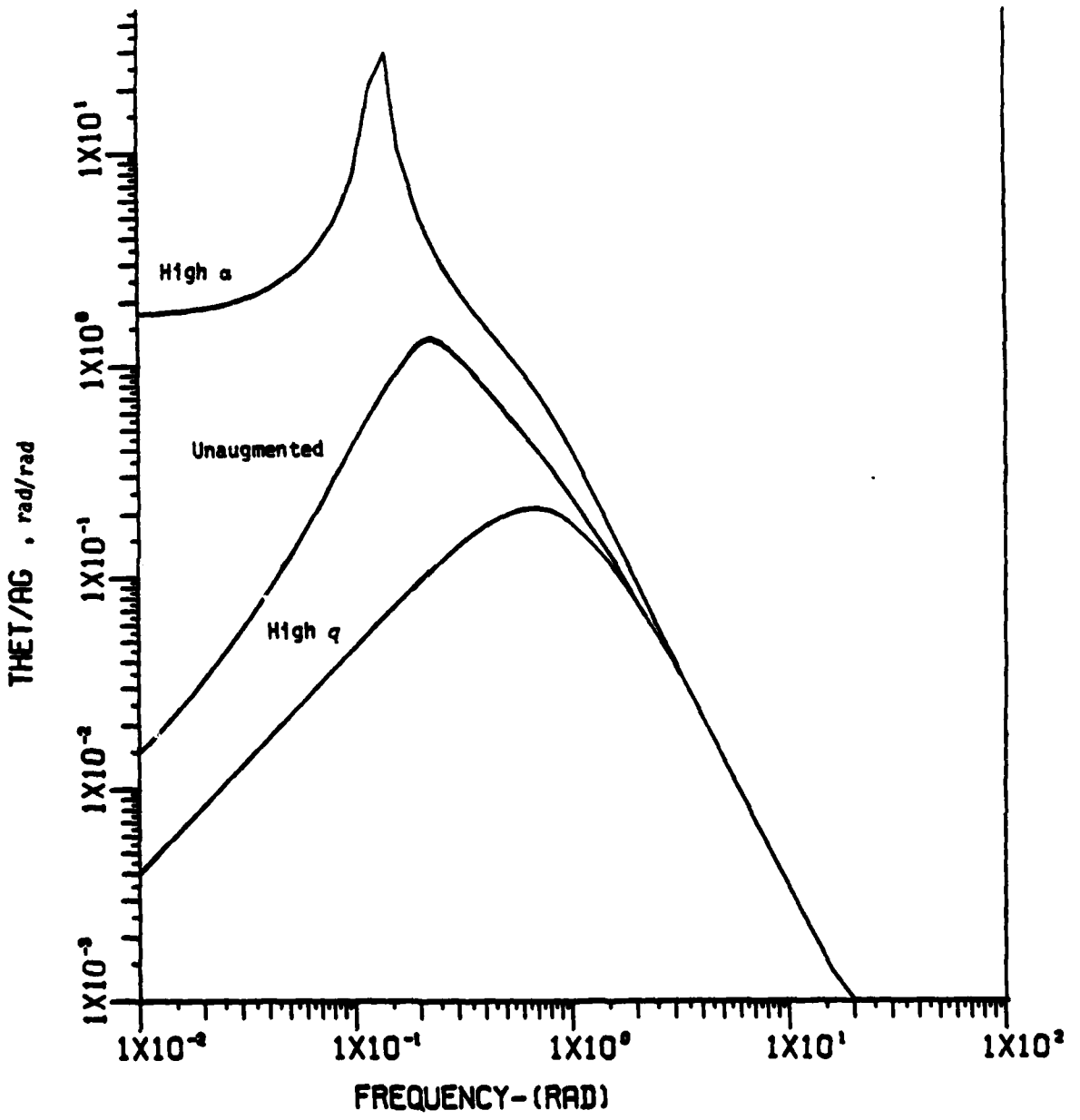


Figure 13. LONG AFT TAIL, TURBULENCE RESPONSE, θ/α_g

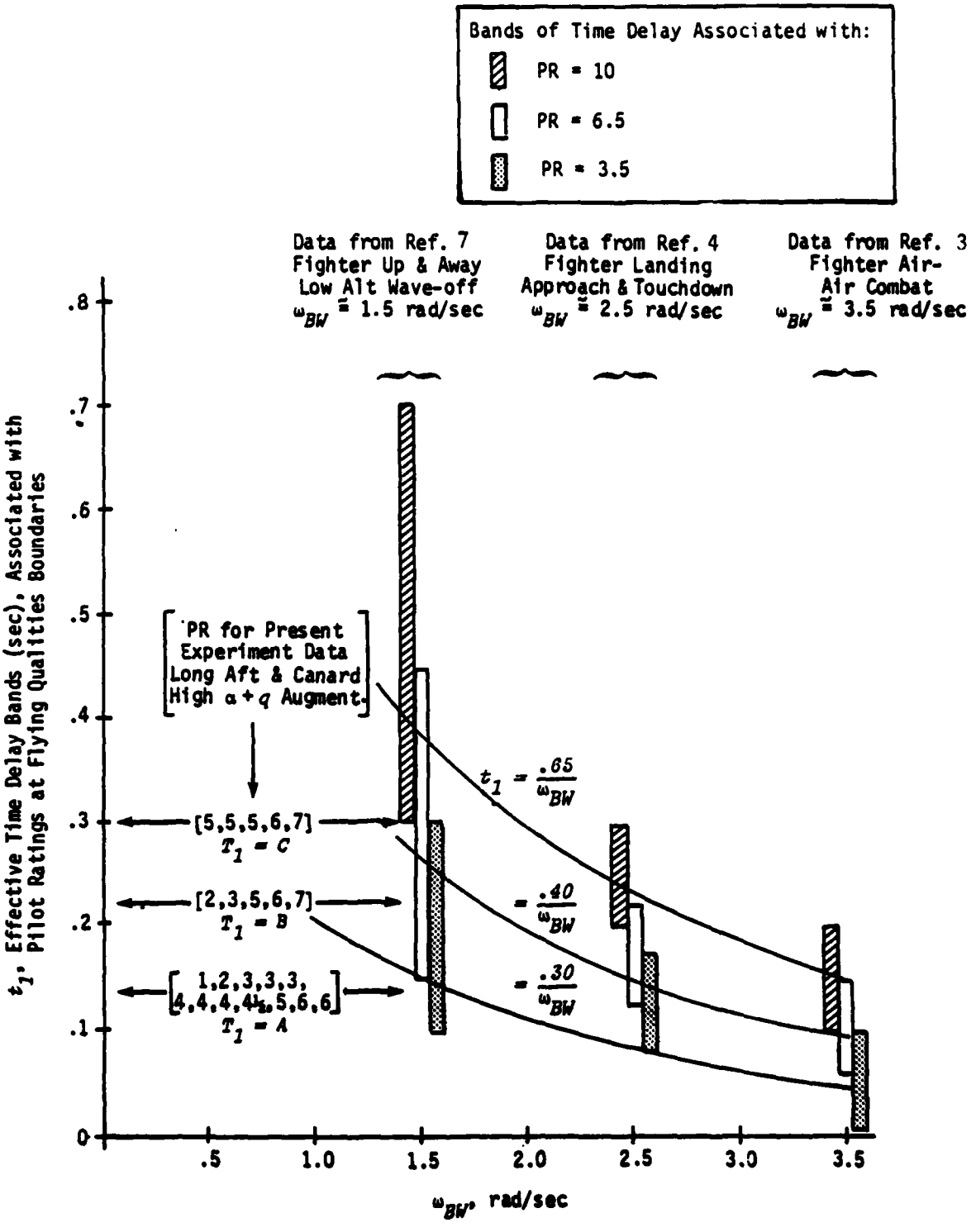


Figure 14. TIME DELAY BANDS ASSOCIATED WITH FLYING QUALITIES BOUNDARIES VS BANDWIDTH

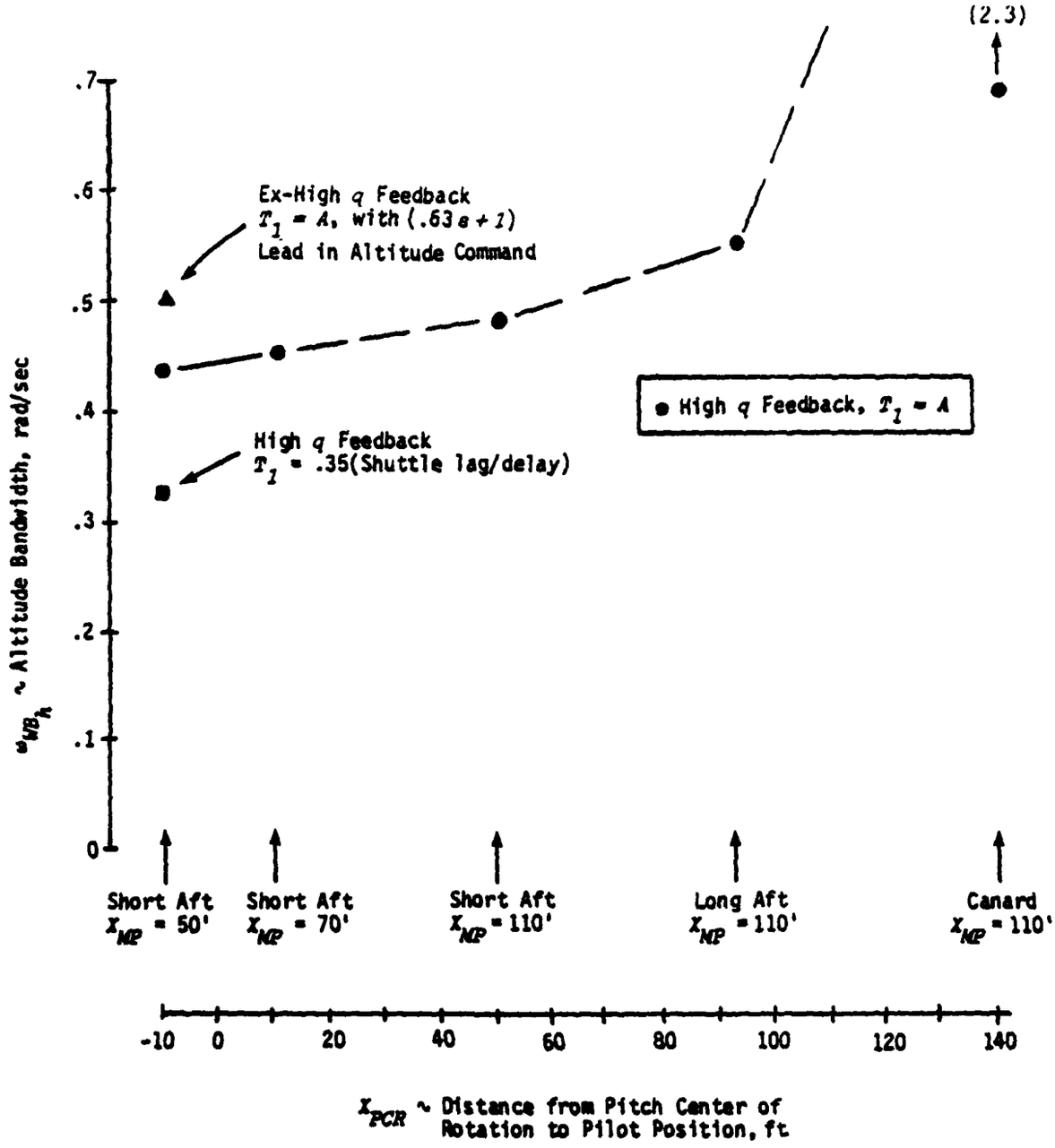


Figure 15. ALTITUDE BANDWIDTH VS PILOT POSITION - CENTER OF ROTATION (X_{PCR})

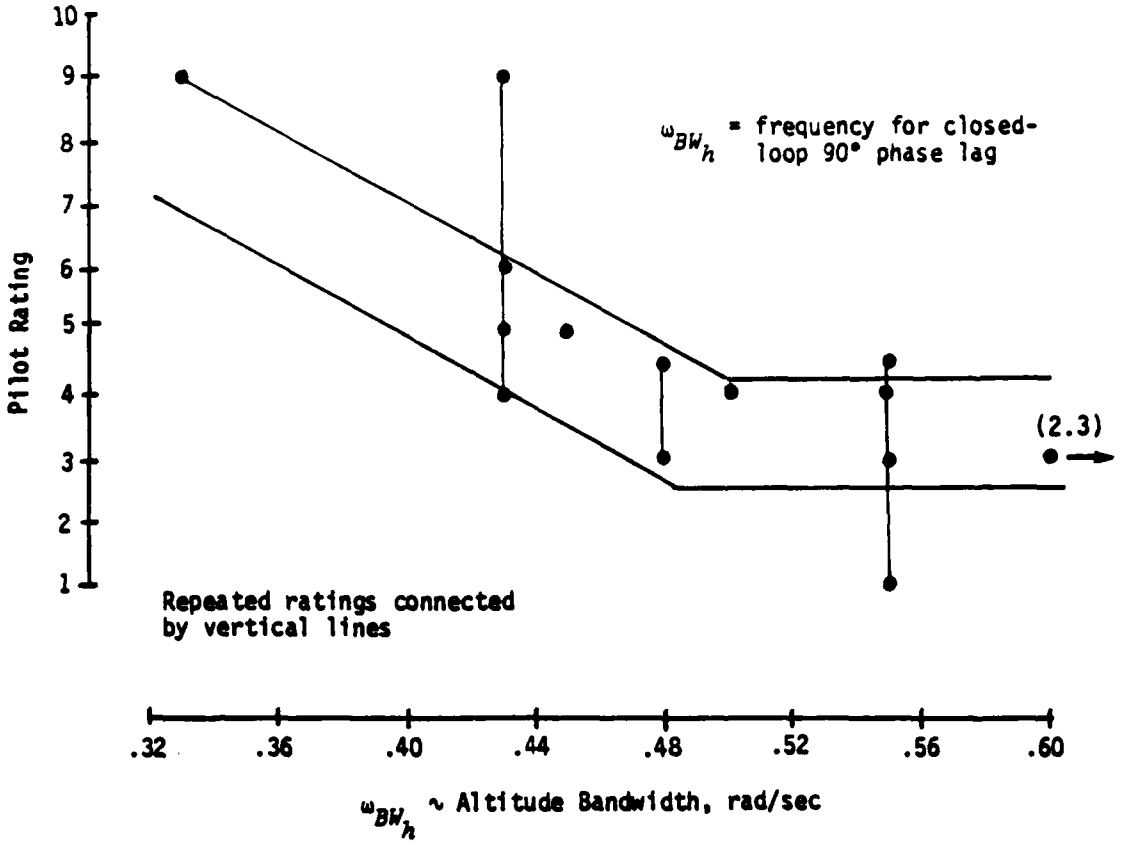


Figure 16. PILOT RATING VS ALTITUDE BANDWIDTH

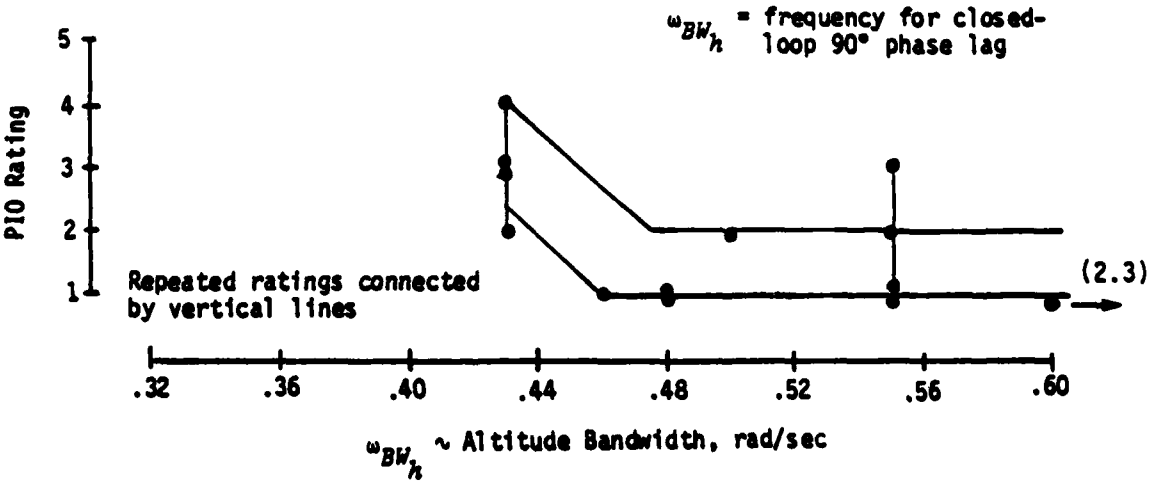


Figure 17. PIO RATING VS ALTITUDE BANDWIDTH

F/A-18 HIGH AUTHORITY/HIGH GAIN DIGITAL FLIGHT CONTROL SYSTEM DEVELOPMENT AND FLIGHT TESTING

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Abstract

The F/A-18 airplane employs a fly-by-wire full authority/high gain digital flight control system (FCS) which at times can completely dominate aircraft response to pilot inputs, resulting in higher order system responses that are a new and significant challenge for the flight test engineer to analyze. This paper overviews the development of the F/A-18 digital FCS, detailing changes to the programmable read only memory (PROM) flight control laws to correct flying qualities problems. In addition, a summary of the advanced stability and control test techniques and data analysis procedures used are presented and it is demonstrated how these techniques can quantify complex changes in flight control laws. These techniques consist of a maximum likelihood parameter identification program used to perform an equivalent system analysis. Data are presented which demonstrate the success the airframe contractor has had in reducing overall system equivalent time delays.

Nomenclature

Symbol	Symbols Definition	Units
b	Measurement bias vector	-
D	Matrix relating measurements to control vector	-
F	Matrix of transfer function modal parameters	-
F_{Long}	Longitudinal stick force	lb
F_{Lat}	Lateral stick force	lb
G	Matrix relating controls to state vector	-
H	Matrix relating measurements to state vector	-
K_θ	Longitudinal pitch gain	rad/lb
K_{θ_m}	Scale factor on measured pitch attitude	-
K_{q_m}	Scale factor on measured pitch rate	-
K_p	Lateral roll rate gain	rad/sec/lb
K_{Prate}	Scale factor on measured roll rate	-
K_ϕ	Scale factor on measured bank angle	-
N_z	Normal acceleration	g
N_z/α	Normal acceleration sensitivity	g/rad
p	roll rate	-
s	laplace operator	-
u	control vector	-
x	state vector	-
y	measurement vector	-
α	angle of attack	rad
ζ	short period damping ratio	-
σ	confidence bounds	-
$\tau_{D_{Long}}$	Longitudinal equivalent time delay	sec
$\tau_{D_{Lat}}$	Lateral equivalent time delay	sec
θ	Pitch attitude	rad
ϕ	Bank angle	rad
ω	short period frequency	rad/sec

Subscripts

( )o	initial condition
( )m	measured

Introduction

Since the first flight in the F/A-18 on 17 November 1978, full scale development has been conducted at the Naval Air Test Center (NAVAIRTESTCEN) under a principle test site concept. The digital FCS has grown considerably in this time frame having undergone over a dozen major control law changes. Flight test verification and validation of these control law changes has resulted in some rather significant and new testing problems. This has resulted in the utilization of a blend of classical approaches to flight testing and advance data analysis techniques. Testing has consisted of ground laboratory verification procedures and in-flight evaluations using classical flying qualities tests and mission oriented tasks. Major problem areas discovered in handling qualities have been in the performance of precisely defined closed loop tasks. Classical stability and control data analysis techniques have provided little insight into understanding the overall pilot/airframe/FCS interface because the advanced FCS can at times completely dominate the response of the airplane resulting in higher order system response. This has been especially true in separating the effects of the digital FCS (time delay) and classical airframe stability parameters (frequency, damping, and time constants). This has been a significant problem during the development of the F/A-18 since many of the flying qualities/FCS improvement efforts have been directed towards reducing digital/overall time delays in the FCS/airframe interface in an effort to correct the handling qualities problems cited during mission tasks. In order to solve this problem, the Navy has utilized the application of a maximum likelihood parameter identification program to quantify the changes/improvements in the flight control laws and to provide a means to correlate FCS performance with pilot assigned handling qualities ratings.

Flight Control System Description

The FCS in the F/A-18A employs a full authority, high gain control augmentation mechanization. Electrical inputs generated by applied forces to a center stick and rudder pedals are processed through flight control computers according to specified control laws. The resultant signals are then routed to the appropriate surface actuators to provide desired aircraft response (figure 1). Primary pitch control is provided by symmetric deflection of horizontal stabilizers. Trailing edge and full-span leading edge maneuvering flaps provide optimum lift-to-drag ratios for maneuvering, cruise, and high angle-of-attack (AOA) flight regimes. A speedbrake located in the upper surface of the aft fuselage provides drag control. Roll control is effected primarily by differential stabilizer deflection and by conventional ailerons. Recent modifications to improve roll response characteristics also provide for differential leading and trailing edge flap deflections. Directional control is provided by dual

rudders. A rolling surface to rudder interconnect (RSRI) is used to provide improved turn coordination. Also, a rudder pedal to roll command signal is used to improve roll at higher AOA. The FCS requires 28 volt DC power from the aircraft's electrical system. Four separate circuits of the hydraulic system provide primary and backup hydraulic pressure to the surface actuators.

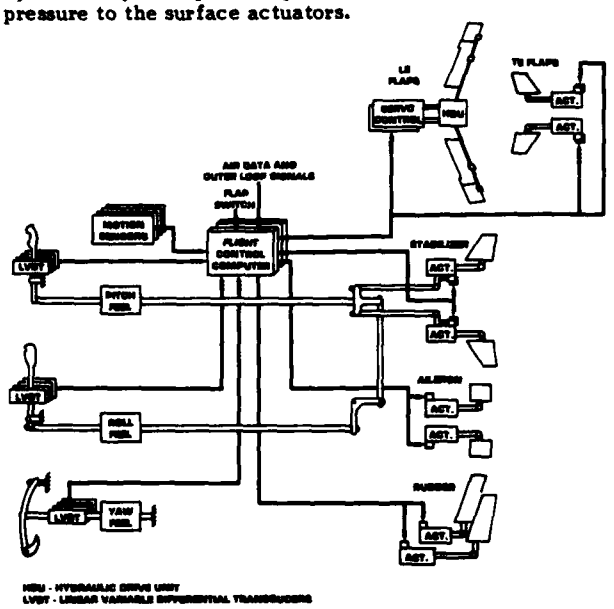


Figure 1 F/A-18A FCS Functional Diagram

Flight Control System Development

Throughout the full scale development flight test program of the F/A-18A airplane, several updates and changes to the basic control laws that provide the signal shaping between pilot command inputs and resultant control surface commands have been made. The versatility of the digital design of the F/A-18A FCS provides a unique and practical way of implementing any desired control law changes. Control laws are programmed on a number of PROM modules which are mounted on removable boards in each of the two flight control computers. Control law changes are introduced by incorporating updated or revised PROM's. A summary of the PROM changes that have been incorporated and flight tested to date is presented in table I. The table shows that, in the 3 years since first flight (17 November 1978), more than a dozen PROM changes have been flight tested. When one considers that, in many cases, the changes represent essentially the incorporation of a new FCS, one can easily see the tremendous versatility inherent in a digital fly-by-wire design.

Table I PROM Configuration Changes(1)

PROM Version	Major Change	Timeframe
3.11-3.12	0 Opened AOA mismatch tolerance	Nov-Dec 1978
3.2-3.16	0 Incorporated $\dot{\theta}$ feedback in power approach (PA) and PA 1/2 0 Added roll prefilter in Up Auto	Feb 1979 (NPE I)
3.16-3.18	0 Added dual mode nose wheel steering	Mar 1979 (NPE I)
3.16-3.19	0 Changed lateral axis in Up Auto 0 Added rudder toe-in 0 Modified flap blowup speed	April-May 1979
3.19-3.23	0 Modified flap blowdown speed to 165 KCAS	May 1979
3.19-3.21	0 Scheduled rudder toe-in with AOA 0 Added AOA feedback in PA 0 Added lead-lag prefilter in PA	July 1979 IST
3.19-4.0	0 Major recompile of control laws 0 Increased sample rate on F_{Long} to 80 Hz 0 Incorporate analog breakout in roll axis	Jan 1980
3.21-4.1	0 Added several changes in pitch axis 0 Added RSRI vice SRI	Jan-Mar 1980 (NPE III)
4.1-4.3.0X	0 Maneuvering leading edge flap (LEF) in PA 0 Revised LEF schedule for high AOA 0 AOA fail detect logic revised 0 Incorporated a 12 lb lateral feel spring	Aug-Oct 1980 (NPE IV)
4.3.0.X-4.3.1.X 4.3.0.X-4.3.1-8	0 Incorporated roll rate improvement mods	Sep-Oct 1980 Navy Special Tests Oct 1980
4.3.1.X-4.3.2	0 Incorporated roll rate II mods (i.e., differential LEF's)	Apr 1981 Navy Special Tests May 1981
4.3.2-6.0	0 Position vice force sensing controls in longitudinal/lateral axes 0 Reduction in time delays 0 Incorporates all roll mods 0 Incorporates outer loop modes (autopilot) 0 Removed lateral integrator	Nov 1981

NOTE: (1) Up Auto - gear up/flaps in auto
PA - gear down/flaps full down
PA 1/2 - gear down/flaps 1/2 down

The major drawback to the versatility, however, has been the time constraints on developing a new PROM version from inception to actual flight testing. An example of the sequence of steps followed in formulating a new PROM version which typifies the time constraints is presented in figure 2. The contractor then completes a verification and inspection procedure on each new PROM version before it is flight tested (figure 3). Despite the time constraints required to develop a new set of control laws, it is still far simpler and more practical than redesigning and incorporating corresponding changes in a conventional FCS. The flexibility and versatility of the F/A-18A digital design provides the capability to fine tune the control laws to provide the best possible flying qualities attainable.

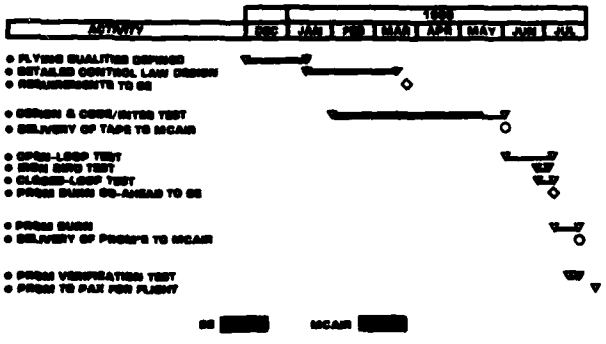


Figure 2 Time Constraints
Version 4.3
Software Development

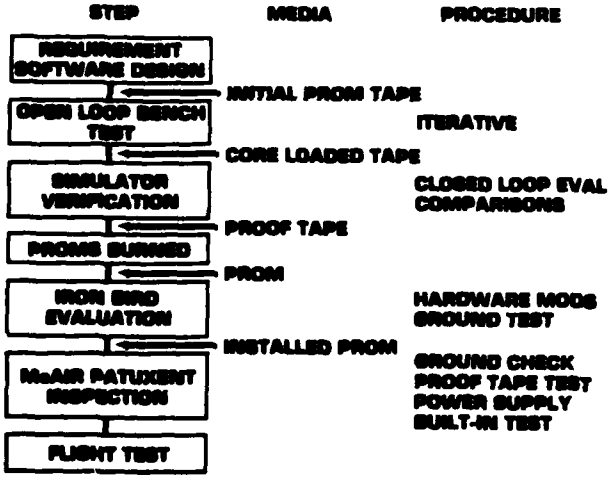


Figure 3 F/A-18 FCS Verification Procedure

Conventional Flight Control System Testing

Flight testing of the F/A-18A has involved both the classical stability and control tests[1] presented in table II and in the specialized frequency sweep techniques that are described later in this article. Additionally, a major emphasis is placed on the definition and performance of precise mission tasks. A list of the mission tasks evaluated during the full scale development flight test program (especially during NPE's) is presented in table III. The primary evaluation criteria used when evaluating the assigned tasks is the Cooper-Harper scale.[2] During the course of the F/A-18A FCS development, handling qualities ratings assigned to precisely defined closed loop tasks have provided the most effective quantifying measurement of the FCS performance. It is the intent of this paper to show how, in addition to the handling qualities ratings assigned to mission tasks, the FCS can also be quantified in the more classical terms of equivalent system frequencies and damping using parameter identification techniques.

Table II Classical Flight Test Maneuvers

Maneuver
Doublet
Pitch and Bank Attitude Captures
Frequency Sweeps
Wind-Up Turn
Wind Down Turn
Sudden Pull Ups
Full Deflection Rolls

Table III Primary Mission Tasks

Mission Task	Performance Criteria
Column Formation 300 KCAS/2 g, 400 KCAS/4 g	Maintain position (20 feet nose-to-tail, 20 feet step-down) ±10 feet at 400 KCAS/ 4 g; ±5 feet at 300 KCAS/2 g.
Aerial Refueling 250 KCAS	Engage and maintain a plugged position.
Air-to-Air Tracking 300 KCAS/2 g 350 KCAS/3 g 400 KCAS/4 g	Track a stabilized target at specified flight condition. Maintain pipper ±2 mils on targets tailpipe while maintaining 1500 feet nose-to-tail distance.
Air-to-Ground Tracking 30° Dive 45° Dive 60° Dive	Maintain pipper ±2 mils on target.

Advanced Flight Test/Data Analysis Approach

In order to solve the problem of quantifying FCS characteristics, NAVAIRTESTCEN has utilized a new application of a maximum likelihood parameter identification computer program.[3] This application of the maximum likelihood technique is to perform an equivalent system analysis in the time domain instead of the more conventional approach of frequency domain analysis.[4] Having decided upon this approach, flight tests were then conducted in F/A-18 BuNo 160775 during NPE III in order to determine the proper flight test maneuvers. (Proper excitation of aircraft response is essential to ensure maximum parameter identifiability.[5]) Several pilot inputs were tested, including step, doublet, constant amplitude/frequency sine wave, and variable frequency sine. Following parameter identification analysis of these maneuvers, it was determined that the variable frequency sine wave (frequency sweep) input resulted in parameter estimates that were meaningful from an engineering sense and had the best statistical characteristics. Thus, the pilot generated frequency sweep was utilized to generate the data for the analysis presented in this paper for both the longitudinal and lateral cases. The frequency sweeps bracketed the frequency range of interest and generally were about 15 - 20 seconds in duration.

Equivalent System Models

The modeling technique used in this analysis was the classical state space formulation for both the differential equations of motion and the measurement system.

$$\dot{x}=Fx+Gu+x \tag{1}$$

$$y=Hx+Du+b \tag{2}$$

The conventional output to stick force transfer functions utilized in equivalent system analysis were used in this evaluation and then converted to state space models. In the longitudinal case, the pitch rate and pitch attitude longitudinal stick force transfer functions were used.

$$\frac{q}{F_{Long}}(s) = \frac{e^{-\tau_{D_{Long}} s} K_\theta \left(s + \frac{1}{\tau_\theta}\right)}{s^2 + 2\zeta\omega\, s + \omega^2} \tag{3}$$

$$\frac{\theta}{F_{Long}}(s) = \frac{1}{s} \frac{q}{F_{Long}}(s) \tag{4}$$

The state space model was as follows:

$$\text{state vector} \quad x = (\theta, q, x_3, x_4)^T \tag{5}$$

$$\text{control vector} \quad u = (F_{Long}, 1)^T \tag{6}$$

$$F = \begin{vmatrix} 0 & 1 & 0 & 0 \\ 0 & -2\zeta\omega & 1 & K_\theta \\ 0 & -\omega^2 & 0 & \frac{K_\theta}{\tau_\theta} \\ 0 & 0 & 0 & \frac{-2}{\tau_{D_{Long}}} \end{vmatrix} \tag{7}$$

$$G = \begin{vmatrix} 0 & x_{1_0} \\ -K_\theta & x_{2_0} \\ \frac{-K_\theta}{\tau_\theta} & x_{3_0} \\ \frac{-4}{\tau_{D_{Long}}} & x_{4_0} \end{vmatrix} \tag{8}$$

Where x_{1_0}, x_{2_0}, x_{3_0}, and x_{4_0} are initial conditions. The measurement equations were:

$$\text{Measurement vector: } y = (\theta_m, q_m)^T \tag{9}$$

$$\text{Bias vector: } b = (b_\theta, b_q)^T \tag{10}$$

$$H = \begin{vmatrix} K_{\theta_m} & 0 & 0 & 0 \\ 0 & K_{q_m} & 0 & 0 \end{vmatrix} \tag{11}$$

$$D = (0) \tag{12}$$

In the lateral analysis, the conventional roll rate and bank angle to lateral stick force transfer functions were used.

$$\frac{P}{F_{Lat}}(s) = \frac{e^{-\tau_{D_{Lat}} s} K_p}{s + \frac{1}{\tau_R}} \tag{13}$$

$$\frac{\phi}{F_{Lat}}(s) = \frac{1}{s} \frac{p}{F_{Lat}}(s) \tag{14}$$

The lateral state space model was as follows:

$$\text{state vector: } x = (\phi, p, x_3)^T \tag{15}$$

$$\text{control vector: } u = (F_{Lat}, 1)^T \tag{16}$$

$$F = \begin{vmatrix} 0 & 1 & 0 \\ 0 & \frac{-1}{\tau_R} & K_p \\ 0 & 0 & \frac{-2}{\tau_{D_{Lat}}} \end{vmatrix} \tag{17}$$

$$G = \begin{vmatrix} 0 & x_{1_0} \\ -K_p & x_{2_0} \\ \frac{4}{\tau_{D_{Lat}}} & x_{3_0} \end{vmatrix} \tag{18}$$

Where x_{1_0}, x_{2_0}, and x_{3_0} are initial conditions. The lateral measurement equations were:

$$\text{Measurement vector: } y = (\phi_m, p_m)^T \tag{19}$$

$$\text{Bias vector: } b = (b_\phi, b_p)^T \tag{20}$$

$$H = \begin{vmatrix} K_\phi & 0 & 0 \\ 0 & K_{p_{rate}} & 0 \end{vmatrix} \tag{21}$$

$$D = (0) \tag{22}$$

Flight Test Results

The parameter identification analysis was conducted during NPE III (PROM 4.1) and NPE IV (PROM 4.3.03) in the fighter escort loading. Parameter identification results for NPE IV longitudinal analysis in configurations Up Auto and PA 1/2 are presented in figure 4 ($2\zeta\omega$, ω^2, K_θ, $\frac{K_\theta}{\tau_\theta}$ and $\frac{1}{\tau_D}$ and associated 2σ confidence bounds). These results were then used to compute the specific modal parameters of interest as shown in figure 5 (ζ, ω, τ_D, $\frac{N_z}{\alpha}$). Damping and frequency estimates in both configurations tested were as expected with time delay bracketing 100 milliseconds in configuration PA 1/2 and ranging from 120 - 150 milliseconds in configuration Up Auto. Normal acceleration sensitivity comparisons in configuration Up Auto show good correlation between flight test and parameter identification results. Longitudinal equivalent system time delay characteristics are presented in figure 6. Data are presented for PROM configurations 3.16/3.18 (NPE I), 4.1.1 (NPE III), and 4.3.03 (NPE IV) with comparisons made between ground test results and parameter identification results. Ground test results are based on hand measurement from strip charts and include only forward loop contributions to equivalent time delay. These ground test results cannot be compared directly with parameter identification results but do indicate trends in the reduction of time delay achieved by the airframe contractor in the different PROM configurations. The parameter identification results show the same trend as the ground test results and indicate that, in configuration Up Auto, the equivalent time delay was reduced from a range of 120 - 160 milliseconds in PROM 4.1.1 to 100 - 140 milliseconds in PROM 4.3.03. Configuration PA 1/2 parameter identification results show that equivalent time delay ranges

from 90 - 110 milliseconds. Although significant reductions in equivalent time delay have been achieved in each subsequent PROM set, additional reductions in time delay need to be achieved. (Significant reductions in time delay are scheduled to be achieved in the final FSD PROM configuration 6.0.) This is illustrated by referring to MIL-F-8785C requirements for time delay which indicate that this parameter should be less than 100 milliseconds for level 1 flying qualities.[6]

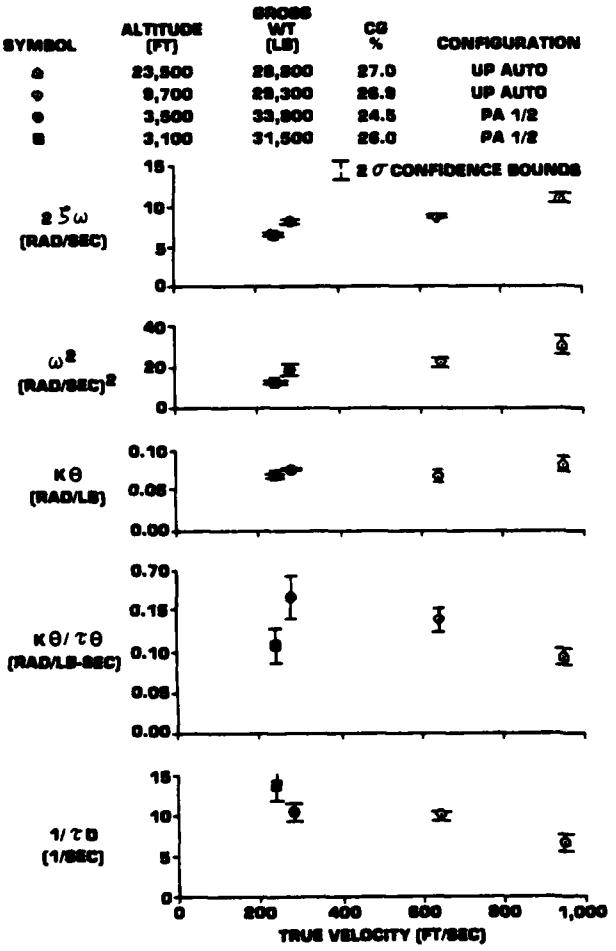


Figure 4 Longitudinal Equivalent System Parameters

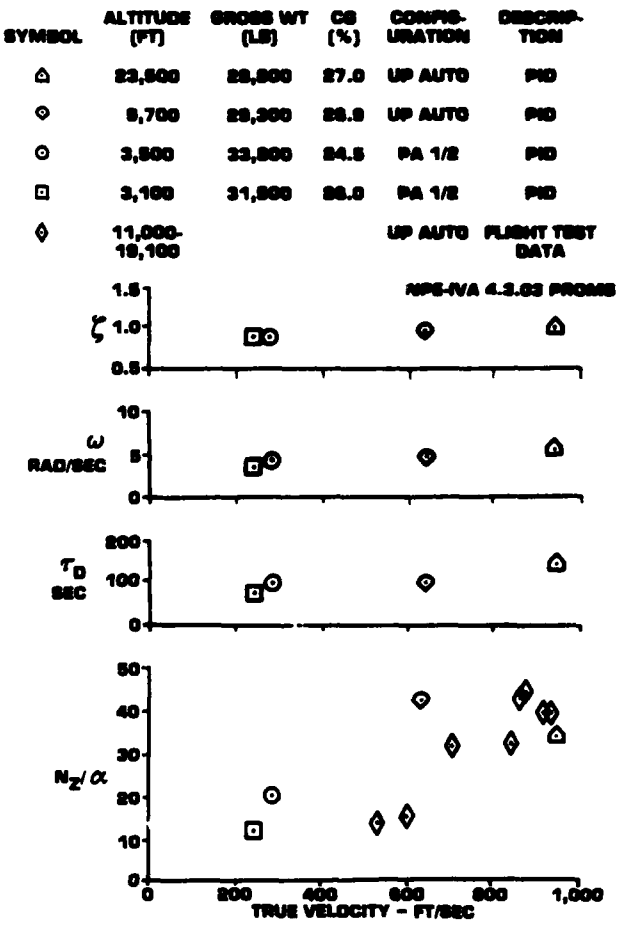


Figure 5 Calculated Short Period Response Characteristics

SYMBOL	ALTITUDE (FT)	GROSS WT (LB)	CG (%)	NPE	PROMS	DESCRIPTION
⊙	30,000			IIIA	4.1.1	PID
□	30,100			IIIA	4.1.1	PID
◇	21,800			IIIA	4.1.1	PID
△	23,800	28,800	27.0	IVA	4.3.0.3	PID
◢	9,700	29,300	26.9	IVA	4.3.0.3	PID
▽	3,800	33,800	24.8	IVA	4.3.0.3	PID
⌂	3,100	31,800	26.0	IVA	4.3.0.3	PID
———				I	3.16/3.18	GROUND TEST
- - - - - -				IIIA	4.1.1	GROUND TEST
▬▬				IVA	4.3.0.3	GROUND TEST

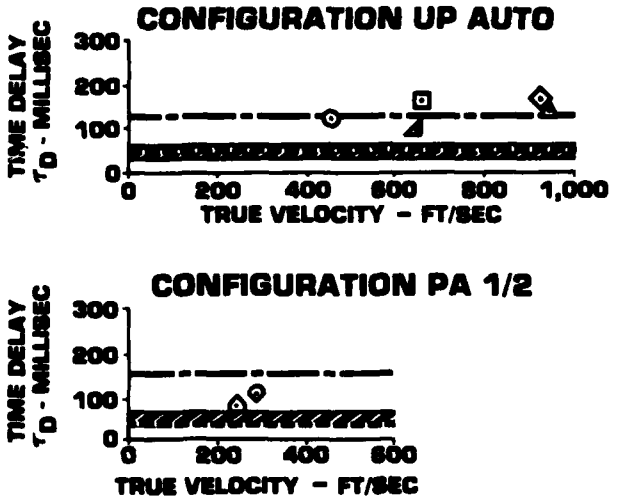


Figure 6 Longitudinal Equivalent Time Delay Comparison

A similar analysis was conducted in the lateral axis and results for configurations PA 1/2 and Up Auto are presented in figures 7 and 8. Figure 7 contains parameter identification results ($\frac{1}{\tau_R}$, $\frac{1}{\tau_{D_{Lat}}}$, K_p) and figure 8 presents time delay characteristics in milliseconds. Roll mode time constant characteristics in configurations PA 1/2 and Up Auto compare favorably with contractor flight test results and give a high level of confidence in the equivalent time delay data presented. Again the ground test results comparisons in figure 8 between PROM configurations indicate that significant reductions in equivalent time delay have been achieved between PROM configurations. Parameter identification results for PROM 4.3.03 show that the equivalent time delay ranges from 120 - 170 milliseconds in configuration PA 1/2 and 100 - 160 milliseconds in configuration Up Auto. These values still are above the 100 millisecond requirements of MIL-F-8785C.[6] Significant reductions in these time delays are expected in the 6.0 PROM configuration.

SYMBOL	ALTITUDE (FT)	GROSS WT (LB)	CG %	CONFIGURATION
▽	9,400	29,300	27.0	UP AUTO
▶	15,400	34,100	25.0	UP AUTO
▼	20,200	28,800	27.1	UP AUTO
▽	20,000	30,800	27.0	UP AUTO
◇	19,700	30,500	26.6	UP AUTO
●	3,700	33,800	24.4	PA 1/2
◆	3,900	34,300	24.8	PA 1/2

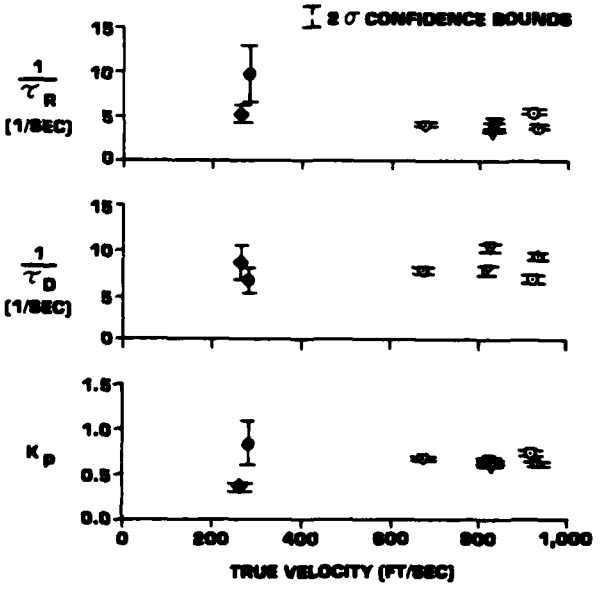


Figure 7 Lateral-Directional Equivalent System Parameters NPE IVA 4.3.0.3 PROM

SYMBOL	ALTITUDE (FT)	GROSS WT (LB)	CG (%)	NPE	PROMS	DESCRIPTION
▽	9,400	26,300	27.0	IVA	4.3.0.3	PID
▼	15,400	34,100	25.0	IVA	4.3.0.3	PID
▽	20,200	28,000	27.1	IVA	4.3.0.3	PID
□	20,000	30,800	27.0	IVA	4.3.0.3	PID
◇	19,700	30,500	26.6	IVA	4.3.0.3	PID
○	3,700	33,600	24.4	IVA	4.3.0.3	PID
◇	3,900	34,300	24.8	IVA	4.3.0.3	PID
———				I	3.16,3.18	GROUND TEST
- - - - - -				III	4.1.1	GROUND TEST
▨				IVA	4.3.0.3	GROUND TEST
.....				IVA	4.3.0.3	GROUND TEST

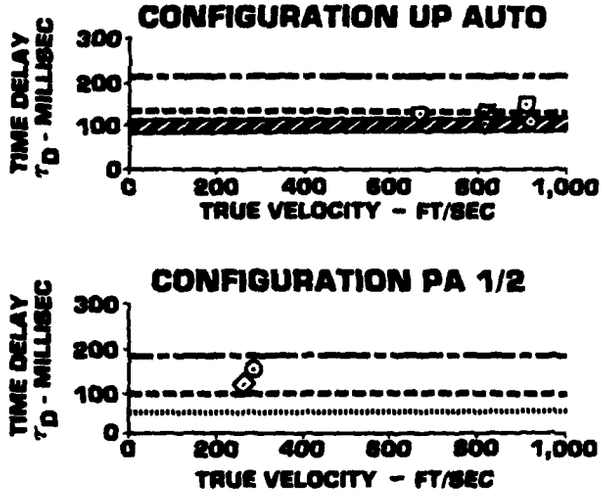


Figure 8 Lateral Equivalent Time Delay Comparison

Summary

Closed loop pilot mission related task flight testing and advanced data analysis technique have been successfully used to evaluate the F/A-18 digital FCS during its development. Classical open loop test technique such as doublet inputs have given little insight into the FCS/airframe interface. Parameter identication techniques utilizing flight test data generated by variable frequency sine wave inputs have been successfully used to quantify airframe stability and FCS equivalent time delay characteristics. The determination of the time delay characteristics has allowed the Navy to document the improvements made in the FCS during its development. Research is currently being conducted to improve on the advanced data analysis techniques used in terms of developing model structure determination and parameter identification algorithms.

References

1. Langdon, S. D., Fixed Wing Stability and Control Theory and Flight Test Techniques, USNTPS-FTM No. 103, of 1 January 1975.

2. NASA Technical Note TNA 5153 of April 1969.

3. Burton, R. A. and Bischoff, D. E., NAVAIRTESTCEN Technical Memorandum TM76-2SA, "More Effective Stability and Control Testing Through Use of System Identification Technology," of 4 November 1976.

4. Hodgkinson, J., "Equivalent System Approach for Flying Qualities Specification," Presented at SAE Control and Guidance Systems Committee Meeting, Denver, March 1979 (MACAIR paper 79-017).

5. Burton, R. A., "Advancement in Parameter Identification and Aircraft Flight Testing" Presented at Specialist Meeting of the Flight Mechanics Panel of AGARD held at NASA Langley Research Center, Hampton, Virginia, on 5-8 November 1974 (AGARD CP-172, paper 15).

6. Military Specification MIL-F-8785C, "Flying Qualities of Piloted Airplane," of 5 November 1980.

FLIGHT TEST BASED HANDLING QUALITY ANALYSIS OF AN AIRCRAFT WITH A HIGH-GAIN/HIGH-AUTHORITY DIGITAL FLIGHT CONTROL SYSTEM

James Vincent
Systems Control Technology, Incorporated

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FLIGHT TEST BASED HANDLING QUALITY ANALYSIS OF AN AIRCRAFT WITH A HIGH-GAIN/HIGH AUTHORITY DIGITAL FIGHT CONTROL SYSTEM

PREPARED FOR

JOINT FLYING QUALITIES AND FLIGHT CONTROLS SYMPOSIUM

DAYTON, OHIO

MARCH 1982

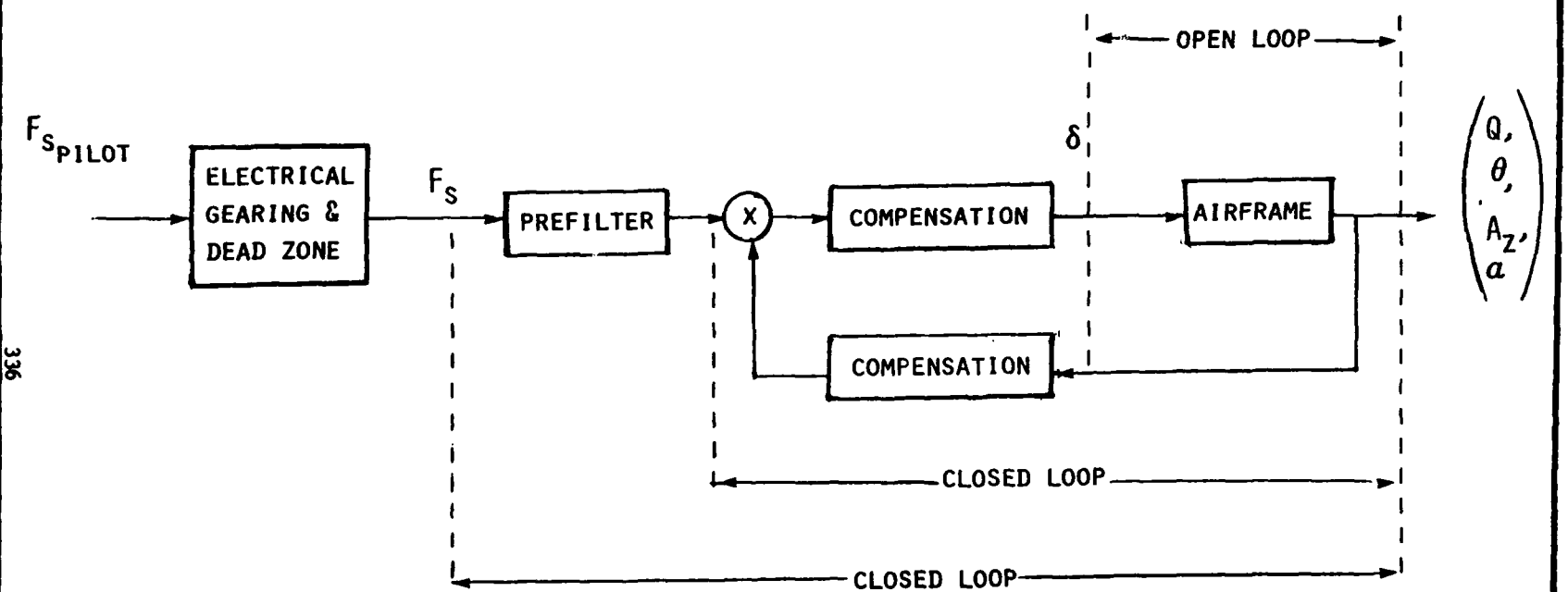
SCT

METHOD OF APPROACH OVERVIEW

- Time Domain Maximum Likelihood Program Used to Identify State Models at Each Flight Condition:
  - State Model Described by Stability Derivitives.
  - Longitudinal Analysis Based on Measurements of Q, θ, A_Z, a.
  - Lateral-Directional Analysis Based on Measurements of P, R, ϕ, ψ, β, A_Y.
  - Program Modified to Directly Identify Measurement and Control Time Delays.
- "Open Loop" Models Identified to Determine Measures of Goodness for Identification Results and Instrumentation System Errors.
- "Closed Loop" Models Identified With and Without Prefilter Represented Explicitly.
- Equivalent System Handling Quality Characteristics are Determined From Identified State Models.

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"OPEN" vs "CLOSED" LOOP IDENTIFICATION



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TYPICAL PARAMETER IDENTIFICATION RESULTS

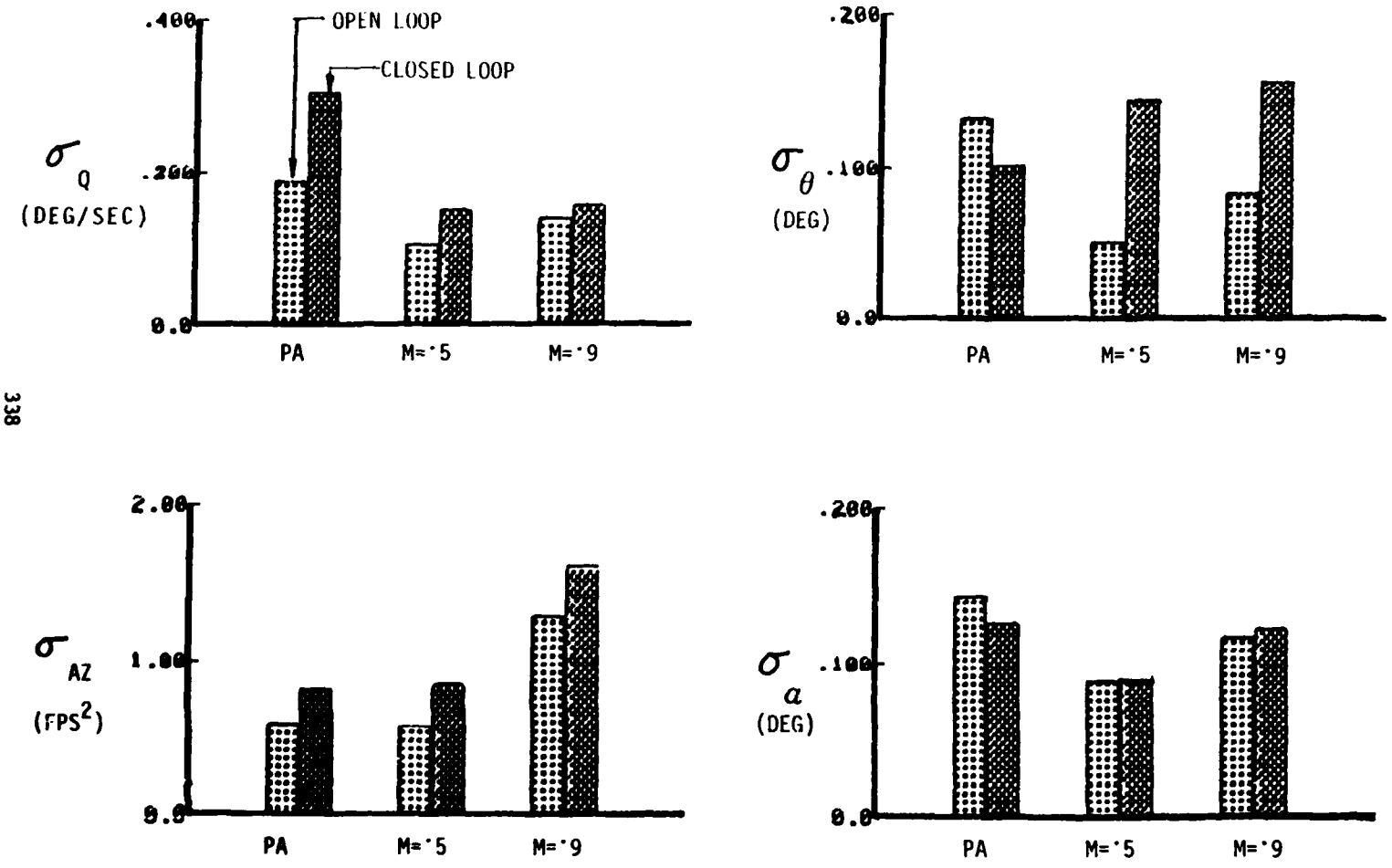
FLIGHT CONDITON 239/26 (M=.3)

PARAMETER	OPEN LOOP EST.	OPEN LOOP $\sigma_{EST.}$ (% EST.)	CLOSED LOOP EST.	CLOSED LOOP $\sigma_{EST.}$ (% EST.)
C_{z_o}	- .25	.3	- .25	.5
$C_{z_{\hat{U}}}$	- .733*	—	- .733*	—
C_{z_α}	- 3.627	3.8	-5.597	.9
$C_{z_{\delta_S}}$	- .595	4.4	0.	—
$C_{z_{\delta_{TEF}}}$	- 1.228	6.7	0.	—
$C_{z_{\hat{FS}}}$	—	—	362.2	3.4
C_{m_o}	.0020	3.3	.0060	1.8
$C_{m_{\hat{u}}}$	.051	5.2	.051	—
C_{m_α}	- .488	2.0	- .524	.9
$C_{m_{\hat{Q}}}$	- 3.53	2.5	-29.46	1.4
$C_{m_{\delta_S}}$	- .628	.3	0.	—
$C_{m_{\delta TEF}}$	.275	2.1	0.	—
$C_{m_{\hat{FS}}}$	—	—	287.4	1.0
PITCH GYRO BIAS	.0010		.0010	
PITCH RATE τ LAG	- .056	1.4	.078	2.1
PITCH ATTITUDE τ_{LAG}	- .025	6.1	.106	3.6
VERTICAL ACCEL. τ_{LAG}	- .150	1.3	- .035	7.1
ALPHA τ LAG	- .081	2.8	.049	5.4

$C_{z_U} = 2C_{L_{1g}}$

SCT

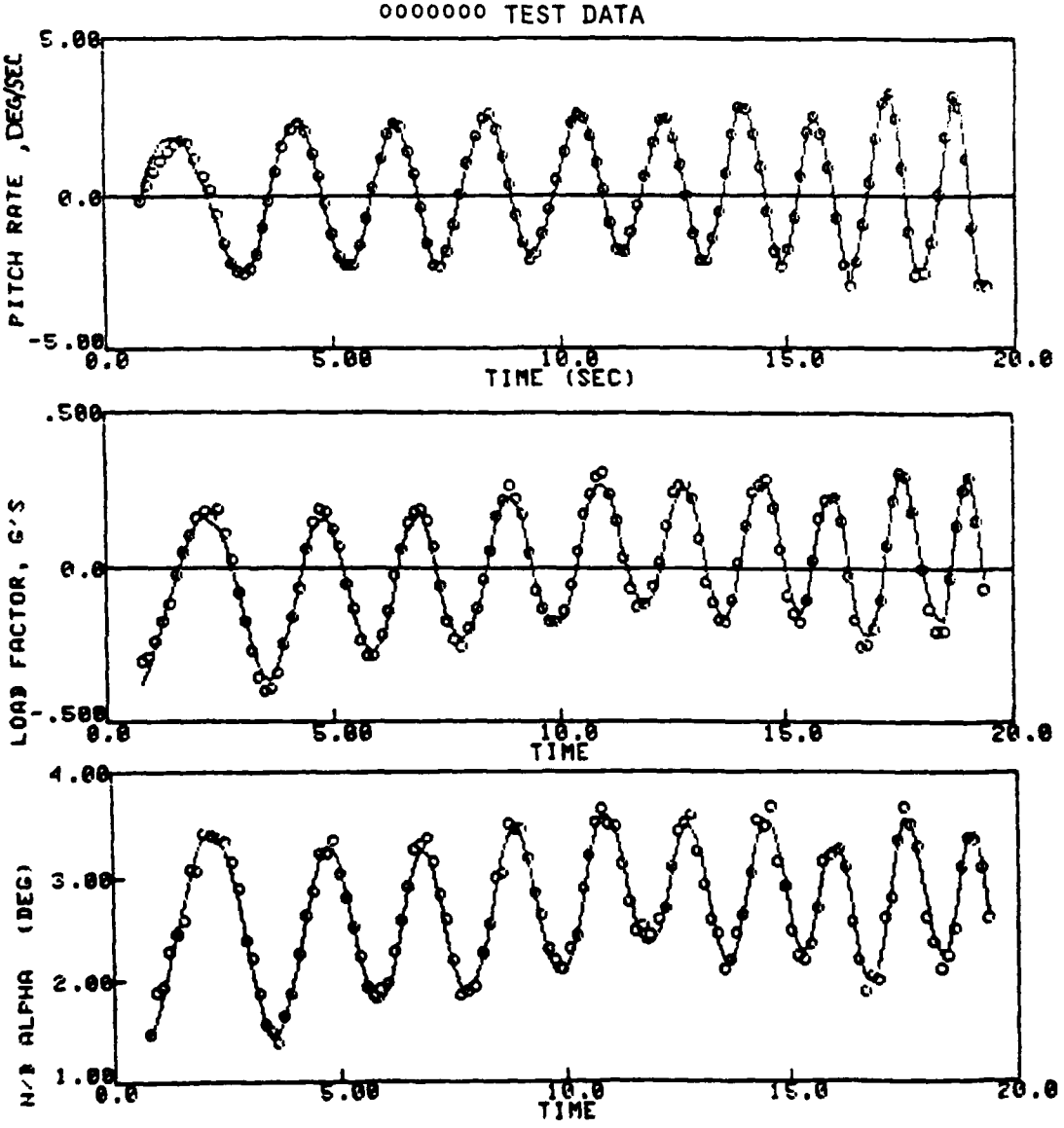
SUMMARY OF LONGITUDINAL "CLOSED LOOP" MODEL IDENTIFICATION ACCURACY



SCT SYSTEMS CONTROL TECHNOLOGY, INC.

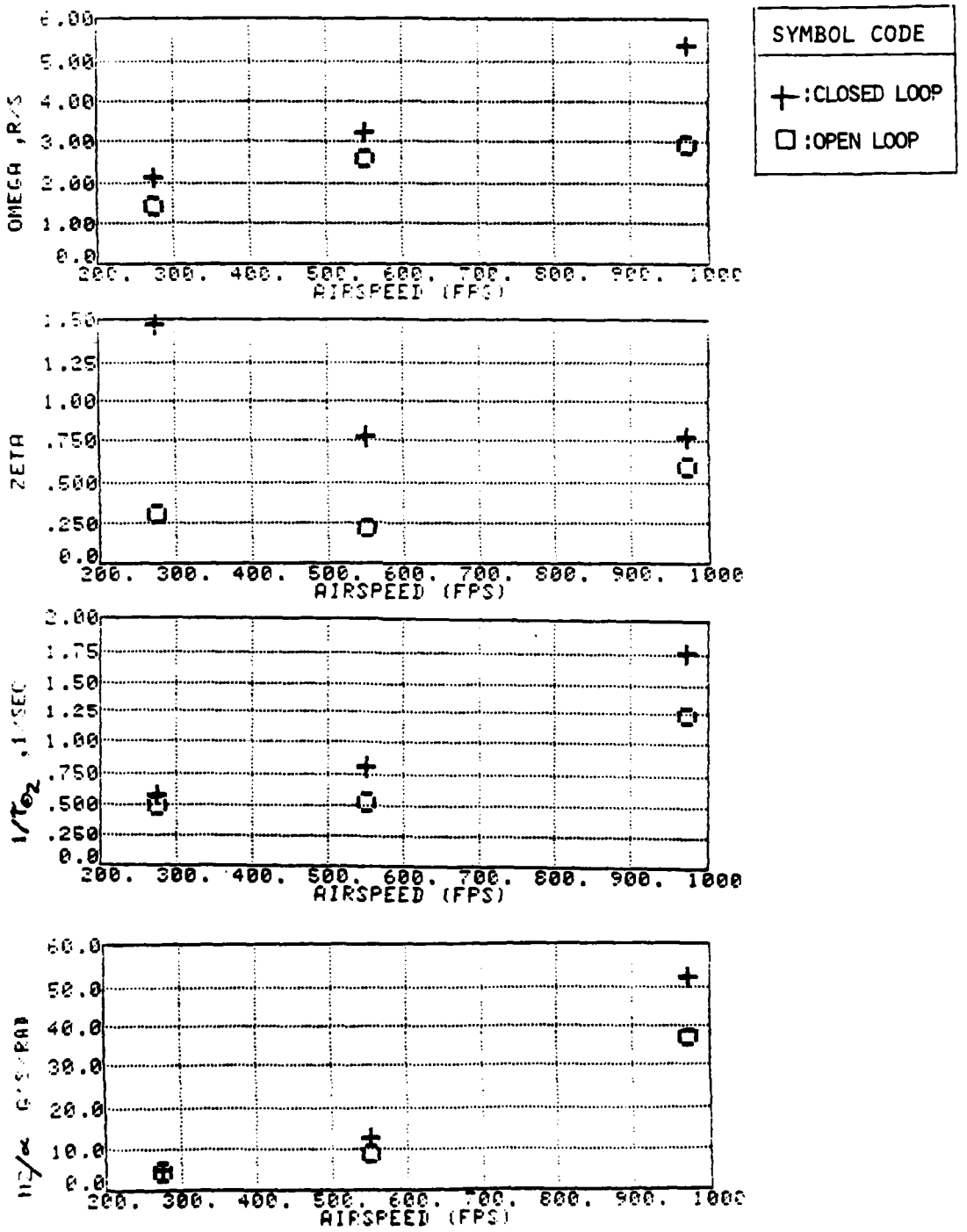
LONGITUDINAL IDENTIFICATION MANEUVER

- o FLIGHT CONDITION: 239/26
  (M='5 ; ALT= 15,000 FT)
- o CLOSED LOOP MODEL (EXPLICIT PREFILTER)
- o LINE CODE
  _____ MODEL
  oooooo TEST DATA



SCT SYSTEMS CONTROL TECHNOLOGY, INC.

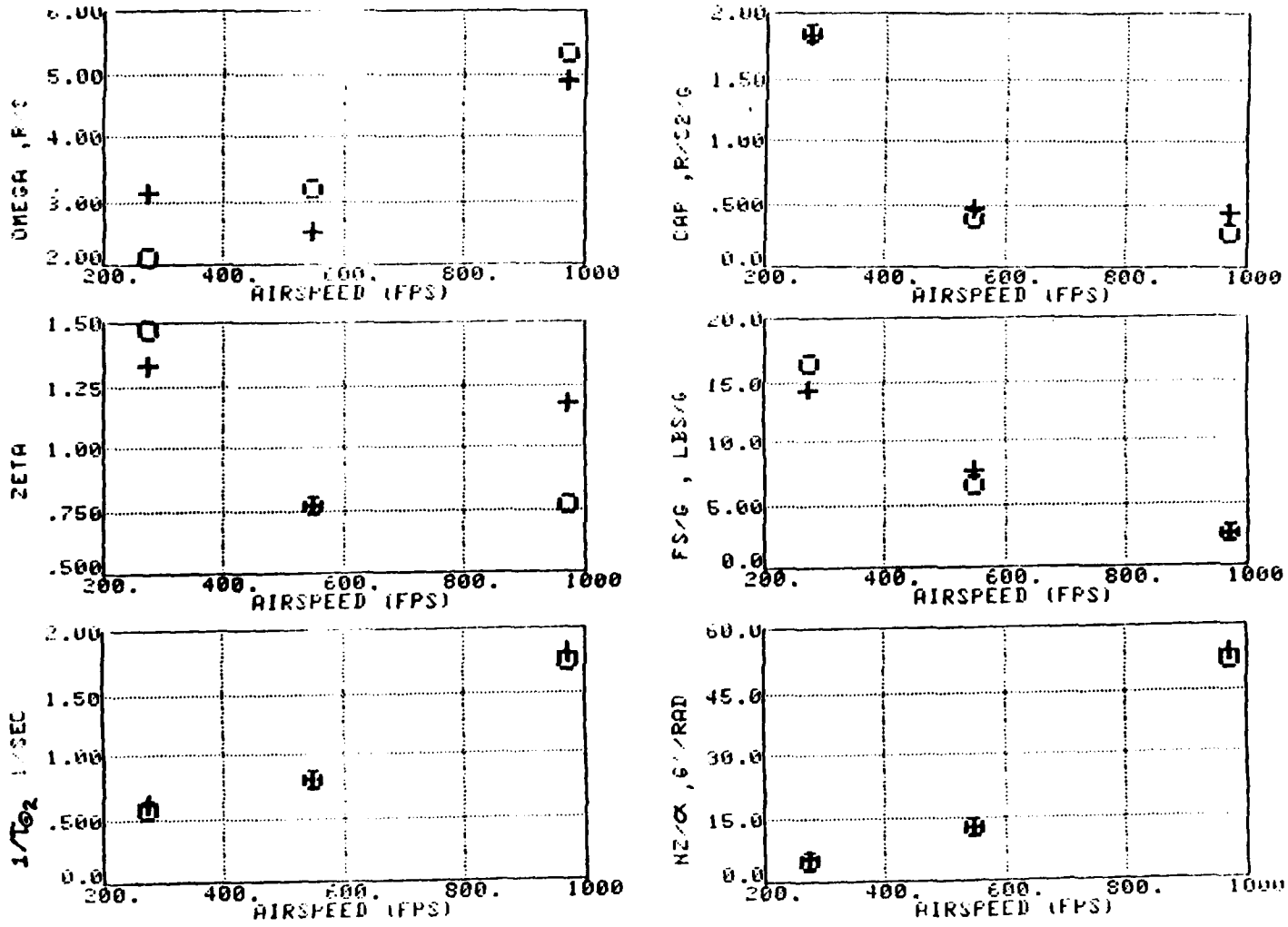
ESTIMATED OPEN & CLOSED LOOP HANDLING QUALITY CHARACTERISITCS



SCT SYSTEMS CONTROL TECHNOLOGY, INC.

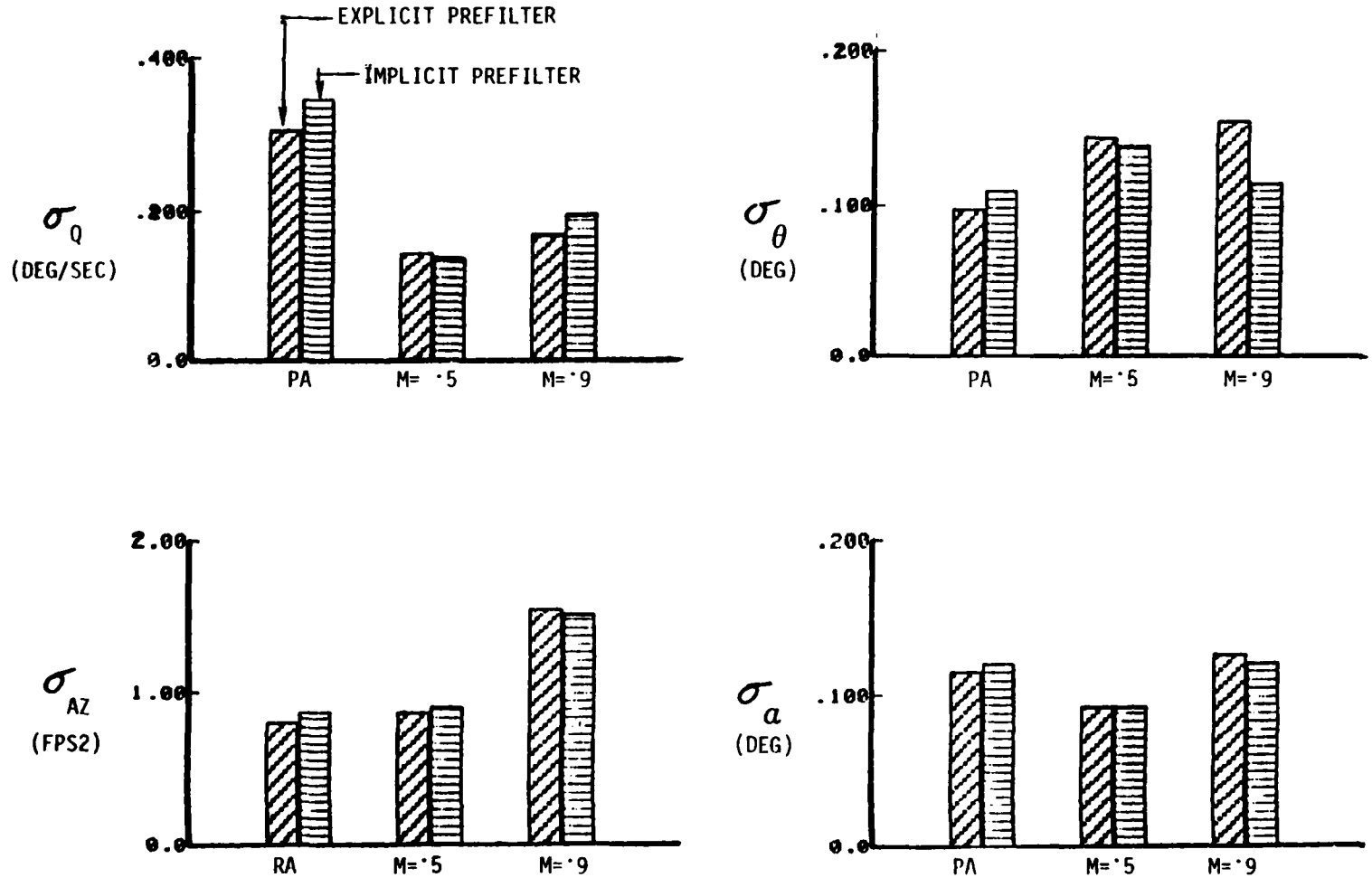
IMPACT OF PREFILTER ON EQUIVALENT SYSTEM HANDLING QUALITIES

(□: EXPLICIT PREFILTER; +: IMPLICIT PREFILTER)



SCT SYSTEMS CONTROL TECHNOLOGY, INC.

EFFECT OF STICK FORCE PREFILTER ON EQUIVALENT SYSTEM MODELING ACCURACY



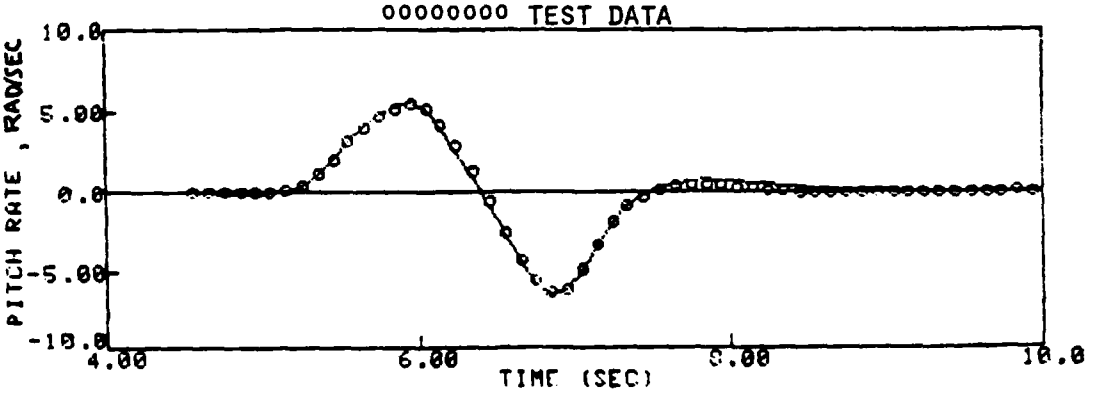
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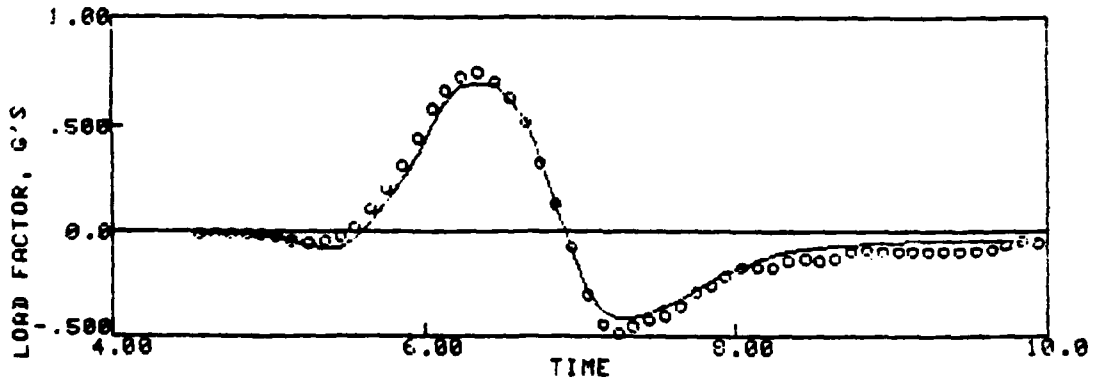
RESPONSE PREDICTION: EQUIVALENT SYSTEM WITH EXPLICIT PREFILTER

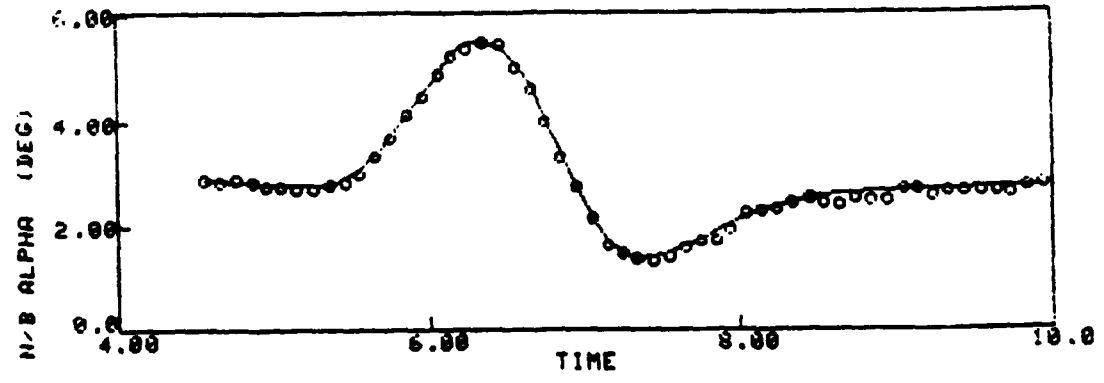
- FLIGHT CONDITION: 239/20 (M=·5)
- LINE CODE

——— MODEL

oooooooo TEST DATA



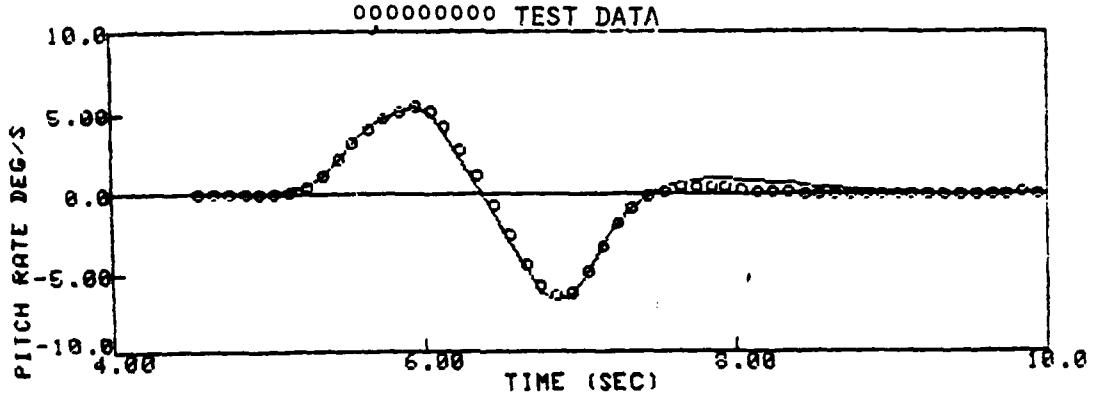


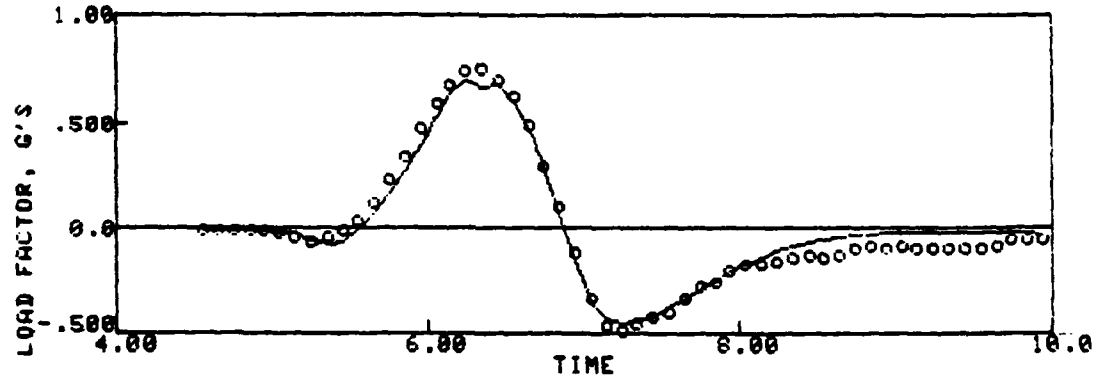


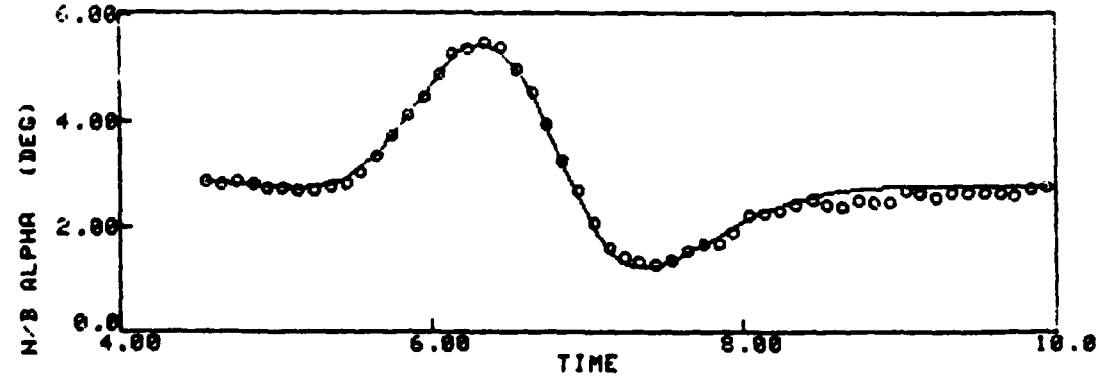
SCT SYSTEMS CONTROL TECHNOLOGY, INC.

RESPONSE PREDICTION: EQUIVALENT SYSTEM WITH IMPLICIT PREFILTER

- FLIGHT CONDITION: 239/20 (M=·5)
- LINE CODE
  - _____ MODEL
  - oooooooo TEST DATA







SCT SYSTEMS CONTROL TECHNOLOGY, INC.

TIME DELAY DEFINITIONS

- OPEN LOOP IDENTIFICATION (CONTROL SURFACE → RESPONSE)

$$\tau_{OL_{ID}} = -\tau_{\substack{\text{CONTROL}\\\text{SURFACE}\\\text{MEAS}}} + \tau_{\substack{\text{SENSOR}\\\text{MEAS}}}$$

- CLOSED LOOP IDENTIFICATION (STICK FORCE → RESPONSE)

$$\tau_{CL_{ID}} = -\tau_{\substack{\text{STICK}\\\text{FORCE}\\\text{MEAS}}} + \tau_{\substack{\text{FLIGHT}\\\text{CONTROL}\\\text{SYSTEM}}} + \tau_{\substack{\text{SENSOR}\\\text{MEAS}}}$$

SCT

IDENTIFIED EQUIVALENT SYSTEM TIME DELAYS

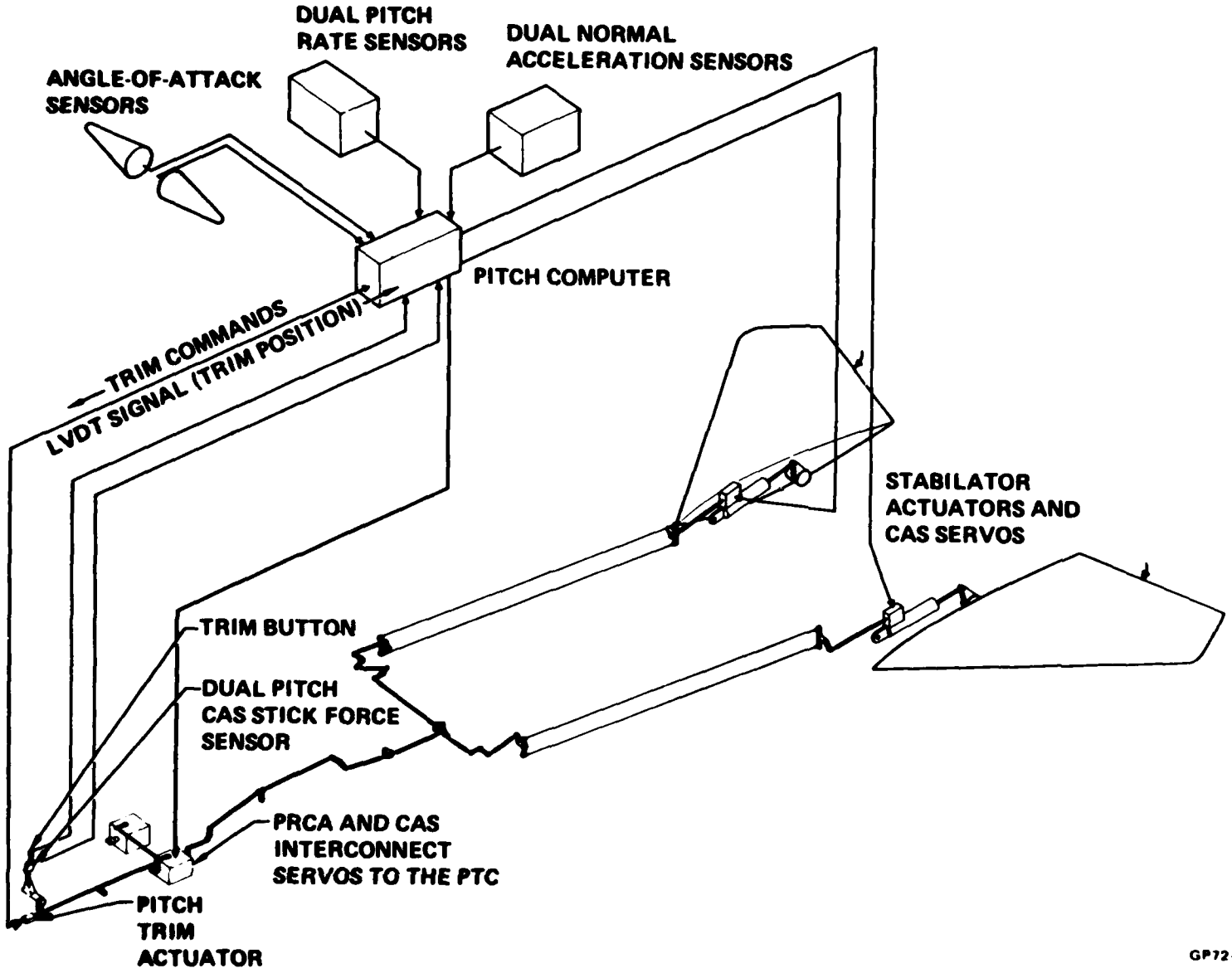
METHOD FOR CALCULATION	FLIGHT CONDITION	PREFILTER REPRESENTATION	IDENTIFIED TIME DELAY (MIL-SEC) τ_Q	τ_θ	τ_{AZ}	τ_a
τ_{CL}	HIGH SPEED	EXPLICIT	73.4	83.3	5.4	39.9
		IMPLICIT	101.6	112.9	39.8	70.0
	MEDIUM SPEED	EXPLICIT	78.1	106.6	- 34.6	49.4
		IMPLICIT	84.8	116.0	- 18.6	55.7
	POWER APP.	EXPLICIT	115.2	127.8	- 59.0	61.5
		IMPLICIT	119.4	129.7	- 52.7	64.8
$\tau_{CL} - \tau_{OL}$	HIGH SPEED	EXPLICIT	112.5	106.4	120.4	109.2
		IMPLICIT	140.7	135.7	165.6	139.3
	MEDIUM SPEED	EXPLICIT	133.8	131.8	115.1	130.1
		IMPLICIT	140.5	141.2	131.1	136.4
	POWER APP.	EXPLICIT	178.8	171.8	127.9	173.8
		IMPLICIT	183.0	173.7	134.2	179.7

SCT

THE IMPACT OF MILITARY SPECIFICATIONS ON THE DESIGN OF THE F-15 FLIGHT CONTROL SYSTEM

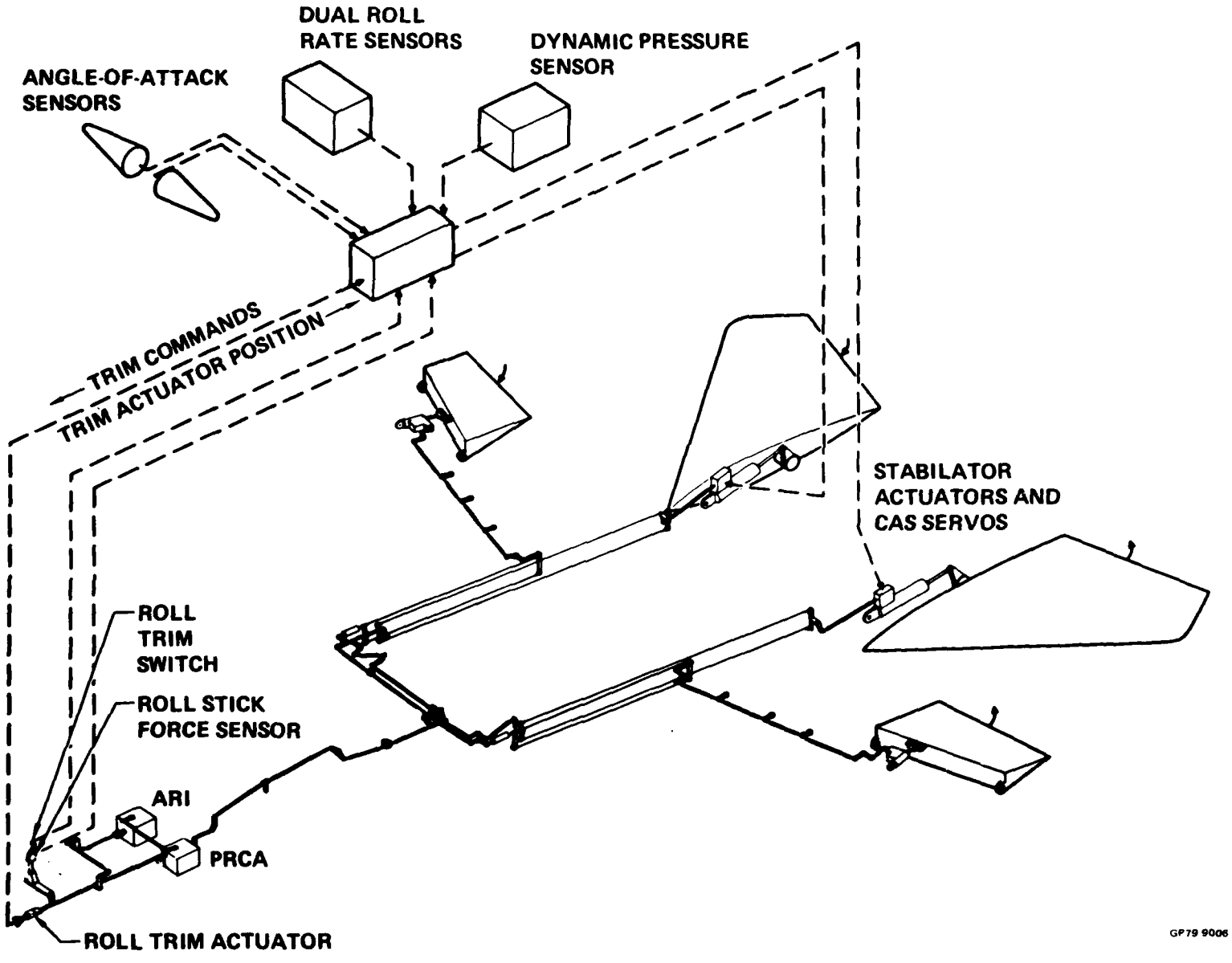
Robert Kisslinger
McDonnell Aircraft Company

LONGITUDINAL CONTROL SYSTEM



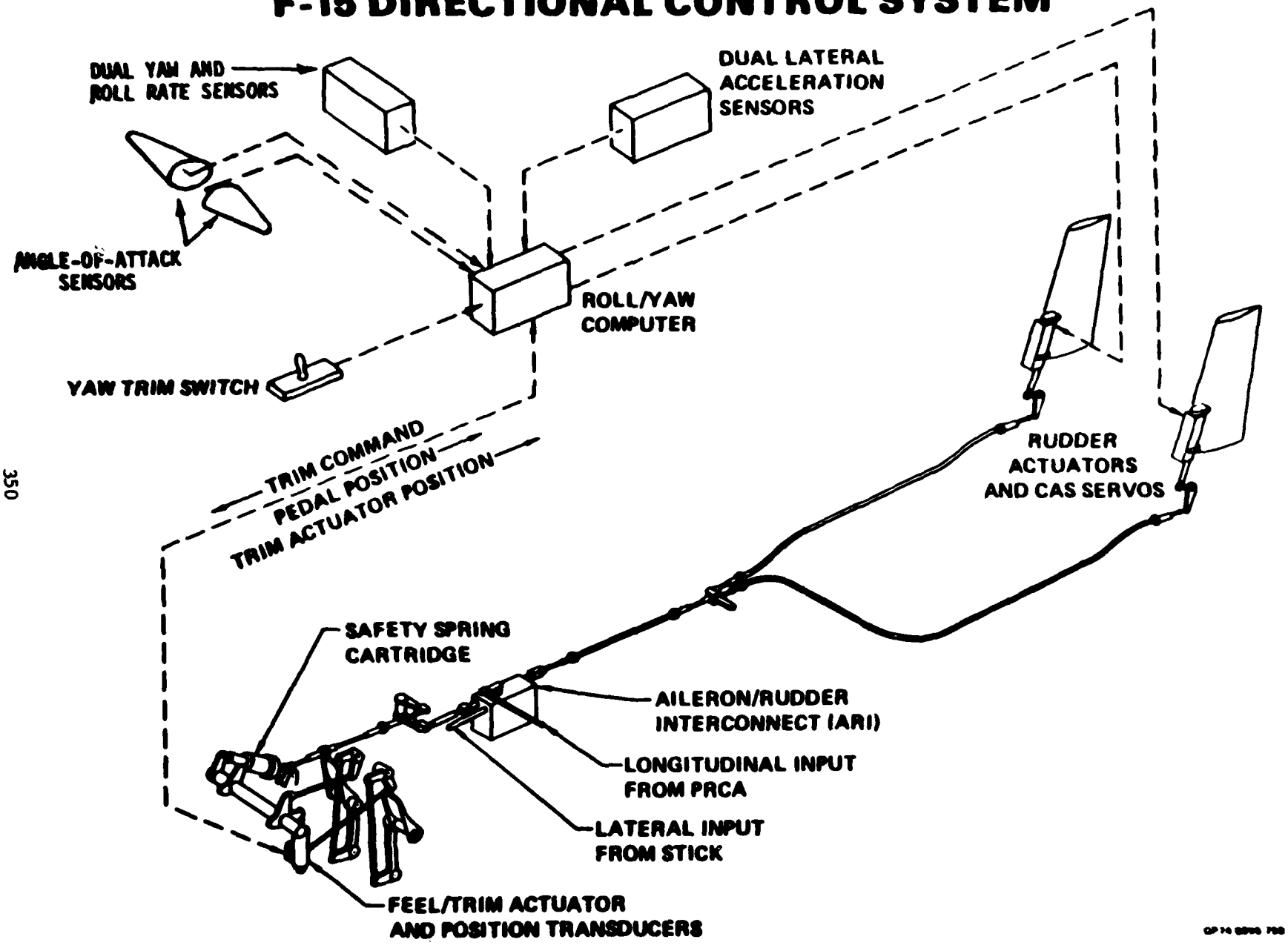
GP72-0753 9

LATERAL CONTROL SYSTEM



GP79 9006 10

F-15 DIRECTIONAL CONTROL SYSTEM



THE IMPACT OF MILITARY SPECIFICATIONS ON THE DESIGN OF F-15 FLIGHT CONTROL SYSTEM

- **MIL-F-9490C(1) REQUIRED A MINIMUM OF THREE INCH CLEARANCE BETWEEN CABLES, RODS, AND ADJACENT STRUCTURE.**

- **THE F-15 FLIGHT CONTROL SYSTEM SPECIFICATION MODIFIED THE MIL-F-9490C(1) REQUIREMENT**
  - A MINIMUM ONE INCH CLEARANCE WAS REQUIRED WITH EXCEPTIONS TO BE APPROVED BY THE AIR FORCE
  - CONTROL ROUTINGS REQUIRED 115 EXCEPTIONS TO BE APPROVED

- **MIL-F-9490D CLEARANCES (1/2 INCH) WERE INCORPORATED INTO THE F-15 FLIGHT CONTROL SYSTEM SPECIFICATION IN AUGUST 1981**

GP23-0001-21

THE IMPACT OF MILITARY SPECIFICATIONS ON THE DESIGN OF F-15 FLIGHT CONTROL SYSTEM

- **MIL-F-8785A**
  - PARAGRAPH 3.5.3 REQUIRES THAT THE PHASE ANGLE OF (CONTROL SURFACE)/(CONTROL FORCE) SHALL BE LESS THAN 30° FOR FREQUENCIES LESS THAN DUTCH ROLL OR SHORT PERIOD FREQUENCIES
  - PARAGRAPH 3.5.3.1 HAS THE SAME REQUIREMENT FOR (COCKPIT CONTROL DEFLECTION)/(CONTROL FORCE)
  - THE F-15 SPECIFICATION CHANGED THE FREQUENCY LIMITS TO 1.5 TIMES THE DUTH ROLL OR SHORT PERIOD FREQUENCIES
  - THE F-15 FLIGHT CONTROL SYSTEM HAD LARGER PHASE SHIFTS THAN THE SPECIFICATION LIMITS
    - FLIGHT TESTING DID NOT DISCLOSE ADVERSE HANDLING QUALITIES DUE TO INCREASED CONTROL SYSTEM LAGS

THE IMPACT OF MILITARY SPECIFICATIONS ON THE DESIGN OF F-15 FLIGHT CONTROL SYSTEM

- SECTION 3.5.6.1 OF MIL-F-008785A REQUIRED THAT THE TRANSIENT FOR THE INTENTIONAL TRANSFER TO ALTERNATE CONTROL MODES SHALL BE LESS THAN ±0.05 g FOR AT LEAST 2 SECONDS FOLLOWING THE TRANSFER

- THE F-15 SPECIFICATION INCREASED THIS LIMIT TO ±0.5 g

- THIS INCREASE WAS REQUIRED FOR THE EXPECTED TRANSIENT WHEN THE CONTROL AUGMENTATION WAS SHUT OFF AND CONTROL REVERTED TO THE MECHANICAL CONTROL SYSTEM

- PARAGRAPH 3.5.5.1 REQUIRES AIRCRAFT MOTIONS AFTER FAILURES SHALL BE LESS THAN ±0.5 g AT THE PILOTs STATION FOR AT LEAST TWO SECONDS AFTER THE FAILURE

- THE F-15 COULD NOT MEET THIS REQUIREMENT FOR SOME AUGMENTATION FAILURES AT LOW AIRCRAFT WEIGHTS FOR SOME SUBSONIC HIGH DYNAMIC PRESSURE FLIGHT CONDITIONS

GP23-0001-23

THE IMPACT OF MILITARY SPECIFICATIONS ON THE DESIGN OF F-15 FLIGHT CONTROL SYSTEM

- **MIL-F-8785A**
  - BECAUSE OF THE AUGMENTATION SYSTEM THERE WAS NOT A SINGLE PREDOMINANT SHORT PERIOD FREQUENCY
  - AT THE TIME OF THE F-15 DESIGN THERE WAS NO ACCEPTED TECHNIQUE TO EVALUATE THE ADDITIONAL MODES ADDED BY CONTROL SYSTEMS.
  - NEWER SPECIFICATIONS HAVE INCLUDED APPROACHES TO THIS PROBLEM

GP23-0001-24

THE IMPACT OF MILITARY SPECIFICATIONS ON THE DESIGN OF F-15 FLIGHT CONTROL SYSTEM

- **THE LEVEL 1 AND 2 FLYING QUALITY RATINGS OF MIL-F-8785A DETERMINED THE MECHANIZATION OF THE F-15 FLIGHT CONTROL SYSTEM**
  - LEVEL 1 DICTATED THE AUGMENTED PERFORMANCE
  - LEVEL 2 DICTATED THE DESIGN OF THE UNIQUE F-15 MECHANICAL CONTROL SYSTEM

GP23-0001-25

APPLICATION OF MIL-F-8785C IN DEVELOPMENT AND FLIGHT TEST EVALUATION OF A PITCH AUGMENTATION SYSTEM FOR A RELAXED STABILITY L-1011

Jerry Rising
Lockheed - California Company

[illegible] NOT BLACK-AND FILMED

NASA/LOCKHEED
AIRCRAFT ENERGY EFFICIENCY

PROGRAM DESCRIPTION

OBJECTIVE

- IMPROVE CRUISE EFFICIENCY BY REDUCING AERODYNAMIC DRAG

APPROACH

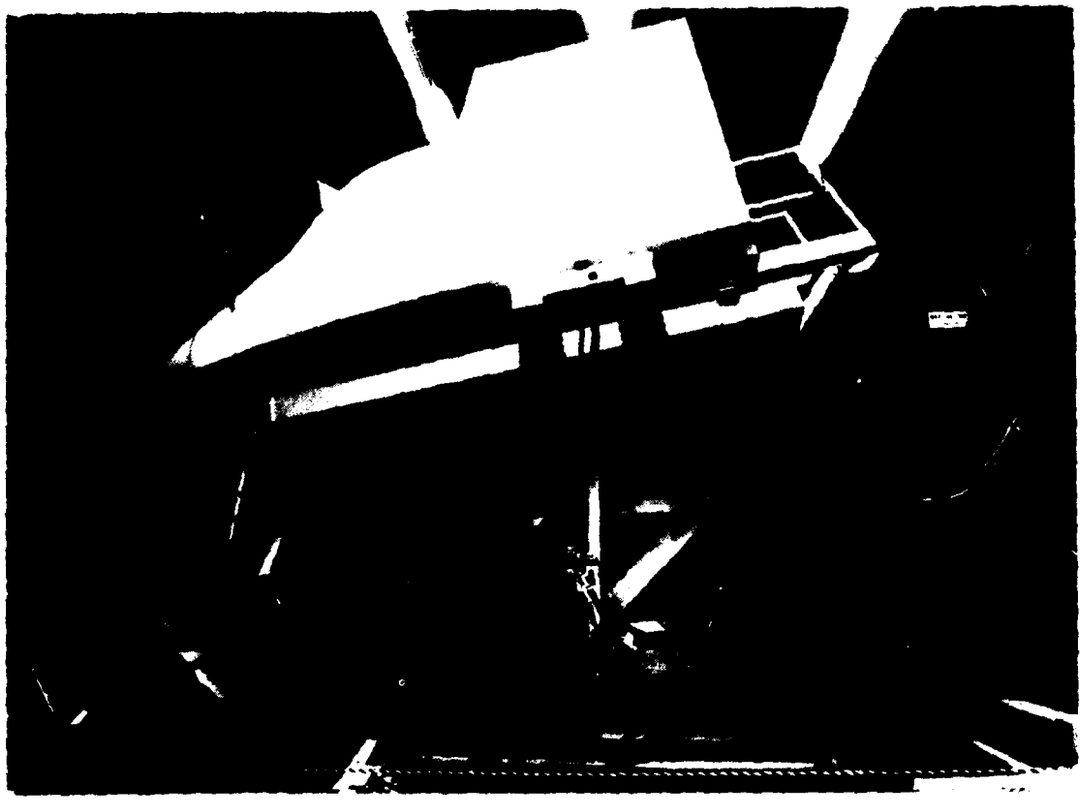
- RELAX THE STATIC LONGITUDINAL STABILITY REQUIREMENT THUS ALLOWING:
  - REDUCED HORIZONTAL TAIL SIZE (DECREASED PARASITE DRAG)
  - FARTHER AFT AIRCRAFT BALANCE (DECREASED TRIM DRAG)
- EMPLOY ACTIVE CONTROLS TO MAINTAIN GOOD HANDLING QUALITIES
- FLIGHT TEST DEMONSTRATION

B-2/JJR ACT 9-14-81

Prior to flight test, a motion base visual flight simulator program was performed to optimize the scheduling of loop gains, lag time constants, and feed-forward washout. The simulation was conducted in the Lockheed Rye Canyon Flight Simulator Facility. This facility contains all the components necessary to conduct a complete man and/or equipment in the loop real time aircraft simulation. The components include: digital and hybrid-analog computers, cockpits with instrument displays, visual displays, motion system sound synthesizer, complete computer software library, and a highly experienced flight simulation staff. The hydraulically driven, four-degree-of-freedom motion system features independent movement in pitch, roll, heave and lateral directions.

NASA/LOCKHEED
AIRCRAFT ENERGY EFFICIENCY

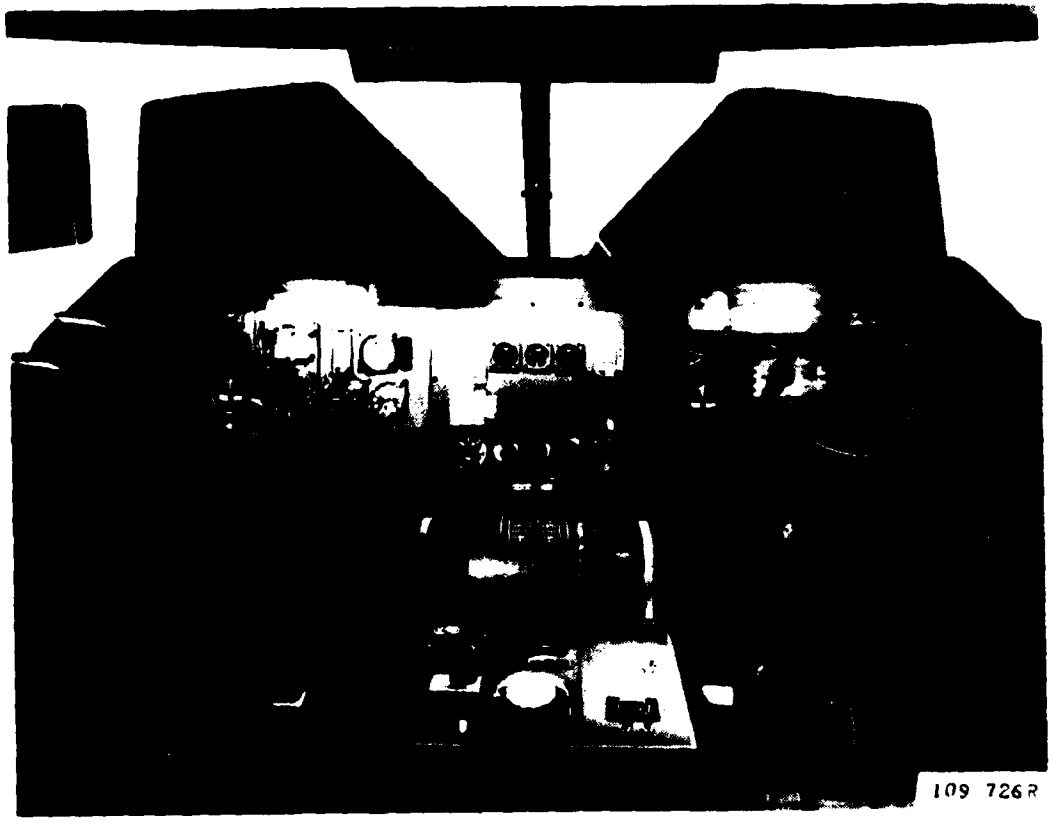
RYE CANYON FLIGHT SIMULATOR MOTION BASE & CAB



The flight simulator cockpit interior provides a realistic Category III environment for both the pilot and co-pilot with all necessary controls, instruments, and indicators to duplicate accurately manual and automatic flight control.

NASA/LOCKHEED
AIRCRAFT ENERGY EFFICIENCY

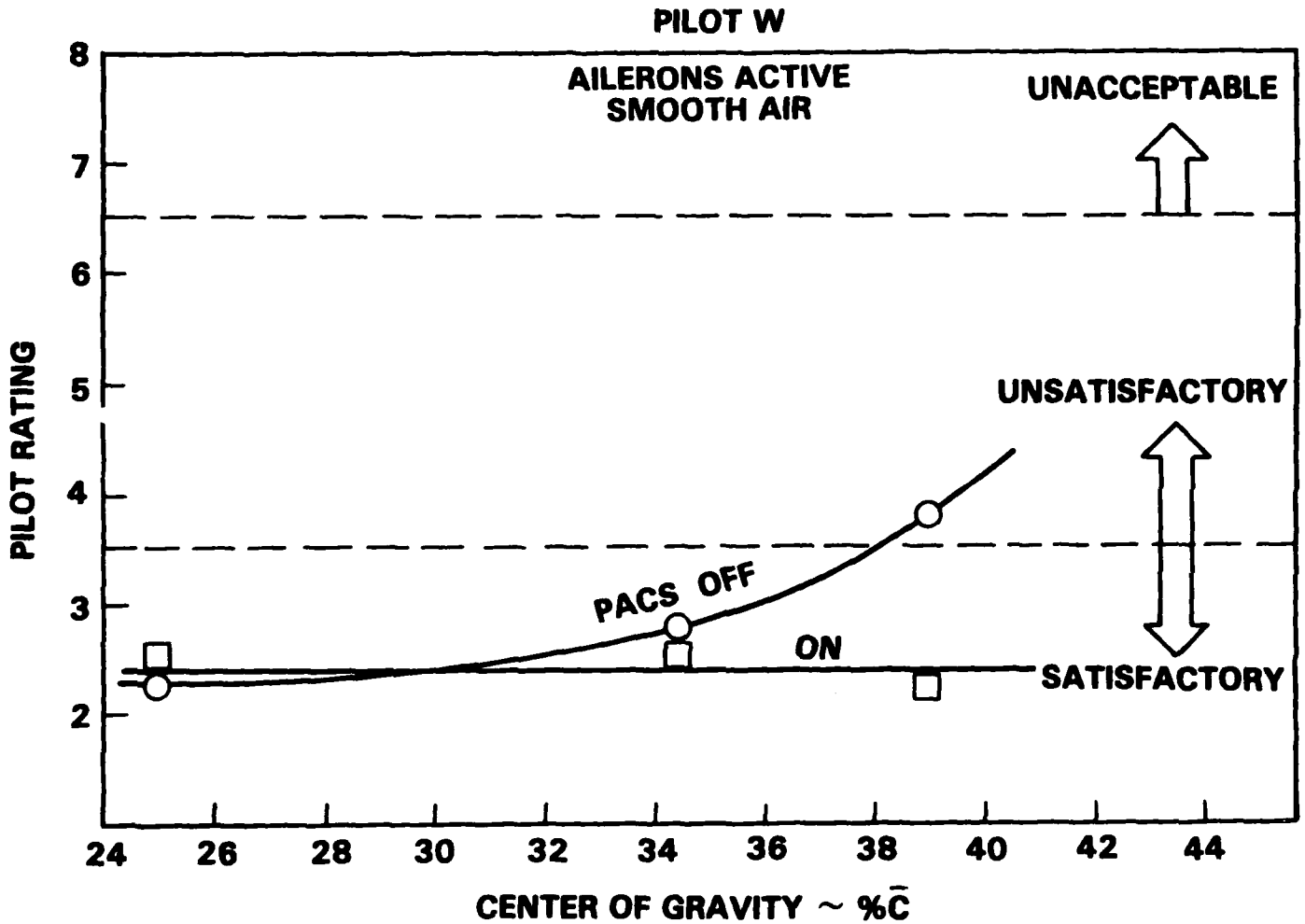
FLIGHT SIMULATOR L-1011 COCKPIT



Pilot ratings obtained during the flight simulator evaluation show that the near-term augmentation system eliminates the tendency for handling qualities to degrade with aft c.g. movement. The simulation results show that the 39%$\bar{c}$ c.g. airplane with augmentation flies as good as the unaugmented airplane at 25%$\bar{c}$ c.g.

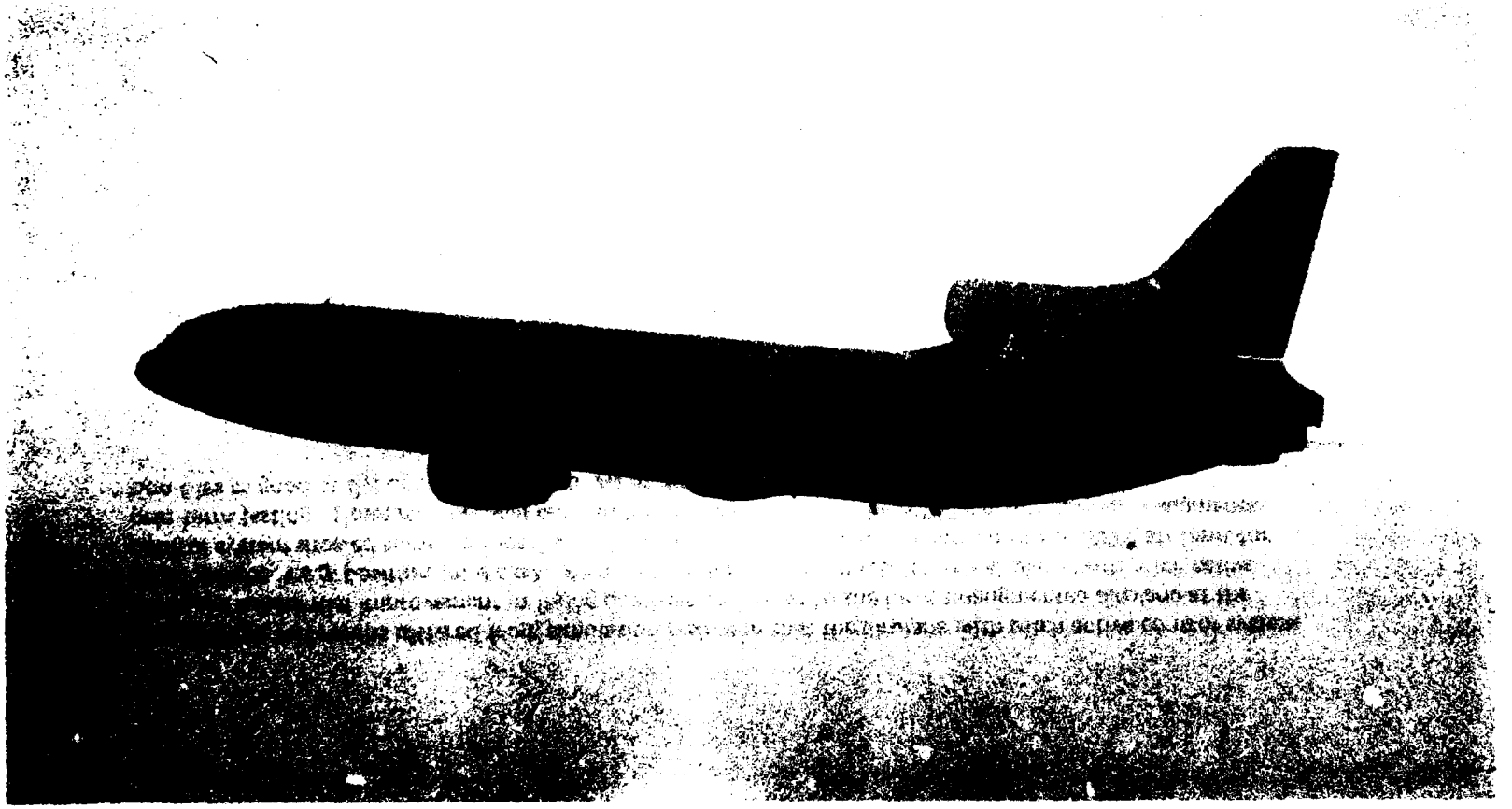
NASA/LOCKHEED
AIRCRAFT ENERGY EFFICIENCY

FLIGHT SIMULATION RESULTS – CRUISE



The near-term pitch active control system was ultimately evaluated in an actual flight test program utilizing the Lockheed in-house research airplane, L-1011 S/N 1001. Three pilots participated in the evaluation, which concentrated on two cruise altitude conditions and an overspeed condition (V_{MO}) at high dynamic pressure. The test program covered 47 hours of flying, 14 for flutter clearance, and 33 for flying qualities evaluation. Flying qualities were evaluated at c.g.'s from 25 to 39%$\bar{c}$, where the airplane with active ailerons is close to being neutrally stable (1 to 2% static margin) at high altitude trim conditions.

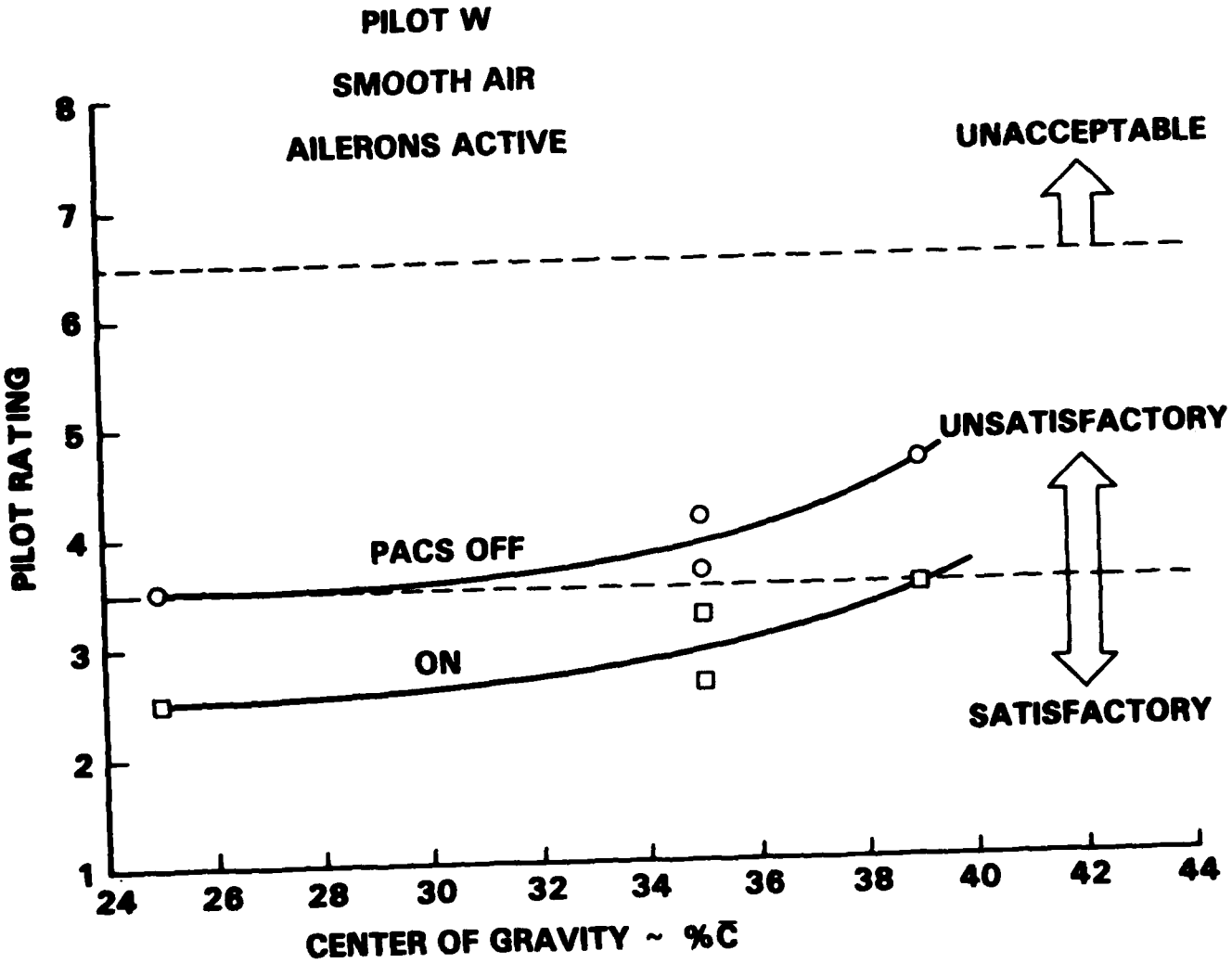
L-1011 S/N 1001
LOCKHEED IN-HOUSE FLYING TESTBED



Actual flight test results differed from simulation results in that the airplane with pitch active control system showed a substantial improvement in flying qualities compared to the basic unaugmented airplane at the 25%$\bar{c}$ reference c.g. position (mid c.g.). Also, unlike the simulation results, the airplane with pitch active control system showed some degradation in flying qualities as the c.g. was moved to the 39%$\bar{c}$ aft limit for near-term testing. However, the final conclusion was the same; i.e., the 39%$\bar{c}$ c.g. airplane with augmentation flies as good as the unaugmented airplane at 25%$\bar{c}$ c.g.

NASA/LOCKHEED
AIRCRAFT ENERGY EFFICIENCY

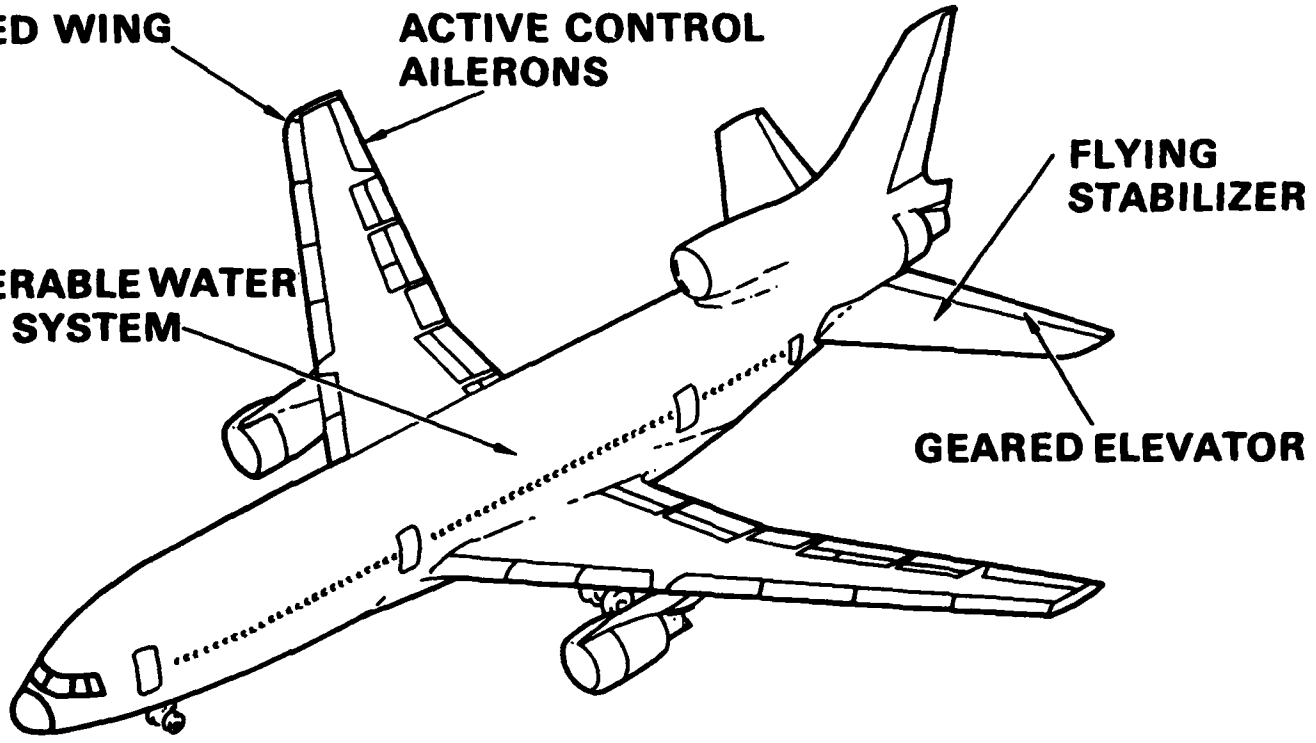
FLIGHT TEST RESULTS – CRUISE



L-1011 S/N 1001 is a multimillion dollar flying testbed with the capability to vary the center of gravity from 25 to 43%$\bar{c}$ which allows flight up to approximately 2% statically unstable with active ailerons engaged. Flight at relaxed stability conditions is made possible by the incorporation of a pitch active control system implemented through the full flying stabilizer for stability and control augmentation. The capability to vary the c.g. from 25 to 43%$\bar{c}$ is made possible by an elaborate combination of fixed and transferable water ballast system.

NASA/LOCKHEED
AIRCRAFT ENERGY EFFICIENCY

FLIGHT TEST AIRPLANE CONFIGURATION (L-1011 S/N 1001)



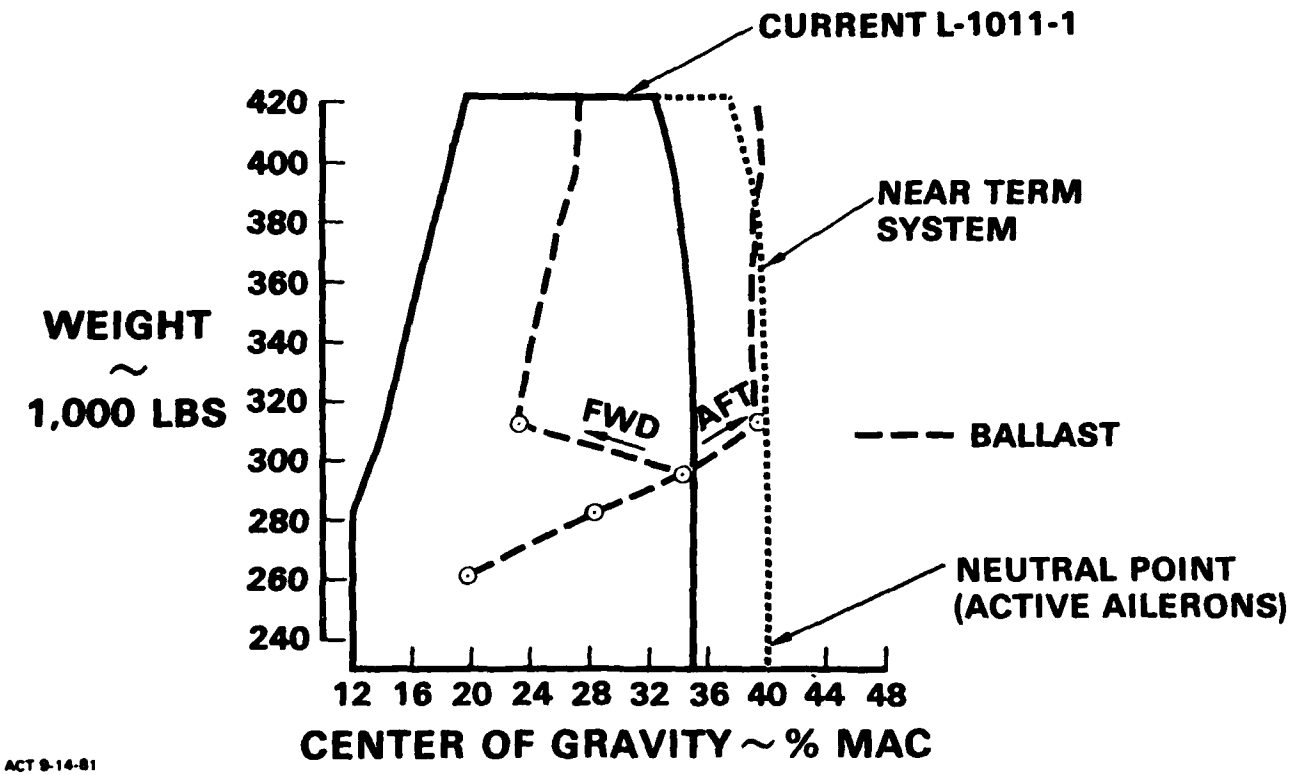
A-12/WAG ACT 9-14-81

The Lockheed flight test investigation of relaxed static stability was achieved by the addition of water ballast to move the center-of-gravity (c.g.) limits farther aft. Flight testing was planned in two phases. During the first phase, now complete, a near-term stability augmentation system was incorporated in L-1011 S/N 1001 to investigate reduced static margins approaching the neutral point. The second phase of flight test will be performed with a slightly modified near-term system to investigate 2% statically unstable conditions.

NASA/LOCKHEED
AIRCRAFT ENERGY EFFICIENCY

CENTER OF GRAVITY BOUNDARIES

NEAR TERM SYSTEM

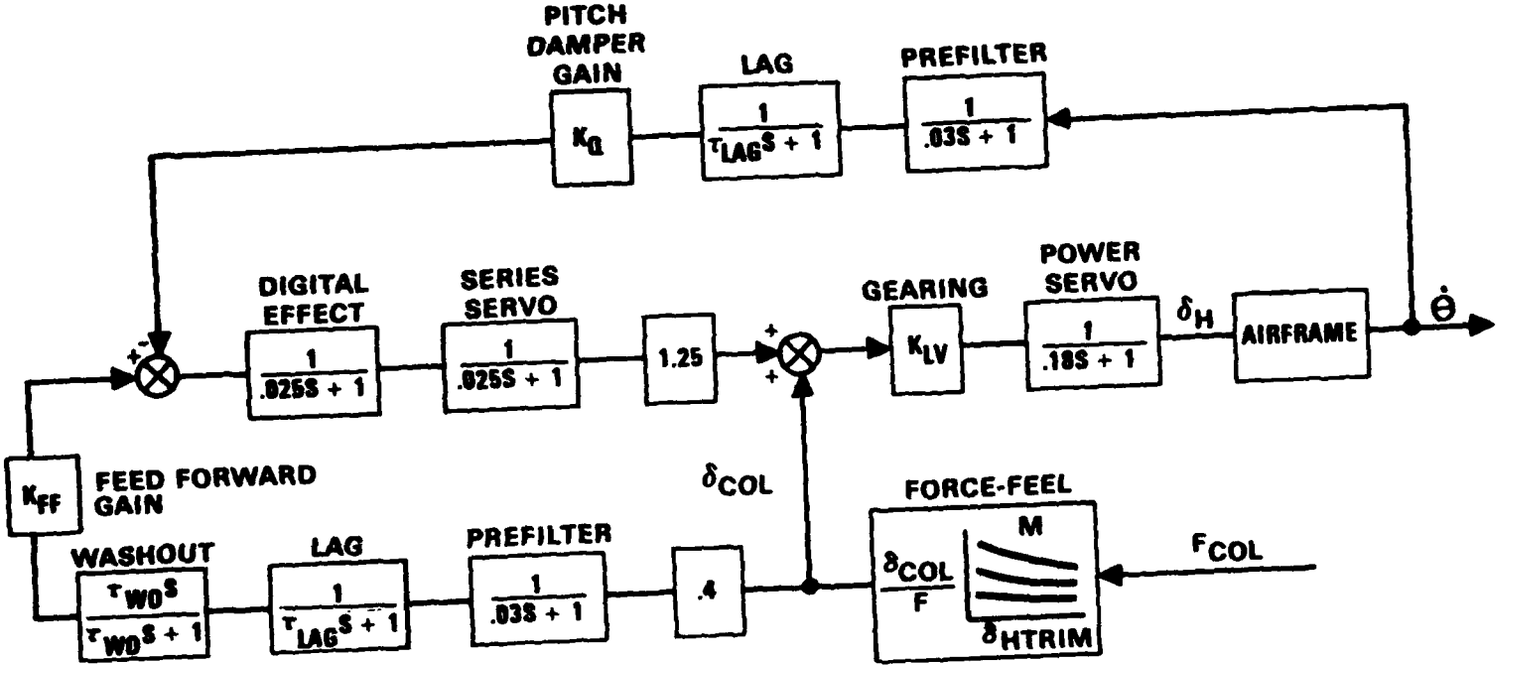


B-24/JJR ACT 9-14-81

The near-term pitch stability augmentation system consists of a lagged pitch rate damper with washed-out column feed forward loop. The damper serves to provide the necessary short-period frequency and damping characteristics while also suppressing turbulence effects, and the feed-forward was designed to 'quicken' the pitch rate response and reduce stick force gradients without affecting system stability.

NASA/LOCKHEED
AIRCRAFT ENERGY EFFICIENCY

PITCH ACTIVE CONTROL SYSTEM
NEAR TERM SYSTEM



B-3/JJR ACT 9-14-81

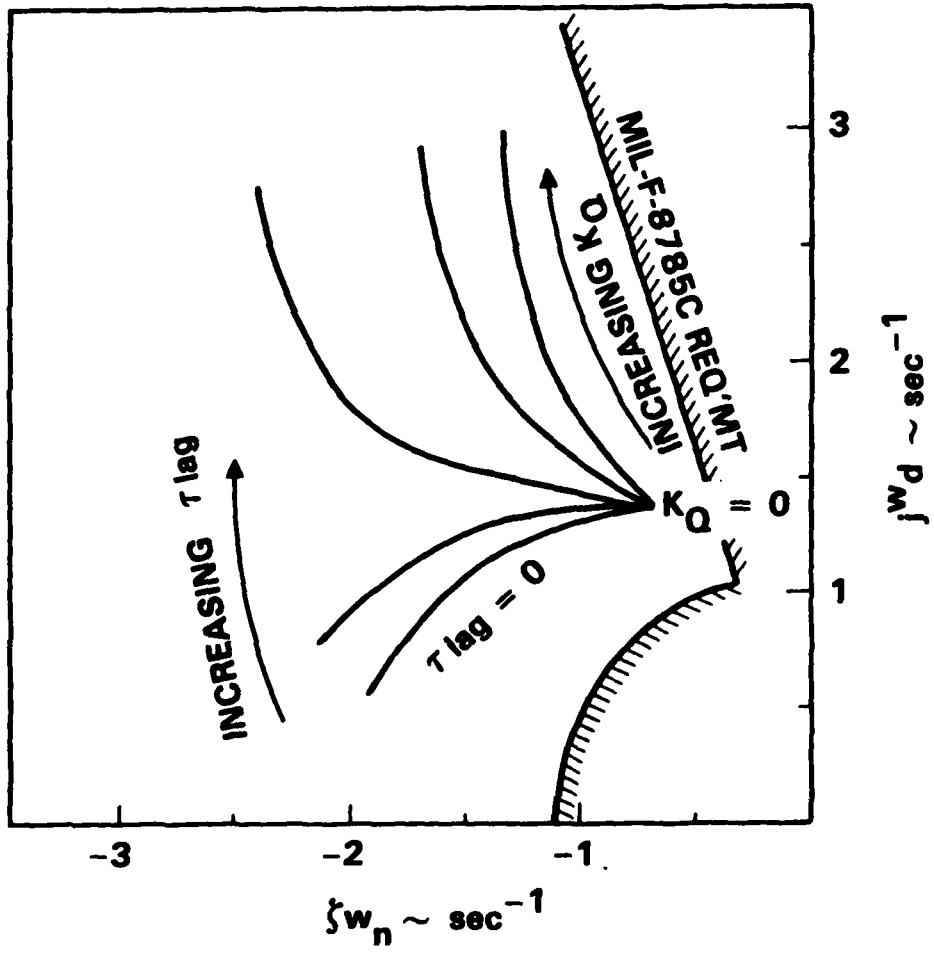
The near-term pitch active control system was designed using MIL-F-8785C as a guide for short-period characteristics. The desired short-period characteristics were obtained by the proper selection of pitch rate feedback gain (K_Q) and lag time constant (τ_{lag}) for a particular flight condition and center of gravity.

NASA/LOCKHEED
AIRCRAFT ENERGY EFFICIENCY

GAIN/LAG EFFECTS ON SHORT PERIOD – CRUISE

M = 0.83, h = 33,000 ft, cg = 25%$\bar{C}$

AILERONS INACTIVE

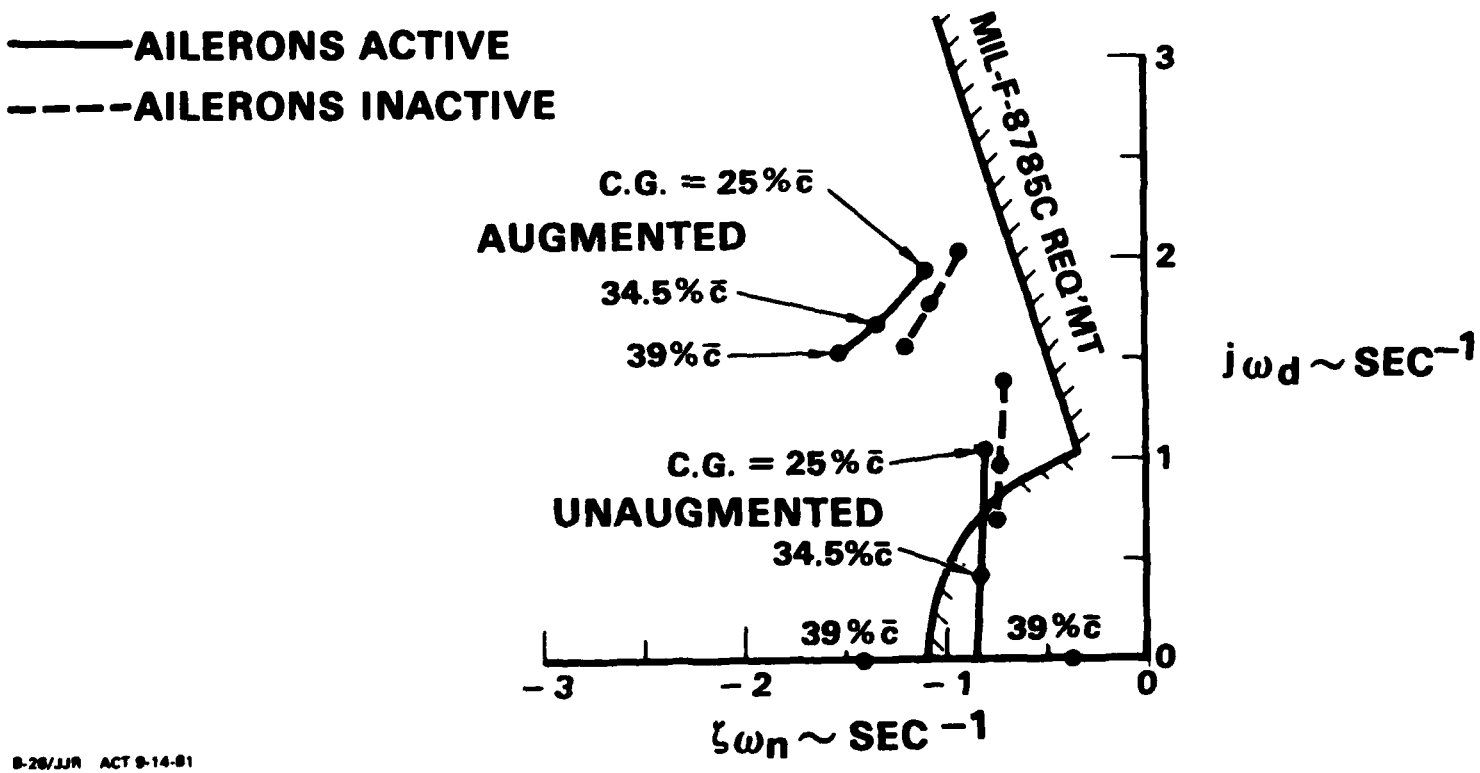


The schedules of pitch rate feedback gain and lag time constant were chosen so that the augmented stability L-1011 has good short-period frequency and damping characteristics for the complete center-of-gravity range (25 to 39%$\bar{c}$) investigated in flight test. The gain and lag schedules are defined as a function of calibrated airspeed.

NASA/LOCKHEED
AIRCRAFT ENERGY EFFICIENCY

SHORT PERIOD CHARACTERISTICS – CRUISE

M = 0.83, h = 33,000 FT



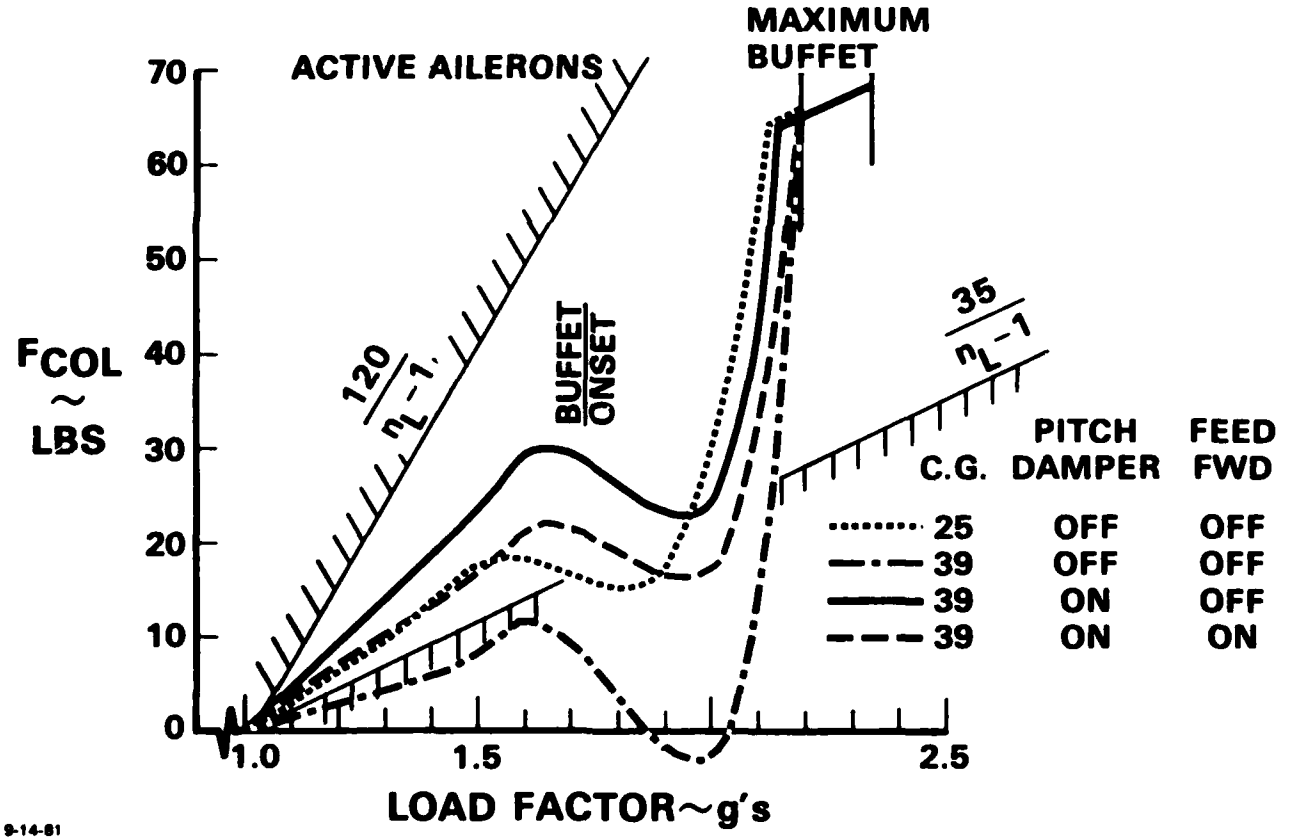
B-26/JJR ACT 9-14-81

In cruise the near-term augmentation system without feed-forward compensation provides slightly higher maneuver stability column force gradients at the relaxed static stability aft limit than the basic airplane has at mid c.g. without augmentation. The effect of feed-forward compensation is to reduce the column force gradients to levels comparable to the basic unaugmented airplane at typical c.g. locations. The initial force gradients comply with MIL-F-8785C requirements; however, there is a deviation from linearity which results in a short-term negative gradient in the 1.6 to 2.0 g range which is unacceptable in terms of MIL-F-8785C requirements. While these negative gradient characteristics may not be desirable, they are not uncommon to Class III transport configurations which cruise at Mach numbers above 0.8. It is suggested that some narrow region of negative gradient may be acceptable as long as a substantial force level is maintained and there is adequate buffet onset or other warning prior to n_L.

NASA/LOCKHEED
AIRCRAFT ENERGY EFFICIENCY

MANEUVER STABILITY — CRUISE

$M_\infty = 0.83$, $h = 33{,}000$ FT

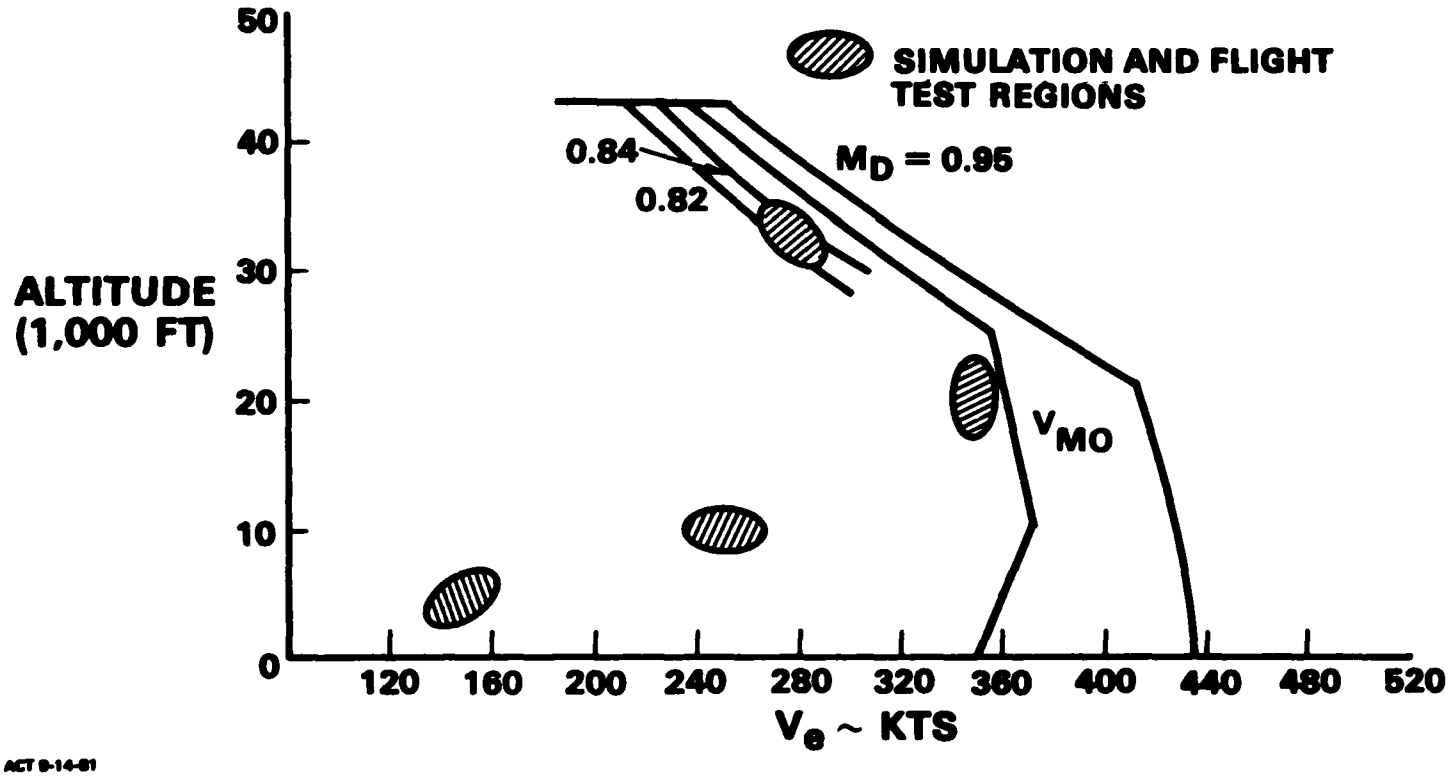


B-S/JJR ACT 9-14-81

Conditions for simulation and flight test are shown by the grey areas in the flight envelope. Most of the flight test activity was performed at the cruise condition where relaxed static stability shows the greatest potential for improved performance.

NASA/LOCKHEED
AIRCRAFT ENERGY EFFICIENCY

FLIGHT ENVELOPE



D-6/JJR ACT 9-14-81

SECTION IV.
INFORMAL REPORTS

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ARVIN/CALSPAN

8 March 1982

DEFINITION OF LEVELS THAT INCLUDE TURBULENCE ENVIRONMENT AND TASK PERFORMANCE STANDARDS

Charles R. Chalk

CRC/jc

ADVANCED TECHNOLOGY CENTER

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APPLIED TECHNOLOGY GROUP

ARVIN

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FLYING QUALITIES LEVEL DEFINITIONS

Level 1

Flying qualities such that desired (fully sufficient) task performance for the mission Flight Phase can be achieved, with a workload that is satisfactory to the pilot, under the set of environmental conditions (specified by the procuring activity) for which performance of the Flight Phase is required and such that Category A Flight Phases can be terminated safely[x] and Category B and C Flight Phases can be completed safely[x] in the most difficult set of environmental conditions required by the procuring activity to be considered in the design of the airplane.

Level 2

Flying qualities such that adequate[†] task performance for the mission Flight Phase can be achieved, with a workload that is tolerable[*] to the pilot, under the set of environmental conditions (specified by the procuring activity) for which performance of the Flight Phase is required and such that Category A Flight Phases can be terminated safely[x] and Category B and C Flight Phases can be completed safely[x] in the most difficult set of environmental conditions required by the procuring activity to be considered in the design of the airplane.

Level 3

Flying qualities such that Category A Flight Phases can be terminated safely[x] and Category B and C Flight Phases can be completed safely[x] in the most difficult set of environmental conditions required by the procuring activity to be considered in the design of the airplane.

---

†Adequate - Equal to what is required; suitable to the case or occasion; barely sufficient.

*Tolerable - Endurable; capable of being borne.

[x]Safely - Free from danger; having escaped injury or damage; unharmed; not hazardous; not involving risk or loss; not likely to cause or to do harm or injury.

- Ratings are valid only for the environment in which they are generated and for the task definition and task performance standard used by the pilot during the evaluation.

- Ratings can not be extrapolated to apply to other environments, other tasks or different task performance standards.

- When performing piloted evaluations, it is necessary: to include environment factors in the experiment: to define the task: and to define task performance standards. These must be explicitly defined for the evaluation pilot and he must consistently perform the defined task and apply the performance standards in formulating the evaluation rating.

- The proposed Level definitions permit different tasks and performance standards to be considered for the most difficult environmental conditions when evaluating a given configuration. Thus, the pilot must be informed of the environmental conditions and the corresponding task and performance standard he is expected to apply during a given portion of the evaluation process.

COMMENTS AND QUESTIONS

Sam Craig: What about those areas (conditions) we've never gotten into?

Answer: You cannot extrapolate pilot ratings into those areas.

Sam Craig: It is a good goal to shoot for knowing this.

Dave Key, US Army: What about your requirement to change configuration from combat to approach and landing to define a Level 1 airplane?

Answer: Acknowledged--no real answer.

Rob Crombie, AFFTC: You have a good point. The performance standards and environment should be defined by the procuring activity.

Dave Moorhouse, FDL: MIL-F-8785C has a reworked matrix. Roger Hoh has the information. The Navy has carrier wake as most severe condition. The problem of the specification being a strict legal document versus a design guide makes pilot rating hard to use directly. The current specification seems to be a workable compromise.

Dick Quinlivan, GE: Another driver may be time required. You may not be able to complete the task in a combat environment.

Bob Woodcock, FDL: Phase B and C are the same for Level 2 and Level 3. Is that right?

Answer: Yes.

Jerry Lockenour, Northrop: What is a Level 1 airplane?

Answer: An airplane capable of doing the job, having a Cooper-Harper rating less than 3½ for all aspects of the flight, i.e., mission and Phases B and C.

Dave Key, US Army: Isn't this compatible with STI?

Answer: Not necessarily.

Jerry Lockenour, Northrop: I don't understand why pilot opinion rating can't be used legally in place of hard requirements related to flying quality levels.

Answer: Hard requirements, such as in Section 3 of the current specification can be designed to and verified. Pilot ratings, either Cooper-Harper values or Levels are subjective in nature and therefore are not hard values. There is also the problem of resolving conflicting ratings from different pilots.

Jack Franklin, NASA Ames: A basic distinction between Levels ratings is performance.

John Gibson, British Aerospace: A problem seems to be getting those conditions we want to investigate in a test situation. Even then, you might not be able to measure it, and you may need to wait a long time to experience that condition again.

DEVELOPMENT OF CONTROLLER REQUIREMENTS FOR UNCOUPLED AIRCRAFT MOTION

Kevin Citurs
McDonnell Aircraft Company

DEVELOPMENT OF CONTROLLER REQUIREMENTS FOR UNCOUPLED AIRCRAFT MOTION

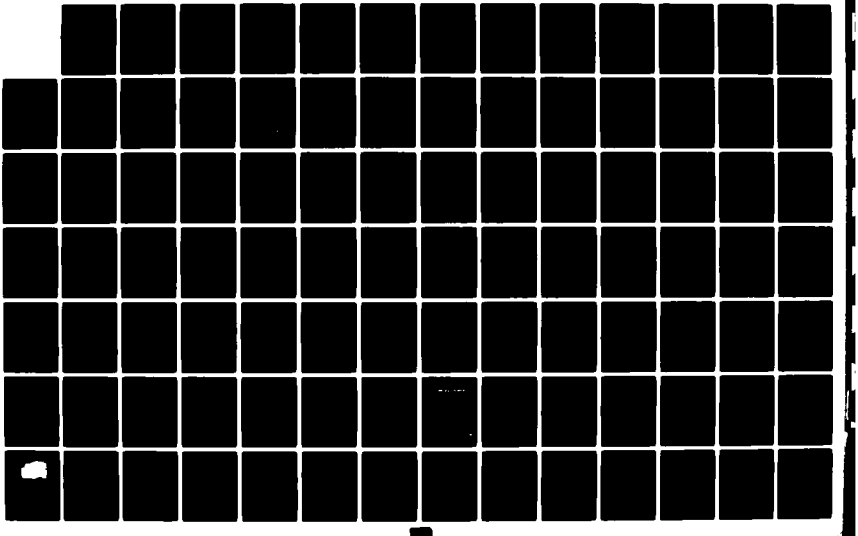
MARCH, 1982

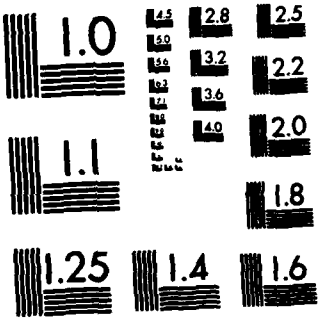
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MCDONNELL AIRCRAFT COMPANY

AD-A121 423 DESIGN CRITERIA FOR THE FUTURE OF FLIGHT CONTROLS PROCEEDINGS OF THE FLIG..(U) AIR FORCE WRIGHT AERONAUTICAL LABS WRIGHT-PATTERSON AFB OH

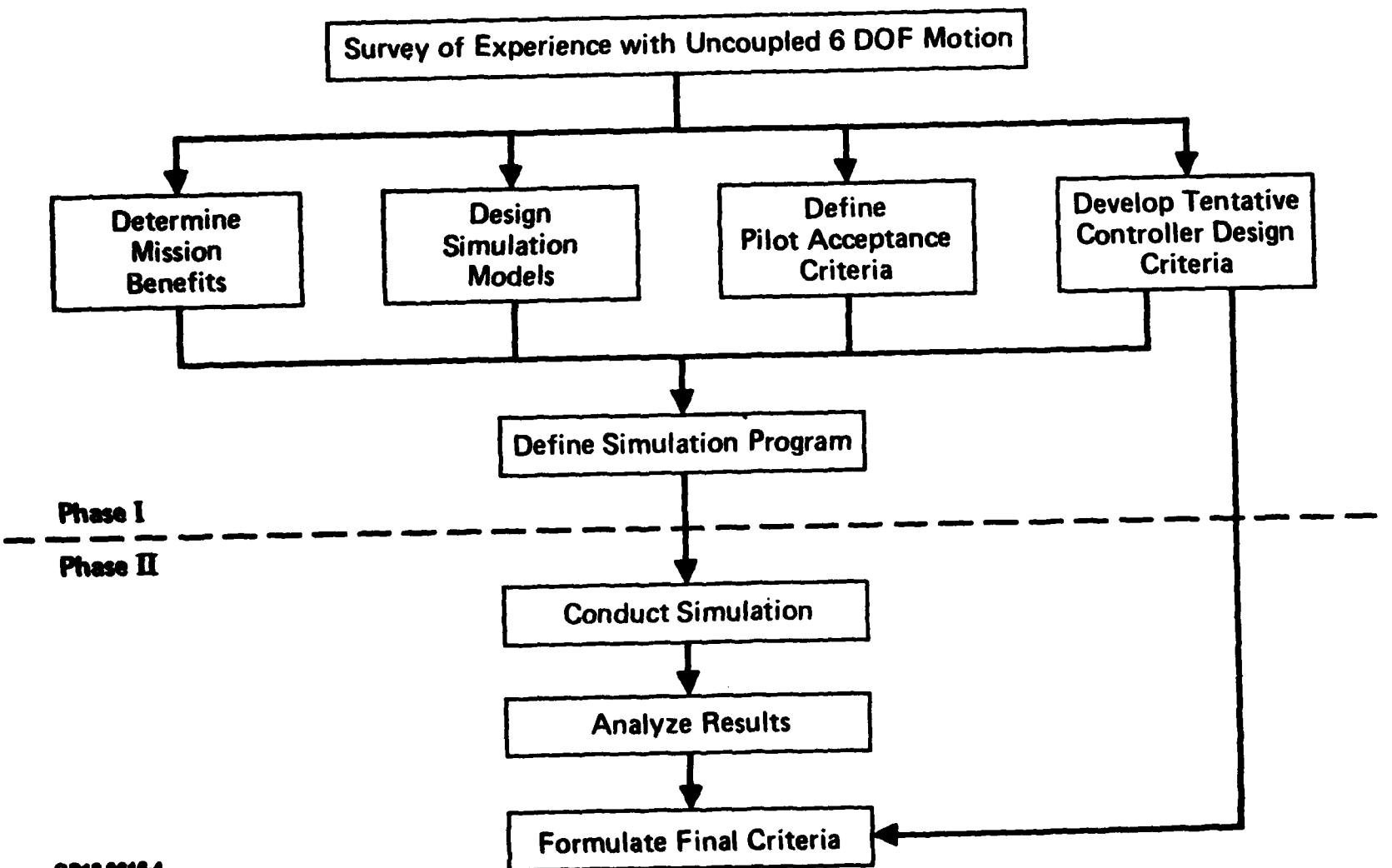
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MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

DEVELOPMENT OF CONTROLLER REQUIREMENTS FOR UNCOUPLED AIRCRAFT MOTION



LONGITUDINAL UNCOUPLED MODES

- VERTICAL PATH CONTROL (VPC) - NORMAL FACTOR CONTROL AT CONSTANT ANGLE OF ATTACK
- VERTICAL TRANSLATION (VT) - VERTICAL ACCELERATION OR VELOCITY CONTROL AT CONSTANT ATTITUDE
- FUSELAGE ELEVATION AIMING (FEA) - FUSELAGE ANGLE OF ATTACK CONTROL AT CONSTANT LOAD FACTOR
- DRAG MODULATION (DM) - VELOCITY CONTROL AT A CONSTANT ENGINE POWER SETTING
- MANEUVER ENHANCEMENT (ME) - BLENDING OF CONVENTIONAL AND EITHER VPC OR VT FOR QUICKER RESPONSE AND/OR IMPROVED RIDE QUALITY

LATERAL UNCOUPLED MODES

- LATERAL TRANSLATION (LT) - LATERAL ACCELERATION OR VELOCITY CONTROL WITHOUT YAW ROTATION OR ROLL MOTION

- WINGS LEVEL TURN (WLT) - HEADING CONTROL (LATERAL LOAD FACTOR) WITH NO SIDESLIP OR ROLL ATTITUDE MOTION

- FUSELAGE AZIMUTH AIMING (FAA) - AZIMUTH CONTROL WITH NO LATERAL LOAD FACTOR

COMMENTS ON THE LITERATURE

- o USE OF DIRECT VERTICAL AND SIDE FORCE POTENTIALLY USEFUL IN SIMPLIFYING LANDING TASKS FOR ALL CLASSES OF AIRCRAFT
- o MANEUVER ENHANCEMENT MODES CAN POTENTIALLY IMPROVE ACCURACY OF CONTROL AND RIDE QUALITIES.
- o WINGS LEVEL TURN SHOWS GREATEST POTENTIAL FOR IMPROVING AIR-TO-SURFACE BOMBING ACCURACY
- o FUSELAGE POINTING MODES BEST IMPLEMENTED AS PART OF INTEGRATED FLIGHT/FIRE CONTROL
- o RUDDER PEDAL CONTROL OF LATERAL MODES IS ACCEPTABLE HOWEVER IN GENERAL NO 'OPTIMUM' CONTROLLER HAS BEEN FOUND
- o NO STUDY HAS ATTEMPTED TO DEFINE CONTROLLER CRITERIA FOR AIRCRAFT CAPABLE OF HIGH AUTHORITY, UNCOUPLED MOTION

CAUTIONS TO CONSIDER

- RECENT IN FLIGHT EXPERIENCE HAS INDICATED CONCERN OVER HIGH ONSET RATES IN NORMAL ACCELERATION AND ROLL

- HIGH LEVELS OF LATERAL ACCELERATION HAVE BEEN SHOWN TO RESULT IN INADVERTANT CONTROL INPUTS DURING CENTRIFUGE TESTS

- SOME FORMS OF MANEUVER ENHANCEMENT RESULTS IN OBJECTIONABLE CONTROL SURFACE ACTIVITY AND ACCELERATION CHARACTERISTICS

CRITICAL MISSION SEGMENTS

- o INGRESS AND EGGRESS TO THE TARGET
- o TARGET DETECTION AND IDENTIFICATION
- o AIR-TO-SURFACE WEAPON DELIVERY
- o AIR-TO-AIR WEAPON DELIVERY
- o AIR-TO-AIR REFUELING AND FORMATION
- o APPROACH AND LANDING

ADDITIONAL APPLICATIONS

- DEFENSIVE MANEUVERING
- TERRAIN FOLLOWING/TERRAIN AVOIDANCE
- PRECISION LANDINGS DUE TO RUNWAY DENIAL
- MINIMIZE RADAR AND VISUAL CROSS SECTION

CONTROLLER/CONTROLLED MODE MATRIX: LONGITUDINAL

CONTROLLER	CONVENTIONAL		MODE								MANEUVER ENHANCEMENT
			DRAG MOD.		VERTICAL PATH CONTROL		VERTICAL TRANSLATION		FUSELAGE AIMING		
	$\dot{\theta}$	θ	$\dot{u}$	u	$\dot{\gamma}$	γ	$\dot{w}$	w	$\dot{\theta}$	θ	
Stick Mounted Button	-	-	① -	① -	② 5	-	5	② 5	-	-	-
Vertical Force	-	-	-	-	2	-	5	5	-	-	-
Throttle Grip Mounted ③	-	-	5	-	4	-	4	4	5	5	-
Stick Control	5	5	-	-	4	-	-	-	3	3	5
Stick Mounted *Thumbwheel*	-	-	① -	-	4	-	4	4	4	-	-

① Throttle control more appropriate location

② Used on GCV-16, AFTI-15

③ Used on AFTI-16

CONTROLLER/CONTROLLED MODE MATRIX: LATERAL

CONTROLLER	MODE									
	FORWARD SLIP		LATERAL TRANSLATION		WINGS LEVEL TURN		FUSELAGE AIMING		CONVENTIONAL BANK	
	$\dot{\phi}$	ϕ	$\ddot{y}$	$\dot{y}$	$\dot{\psi}$	ψ	$\dot{\psi}$	ψ	$\dot{\phi}$	ϕ
Rudder Pedal (Normal Function Disconnected)	-	-	-	③ ② 4	③ ② 5	-	③ ② 5	-	-	-
Stick Mounted Button	-	-	-	② 4	② 4	-	② 4		-	-
Stick Mounted Thumbwheel	-	-	-	3	-	-	-	-	-	-
Conventional Stick	5	3	-	3	-	-	-	-	5	5
Stick Mounted Twist Grip	-	-	-	-	5	-	5	-	-	-
Stick Mounted Thumb Lever	-	-	-	2	5	-	5	-	-	-
Thrust Vector Control Blended with Normal Functions	-	-	-	-	-	-	-	-	-	-
Throttle Mounted Controllers	-	-	-	1	1	-	1	-	-	-
Brake Pedals	-	-	-	4	5	-	5	-	-	-
Automatic Implementation on ILS Localizer	2	-	-	5	-	-	-	-	-	-

TASK/CONTROLLED MODE MATRIX: LONGITUDINAL

TASK	MODE					
	CONVENTIONAL	DRAG MOD.	VERTICAL PATH CONTROL	VERTICAL TRANSLATION	FUSELAGE AIMING	MANEUVER ENHANCEMENT
Air Combat	5	5	3	-	5	5
Formation	5	5	1	5	-	5
Refueling	5	5	1	5	-	5
Coupled Fire-Flight	-	-	-	-	5	5
En-Route Maneuvers	5	2	2	4	-	5
Bombing	5	3	5	2	-	5
Strafing	5	1	3	1	5	5
Landing (Manual)	5	0	3	5	-	5
Landing (Instrument)	5	-	3	5	-	5

TASK/CONTROLLED MODE MATRIX
LATERAL

TASK	MODE				
	FORWARD SLIP	LATERAL TRANSLATION	WINGS LEVEL TURN	FUSELAGE AIMING	CONVENTIONAL BANK
Air Combat	3	3	5	5	5
Formation	-	5	3	-	5
Refueling	-	5	-	-	5
Coupled Fire-Flight	-	-	-	5	5
En-Route Maneuvers	-	1	5	-	5
Bombing	-	4	5	-	5
Strafing	-	-	3	5	5
Landing (Manual)	4	4	5	-	5
Landing (Instrument)	-	5	5	-	5

CHARACTERISTICS TO CONSIDER

1. BREAKOUT FORCES
2. FORCE-DEFLECTION GRADIENTS
3. HYSTERESIS
4. CENTERING
5. POSITIONING ACCURACY
6. INPUT LIMITING
7. TIME LAGS
8. AXIS OF ACTUATION
9. HARMONY
10. CROSS-TALK

COMMENTS AND QUESTIONS

Roger Hoh, STI: We don't even understand centersticks and sidesticks. I wonder how we can get this involved with something this exotic. More work needs to be done on the basics.

Robert Bateman, SRL: Sidestick versus centerstick controllers. You like what you expect. How have you taken pilot expectations into account? Must also have consistent response.

Answer: True. We have tried to in the set-up of the matrix of test points but there are limitations.

Jack McAllister, GD: In response to Roger Hoh, those controllers which work to some degree should be used to identify why they are good (with variations). It's hard to say which controllers have worked, based on the literature.

Jerry Lockenour, Northrop: You want to concentrate on uncoupled modes. To date, conventional controllers have not worked.

Answer: We will make changes as required.

John Schuler, Boeing: Carlson had some work which might be helpful.

Mick Van Gool, NLR: Familiarization will require a tremendous amount of time. My experience shows pilots need a lot of time to accept something new.

Answer: Agreed. We will have to fit simulation time to our budget.

Dave Schmidt, Purdue: How long?

Mick Van Gool, NLR: Several hours. First they assess it by conventional means, then change.

Dick Quinlivan, GE: Motion effects are also important.

THE IDEAL CONTROLLED ELEMENT FOR REAL AIRPLANES IS NOT K/s

ROLL-RATCHET PHENOMENON

Charles R. Chalk
Calspan Advanced Technology Center

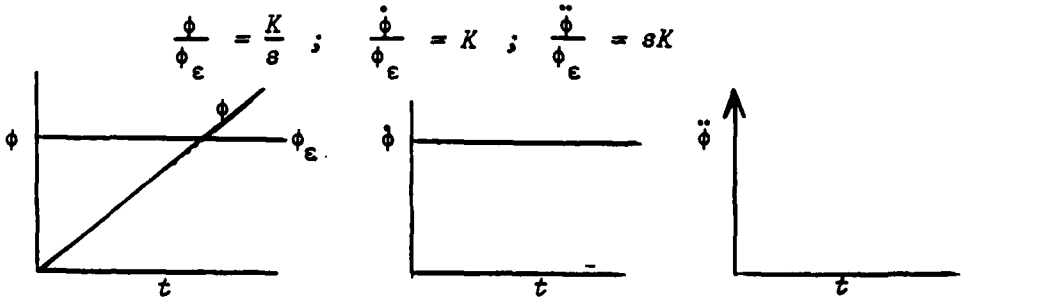
THE IDEAL CONTROLLED ELEMENT FOR REAL AIRPLANES IS NOT K/s

The early experiments performed to generate data to support development of mathematical models of the human operator used simple controlled element transfer functions, i.e. K, K/s and K/s^2. In these experiments, the pilots were seated in a fixed chair and were required to perform a compensatory tracking task which consisted of correcting errors displayed by lines or dots on a CRT. This work led to the "crossover" model and the conclusion that the ideal controlled element transfer function is K/s. This conclusion has been so completely accepted by disciples that it is used to challenge results from T-33 in-flight experiments which show degradation in pilot rating with increased roll damping where the controlled element transfer function approaches K/s.

$$\frac{\phi}{\phi_\epsilon} = \frac{K}{s(s+\lambda_R)} \longrightarrow \frac{K}{s} \text{ when } \lambda_R \longrightarrow \infty$$

When the physical system being controlled has mass and the response state being controlled is position, the K and K/s transfer function forms are physically impossible because infinite acceleration capability would be required for abrupt commands.

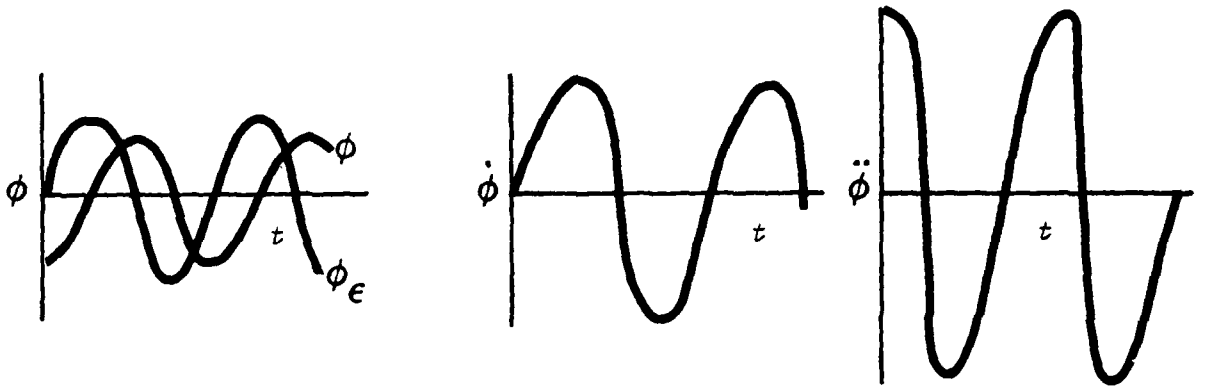
Consider:



Step Command $\sim \phi_\epsilon$
Ramp Response $\sim \phi$

Step Response $\sim \dot{\phi}$

Impulse Response $\sim \ddot{\phi}$
Infinite Amplitude



Sine Wave Command

Sine Wave Response with 90° Phase Lag
$\phi \sim \frac{K}{\omega} \phi_\epsilon$ Amplitude

Sine Wave Response in Phase
$\dot{\phi} \sim K\phi_\epsilon$ Amplitude

Sine Wave Response with 90° phase lead
$\ddot{\phi} \sim K\omega\phi_\epsilon$ Amplitude.
Amplitude becomes very high at high frequency.

Although the K and K/s transfer function forms can be well approximated when using electron beams, they cannot be achieved in airplane systems because control deflections require a finite time to achieve, control surfaces can only generate finite forces, and airplane structures are not completely rigid. Experiments in the NT-33A variable stability airplane indicate, however, that the pilot starts to complain before the limits of the in-flight simulator are reached when attempts are made to simulate a pure K/s transfer function for roll angle response to commands.

The pilot comments contain reference to excessive roll acceleration and lateral acceleration experienced in achieving desired roll rate. These accelerations can be avoided if the pilot uses slower applications of control input but this requires conscious effort. There are times when he reacts instinctively and suddenly and, in these situations, a pilot-airplane closed-loop "oscillation" takes place in roll. The "oscillation" is relatively high frequency, 11-17 rad/sec, and is described as roll "ratchet." The time history in Figure 1 illustrates a pilot-airplane closed-loop oscillation that occurred during evaluation of Configuration 6-3 in Reference 3, which was described as roll ratchet.

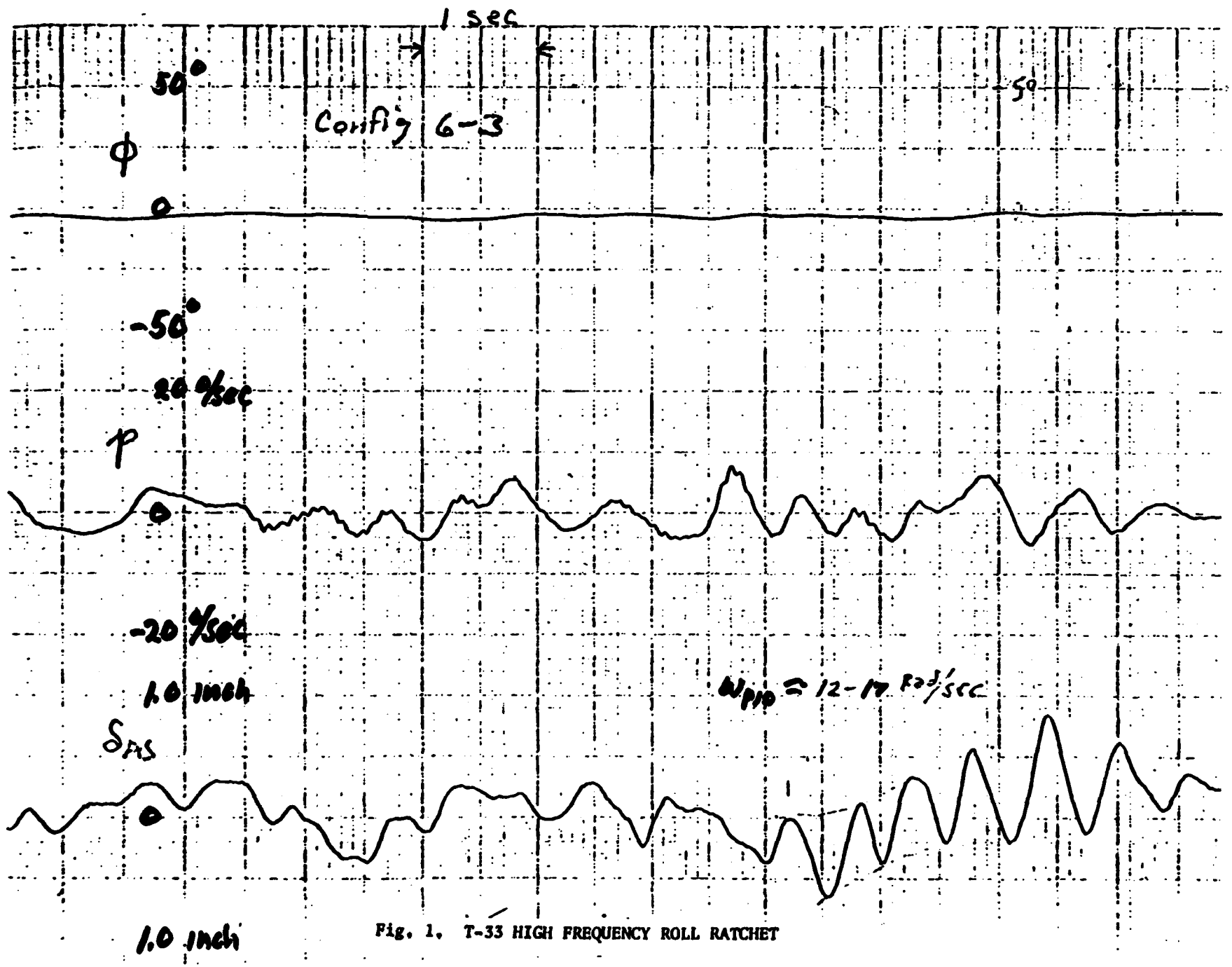


Fig. 1. T-33 HIGH FREQUENCY ROLL RATCHET

The approximate transfer function for this configuration is

$$\frac{\phi}{F_{AS}} = \frac{19.2}{s(s+5)} e^{-.125s} \quad \text{deg/lb}$$

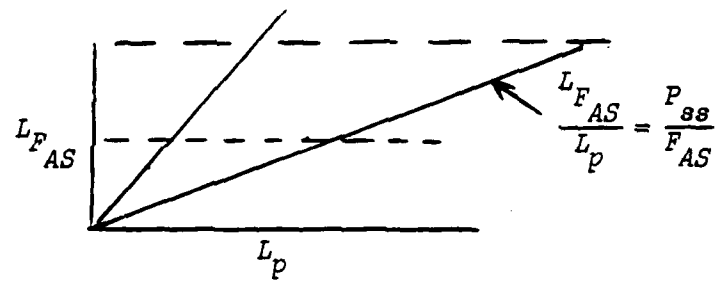
where the equivalent time delay represents contributions from transfer delay and higher order dynamic lags in the roll command channel.

The high frequency roll acceleration gain of the transfer function is 19.2 deg/sec^2-lb and the steady state roll rate is $\frac{19.2}{5} = 3.84$ deg/sec-lb. If one hypothesizes that both the high frequency roll acceleration gain and the steady state roll rate gain are independently important to flying qualities, then constraints on the effective roll damping are implied.

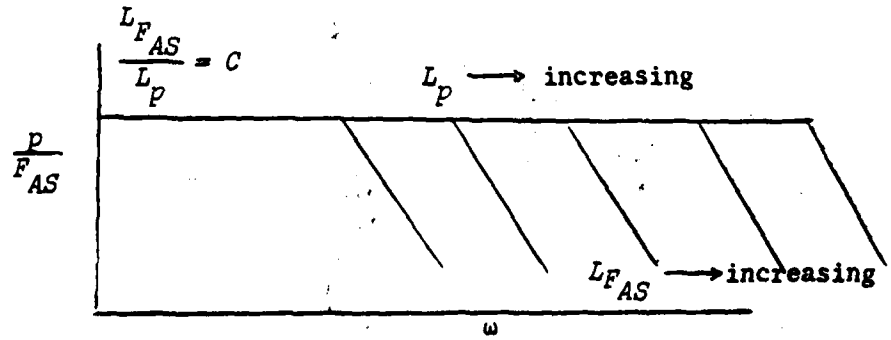
$$\text{Lower limit} < L_{F_{AS}} < \text{Upper limit}$$

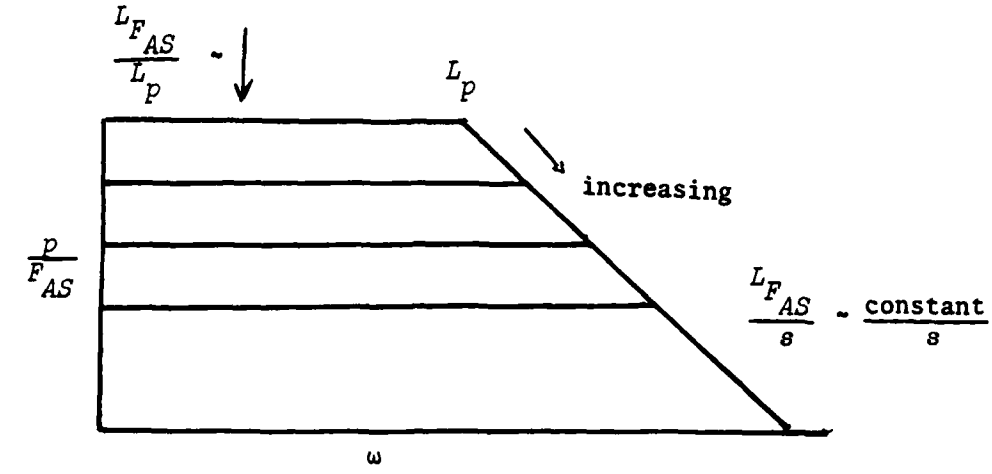
$$\text{Lower limit} < \frac{L_{F_{AS}}}{L_p} < \text{Upper limit}$$

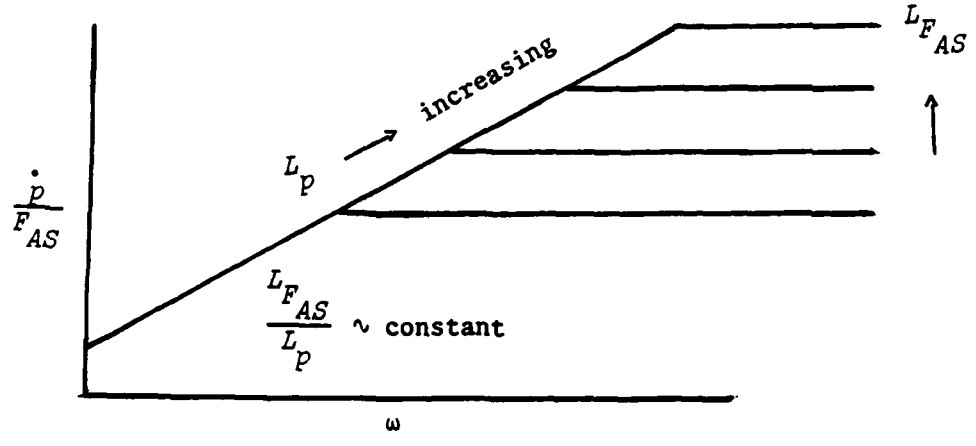
$$\therefore \text{Lower limit} < L_p < \text{Upper limit}$$

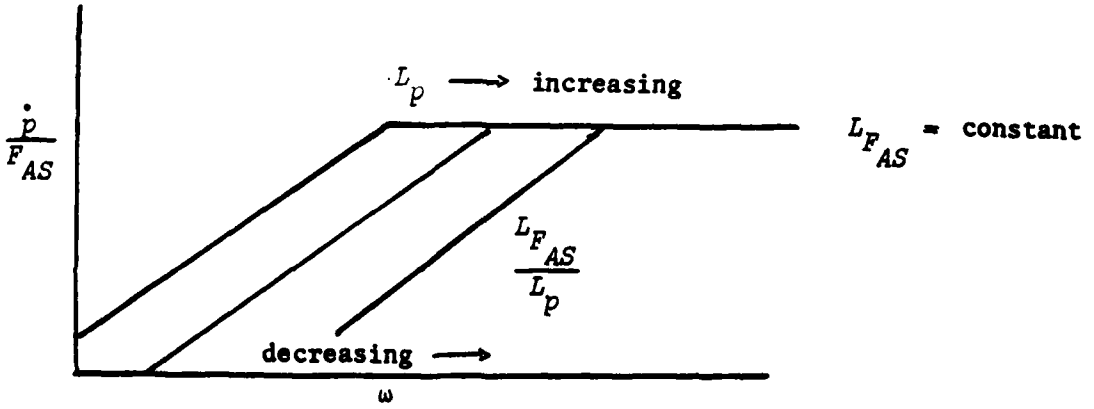


Frequency Response




$\frac{L_{F_{AS}}}{L_p}$ ~
L_p
increasing
$\frac{p}{F_{AS}}$
$\frac{L_{F_{AS}}}{s}$ ~ $\frac{\text{constant}}{s}$
ω


$L_{F_{AS}}$
increasing
L_p
$\frac{\dot{p}}{F_{AS}}$
$\frac{L_{F_{AS}}}{L_p}$ ~ constant
ω


L_p ⟶ increasing
$L_{F_{AS}}$ = constant
$\frac{\dot{p}}{F_{AS}}$
$\frac{L_{F_{AS}}}{L_p}$
decreasing ⟶
ω

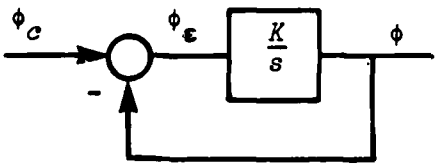
Independent constraints on control "sensitivity" and steady state roll rate response may be important to pilot acceptance of roll flying qualities. For classical roll transfer functions, this implies limits on roll damping. For higher order systems, it may be best to state a requirement as a ratio of $\dot{p}/F/p/F$.

Since the pilot-airplane system exhibits a lightly damped oscillation during roll ratchet, it should be possible to model the closed-loop dynamics and to calculate parameter values that would result in zero damped complex roots at the frequency observed in the flight records.

Consider first the case where the airplane transfer function is K_c/s and the pilot transfer function is a K_p. Then $Y_p\ Y_c = K/s$ and the closed-loop dynamics are determined by the value of the loop gain K. See Figure 2 for block diagram and Nichols diagram of the open-loop and closed-loop dynamics. This system cannot be driven unstable by increases in loop gain.

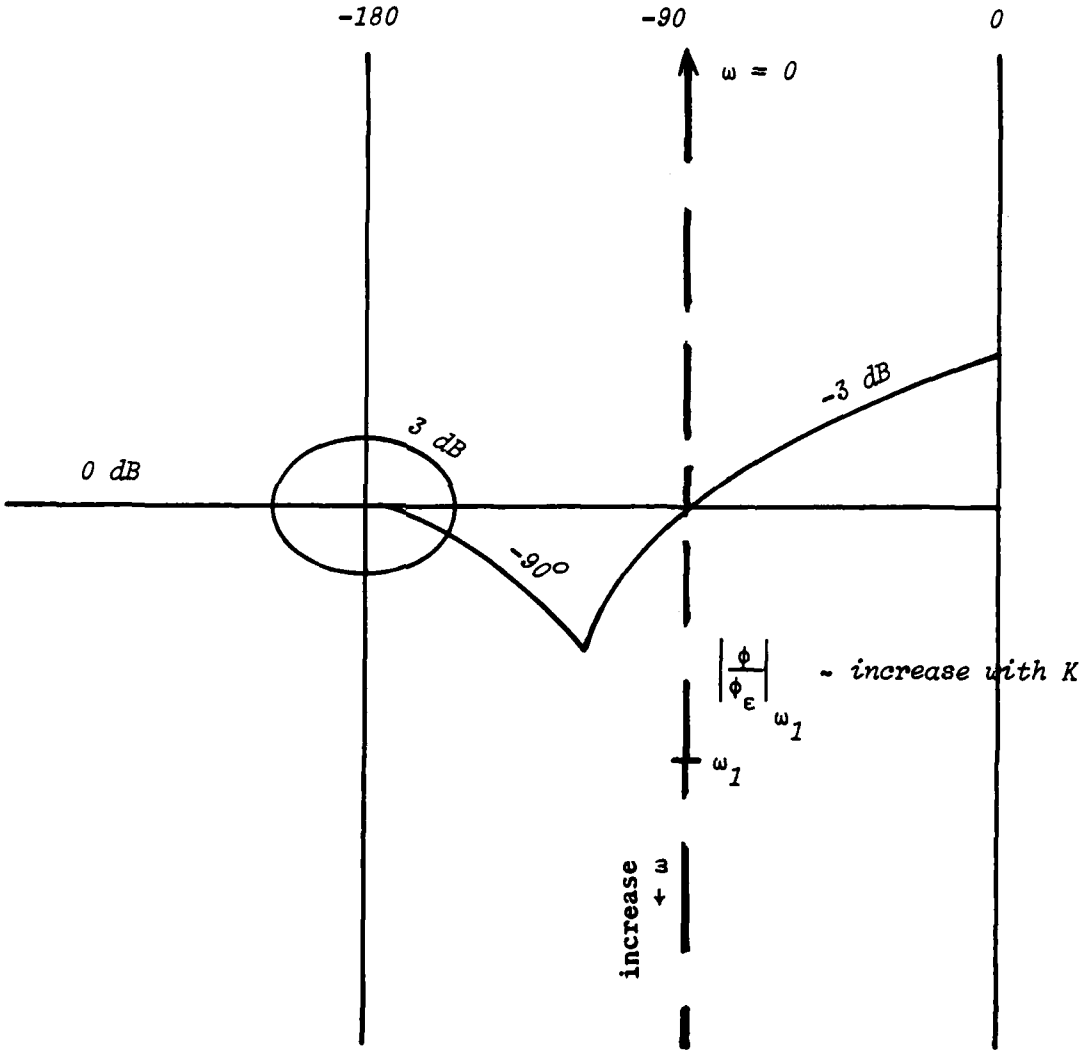
It should be noted that in closed-loop analysis, the system dynamics are dependent on loop gain $K = K_p\ K_c$ and there is no consideration given to how the loop gain is partitioned between the pilot K_p and the airplane K_c. Experimental results indicate, however, that the pilot rating is influenced by the partitioning of the loop gain. See Figure 3 (from Reference 1) which shows how the pilot rating degrades when the portion of the loop gain attributed to the airplane is either increased or decreased from an optimum value. The data in Figure 3 indicates a broad tolerance (i.e., a factor of 20 between the lowest gain and the highest gain for which the pilot rating was PR = 3.5) by the pilot to variations in the airplane gain but it also indicates that there are limits to the pilot's ability or willingness to compensate the loop gain in order to achieve desired closed loop dynamic behavior.

Consider next the effect of adding time delay to the control loop. The time delay causes increasing phase shift with increased frequency and the closed-loop system will exhibit instability at high loop gain. Figure 4 summarizes the block diagrams and equations for three different forms of the



$$\frac{\phi}{\phi_\epsilon} = \frac{K}{s}$$

$$\frac{\phi}{\phi_c} = \frac{K}{(s+K)}$$



As $K \to \infty$ the closed loop root also $\to \infty$. The system cannot be driven unstable by increased loop gain.

Fig. 2. CLOSED LOOP DYNAMICS FOR $Y_p Y_c = \frac{K}{s}$

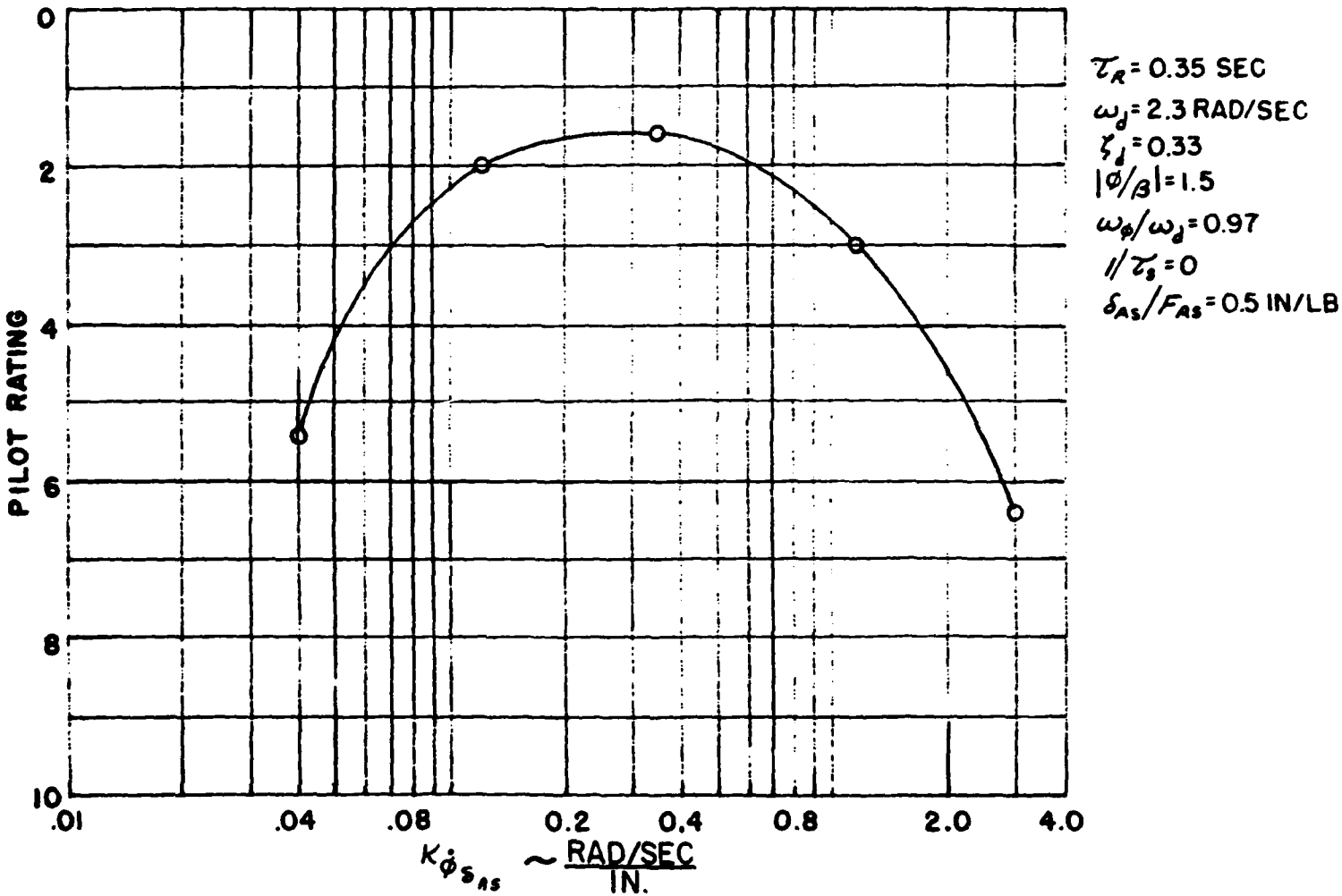
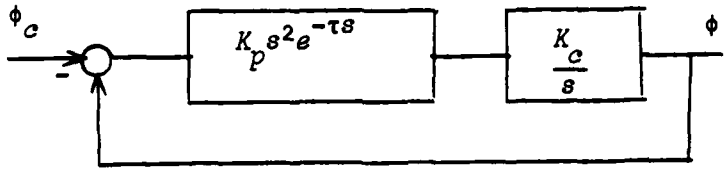


Fig. 3. PILOT RATING VERSUS STEADY STATE ROLL RATE PER INCH OF AILERON STICK DISPLACEMENT.



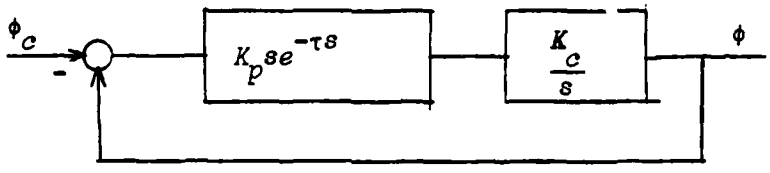
$$Y_p Y_c = Ks e^{-\tau s}$$

$K = 1/\omega$ for $\sigma_n = 0$

$\omega = \frac{(2n+1)\pi}{2\tau}$ $\quad n$ ~ odd

$\omega = 12$ rad/sec for $\tau = .39$ sec

$\omega = 17.4$ $\quad \tau = .27$ sec



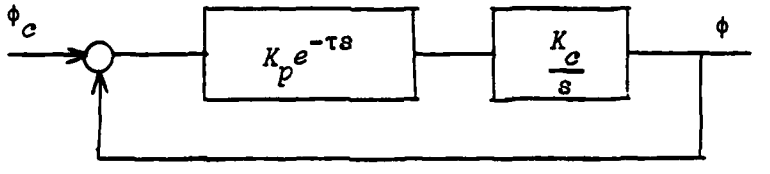
$$Y_p Y_c = K e^{-\tau s}$$

$K = 1$ for $\sigma_n = 0$

$\omega = \frac{n\pi}{\tau}$ $\quad n$ ~ odd

$\omega = 12$ rad/sec for $\tau = .26$ sec

$\omega = 17.4$ $\quad$ for $\tau = .18$



$$Y_p Y_c = \frac{K}{s} e^{-\tau s}$$

$K = \omega$ for $\sigma_n = 0$

$\omega = \frac{(2n-1)\pi}{2\tau}$ $\quad n$ ~ odd

$\omega = 12$ rad/sec for $\tau = .13$ sec

$\omega = 17.4$ $\quad$ for $\tau = .09$

Fig. 4. BLOCK DIAGRAMS FOR CONTROL OF ϕ, $\dot{\phi}$, $\ddot{\phi}$ WITH TIME DELAY IN THE LOOP

pilot model, i.e. $K_p e^{-\tau s}$, $K_p s e^{-\tau s}$ and $K_p s^2 e^{-\tau s}$ and one form of the airplane transfer function K_c/s. These simplified cases represent pilot loop closures based on angular position, rate and acceleration. All three of these models will exhibit closed-loop instability at the gains and frequencies indicated on Figure 4. The values of time delay required to cause closed-loop oscillations at the frequency range, 12-17.4 rad/sec, observed in the roll ratchet illustrated in Figure 1 for Configuration 6-3 are also noted on Figure 4. Nichols diagrams for the cases illustrated on Figure 4 are drawn on Figure 5 for the values of time delay that will cause the closed-loop system to go unstable at $\omega = 15.7$ rad/sec in each case.

$$Y_p\, Y_c = \frac{15.7e^{-.1s}}{s} \quad ; \quad 1.0e^{-.2s} \quad ; \quad \frac{se^{-.3s}}{15.7}$$

The $K/se^{-.1s}$ case starts at -90° and $+\infty$ for low frequency. For increasing frequency the magnitude decreases and the phase becomes increasing negative. The curve passes through 0 dB at -180° for $\omega = 15.7$ rad/sec. The $Ke^{-.2s}$ case starts at 0 dB and 0° phase for $\omega = 0$. The amplitude is independent of frequency but the phase becomes increasingly negative as ω is increased. The curve passes through 0 dB and -180° for $\omega = 15.7$ rad/sec. The $Kse^{-.3s}$ case starts at $+90^\circ$ phase and $-\infty$ dB amplitude for $\omega = 0$. For increasing frequency, the amplitude increases and the phase becomes increasingly negative. The curve passes through 0 dB and -180° for $\omega = 15.7$ rad/sec.

The data in Figure 3 (from Reference 1) indicates a pilot rating of PR = 1.5 was given for a configuration with the following roll transfer function

$$\frac{\phi}{F_{AS}} = \frac{.438}{s(s+2.86)} \text{ rad/lb}$$

Where the high frequency control gain $L_{F_{AS}} = .438$ corresponds to the optimum steady state roll rate per in, $\frac{p_{ss}}{\delta_{AS}} = .30$ rad/sec-in, indicated in Figure 3. The open-loop transfer function $Y_p\, Y_c$ for bank angle control is

$$\frac{\phi}{\phi_\varepsilon} = Y_p\, Y_c = \frac{K_p\, e^{-\tau s}.438}{s(s+2.86)}$$

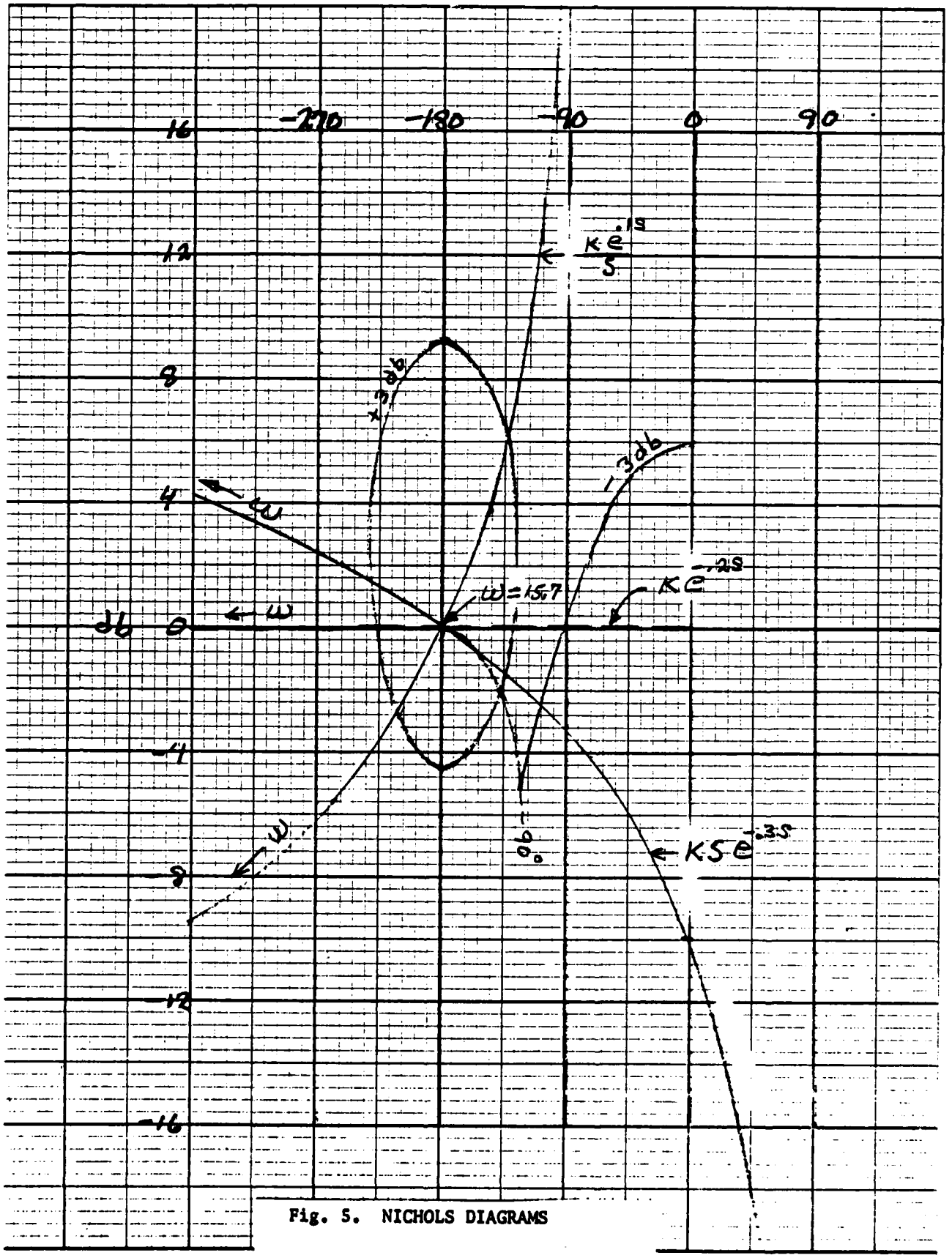


Fig. 5. NICHOLS DIAGRAMS

If a nominal time delay of τ = .25 sec is assumed, this system will go unstable at ω = 3.0 rad/sec for a pilot gain K_p = 28.4 lb/rad. The steady roll rate response of the open loop $s\ Y_p Y_c$ to a step error in bank angle is $\frac{p_{ss}}{\phi_\epsilon}$ = 4.35 rad/sec/rad

$$\left.\frac{s\phi}{\phi_\epsilon}\right|_{ss} = \left. s\ Y_p\ Y_c\right|_{ss} = \frac{28.4(.438)}{2.86} = 4.35 \text{ rad/sed/rad}$$

When $Y_p\ Y_c$ is idealized to $\frac{K}{s} e^{-.25s}$ the system will go unstable at ω = 6.28 rad/sec for a loop gain $K = \omega = 6.28$. The steady state roll rate response of the open loop $s\ Y_p\ Y_c$ to a step error in bank angle is

$$\frac{p_{ss}}{\phi_\epsilon} = 6.28 \text{ rad/sec/rad}$$

This limiting case can be approximated by assuming the roll damping and the control derivative of the example taken from Reference 1 are both increased by a factor of 100. Then

$$\frac{\phi}{\phi_\epsilon} = Y_p\ Y_c = \frac{K_p\ e^{-.25s} 43.8}{s(s+286)}$$

This system will go unstable at ω = 6.19 rad/sec for K_p = 40.4 lb/rad-sec. The steady state roll rate response of the open loop $s\ Y_p\ Y_c$ to a step error in bank angle is

$$\frac{p_{ss}}{\phi_\epsilon} = \frac{40.4(43.8)}{286} = 6.19 \text{ rad/sec/rad}$$

The pilot rating data in Figure 6 (from Reference 1) indicates that increasing the roll damping such that $\tau_R \to 0$ causes a degradation in the pilot rating and the pilot comments indicate objections to the roll accelerations experienced when trying to obtain desired roll rate response and that a tendency to become involved in pilot-airplane closed loop oscillations existed when the roll damping was increased. See comments in Figure 7.

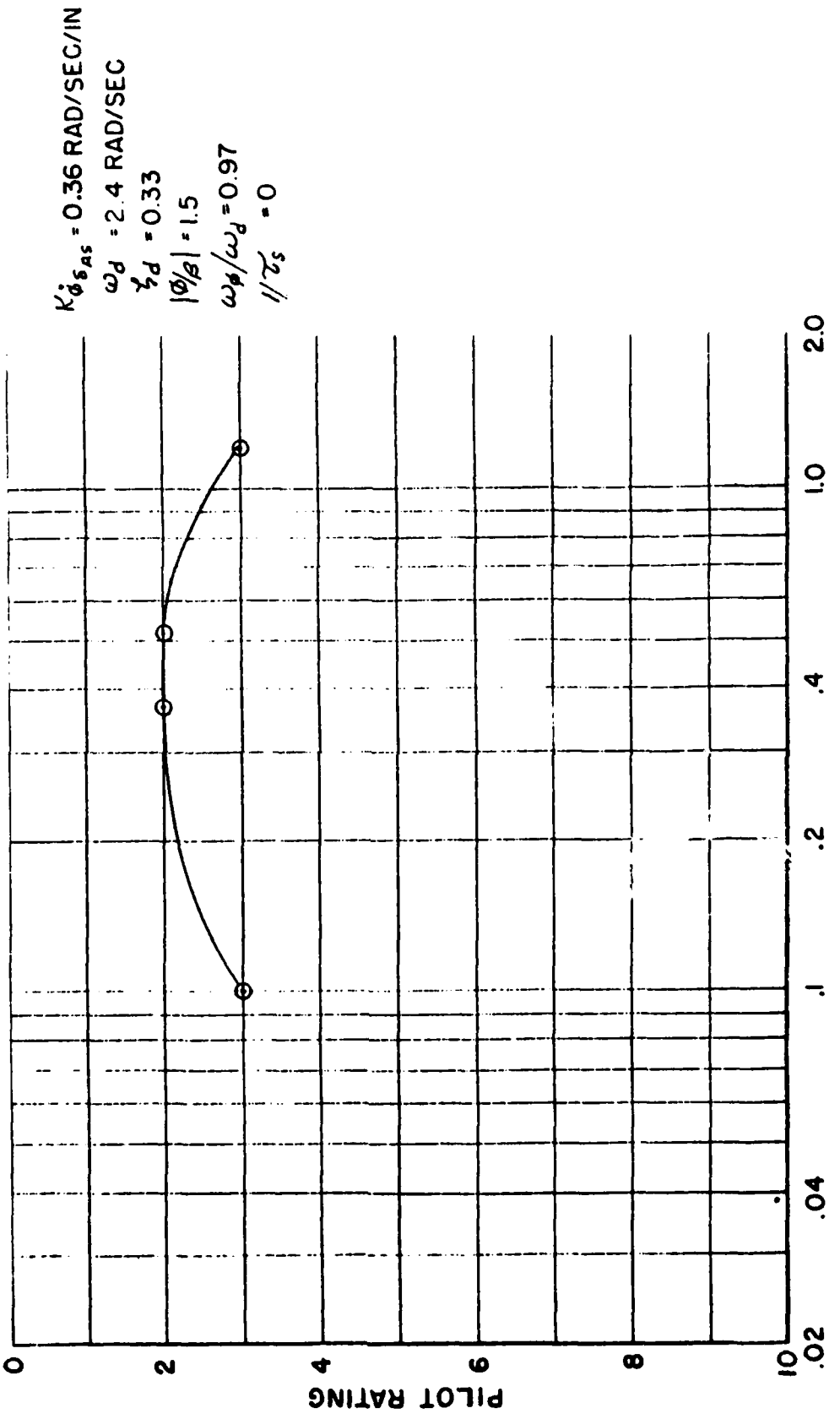


Fig. 6. PILOT RATING VERSUS ROLL MODE TIME CONSTANT

Fig. 7. PILOT COMMENTS FROM REFERENCE 1

2. Effects of τ_R for a Good Base Configuration

The roll mode time constant, τ_R, was varied from 0.1 seconds to 1.2 seconds with only a small change in pilot ratings. The highest ratings were given for values of τ_R = .37 and .52 seconds. There is a deterioration in rating for higher and lower values of τ_R. Here again, as the task does not put much premium on maneuverability (as contrasted with the requirements for air-to-air combat in fighters), a wide range of variation is acceptable. When τ_R becomes large, the ailerons are essentially acceleration-ordering because the pilot seldom waits long enough between aileron inputs for the roll rate to reach its steady value (approximately three times τ_R when the Dutch roll is undisturbed). The pilot generally prefers to order either roll rate or bank angle, so he tends to fly configurations with large τ_R using a series of aileron pulse inputs. These inputs produce steady roll rates initially, and steady state changes in bank angle if he waits long enough. This type of control is generally adequate (though not desirable) in situations where there are few, if any, external disturbances, where the pilot can devote considerable attention to the task, and where the penalty for imprecise control is not catastrophic.

When τ_R is reduced to very low values (around 0.1 seconds and less) while maintaining a constant value of $K_{\dot{\phi}_{SAS}}$, the steady roll rate becomes more and more nearly in phase with the aileron input. Hence, the roll accelerations in achieving a particular roll rate are steadily increased as τ_R is lowered. The roll accelerations become objectionably high around τ_R = 0.1 seconds, and to reduce these accelerations, the pilot begins to use slower applications of aileron control. (1) However, there are times when he reacts instinctively and suddenly, and it is these situations which bring on the poorer ratings. He reduces his roll channel gain as τ_R is reduced, but in an emergency situation, he reverts to a higher gain and his control problem becomes difficult. (2) A pilot-airplane closed-loop oscillation takes place in roll until he can reduce his gain once more.

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1. Could imply lag compensation.
2. He may also use, or forget to use, lag compensation

Note that in the above discussion, the loop gain that caused the closed loop system to be neutrally stable was used. Although a lower loop gain would likely be used by the pilot, the limiting case is useful for comparison. The discussion and examples serve to establish that the crossover frequency and the steady roll rate response to bank angle error is established by the loop gain, K, in the idealized model

$$\frac{\phi}{\phi_\varepsilon} = \frac{K\, e^{-\tau s}}{s}$$

$$\omega_c = K = \frac{(2n-1)\pi}{2\tau}$$

$$\frac{p_{ss}}{\phi_\varepsilon} = K$$

The idealized model has no acceleration limits, i.e. the angular accelerations associated with this model are a result of the frequency content of ϕ_c during closed-loop operation and are dependent on the abruptness of pilot control force applications in an open loop sense. To emphasize this point, consider the initial roll acceleration resulting from a step bank angle error for the three cases discussed above. Again, the limiting loop gain is assumed.

$$\dot{p}_{t=0^+} = \frac{s\ 12.44\ e^{-.25s}}{(s+2.86)} \quad \frac{\phi_\varepsilon}{s}\, s \longrightarrow \dot{p}_{t=0^+} = 12.44\ rad/sec^2$$

$$\dot{p}_{t=0^+} = \frac{s\ 1769\ e^{-.25s}}{(s+286)} \quad \frac{\phi_\varepsilon}{s}\, s \longrightarrow \dot{p}_{t=0^+} = 1769$$

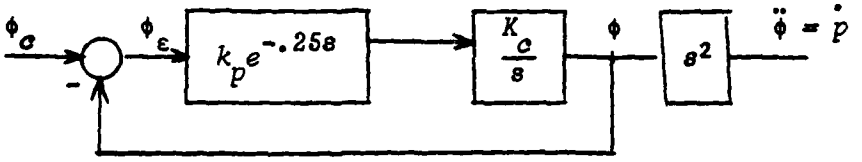
$$\dot{p}_{t=0^+} = s\ 6.28\ e^{-.25s} \quad \frac{\phi_\varepsilon}{s}\, s \longrightarrow \dot{p}_{t=0^+} = \infty$$

where $\frac{\phi_\varepsilon}{s}$ = 1.0 rad step input

The amplitude vs. phase plot of $\frac{\dot{p}}{\phi_\varepsilon}$ for the example from Reference 1 and the idealized $K/se^{-\tau s}$ case are plotted in Figure 8 using the limiting loop gain that would cause instability assuming the pilot was controlling bank angle with the transfer function $K_p e^{-.25s}$. This plot illustrates again that the roll acceleration response at high frequency is much higher for the idealized K/s

controlled element. Note also that the $\dot{p}/\phi_\varepsilon$ magnitude reaches a maximum value at high frequency when the airplane transfer function has a finite value of the roll mode root.

The amplitude-phase plots on Figure 8 are for the loop gain that causes a zero damped closed-loop root when bank angle is being controlled by the pilot model $K_p e^{-.25s}$.



The amplitude-phase plots on Figure 8 are not Nichols diagrams of the system, i.e., the closed loop response cannot be obtained by superimposing the non-linear closed-loop grid on the open loop $\dot{p}/\phi_\varepsilon$ amplitude-phase plot. This is because $\dot{p}$ is not being fed back in the closed loop model. The closed loop dynamics are obtained from the amplitude phase plot of ϕ/ϕ_ε.

Lateral-directional approach and landing flying qualities experiments performed in the TIFS, References 4 and 5, have shown that lateral acceleration at the pilot station can become a problem during rolling maneuvers when the pilot is located high above the roll axis and the airplane has high roll damping. An empirical parameter was developed based on the data in Reference 4 which correlates with the pilot rating data obtained in both References 4 and 5. The parameter is the ratio of the maximum lateral acceleration at the pilot station to the maximum roll rate following a step roll controller command.

$$\frac{n_{y_{p_{max}}}}{p_{max}}$$

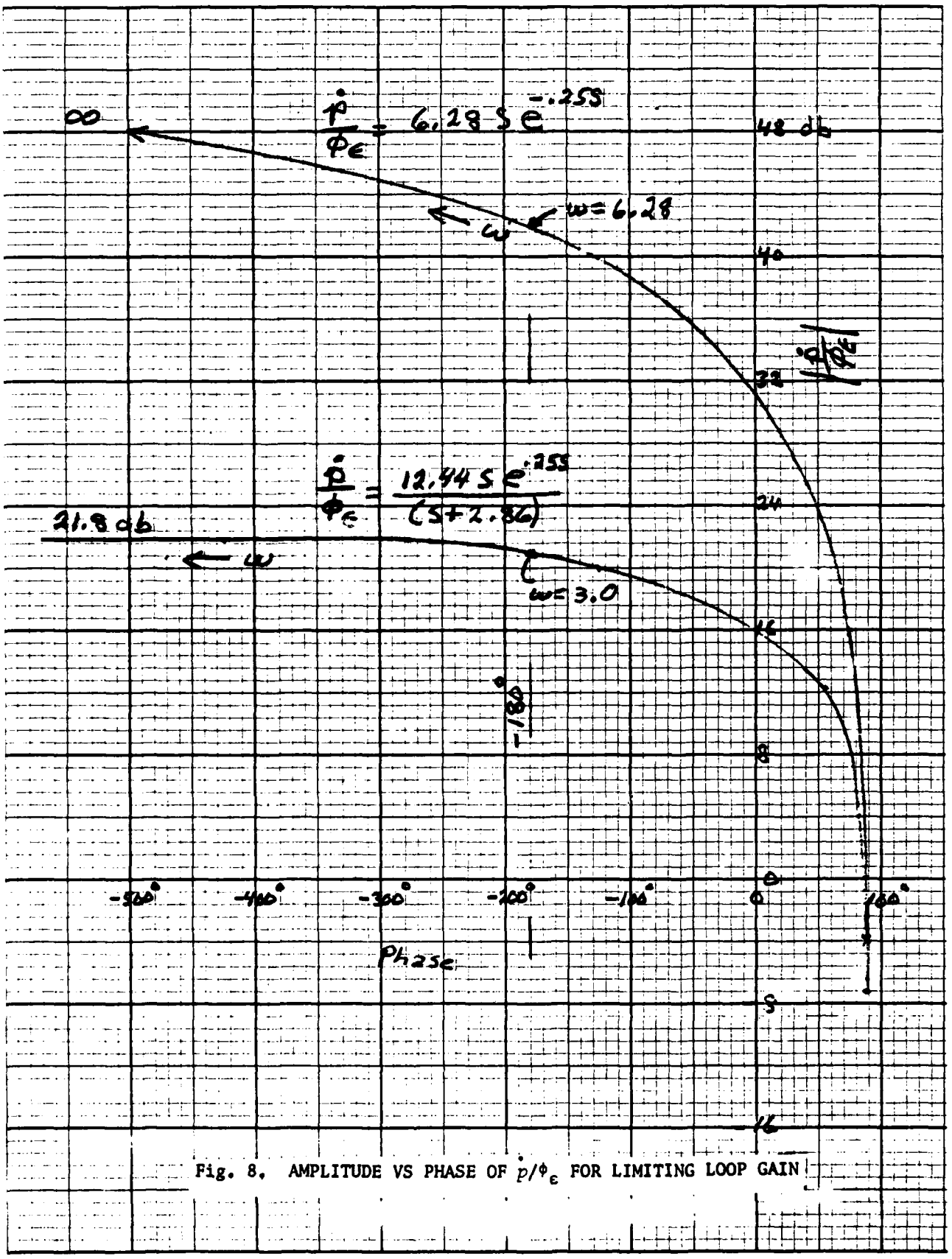


Fig. 8. AMPLITUDE VS PHASE OF $\dot{p}/\phi_\epsilon$ FOR LIMITING LOOP GAIN

The pilots objected to large sharp lateral accelerations that resulted mainly from roll angular acceleration and cockpit location above the roll axis.

$$n_{y_p} \approx - \dot{p} Z_p$$

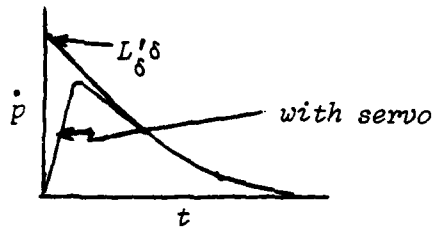
For a classical airplane transfer function and ignoring control servo dynamics, the parameter n_{y_p}/p can be approximated as follows:

$$n_{y_p} \doteq - \frac{\dot{p} Z_p}{g} = - \frac{L'_\delta \delta Z_p}{g}$$

$$p_{max} \doteq p_{ss} \doteq \frac{L'_\delta}{\lambda_R}$$

$$\frac{n_{y_{p_{max}}}}{p_{max}} = - \frac{\lambda_R Z_p}{g} \doteq \frac{L'_p Z_p}{g} \text{ g/rad/sec}$$

Actual measurements from time histories will yield smaller values of the ratio than the simple equation, primarily because the maximum $\dot{p}$ is attenuated by servo dynamics as illustrated by the following sketch.



The simple equation indicates that the principal airplane characteristics that contribute to the empirical parameter, n_{y_p}/p, are roll damping and height above the roll axis (the X stability axis if the airplane rolls without sideslip). For nominal values of roll damping, fairly large values of Z_p are required to cause a violation of the n_{y_p}/p criterion illustrated on Figure 9. This criteria was developed for large airplanes in the approach and landing task. It is likely that significantly higher values would be

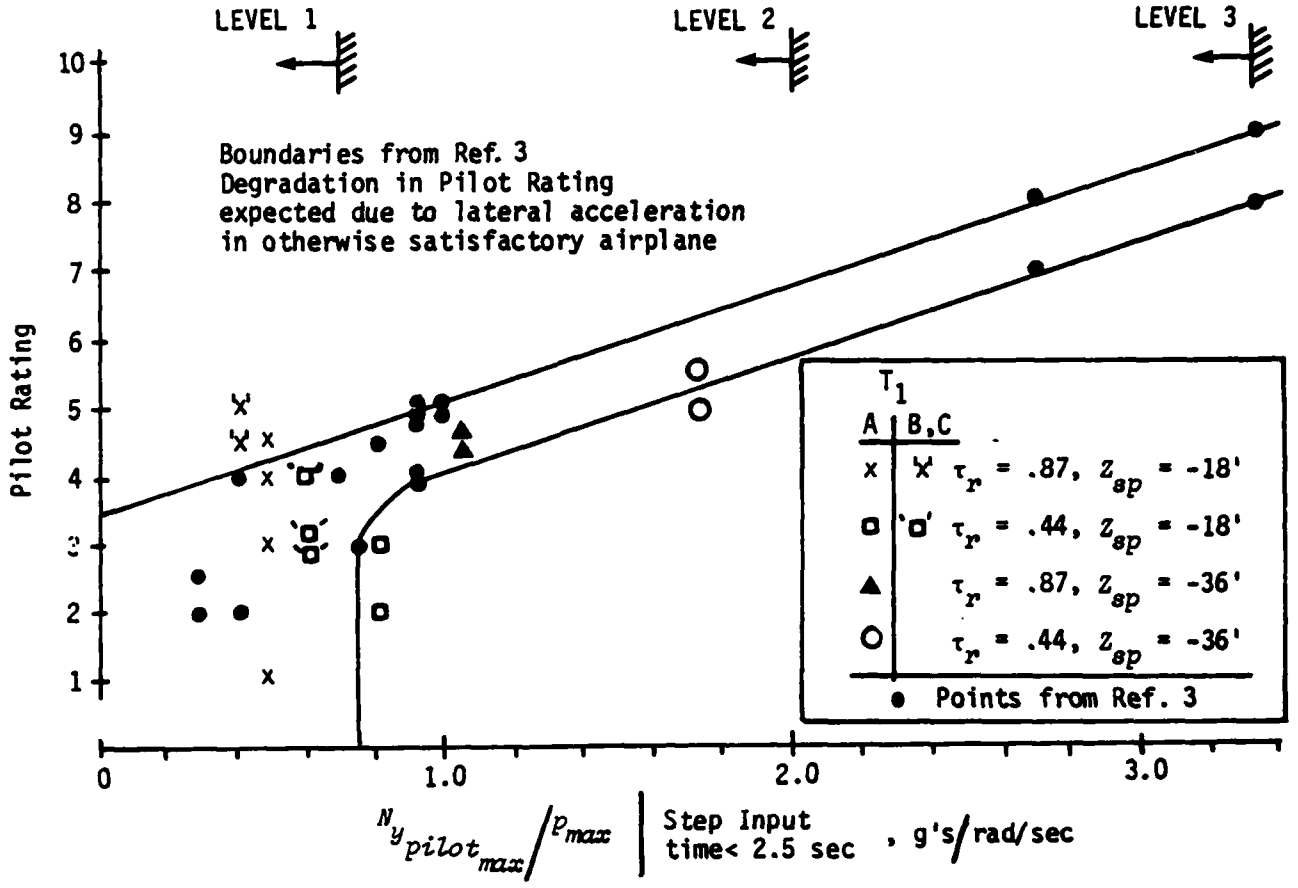


Fig. 9. PILOT RATING VS LATERAL ACCELERATION CRITERIA

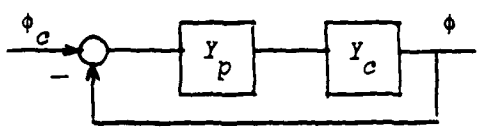
tolerated for fighter airplanes. The parameter, however, depends on the product of roll damping and height above the roll axis and, thus, even for small airplanes if the roll damping gets very large, the lateral acceleration response at the pilot's head may become objectionable. In the case of the NT-33, the evaluation pilot's head is approximately three ft above the X stability axis. Comparison with one of the cases in Reference 5 indicates lateral acceleration may become a significant objection in the T-33 if the roll damping is increased above $\lambda_R \doteq 14$ 1/sec

$$\frac{-Z_P}{\tau_R} = \frac{36}{.87}\bigg|_{Ref.5} = \frac{3}{\tau_{R_{T-33}}}$$

$$\tau_R = .071 \quad sec$$

$$\lambda_R = 13.8 \quad 1/sec$$

So far, this memo has discussed the consequences of having very high or infinite roll damping on the angular and linear accelerations that the pilot must endure during rolling maneuvers. Also, it has discussed the effect of roll damping, time delay and pilot model form (K, Ks, Ks^2) on the closed-loop bandwidth. The goal, however, is to develop a plausible theory and model of the pilot-airplane system that will exhibit the closed-loop "roll ratchet" phenomena. As a step in this quest, consider the following



$$\frac{\phi}{\phi_c} = \frac{Y_p Y_c}{1 + Y_p Y_c}$$

The characteristic roots of the closed-loop system are found by equating $1 + Y_p Y_c = 0$. Therefore

$$Y_p = -\frac{1}{Y_c}$$

at the characteristic roots.

Assume

$$Y_p = [\ddot{K}\, s^2 + \dot{K}\, s + K]\; e^{-\tau_p s}$$

Y_c = known for configuration 6-3 of Reference 3

Evaluate $Y_p = -\frac{1}{Y_c}$ at $s = 0 \pm j\omega$ where ω is the frequency of the zero damped roll ratchet oscillation.

$$-\omega\ddot{K} + j\omega\dot{K} + K = \frac{e^{180j}\, e^{57.3\omega\tau_p j}}{|Y_c|\, e^{\measuredangle Y_c j}}$$

Separate Real and Imaginary parts

$$K - \omega^2\ddot{K} = \frac{1}{|Y_c|}\; cos\; (180 - \measuredangle Y_c + 57.3\; \omega\tau_p) \qquad (1)$$

$$\dot{K} = \frac{1}{|Y_c|}\; sin\; (180 - \measuredangle Y_c + 57.3\; \omega\tau_p) \qquad (2)$$

The complete transfer function Y_c for configuration 6-3 is listed in Table 1 and 1a. Table 1 also has an approximation for ϕ/F_{AS} penciled in to aid the reader in identifying the significant dynamic factors. The .075 sec. time delay is the pure transport delay used in the simulation that is not accounted for by the linear model defined by the tabulated numbers. Amplitude and phase data were calculated from the complete transfer function, Figure 9, as a function of ω and this data was used for $|Y_c|$ and $\measuredangle Y_c$ when solving for K, $\dot{K}$, $\ddot{K}$ and τ_p using equations 1 and 2. The frequency of the oscillation in Figure 1 varies from $\omega \approx 17.4$ rad/sec at the beginning of the oscillation to $\omega \approx 11.2$ rad/sec toward the end of the record. Equations 1 and 2 were solved for $\omega = 11.2$, 12, 14, 16, 17.4 rad/sec and the results are plotted in Figures 10, 11 and 12. These plots indicate the infinite combinations of K, $\dot{K}$, $\ddot{K}$ and τ_p that will cause a zero-damped closed-loop oscillation at the frequencies observed in the flight record of Figure 1.

TABLE 1, CONFIGURATION 6-3

$$\frac{\phi}{F_{AS}} \doteq \frac{19.2\, e^{-.0755}\quad 39(66)^2}{S(S+5)(S+39)[S^2+2(.8)66S+66^2]} \quad \text{deg/lb}$$

CASE # 6 LATERAL.F-18(SIM) 30 DEG FLAP

VO=	2.2300E+02	ALPH=	5.5000E+00	GAMA=	-3.0000E+00	IX=	2.2540E+04	IZ=	1.3068E+05	IXZ=	0.0
G=	3.2200E+01	YB=	-8.8000E-02	YP=	2.5000E-03	YR=	4.0000E-03	YDH=	-5.0000E-03	YDA=	-1.4000E-03
YDR=	2.9000E-02	NB=	1.1140E+00	NP=	-5.2000E-02	NR=	-8.5400E-02	NDH=	1.9640E-01	NDA=	-2.4000E-02
NDR=	-4.7000E-01	LB=	-4.6000E+00	LP=	-1.0500E+00	LR=	7.6800E-01	LDH=	1.8700E+00	LDA=	2.4600E+00
LDR=	7.9000E-01	K1=	1.4200E+00	K2=	2.1000E+00	F14=	5.9700E-01	K4=	3.0000E+01	K5=	0.0
K6=	1.0000E+00	K7=	8.4000E-01	K8=	0.0	K9=	0.0	K10=	1.0000E+00	K11=	5.5000E-01
KP=	4.5000E-01	F51=	-2.8000E-01	K12=	6.3300E+00	K13=	6.3300E+00	F2=	2.0000E+00	T1=	1.0000E-02
T2=	2.0000E-02	T3=	2.0000E-01	T4=	2.0000E-02	T5=	1.0000E-01	T6=	1.0000E+00	OH=	5.5000E+01
ZH=	9.1000E-01	OA=	6.3000E+01	ZA=	7.8000E-01	OR=	6.4000E+01	ZR=	8.0000E-01	LX=	-2.0000E+00
LZ=	0.0	LXP=	5.0000E+00	LZP=	0.0	K18=	0.0	K19=	1.0000E+00	K20=	7.8000E-01
YB18=	-1.7360E-01	YDR3=	1.0500E-02	NDR3=	-8.0000E-01						
TB=	1.0000E+01	KBP1=	1.5000E+00	KBP2=	9.6000E-02	KBR=	-9.9500E-01				

********** CH. EQ. **********

1.00000D+00 5.43103D+02 1.35614D+05 2.05685D+07 2.10422D+09 1.52368D+11 7.97010D+12 3.01911D+14 8.18389D+15 1.54755D+17
1.96432D+18 1.59392D+19 7.84309D+19 2.20412D+20 3.28453D+20 2.58557D+20 1.45439D+20 1.04375D+19 -1.82802D+17

REAL	IMAG	-2*Z*W	O**2	ZETA	OMEGA	TAU
-1.00000D-01						1.00000D+01
-5.31063D+01	3.93543D+01	-1.06213D+02	4.36904D+03	8.03440D-01	6.60987D+01	
-5.26278D+01	3.65657D+01	-1.05256D+02	4.10673D+03	8.21234D-01	6.40838D+01	
-4.62708D+01						2.16119D-02
-3.95057D+01						2.53128D-02
-2.23082D+01						4.48266D-02
-4.97980D+00						2.00811D-01
-2.72074D+00						3.67547D-01
-3.32197D-01	8.54498D-01	-6.64394D-01	8.40521D-01	3.62344D-01	9.16800D-01	
1.45052D-02						-6.89407D+01
-5.00500D+01	2.28035D+01	-1.00100D+02	3.02500D+03	9.10000D-01	5.50000D+01	
-1.00000D+02						1.00000D-02
-5.00000D+00						2.00000D-01
-1.00000D+01						1.00000D-01

TABLE 1a. CONFIGURATION 6-3

CASE # 6 LATERAL,F-18(TIM) 30 DEG FLAP

NUMERATORS OF TRANSFER FUNCTIONS /FAS

********** BETA/FAS **********

-3.49760D+03 -2.53143D+06 -5.82845D+08 -6.96955D+10 -4.99166D+12 -2.24768D+14 -6.38221D+15 -1.11576D+17 -1.15269D+18 -6.39703D+18
-1.47519D+19 1.81575D+18 3.64336D+19 1.24092D+19 8.79813D+17

REAL	IMAG	-2*Z*W	O**2	ZETA	OMEGA	TAU
-5.40727D+01	3.73876D+01	-1.08145D+02	4.32169D+03	8.22529D-01	6.57396D+01	
1.36653D+00						-7.31783D-01
-1.00000D-01						1.00000D+01
-2.55269D-01						3.91744D+00
-2.40476D+00						4.15841D-01
-5.00000D+00						2.00000D-01
-1.00000D+01						1.00000D-01
-1.44866D+01	5.61815D+00	-2.89732D+01	2.41425D+02	9.32342D-01	1.55378D+01	
-4.46594D+01						2.23917D-02
-5.00500D+01	2.28035D+01	-1.00100D+02	3.02500D+03	9.10000D-01	5.50000D+01	
-4.25490D+02						2.35023D-03

Multiply by $0.83\ e^{-.0755}$

********** P/FAS **********

-8.95838D+05 1.46423D+08 8.58944D+10 1.31650D+13 1.04753D+15 4.88336D+16 1.34960D+18 2.11705D+19 1.75712D+20 7.14594D+20
1.30872D+21 1.07493D+21 6.70091D+20 5.39408D+19 -3.55797D+17

REAL	IMAG	-2*Z*W	O**2	ZETA	OMEGA	TAU
-3.44973D-01	8.29184D-01	-6.89946D-01	8.06552D-01	3.84122D-01	8.98082D-01	
6.12536D-03						-1.63256D+02
-1.00000D-01						1.00000D+01
-2.55517D+00						3.71034D-01
-5.00000D+00						2.00000D-01
-1.00000D+01						1.00000D-01
-5.35481D+01	3.93162D+01	-1.07096D+02	4.33553D+03	8.13248D-01	6.58447D+01	
-2.13287D+01						4.68851D-02
-4.55556D+01						2.14337D-02
-5.00500D+01	2.28035D+01	-1.00100D+02	3.02500D+03	9.10000D-01	5.50000D+01	
4.57107D+02						-2.18767D-03

********** R/FAS **********

5.32167D+05 2.02610D+08 3.40568D+10 3.30520D+12 2.02211D+14 7.97652D+15 1.99427D+17 2.99116D+18 2.48359D+19 1.06411D+20
2.25059D+20 2.52004D+20 2.02535D+20 9.94392D+19 8.14910D+18

REAL	IMAG	-2*Z*W	O**2	ZETA	OMEGA	TAU
-1.75538D-01	9.46288D-01	-3.51975D-01	9.26434D-01	1.82842D-01	9.62514D-01	
-1.00000D-01						1.00000D+01
-1.00000D+00						1.03000D+00
-2.54192D+00						3.93404D-01
-5.00000D+00						2.00000D-01
-1.00000D+01						1.00000D-01
-2.50000D+01						4.00000D-02
-4.83689D+01	3.47175D+01	-9.67377D+01	3.54485D+03	8.12394D-01	5.95386D+01	
-5.00500D+01	2.28035D+01	-1.00100D+02	3.02500D+03	9.10000D-01	5.50000D+01	
-6.66937D+01						1.49939D-02
-7.26[illegible]D+01						1.37594D-02

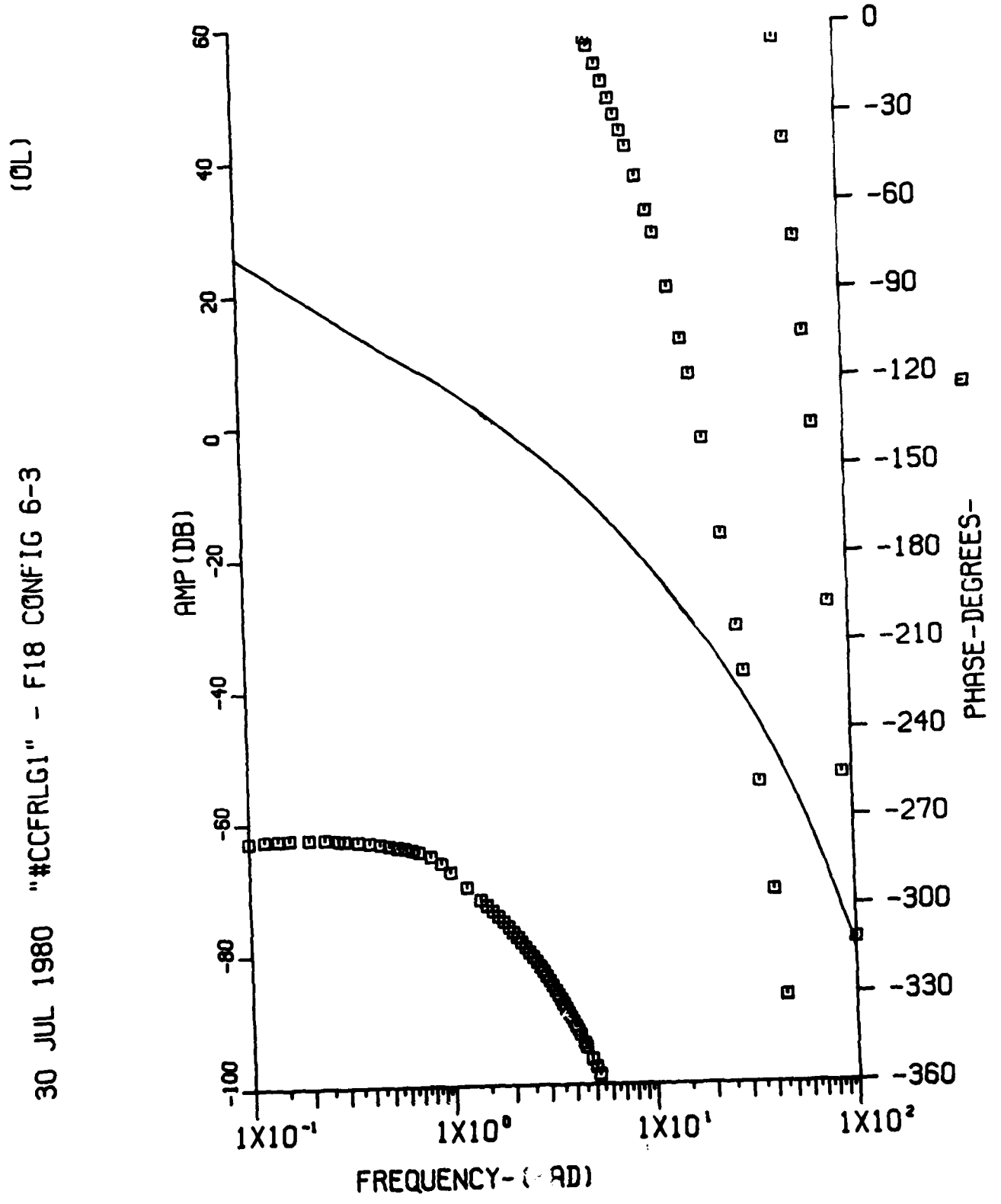


Fig. 9. ϕ/F_{AS} FOR CONFIGURATION 6-3

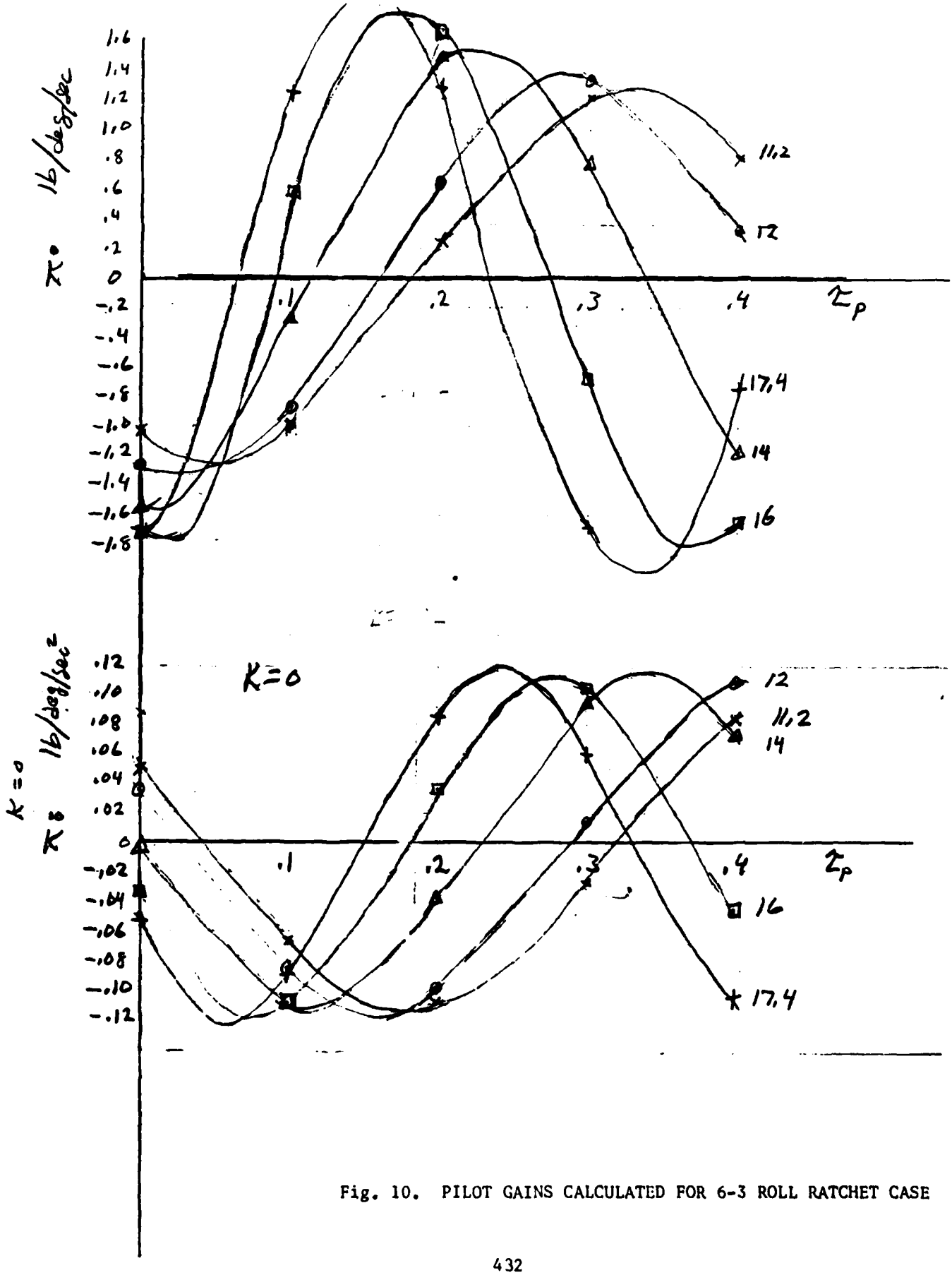
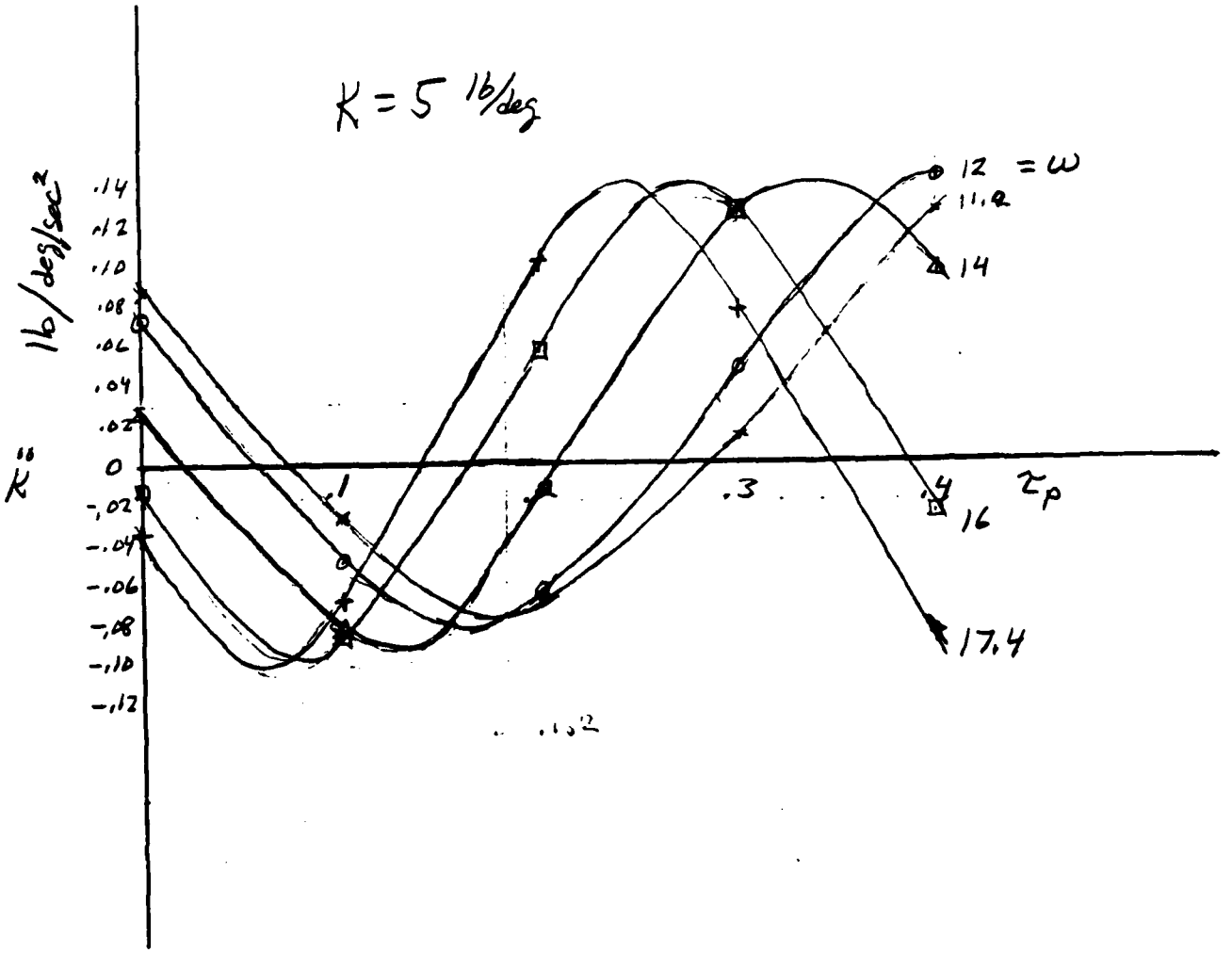


Fig. 10. PILOT GAINS CALCULATED FOR 6-3 ROLL RATCHET CASE

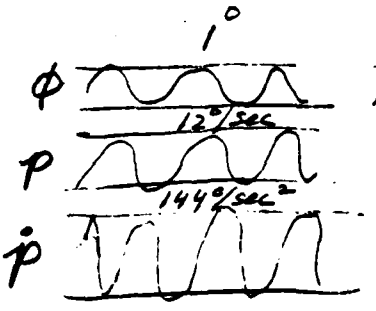


Time History Indicates

$\frac{F}{\phi} < 4.5$ lb/deg

$\frac{F}{p} < .37$ lb/deg/sec

$\frac{F}{\dot{p}} < .031$ lb/deg/sec²



F = 4.5 lb

" Roughly "

Assume 12 rad/sec

Fig. 11. PILOT GAINS CALCULATED FOR 6-3 ROLL RATCHET CASE

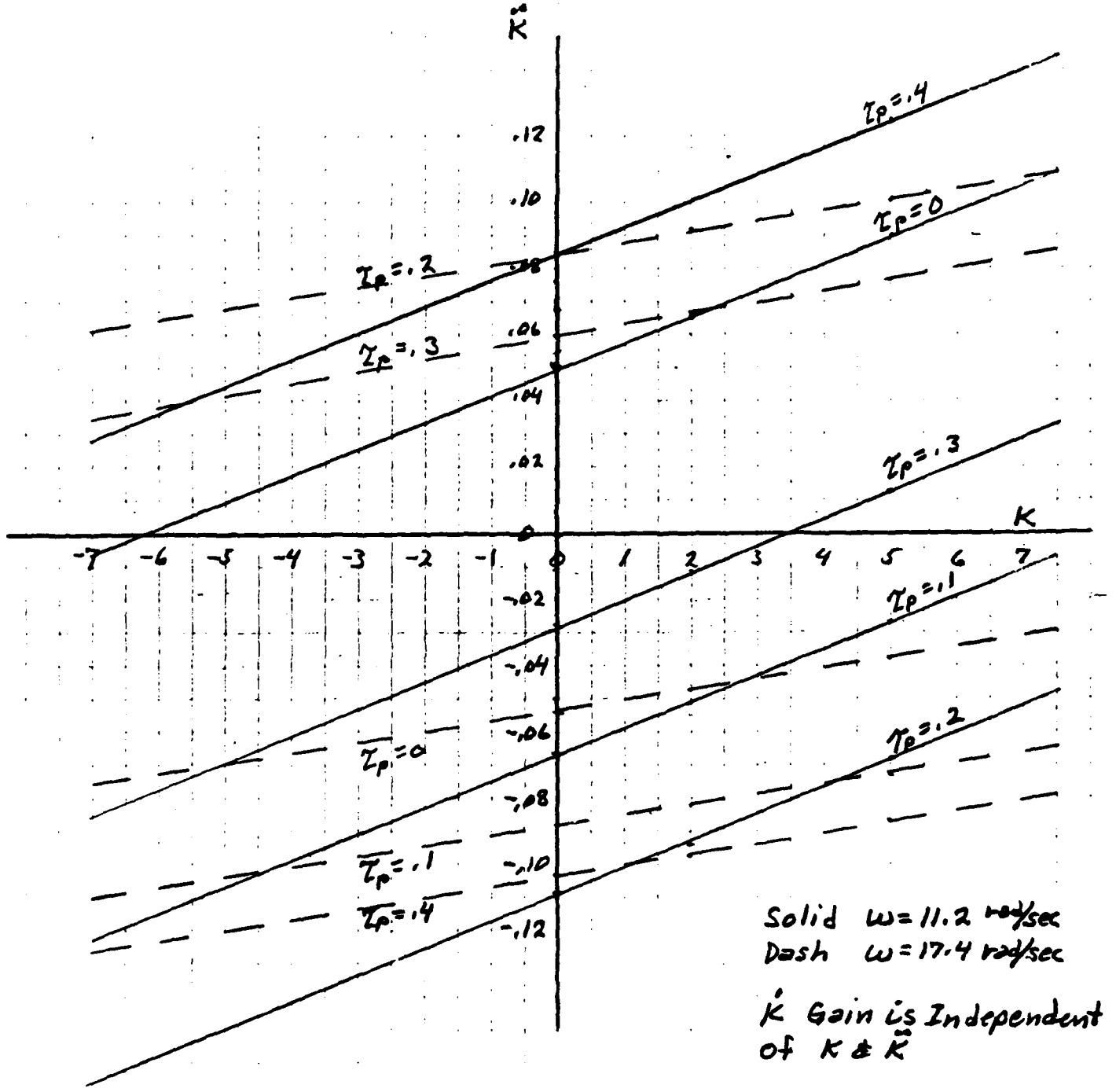


Fig. 12. PILOT GAINS CALCULATED FOR 6-3 ROLL RATCHET CASE

The results of this analysis present a very complex picture of the pilot model parameters. This complexity is primarily a result of the frequency variation exhibited in Figure 1. In attempting to interpret the results presented in Figures 10, 11 and 12, it is probably valid to ignore negative gains and to restrict consideration of time delay to values of the order $\tau_p \sim .15 - .4$ sec. The sine wave curves on Figures 10 and 11 can be viewed as cross-sections of the wave-shaped solution surface. In any event, a model of the form assumed for this analysis would have to have time-varying coefficients to exhibit the frequency variation observed in Figure 1.

The pilot comments, see Figure 7, (page 16 from Reference 1) for airplanes with high roll damping indicate that the pilots try to use slower stick inputs to avoid abrupt responses. There are times, however, when they react instinctively and suddenly and are likely to become involved in a pilot-airplane closed-loop roll oscillation until they can modify their behavior, i.e., open the loop, reduce gain, develop lag equalization, etc..

One possible model that roughly corresponds to these comments is as follows. Assume the controlled element is $\frac{1}{s}$ and the pilot is modeled as having developed lag equilization, $\lambda_p = 3$, to avoid high acceleration responses and that he exhibits a nominal time delay of $\tau_p = .25$ sec. Then

$$Y_c = 1/s$$

$$Y_p = \frac{e^{-.25s}}{s+3}$$

A Nichols plot of $Y_p Y_c$ is shown on Figure 13. A loop gain of $K = 4.52$ will result in a bandwidth of $\omega_{BW} = 1.8$ rad/sec. If it is assumed that the pilot forgets to use the lag equilization but tries to use the same loop gain, the transfer function becomes

$$Y_p Y_c = \frac{4.52e^{-.25s}}{s}$$

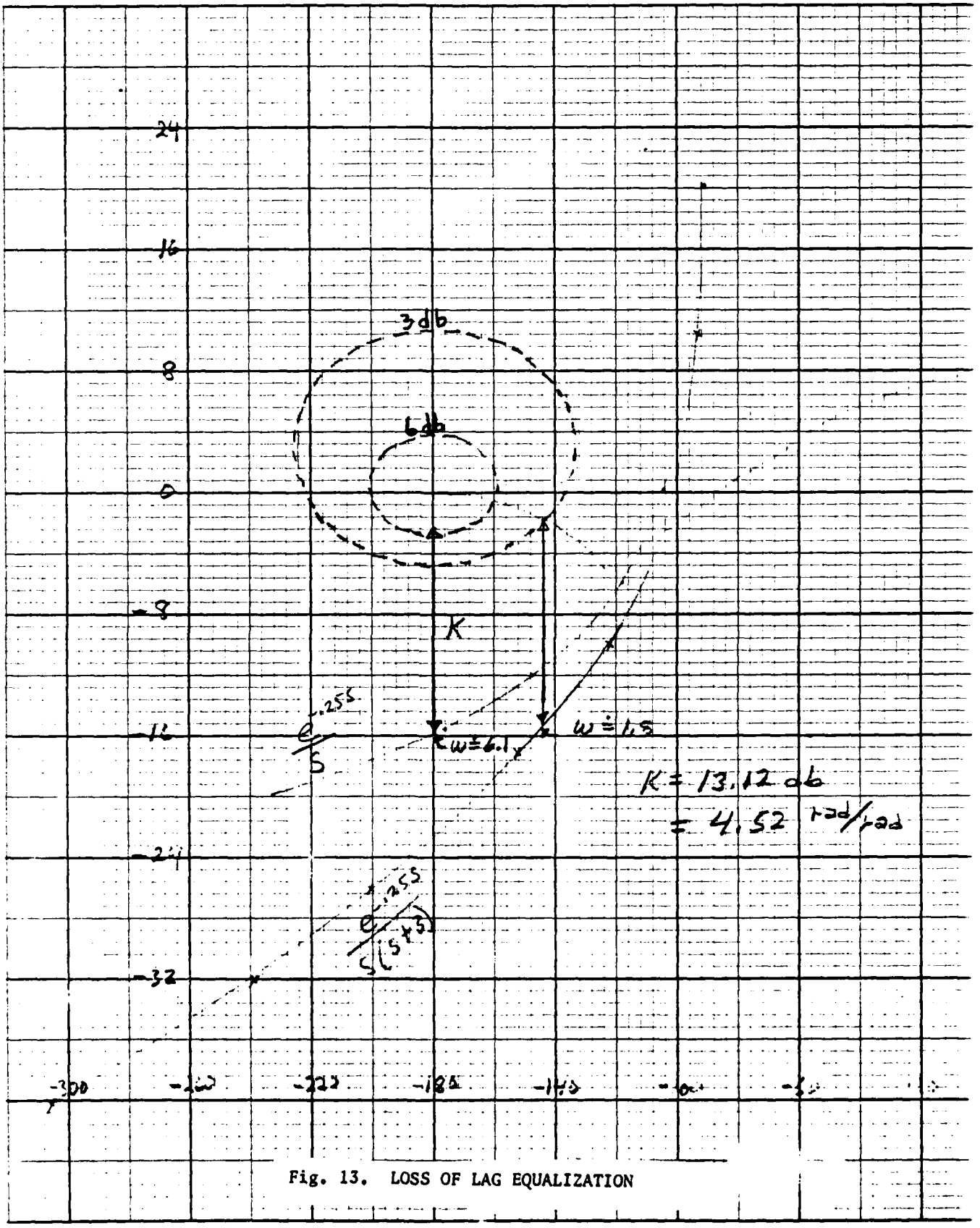


Fig. 13. LOSS OF LAG EQUALIZATION

and the closed-loop system would tend to be destabilized. Figure 13 indicates a closed-loop resonance at a frequency of $\omega = 6.1$ rad/sec.

This rather simple model tends to show the observed behavior but the frequency of the closed-loop resonance which occurs after the lag equilization is dropped is much lower than that observed in roll ratchet incidents.

Consider next that the full adapted pilot uses lag equilization as above to obtain satisfactory bandwidth in controlling bank angle and to avoid abrupt responses and high angular accelerations. Then assume that, as the result of an abrupt disturbance or an abrupt change in the target motion, the pilot becomes involved in attempting to control the roll angular acceleration. The model would change from

$$Y_p Y_c = \frac{K e^{-\tau_p s}}{s(s+\lambda_p)}$$

to

$$Y_p Y_c = \ddot{K} s e^{-\tau_p s}$$

The Nichols diagram for this latter dynamic system is illustrated in Figure 5 which was drawn for $\tau_p = .3$ sec and exhibits instability at $\omega = 15.7$ rad/sec for a loop gain $\ddot{K} = \frac{1}{\omega} = \frac{1}{15.7}$. When the perception modality is switched from visual observation of bank angle error to perception of angular acceleration by means of the vestibular system, neck muscle spindle sensing and body pressure sensing, it is not obvious how the pilot's gain would be modified but experimental evidence suggests that a high enough gain would be adapted to cause closed-loop resonance.

The time history illustrated in Figure 14 was taken during a bank angle tracking task performed during the in-flight evaluations to be reported in Reference 2. The task was displayed to the pilot by means of a head-up display so records of the error displayed, the pilot's stick force response and the resulting roll rate are available. A number of observations can be made after study of the closed-loop responses in Figure 14.

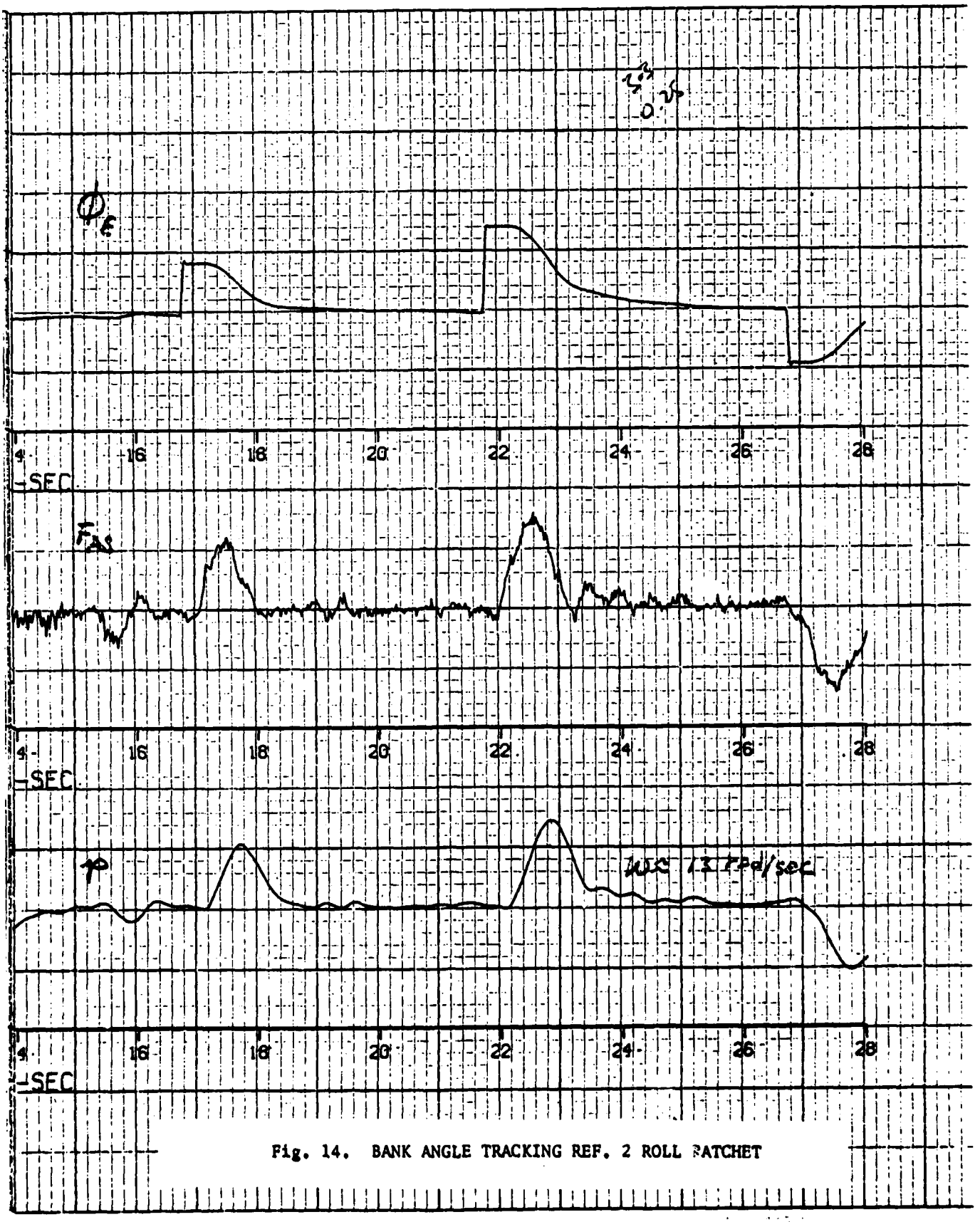


Fig. 14. BANK ANGLE TRACKING REF. 2 ROLL RATCHET

- The pilot exhibits .25 - .30 sec time delay in applying stick force following a step change in the bank angle command.

- The stick force and roll rate time histories exhibit roll ratchet at $\omega \simeq 13$ rad/sec.

- The roll ratchet oscillation appears in both of the two recorded responses to step bank angle commands. The magnitude is larger in the second response.

- The second response exhibits a longer tail in reducing the bank angle error to zero. This observation is consistent with the angular acceleration model, i.e., the closed-loop system exhibits a root that is approaching a zero at the origin. The closed-loop system will exhibit droop.

- In responding to the step bank angle command, it can be observed that the pilot abruptly applies about 3.5-4 "lines" of stick force independent of tne magnitude of the bank angle step command. He then modifies the stick force approximately .25 - .3 sec after start of the initial force application. The second force application is of higher amplitude in the second record than it is in the first record. The bank angle command was larger in the second record. Note also that the second force application in each record occurs when the p response starts to move, i.e., when the angular acceleration is applied but before there is a noticeable change in the bank angle or reduction in the ϕ_ε trace from the step command initial value.

These observations tend to confirm that the pilot may be operating on angular acceleration information (or lateral linear acceleration at his head) in performing the bank angle tracking task. The observed time delays would cause closed-loop instability at the observed oscillation frequency if the pilot were closing the loop on acceleration feedback.

The time history records in Figure 15 for Configuration 5-2 from Reference 2 became available after this memo was drafted. Several observations can be made from study of these time histories of the pilot performing the bank angle tracking task which consisted of random combinations (size and sign) of step bank angle commands plus a ramp bank angle command. The traces show the bank angle error, the pilot-applied aileron stick force and the airplane roll rate. The records show:

- Roll ratchet at $\omega \simeq 14$ rad/sec.

- The roll ratchet is more continuous or occurs more frequently than in the example shown on Figure 14. The roll damping of the configuration in Figure 15 was higher.

- The pilot seems to apply the same magnitude of aileron stick force regardless of the magnitude of the bank angle command. He then holds this force for varying lengths of time until the bank angle error is corrected to zero. The time to zero the bank angle is, therefore, longer for bigger commands. See data plotted in Figure 16.

  F_{AS} ~ maximum force

  $\phi_\epsilon\Big|_{t=0}$ ~ magnitude of bank angle command

  Δt ~ time required to zero ϕ_ϵ after each command.

- In responding to the large, $\phi_c = -70^o$, bank angle command at $t = 15.2$ sec, the pilot initially applied 2.5 lb and then more slowly added 1.75 lb for a total of 4.25 lb.

- The pilot's stick force response to the, $\phi_c = 70^o$, command at 45.2 sec was delayed approximately 1.4 sec.

- The shape of the initial stick force application in each response suggests a first order response with a time constant of T = 0.3 sec, i.e., a first order root at λ = 3.3 rad/sec.

- Between t = 28 sec and t = 38 sec, the bank angle command was a steady ramp. During the interval t = 28-32 sec, the roll ratchet oscillation is superimposed on the F_{AS} and p time histories. The segment from t = 32-38 contains a low frequency oscillation at ω = 2.7 rad/sec with the roll ratchet oscillation superimposed in the F_{AS} and P time histories.

When responding to the step commands, the pilot is not acting as a linear proportional controller. Instead, he seems to be operating as a bang-bang controller which uses signs and thresholds of the magnitude of the bank angle error to switch the control force between discreet levels with the control force applied through a first order lag. Since the pilot is capable of applying more than 2.5 or 5 lb of control force and the T-33 is capable of steady roll rates in excess of the 30-50 deg/sec values used in this task, it must be concluded that the pilot has voluntarily adopted this control strategy.

Examination of records for the same segment of the tracking task performed for other configurations by the same and additional pilots indicates similar behavior for some of the records and a more proportional response for others. Thus, the record shown in Figure 15 is not an anomaly but it does not represent a control technique that was always used.

It is suggested that this control technique may have been adopted because it helps to minimize the roll ratchet problem and permits the pilot to limit the roll acceleration responses. It may be effective in minimizing the tendency to become involved in the roll ratchet oscillation by avoiding proportional closed-loop control through the substitution of sequences of open-loop response. It may also be that this technique is just easier for the pilot to perform although it does result in varying times to correct errors.

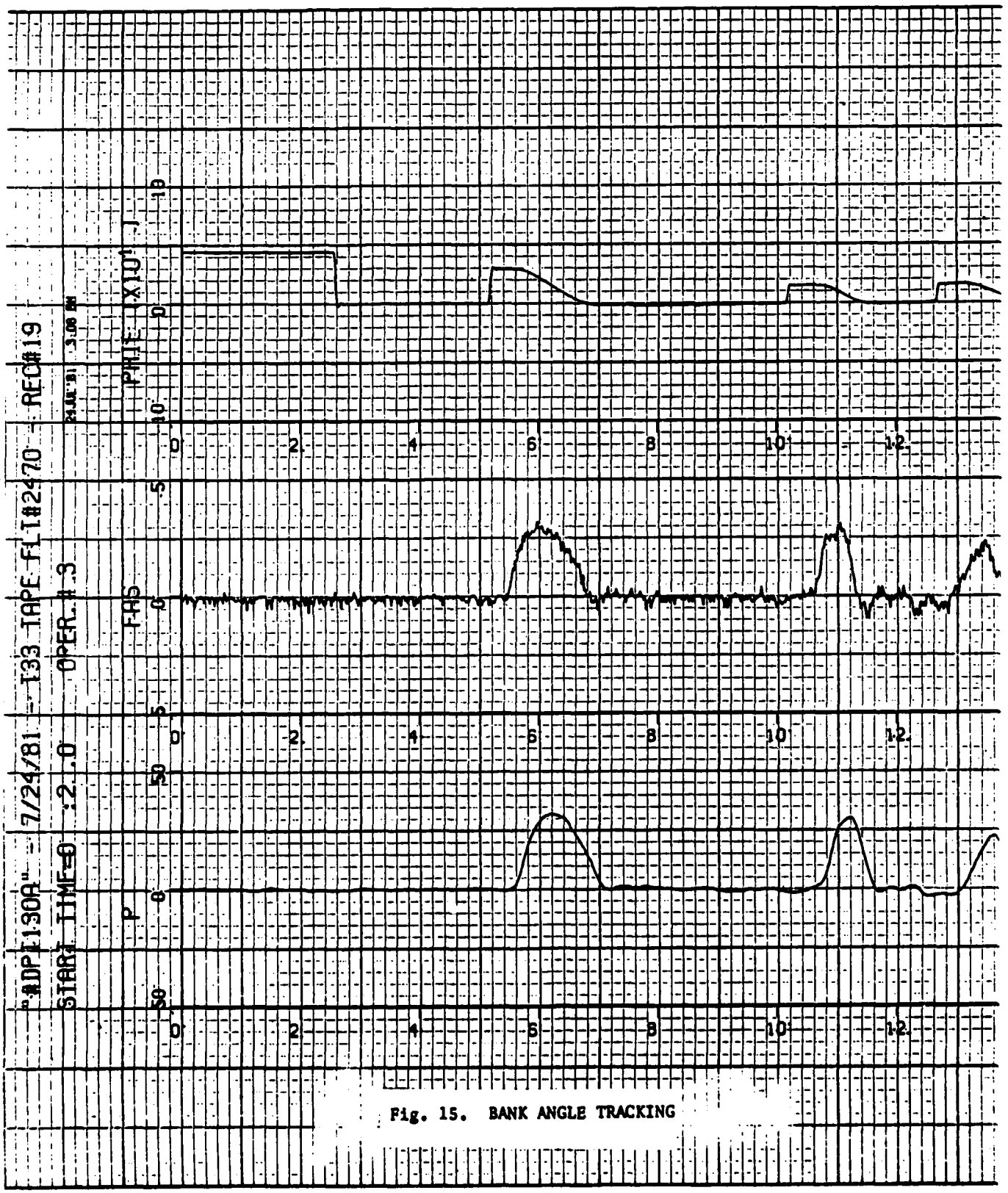


Fig. 15. BANK ANGLE TRACKING

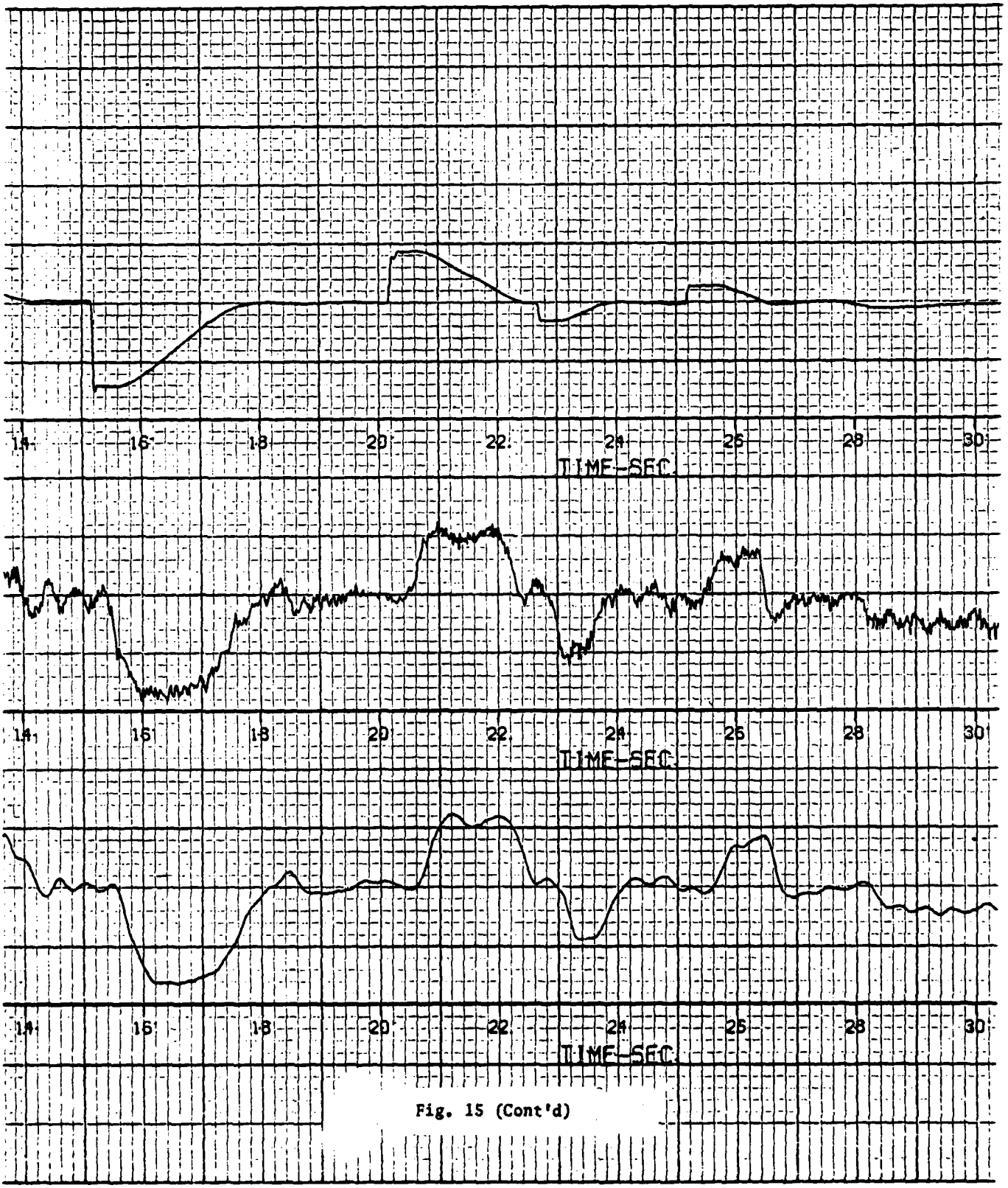

14
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TIME-SEC.
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TIME-SEC.

Fig. 15 (Cont'd)

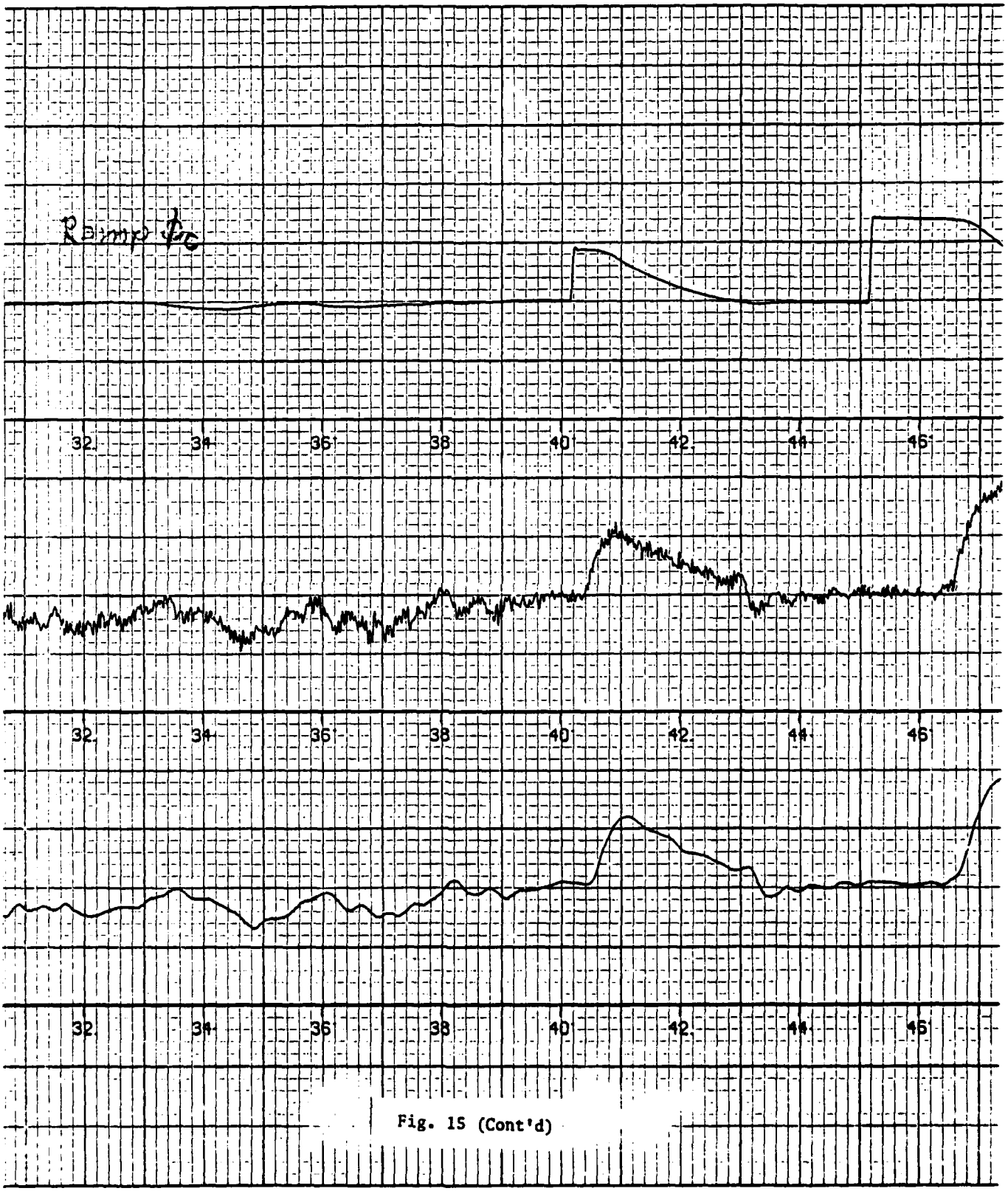

Ramp fc
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Fig. 15 (Cont'd)

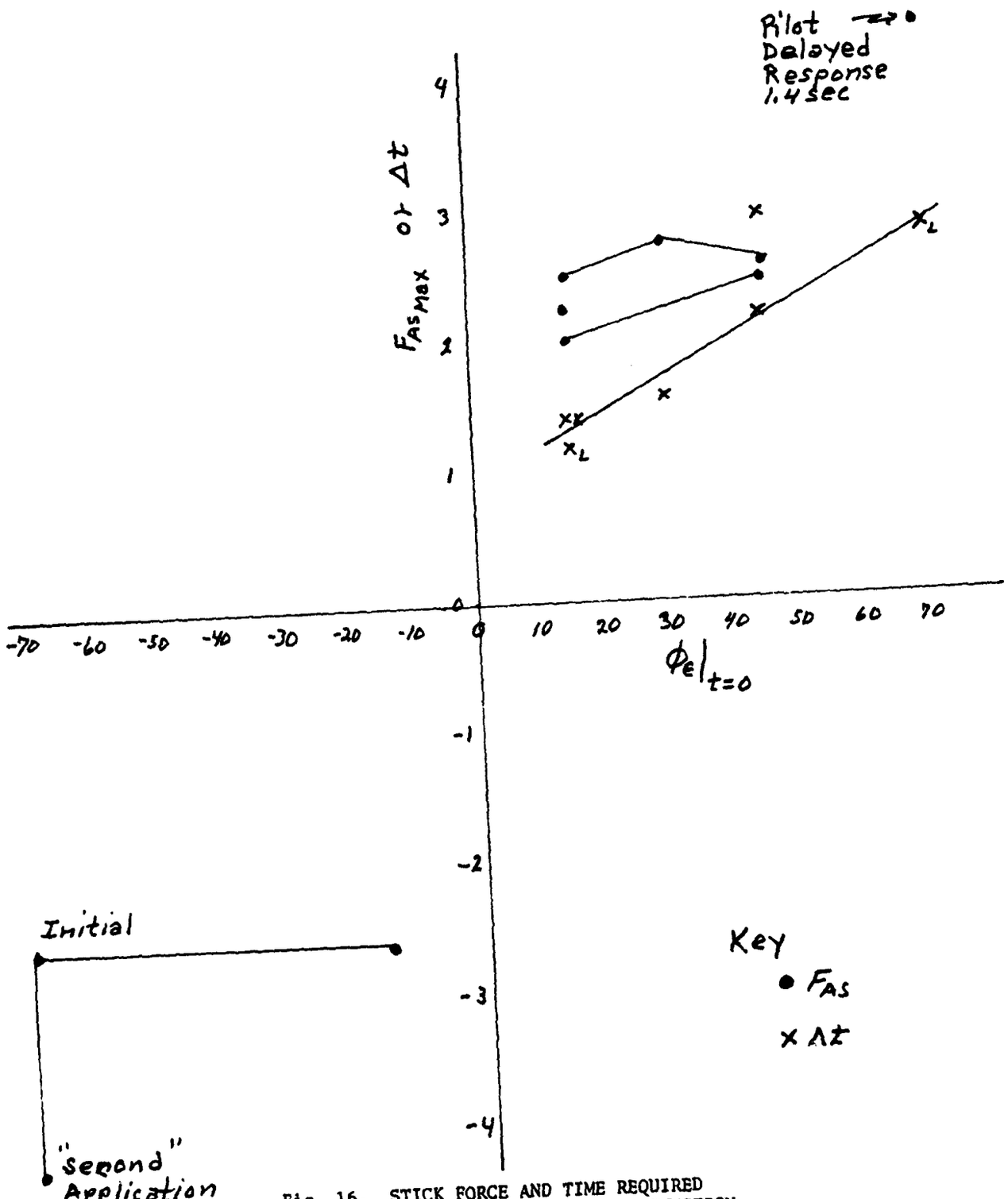


Fig. 16. STICK FORCE AND TIME REQUIRED TO ZERO BANK ERROR AS A FUNCTION OF BANK ANGLE COMMAND MAGNITUDE

Conclusions

- The roll angular acceleration and the lateral linear accelerations at the pilot station are important considerations in flying qualities.

- The angular and linear accelerations can become objectionably high when the roll damping is very high τ_R < .15 sec and the height above the X stability axis is large.

- Roll ratchet is best explained by a model that assumes the pilot is closing the aileron loop on angular acceleration response cues.

- The ideal roll transfer function is $\phi/F_{AS} = \frac{K}{s(s+\lambda)}$, not $\frac{K}{s}$. This is because the angular acceleration response to pilot inputs becomes too large as $\lambda \to \infty$. The response becomes too abrupt and the pilot-airplane closed-loop system is destabilized by the pilot's time delay.

References

1. Harper, R. P., Jr.: "In-Flight Simulation of the Lateral-Directional Handling Qualities of Entry Vehicles," Calspan Report No. TE-1243-F-2, February 1961.

2. Monagan, S. J., R. E. Smith, R. E. Bailey: "Lateral-Directional Flying Qualities of Highly Augmented Fighter Aircraft," Calspan Report No. 6645-F-8, August 1981.

3. Smith, R. E.: "Evaluation of F-18A Approach and Landing Flying Qualities Using an In-Flight Simulator," Calspan Report No. 6241-F-1, February 1979.

4. Weingarten, N. C.: "An Investigation of Low Speed Lateral Acceleration Characteristics of Supersonic Cruise Transports Utilizing the Total In-Flight Simulator (TIFS)." Calspan Report No. 6241-F-2, March 1979.

5. Weingarten, N. C., C. R. Chalk: "In-Flight Investigation of Large Airplane Flying Qualities for Approach and Landing," Calspan Report No. 6645-F-5, 1981.

COMMENTS AND QUESTIONS

John Gibson, British Aerospace: We saw the same thing, but it seemed to be more of a bobweight problem (referring to roll-ratcheting). The actuator has been changed and will be flight tested.

Randy Bailey, Calspan: Response was related to a precise task in the T-33; transients were abrupt. Not the same as the DIGITAC or F-16. Seem to be different types of ratcheting.

Roger Hoh, STI: Roll acceleration seems to be the problem; looking at a_{y_p} for different configurations shows it doesn't correlate. Princeton data showed no effect at Γ_R=.1. This may all have more to do with the manipulator. Force stick versus position stick could have something to do with this. F-18 changed from force to position manipulator. Conflicting data shows we don't know the answer. Force stick could have ratcheting problem; position stick less. More study is needed.

Mick Van Gool, NLR: Time delays change the whole thing. Additionally, visual delays from on-screen motion were signifigant.

Tom Black, OSU: Previous report (Kevin Citurs from McDonnell) showed we'll give the pilots anything. This shows you can push the pilot too far, especially if you force him to revert to habits he learned in basic flight training.

John Hodgkinson, McDonnell: Are you going to penalize someone we want to push out to a high frequency in a K/s system. Pushing for performance is OK, but K/s system will exhibit ride quality problems.

Ron Anderson, FDL: K/s is a valid component in region of crossover, based on a well-defined target in compensatory tracking.

Dick Quinlivan, GE: Lesson learned by applying roll CAS to F-4. Simulation with τ_R variable. Tried several tasks and the acceptable τ_R changed.

Bob Woodcock, FDC: Ralph A'Harrah showed attempt to get large accelerations can saturate surfaces. Not specifically applicable here, but a similar area.

Roger Hoh, STI: How much work should be done in this area? Should the design guidance be updated to include requirements on τ_R?

Randy Bailey, Calspan: MIL-F-83300 has limits on τ_R and roll power.

DOUGLAS POSITION PAPER ON THE PROPOSED MIL-F-8785C REVISION

William W. Rickard
Douglas Aircraft Company

Editors Note: A formal paper was not submitted. However, the following comments were obtained from notes taken during Mr Rickard's presentation.

1. STI is to be commended for an excellent job. The task of revising the flying qualities specification is a monumental effort, and STI has achieved a degree of success in this project.

2. Discussions concerning any particular format is not an issue at Douglas. Either a "by axis" or a "by controller/input" format is acceptable. The major issue is not the organization of the requirements but the goal of building an airplane with good flying qualities. This highlights the trend toward tailoring of the specification to an individual acquisition -- a coming thing with the Standard and Handbook.

3. The application of the equivalent system approach is a good way to look at higher-order systems and still keep a similar perspective of classical parameters (now equivalent parameters). Though some are using the dominant mode approach, we indorse the AF position that this approach is unacceptable.

4. Several comments which are mentioned for thought:

   a. Does the specification attempt to protect us from digital systems? When considering this, sample rate, mismatch values, RMS errors, etc must be included. Sample rate also has an effect on time delay.

   b. What happened to static stability requirements?

   c. When considering unstable configurations, you are looking at Level 3 according to the specification. What are the roots to be compared with? Requirements are needed.

   d. Stall speeds. There is inconsistency between what FAA requires and what military requirements are. There may be a need to have different values but Douglas does not agree.

   e. More specifics should be included defining operation near the ground, especially the requirements covering crosswinds and wind magnitudes.

   f. The FAA includes a recognition time delay as well as requirements on aircraft response for specific failures. For example, Category C requires 1 second plus recognition time, Category B requires 3 seconds plus recognition time. Should the military consider such an approach?

   g. Several inconsistencies with MIL-F-9490 need to be resolved, i.e., mode-switching transients and residual oscillations along with several others.

h. Usage of FAA experience and data in the Handbook could be improved. A wealth of lessons learned and past experience is not being tapped as much as it might be.

i. ω_{sp} vs n/α boundaries don't agree with data from large aircraft, specifically Level 2 and Level 3 boundaries. The specifications seem to be biased toward Class IV aircraft.

COMMENTS AND QUESTIONS

Bob Meyer, Lockheed: Meeting some of the requirements of MIL-F-8785C gives some problems for Class II aircraft, i.e., roll response, ω_{sp} vs n_α. Any data available for other aircraft would be appreciated.

Derald Skalla, Westinghouse: A-4 didn't meet the roll requirement. It is imperative aircraft specifications are tailored to each procurement.

Answer: Even so, the final test is the pilot's opinion.

Roger Hoh, STI: We tried to maintain requirements for static stability plus time to double amplitude but noted an inconsistency. Recently settled on 6 second T_D. Rate-command-attitude-hold (RCAH) is acceptable. It all comes down to the point of will the airplane stay hands off and respond sharply.

Jerry Lockenour, Lockheed: Is time to double amplitude with Control Augmentation System (CAS) off? What about landing with CAS off?

Answer: You need to look at probabilities.

Roger Hoh, STI: We have data showing T_D=2 seconds is OK for full attended flight.

Mick Van Gool, NLR: An experiment concerning T_D is now in the planning stage.

Ed Rynaski, Calspan: F-16 experience makes this less relevant. Failure transients drive the system almost immediately.

Tom Black, OSU: Mission and task need to be accounted for.

Answer: Specification isn't all that specific for Class III.

Roger Hoh, STI: Agree to some extent. Class III airplanes are flying below the boundary everyday.

We can now augment our airplanes to give better response to near-touchdown gusts.

Sam Craig: Any airplane near terminal conditions, you stop controlling. The requirements don't recognize this. Maximum frequency used for this needs to be looked at, since you want to reduce touchdown dispersion. You always drive it unstable.

Jerry Rising, Lockheed: You have to consider the cruise also.

John Schuler, Boeing: The 747 as a receiver (when used as a cruise missile carrier) has pilot opinion rating of 1, but doesn't meet specifications for Class III.

Roger Hoh, STI: You are comparing operational versus flight test. You are able to get around some problems by training. Again it's task/condition-dependent. We are looking at the corners of the specification.

John Hodgkinson, McAir: Why wouldn't you want to increase $w_{n_{sp}}$ for a large airplane?

Sam Craig: There is a cost penalty.

Answer: Especially in efficiency.

Jack McAllister, GD: The criteria you need as a designer aren't there when you need them. Case in point - the F-16. Performance sells airplanes at the expense of flying qualities. That's the way it seems for new airplane procurements.

Answer: Class III requirements suffer due to the form of the requirements being more compatible with Class IV airplanes.

Dick Quinlivan, GE: Pure size and physical cues must be different in large aircraft. Do these ideas show up in the specification?

Answer: Some work was tried, but it didn't work out.

John Schuler, Boeing: Didn't TIFS do something on this?

Answer: Yes. A paper is being presented covering Large Airplane Flying Qualities research.

Ed Rynaski, Calspan: Landing in shears can be done automatically, with direct lift, precisely. Manual control of moments cannot give precision flight path control. Attitude is less important than flight path.

Roger Hoh, STI: What you have to design for is the critical condition, i.e., the flying qualities "cliff."

Ed Rynaski, Calspan: Discussion on precision landing. You need to overdrive θ to get α, plus no one wants to push on the stick near touchdown. Need exists for critical task, shear requirements on landing. Also need to consider effects of excess thrust.

Dick Huff, US Navy: A α or $\dot{h}$ inner loop gives quicker response than needed. An autopilot is three or four times faster. APC for speed control. DLC on/off.

REVIEW OF HIGH ANGLE-OF-ATTACK REQUIREMENTS FOR THE MIL-HANDBOOK

David Mitchell
Systems Technology, Incorporated

OVERVIEW

- Combined-axis requirements (3.8) revised since release of MIL Handbook
- Requirements reworded in spirit of MIL Standard
- Enhanced Guidance for Application and Lessons Learned Sections

APPROACH

- Review philosophy on High AOA requirements
- Review modifications to High-AOA requirements
  - Changes in wording/emphasis
  - Rationale for changes
  - Lessons learned

HIGH-ANGLE-OF-ATTACK REQUIREMENTS

- High AOA, stalls, departures, control harmony covered as combined axes
- Most requirements unchanged from MIL-F-8785C
- Quantitative requirements may be impractical
- First attempt at quantifying departures
- Largest areas for improvement are in design guidance and lessons learned
  - Major focus on collecting background data
  - Emphasis on mission-oriented requirements

CHANGES TO HIGH-AOA REQUIREMENTS

3.8.4 Flight at High Angle of Attack

- Not included in draft Handbook
- Discuss high-AOA philosophies
  - Definition of high-AOA: stall approach and above
  - Using agencies advocate restraint in specifications
  - High-AOA Requirements should not:
    * Dictate aircraft configuration
    * Dictate FCS complexity
    * Compromise primary mission performance

NEW HIGH-AOA REQUIREMENT

3.8.4.1 Warning cues. Warning or indication of approach to stall, loss of aircraft control, and incipient spin shall be clear and unambiguous

Restatement of "warning and indication" – dangerous flight conditions

Considerations:

- Want to emphasize importance of warning cues at high AOA
- Many warning cues marginal to inadequate
- Artificial cues should be discouraged
  - Stick shakers masked by natural buffet
  - Aural tones operate on cluttered pilot information channels
- Encourage natural warning of AOA and energy state:
  - Stick force (per knot or g)
  - Stick position
  - Buffet level
  - Uncommanded airplane motion

CHANGES TO HIGH-AOA REQUIREMENTS (Continued)

3.8.4.2.3 Stall Prevention and Recovery

Allow use of power before speed begins to increase

- Once wing is unstalled, power aids in flying out of stall
- Consistent with training for Class I and III airplanes

Class III airplanes in landing approach suggest pitch control power for $\ddot{\theta} \geq 0.08$ rad/sec^2 at stall

CHANGES TO HIGH-AOA REQUIREMENTS (Continued)

3.8.4.2.4 One-Engine-Out-Stalls

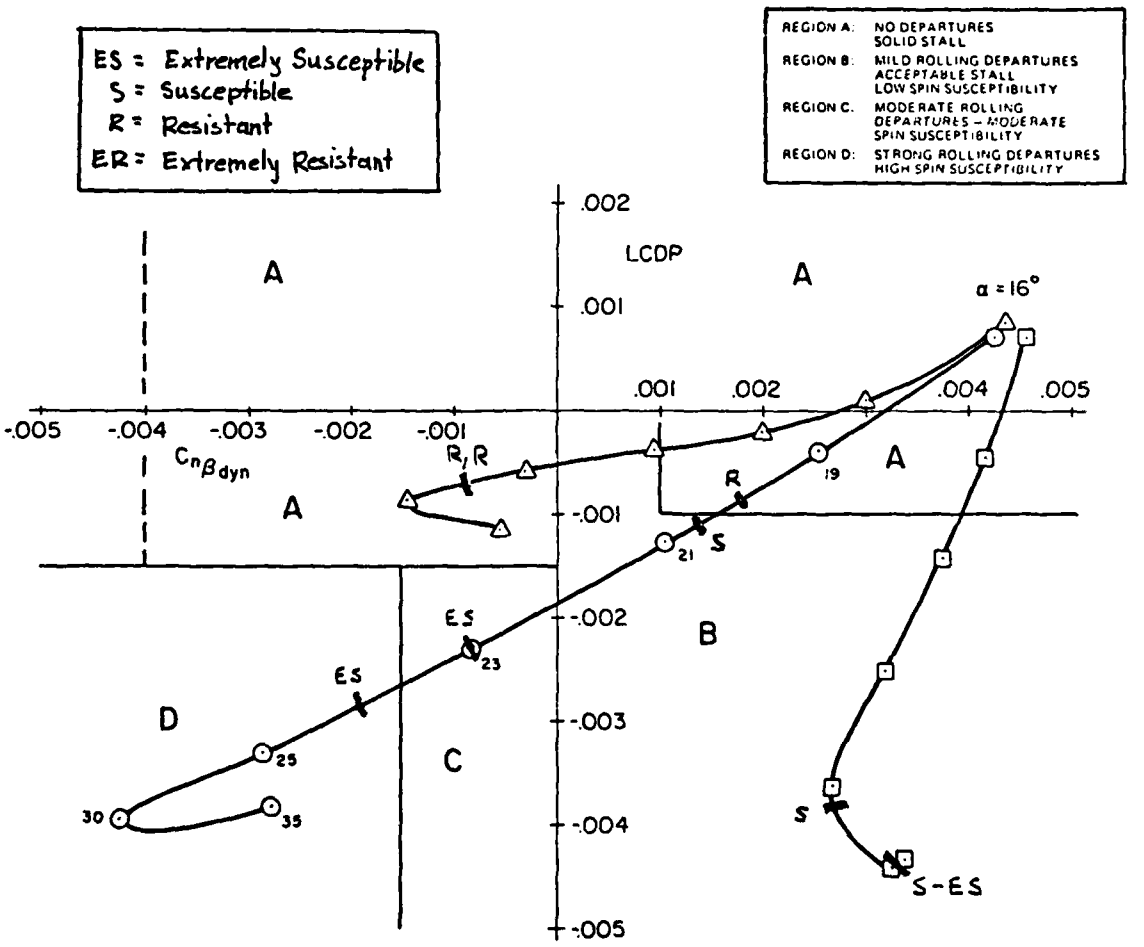
- No change to requirement
- Lessons learned – can produce departures and flat spins
  - F-14A
  - Beechcraft Baron

CHANGES TO HIGH-AOA REQUIREMENTS (Continued)

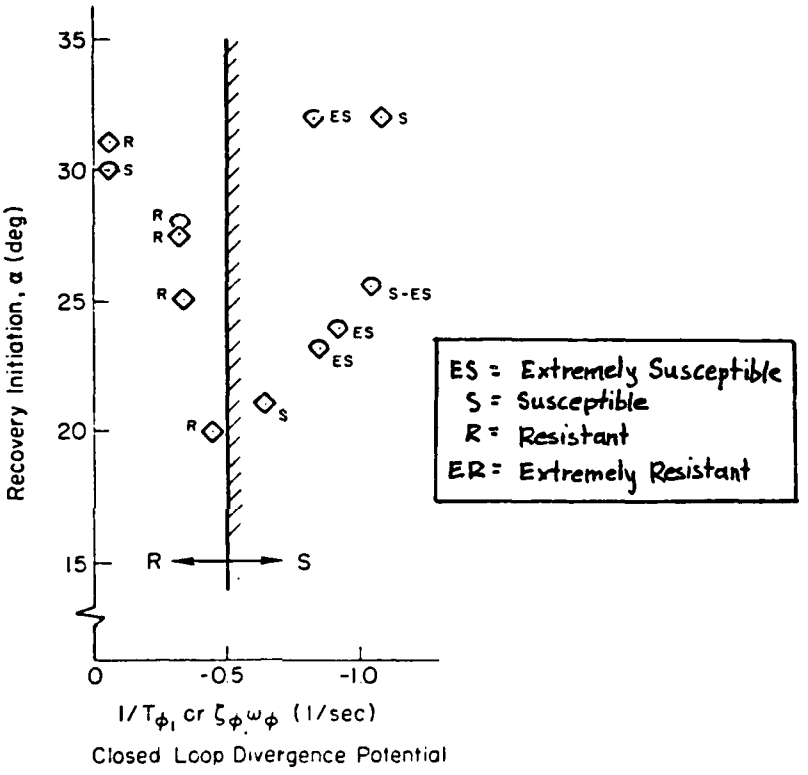
3.8.4.3.1 Departure from Controlled Flight

- Require warning cue (3.8.4.1) of approach to departure
- Aircraft must be "resistant" – not "extremely resistant"
- First attempt at quantifying departures:
  - LCDP > -0.001
  - $1/T_{\phi_1} > -0.5$
  - Uncommanded motion < 20 deg/sec

DEPARTURE SUSCEPTIBILITY RATINGS VS. LCDP



DEPARTURE SUSCEPTIBILITY RATINGS VS. $1/T_{\phi_1}$



CHANGES TO HIGH-AOA REQUIREMENTS (Concluded)

3.8.4.3.2 Recovery from Post-Stall Gyrations and Spins

- Allow pilot to determine direction of motion for recovery
  - Consistent with existing recovery techniques
- Recommend either turns or altitude for recovery
  - Amendment 1 (8785B) altitude loss numbers
  - Altitude loss is primary pilot concern
  - Different spin modes affect turn/altitude relationship
    - * Oscillatory mode
    - * Steep mode
    - * Flat spin

COMMENTS AND QUESTIONS

Robert Batemen, SRL: Propulsion people should be here, since one engine will likely stall in spin. Could you require throttle to be retarded?

Answer: There are provisions for one engine-out stalls. We have not excluded the possibility of retarding a throttle.

Chick Chalk, Calspan: Maneuver limiting systems defeat the need for natural warning cues. Need to encourage natural cues.

Answer: What about F-16 deep stall problem?

Rob Crombie, AFFTC: Maybe the pilot needs it more since he wouldn't expect a problem.

Hesk Streif, Northrop: Pitch recovery from stall involves $\ddot{\theta}$. Shouldn't that be changed for a stable stall? Should there be different requirements if an airplane stalls stable or stalls unstable?

Jerry Rising, Lockheed: We wanted control power comfortable to the pilot for recovery. Pilot used less than full power for Class III airplanes.

John Schuler, Boeing: The requirement might specify less and still be acceptable.

Jim Chin, Grumman: Would you expect $\ddot{\theta}$ for recovery to be different for Class I or Class II airplanes?

Hesk Streif, Northrop: S-2 is not Class III -- look at the report.

Jerry Lockenour, Northrop: Why not say "recover before you hit the ground" instead of requiring number of turns or altitude loss.

Jerry Gallagher, NTPS: You're relaxing the requirement by allowing the pilot to recognize the direction of the motion in a post-stall gyration or full spin. This is not consistent with operations. Why eliminate direction of motion criterion?

Answer: This goes along with procedures.

Sam Craig: Spin direction must be discernable. Burden is on pilot to figure out how to recover. If you want anti-spin, add the requirement. Even so, the requirements must ensure airplane is recoverable.

SOME SPECIAL CONCERNS FOR THE FUTURE OF FLIGHT CONTROL

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(The following is an edited version of the notes presented on 3 Mar 82)

When we look at the future directions of flight control, we need to keep our focus on the combat missions our men and machines will be asked to perform. In the context of these missions and the emerging threat, it seems appropriate to express some concerns I have for our future course.

1. Are we seeking an appropriate marriage of the flight control system with the other aircraft systems to achieve the best possible weapons systems? In some instances it seems we have lost track of the integration process and the fact that we are building weapon systems with a designated mission. Our measures of merit seem to drift and take on a peacetime flavor.

Weapon systems should be designed to kill the enemy and survive at a rate much more efficiently than him. We cannot afford to lose sight of the purpose of our weapons delivery systems or the key elements that determine their effectiveness. We have a systems error budget which constrains us. The error budget equates to miss distances and loss of effectiveness. Flight control systems must be developed such that they assist in minimizing this total error budget.

2. New capabilities in technology will impact the next generation of aircraft. To survive, we may be required to fly very low and fast, below enemy surveillance, in terrain-following/terrain-avoidance profiles, etc. Advancements in flight control technology will allow us to operate effectively in this new mission mode. Runway denial needs to be addressed as well. Can we takeoff and land on short runways? If we cannot, we will probably suffer more than we should. In short, requirements and new capabilities applicable to future weapons systems must be brought into closer alignment with Air Force needs.

3. I have heard discussions concerning the details of the flying qualities and flight control system specifications. We are concerned about precision attitude control and flight path control, and we should be. However, I do not think we will achieve a harmonious marriage if you try to combine a pitch attitude gunsight with flight path control modes. We have several examples, measured in the high cost of flight test programs, wherein we seem to have stopped short of the problem, in a total weapons system context. No matter how good the weapon computations and sights, a mismatched set of flight control laws, developed independently, can negate or override any gains promised by good sight technology. Similarly, an excellent flight control system for either pitch rate or flight path control can be totally offset by the damping factor in a weapons sight. And the entire picture changes at night or in weather. I believe we need to take a broader view.

4. We need to ask, "How fast is the future becoming the present---especially with regard to technology?" VHSIC (Very High-Speed Integrated Circuits) may make some of today's problems moot points. We are worried about digital delays and digital effects. Given time and focus, and new architectures, this concern will be overcome.

5. I think we have some good projects, such as the Integrated Flight/Fire Control (IFFC) advanced development program. We are blending flying qualities, flight control and fire control systems to make a killing machine. AFWAL is moving to integrate technology via the Pave Pillar programs. In the short term, requirements will change. The specifications will change. UNTAP puts the pilot back in the loop and blends his skills. Specifications have to be designed to deal with new and more sophisticated levels of system integration.

6. Sometimes, I think we are getting too close to the mathematics, and we lose sight of what we are designing. We need to blend our 6.1, 6.2 and 6.3 efforts together with the contractors' IR & D programs to move faster in the direction of demonstrating new, effective weapons systems. We know flying qualities research works. We know flight control systems work. We must continue this research and transition its rewards in an

integrated fashion into the next generation. Are we ready for a combined specification? We can pursue the possibilities.

7. We had the TAWDS system. It was the best blend of control elements to do a mission. We went to McAir to match up control parameters in order to get an effective weapons delivery system. A pilot model was worked on. The results? We could get the pilot model to fly bomb runs similar to the actual F-4 aircraft. I believe that we do too many things over and over again.

8. Digital systems are coming along. Triplex, quadriplex, redundancy-all key words. Multi-mode systems. Multi-function displays. The plan is to incorporate the best blend of all weapons system control elements into a better fighting machine. My concern is that I have not seen the work to set the technical requirements and specifications to employ these new capabilities. We need to define parameters which are important to weapons system effectiveness. Perhaps a K* parameter which defines the best combinations of control system elements which will accomplish the kill/survive scenario of war. Pilot factors must also be included. We need to define the important parameters better than we are doing today.

In summary, integrated systems, greatly improved mission effectiveness, K* --- these are the directions we must pursue if we are to maintain technological superiority in our future fighters and bombers.

ARVIN/CALSPAN

EVALUATING THE FLYING QUALITIES OF TODAY'S FIGHTER AIRCRAFT

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EVALUATING THE FLYING QUALITIES OF TODAY'S FIGHTER AIRCRAFT*

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SUMMARY

The flying qualities of today's fighter aircraft are to a large extent the product of their advanced flight control system design. Unfortunately, the potential of the new electronic flight control technology used in modern designs has not been realized. New flying qualities problems have often been created in the process of solving the old ones. The intent of this paper is to review the lessons of the recent past as a foundation for the next steps toward more complex flight control designs. Typical flying qualities problems are presented and the potential reasons for these problems are discussed from an involved test pilot/engineer viewpoint. Suggested ways in which the flying qualities development process might be improved are included in the discussion.

INTRODUCTION AND PURPOSE

Modern fighter flight control systems use digital or analog computation techniques in combination with their advanced "fly-by-wire" technology to gain potential advantages such as improved mission performance and weight/cost reduction. Examples of modern fighter aircraft which incorporate such advanced flight control system designs are the F-16, YF-17, F-18 and Tornado. Unfortunately, the potential of this expanded flight control technology has not been realized. In fact, new flying qualities problems have often been created in the process of solving the old ones.

With the operational acceptance of full-authority electronic augmentation systems, the designer literally has the capability to tailor the flying qualities of the aircraft as desired for each mission task. Typically, these advanced design efforts have produced overly complex designs characterized by "higher order" responses to the pilot's inputs. The additional control system dynamics, or higher order effects, can potentially cause serious flying qualities problems while performing precision tasks.

These new flying qualities problems are most often related to the time delays which can cause dramatic degradation in flying qualities for precision tasks. The source of these time delays can be from the higher order complexity of the flight control system design or, in the case of digital systems, inherent time delays. Digital flight control systems tend to be the worst offenders since the power of the computer unfortunately facilitates the design of very complex systems.

The flying qualities of today's fighter aircraft are to a large extent the product of the flight control system design. Given the design power inherent in the modern "fly-by-wire" flight control system, it is therefore not unreasonable to state that fighter flying qualities should now be "perfect". At the very least the discussions of the flying qualities of today's fighter aircraft should be centered around "degrees of perfection" rather than the more typical concerns about significant degradations in flying qualities. Application of the new control system technology has clearly not reached its potential in the context of classic fighter aircraft designs. Before the next step is taken to enhance fighter maneuverability by the incorporation of additional control surfaces and attendant complexity, a review of the lessons of the recent past is in order.

The purposes of this paper are to:

- Review the typical flying qualities problems associated with today's fighter aircraft.
- Establish the case that the flying qualities development process has not been working properly in the context of experiences related to several recent fighter aircraft with sophisticated modern flight control systems.
- Explore the potential reasons for the problems with the flying qualities development process.
- Suggest ways in which the flying qualities development process can be improved.

The major theme of the paper, in the context of this symposium on "Combat Aircraft Maneuverability", might best be summarized in the words of the American philosopher, George Santayana who noted that "those who cannot remember the past are condemned to repeat it."

* The work from which this paper is drawn was supported under contract by the United States Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio

VIEWPOINT

This paper is written from the author's vantage point as a test pilot/engineer who has spent a considerable time as an observer/safety pilot in the USAF NT-33 in-flight simulator operated under contract by Calspan (Figure 1). During this association with the NT-33 numerous research programs have been conducted which were directed specifically at the flying qualities of highly augmented fighter aircraft (for example, References 1 through 4). In addition, simulation programs for specific aircraft such as the YF-16, YF-17 and F-18 were performed (References 5 and 6). Although not directly involved in the Calspan simulations of the Space Shuttle aircraft with its complex digital flight control system (References 7 and 8), the author was involved in supportive analytical efforts related to these programs. While the Shuttle is obviously not a fighter aircraft, it serves as a pertinent background example for this paper.

The opinions expressed in this paper are those of the author alone and are based on the technical exposure outlined above.

BACKGROUND

The flying qualities record for today's fighter aircraft with advanced electronic flight control systems has been generally unimpressive. In some instances the flying qualities achieved for a fundamental task such as precision landing have been significantly worse than for aircraft designed 25 years ago without the benefit of today's advanced technology. Why? Clearly, there is no one simple answer to this dilemma - the problem, as usual, is the result of many factors.

The flying qualities development process is reviewed in detail in the next sections and the potential problem areas are highlighted. The purpose in this section is to give the whole discussion credibility by establishing that indeed potentially significant flying qualities problems can be caused by today's advanced flight control system designs and the associated development process.

Specific Aircraft

The F-16, YF-17, Tornado (reference 9) and F-18 fighter aircraft and the Space Shuttle (Reference 10) have one feature in common: all of these vehicles had serious, and in some cases dangerous flying qualities problems, exposed well down the development process. Rather than enhancing the aircraft flying qualities, the advanced control system designs often unwittingly produced a dramatic degradation in flying qualities for precision tasks.

Although the development process should by nature be a period of trial and error, the significant point in these examples is that the problems were not exposed early enough in the development process. The inability to accept the trial and error nature of the development process often, in fact, inhibits the entire process.

An inherent attribute of advanced flight control designs is the potential flexibility of the electronic system. While this feature can certainly be used to advantage, reliance on it to overcome major flying qualities problems late in the development process is most often a time consuming and expensive proposition.

General Research

In general, the modern flight control system for today's fighter aircraft is complex. In part, this additional complexity is associated with the desire to achieve improved mission performance and enhanced flying qualities. It appears, however, that a portion of this complexity is associated with a desire to exercise the new flight control design capabilities. This tendency toward design complexity, coupled with a lack of understanding of the potential damaging effects of this complexity on the flying qualities of the aircraft, typically leads to problems.

The pilot is concerned with performing his mission tasks quickly and accurately and is generally unimpressed with control system sophistication, particularly if the end result is a degradation in flying qualities. Typically, the additional control system dynamics introduced by the advanced control system design manifest themselves in the form of an equivalent time delay. Additional control system dynamics in the form of either this higher order time delay or as prefilter lag can potentially cause serious flying qualities degradations when performing precision tasks such as tracking, air refueling or landing.

Digital flight control systems are particularly vulnerable to higher order flying qualities problems not only because of the inherent time delay of the digital system but also because the digital computer invites design complexity.

The effects of the additional control system dynamics in the form of equivalent or pure time delay are illustrated in Figures 2 and 3. Results of two NT-33 in-flight simulation experiments (References 2 and 3) directed at approach and landing longitudinal flying qualities for highly augmented fighter aircraft are presented in Figure 2. These results are consistent with other research work; for example, Reference 11. The most recent NT-33 experiment (Ref. 4) was performed to investigate the effects on fighter lateral flying qualities of typical advanced flight control system dynamics including time delay.

The results for the air-to-air tracking and air refueling tasks are illustrated in Figure 3 as a function of equivalent time delay and equivalent roll mode time constant.

These selected results serve to establish the point that additional higher order flight control system dynamics can have a significant effect on fighter flying qualities.

It is not clear, however, that advanced flight control systems must of necessity be higher order. Using the NT-33 in-flight simulator, Chen in Reference 12 makes a strong but to date largely ignored case that aircraft with excellent flying qualities can be designed using full authority electronic augmentation without increasing the order of the overall dynamic system.

At this point the existence of a problem with the flying qualities development process has been established; it is evident that the process has not been working properly. The numerous potential problem areas are discussed in the next section.

FLYING QUALITIES DEVELOPMENT PROCESS

A simplified block diagram of the typical flying qualities development process is illustrated in Figure 4. The process is by necessity iterative and involves two major phases: the design phase and the evaluation phase. These phases can both involve simulation and are closely intertwined; the evaluation phase includes the evaluation of the actual aircraft.

Potential problem areas are discussed in the next subsections followed by an example of how the process can produce aircraft with outstanding flying qualities when working properly. Many of these problem areas are interrelated which makes the discussion somewhat difficult. The intent is therefore to present the pertinent points; the order of this discussion does not reflect the priority of the subjects.

Design Philosophy

The design philosophy is fundamental to the overall process. Typically, the more complex approach is chosen which leads to an aircraft with complex higher order response characteristics to pilot inputs. Existing background flying qualities data are now either not used or not applicable and ground simulation is then relied upon for flying qualities evaluation and development. This process generally leads to serious flying qualities problems.

- A case in point would be a recent advanced fighter design. The basic unaugmented aircraft dynamic characteristics were almost identical to those of the venerable NT-33 aircraft in the approach and landing flight phase. Using the latest design techniques and the powers of an advanced electronic flight control system, the designers created an initial system which was over 50th order. Although judged to be satisfactory in the ground simulator, in-flight simulation evaluations using actual landings showed that it did not land as well as the ancient NT-33. In fact, potentially serious pitch PIO problems existed near the ground.

  A very simple augmentation system would have done the job and produced very fine flying qualities. Again, the examples of Reference 12 substantiate this point. It is worth noting that a single set of simple feedback and command gains can be used in the variable stability NT-33 to produce outstanding longitudinal flying qualities from landing approach to 350 KIAS.

- The simplest augmentation system design is usually the best choice. (But typically this approach is not very satisfying to the design engineer.)

Design Criteria

Given that there may be valid requirements which necessitate the design of higher order flight control systems, then applicable design criteria or specifications must be developed.

Considerable effort has been made in recent years to gather the applicable flying qualities data base and to develop appropriate design criteria and flying qualities specifications. In the view of the author, it is far more important to accept a somewhat imperfect design criterion or specification which allows the designer to eliminate potentially troublesome concepts early, than to wait for the creation of the perfect specification which covers all possible cases.

The Neal-Smith criterion for precision fighter longitudinal tasks was developed at Calspan using a data base gathered in the NT-33 aircraft (Reference 1) and has been used successfully as a design guide for the past 10 years. A recent study (Reference 13) extended the criterion to the landing approach task with reasonable success.

Another approach which has been used with equal success is the Equivalent System technique developed and refined by Hodgkinson et al. (Reference 14) and included in the criteria study of Reference 13.

The recent flying qualities study of lateral higher order systems performed in the NT-33 (Reference 4) should provide a solid data base for development of appropriate lateral flying qualities criteria for highly augmented fighter aircraft.

- Applicable data and criteria exist to provide the necessary guidance to avoid the major flying qualities problems which are too often a part of today's fighter designs. Unfortunately, they are not always used.

- Efforts to create "perfect" flying qualities specifications should not be allowed to dilute the effectiveness of existing criteria. For example, the projected equivalent system approach in the suggested revisions to U.S. military flying-qualities specification, has become so complicated in the pursuit of technical purity that its usefulness is potentially diminished.

Evaluation Tools

The development process for advanced fighter aircraft relies heavily on simulation for evaluation and revision of the aircraft's flying qualities. Unfortunately, these pilot evaluations are often restricted to ground simulations. Experience with advanced fighter aircraft has indicated that in-flight simulation has an essential role in the development process.

- YF-16 (Reference 6): essentially designed on a ground simulator since data for the advanced side stick controller did not exist. Result was a near disastrous lateral PIO on first inadvertent flight. Same problem was observed earlier during in-flight simulations but the problem was judged to be a poor pilot!

- YF-17 (Reference 6): the final first flight design which evolved from the use of a relatively sophisticated ground simulator resulted in a potentially catastrophic divergent pitch PIO when actual landings in the NT-33 in-flight simulator were attempted. Subsequent inclusion of in-flight simulation in the development process resulted in an aircraft with outstanding flying qualities.

- YF-18 (Reference 7): in-flight simulation in the NT-33 exposed initial flying qualities deficiencies which were not apparent in sophisticated ground simulation evaluations.

- Space Shuttle (Reference 11): serious pitch PIO problems observed in Free Flight #5 (first precision landing on a runway) were not detected during extensive ground simulation evaluations. Problems were clearly evident in subsequent in-flight simulations using the USAF TIFS aircraft (References 7 and 8).

General research programs to investigate the effects of additional flight control dynamics on fighter flying qualities (References 1 to 4 and Reference 11) have consistently shown that the task and associated pilot "stress" level are critical for proper evaluation of these aircraft with advanced control systems. The exposure of "flying qualities cliffs", or explosive degradation in flying qualities, common to aircraft with complex higher order responses cannot be assured (or even expected) in a ground simulator. The results presented in Figure 5 serve to substantiate this point.

In summary,

- Both ground and in-flight simulation have essential roles in the development process.

- Advanced flight control systems with complex higher order responses to pilot inputs are particularly vulnerable to inaccurate evaluations in ground simulation, and should be evaluated in an in-flight simulator using realistic tasks.

- Inclusion of in-flight simulation as an integral part of the development process can significantly reduce the number of expensive design iterations required in the actual aircraft. Better flying qualities can be produced in a more efficient manner.

Communication

Perhaps the most important ingredient for a successful application of the flying qualities development process is communication. Communication is essential between managers, project engineers and test pilots. For advanced aircraft whose flying qualities can be dictated by full-authority augmentation systems, a "team" approach is imperative.

- Managers/Engineers:
  - The control system design team should include engineers who are familiar with the effects of additional dynamics on flying qualities.
  - Too often those engineers who are most proficient with the latest electronic devices, such as digital computers, are given unilateral control of the design. The result is typically an overly complex design with poor flying qualities.
  - Unfortunately, there is some evidence of "technical arrogance" among those involved in the design of today's fighters; this attitude leads to a rather insular approach to the design process. The results of a recent survey by A'Harrah (Reference 15) on the effectiveness of the present military flying qualities specification provodes some insight into this point. According to the survey, the major factors contributing to the flying qualities problems of today's aircraft were time and money constraints. Yet the flying qualities problems associated with the latest fighter aircraft could have been minimized if the available technical data and expertise had been properly utilized.
- Test Pilots:
  - They must try to be "average" since the aircraft will be flown by "average" pilots.
  - To the extent possible they must "tell it like it is"; too often those pilots who do so are "punished". The result is a tendency to say what is least controversial. Of course, the managers/engineers must listen to him!
  - If the effects of macho and politics are not minimized in the cockpit, valid pilot evaluations are not possible.

Without effective communication among the key players in the development team, the flying qualities process cannot operate efficiently.

Can The Process Work?

In making the point that there are problems in the flying qualities development process, the negative side has been emphasized. The process can work and does work after a fashion but all too often the potential flying qualities benefits of the advances in flight control technology are not realized.

The YF-17 development program is a positive example of the process functioning properly.

- The designers created the flight control design using their own design guidelines (not existing design criteria) and a relatively sophisticated ground simulator. Unfortunately, the associated visual display was less than adequate. Even so, it is doubtful if the flying qualities problems would have been exposed with a better display.
- As a result of the near disastrous YF-16 experience, the NT-33 in-flight simulator was utilized for pre first-flight evaluations. These evaluations (Reference 5) exposed very serious pitch PIO problems during the final stages of landing.
- Design changes were then implemented and tested on the in-flight simulator and dramatically better flying qualities evolved.
- The YF-17 aircraft with a relatively complex, high authority augmentation system is an aircraft with outstanding flying qualities and is used by the pilots who have flown it as a reference for good flying qualities.

CONCLUDING REMARKS

This paper was written in part out of the frustration of observing the flying qualities of today's fighter aircraft fall far short of the levels potentially achievable with modern "fly-by-wire" technology. Evaluating the flying qualities of today's fighter aircraft leads one to the conclusion that the development process is not functioning properly; the final products are too often not as good as those produced without the benefit of the advanced electronic control system technology. The following summary observations are offered.

- The potential of advanced full-authority augmentation systems is a fact but in practice the potential has not been achieved.

- For this potential to be achieved, a logical flying qualities development process must be created which includes sound technical communication among the managers, engineers and test pilots.

- The evaluation process should include the use of both ground and in-flight simulation facilities. If only ground simulation facilities are used in the development of aircraft with complex flight flight control systems, there is a high risk that major flying qualities problems will not be exposed.

- Complexity should be sacrificed for simplicity every time.

The observations presented in this paper are made in the context of the potential and logical use of advanced electronic flight control systems in combination with additional control surfaces to enhance fighter combat maneuverability. It is hoped that this evaluation of flying qualities of today's advanced fighters and the associated development process will ensure that the problems of the past will not be repeated.

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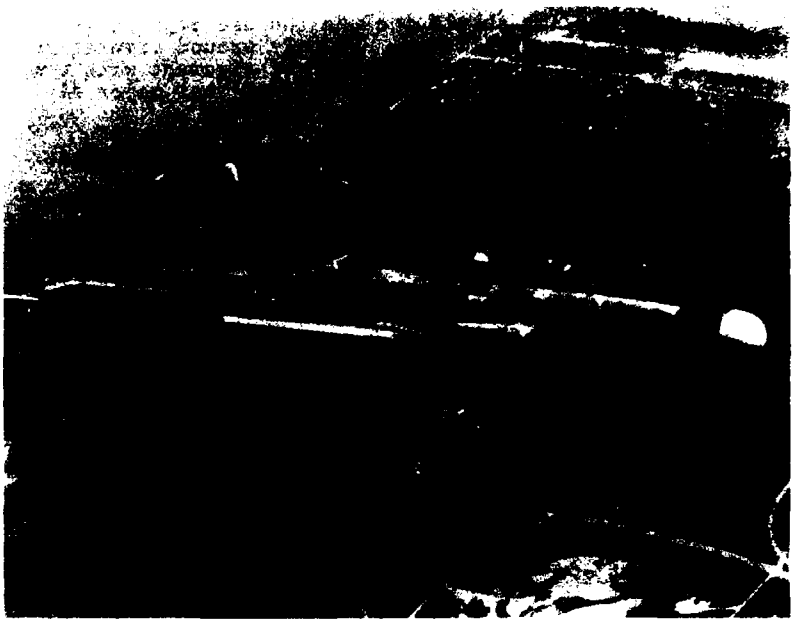


Figure 1: USAF VARIABLE STABILITY NT-33 AIRCRAFT OPERATED BY CALSPAN

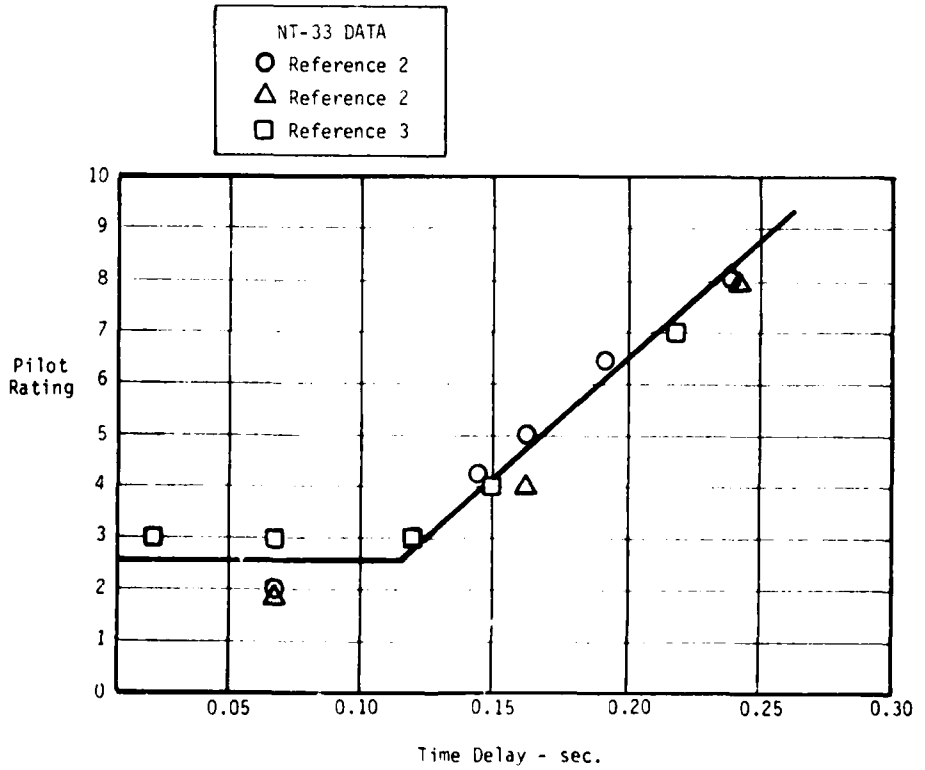


Figure 2: EFFECTS OF TIME DELAY ON FIGHTER APPROACH AND LANDING PITCH FLYING QUALITIES

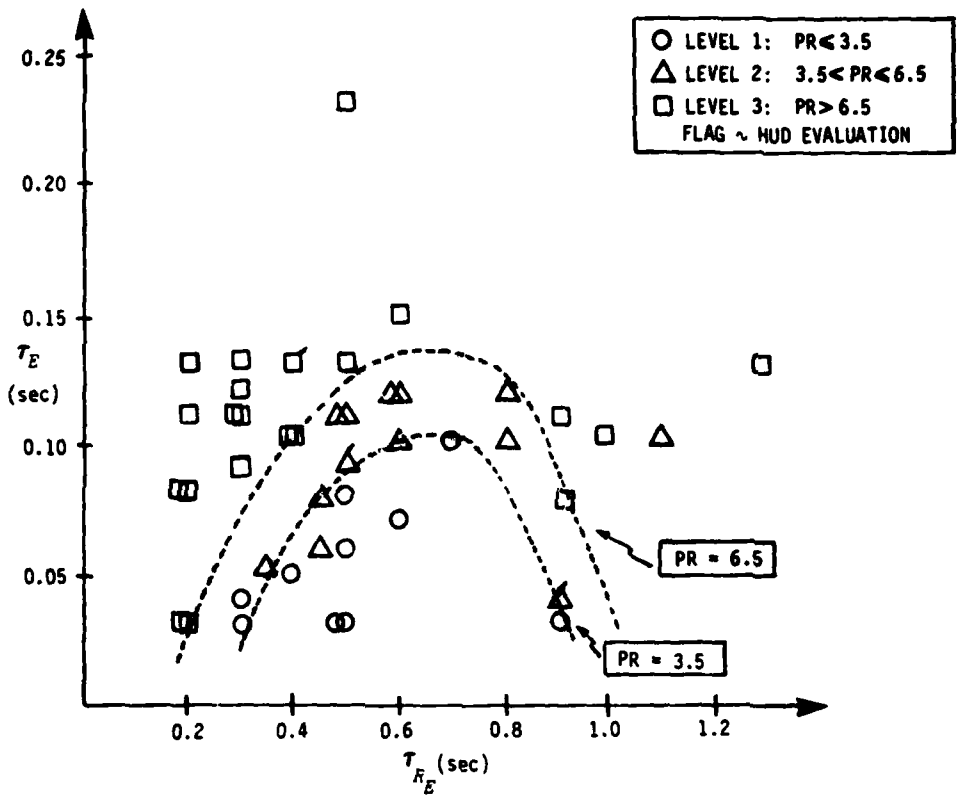


Figure 3: LATERAL FLYING QUALITIES DATA FOR PRECISION FIGHTER TASKS IN TERMS OF EQUIVALENT PARAMETERS

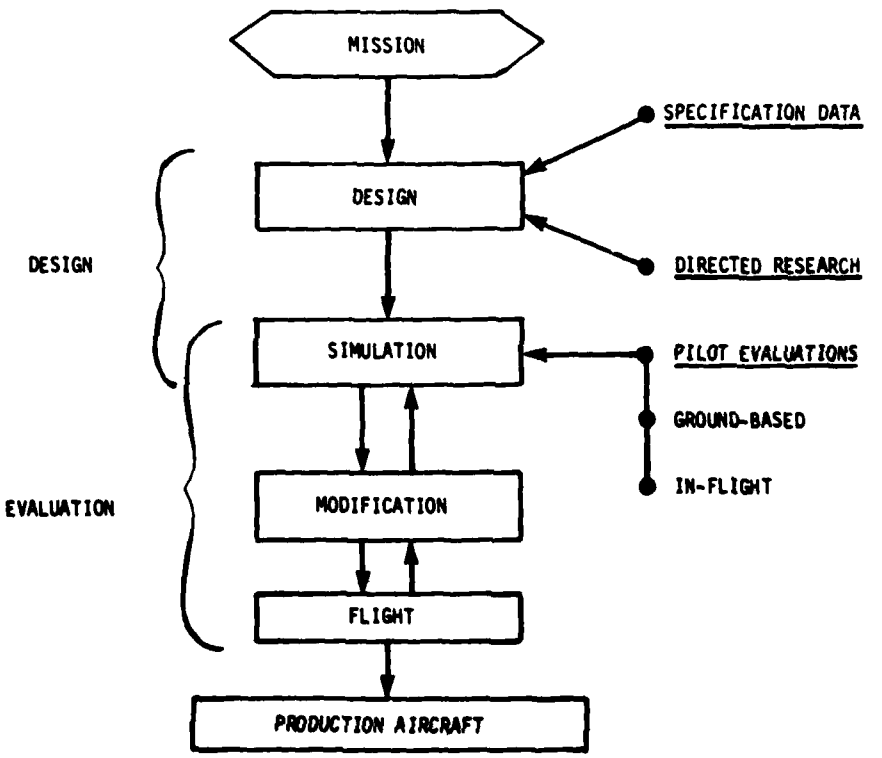


Figure 4: FLYING QUALITIES DEVELOPMENT PROCESS

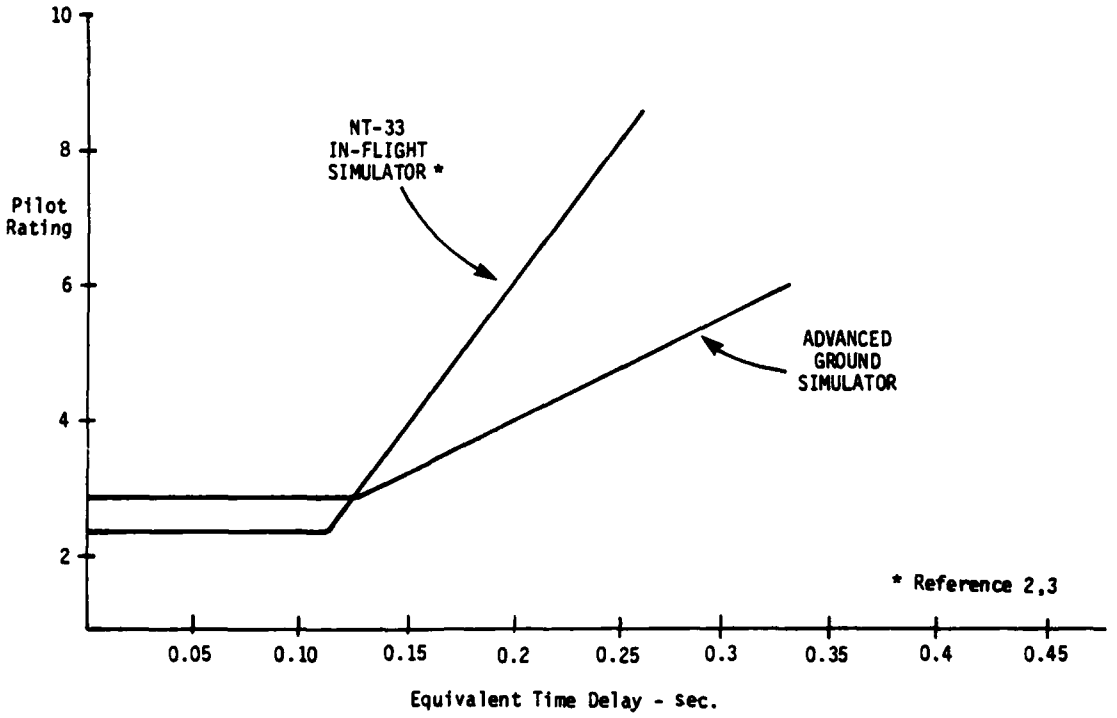


Figure 5: COMPARISON OF IN-FLIGHT AND GROUND SIMULATOR RESULTS FOR THE SAME TASK

COMMENTS AND QUESTIONS

John Maynes, Northrop: Were there in-flight simulations before the first of the Space Shuttle?

Answer: Yes, but the PIO didn't show up. After the drop test produced the PIO, follow-on work was conducted.

The Use of Equivalent System Models with High-Speed, Highly Augmented Aircraft

by Bruce G. Powers
NASA Ames Research Center
Dryden Flight Research Facility

The use of an equivalent, lower order system model to approximate a higher order system provides a convenient way to apply the handling qualities criteria developed in the past to the highly augmented aircraft of the future. This paper will describe some of the problems encountered in using lower order systems to represent high-speed, highly augmented vehicles and indicate some of the work currently in progress in this area at Dryden.

The lower order model is shown in figure 1. The pitch rate/pilot input amplitude frequency response is characterized by the numerator root $1/\tau_\theta$ which is approximately equal to L_α and the short period frequency W_n. At low speeds L_α is about the same magnitude as W_n and the amplification and attenuation due to $1/\tau_\theta$ and W_n are often indistinguishable. As Mach number increases, L_α decreases approximately as the inverse of speed and the short period frequency is usually augmented to provide approximately a constant value. As a result, the numerator root and the short period frequency become significantly separated. At M=3, typical values of W_n would be on the order of 1.0 rad/sec and L_α would be 0.1 rad/sec.

One reason for using more complex control systems is to take advantage of the performance benefit that can be obtained from relaxed static stability. This is often accomplished by using integral compensation (i.e., pitch rate command) and the effect of this type of control system is shown in figure 2. For the conventional airplane (i.e., lower order system), the pitch rate frequency response shows a definite breakpoint at L_α and at W_n. This

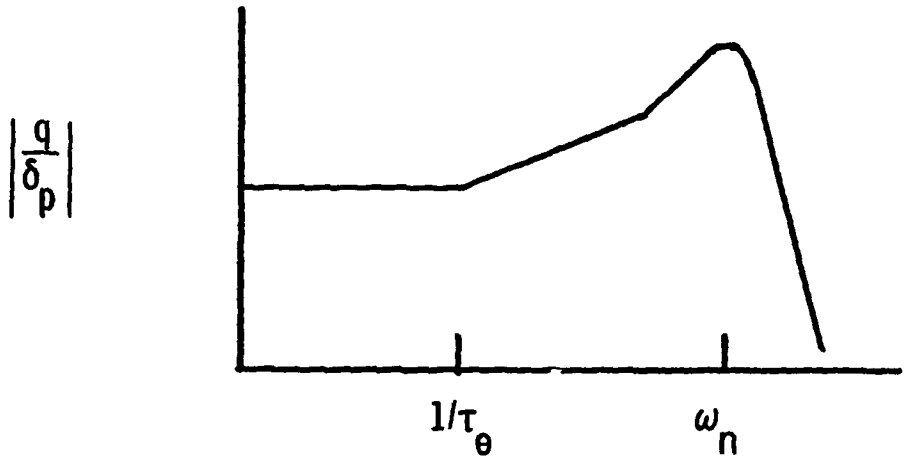
produces a normal acceleration frequency response that is essentially flat out to a frequency of W_n. With the integral compensated system, the pitch rate response is essentially flat to W_n which results in a normal acceleration response that begins to attenuate at L_α as seen in figure 2.

The net result is that the frequency response of the integral compensated system cannot be represented by the standard lower order equivalent system model. The result might imply that integral compensated airplanes will have poor handling qualities. Hodgkinson and others have shown that higher order systems that cannot be satifactorily approximated by a lower order model usually have poor handling qualities. A second possibility suggested by STI and others is that integral compensated systems do provide satisfactory handling qualities but the present handling qualities data base does not apply to these aircraft. This result is not restricted to high-speed flight; however, at the lower speeds, the separation of L_α and W_n is small enough that the problem is usually not that apparent.

Flight data exists for five different vehicles at M=3. The YF-12, the XB-70, and the X-15-1 are vehicles with relatively simple augmentation systems and are representative of lower-order-model systems. The Shuttle and the X-15-3 are vehicles representative of integral compensated vehicles. The frequency responses and the pilot evaluation for these vehicles are currently being analyzed. The flight evaluations are all for Category B tasks and it is suspected that task may be a significant factor. As a result, a Shuttle simulation study is being conducted to examine various levels of precise tracking to look at the task effect. It is hoped that these studies will provide some insight into the nature of the problem.

EQUIVALENT SYSTEM MODEL PARAMETERS

$$\frac{q}{\delta_p} = \frac{K(s + 1/\tau_\theta)e^{-\tau s}}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$



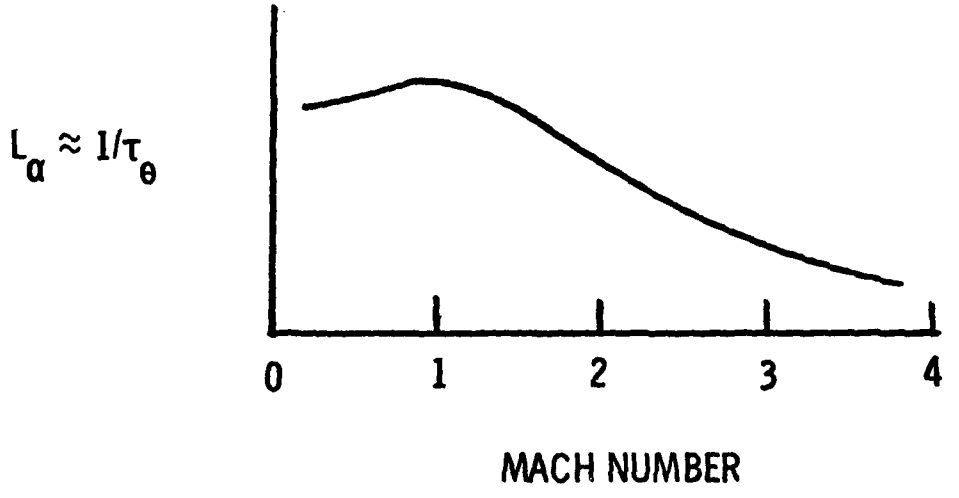
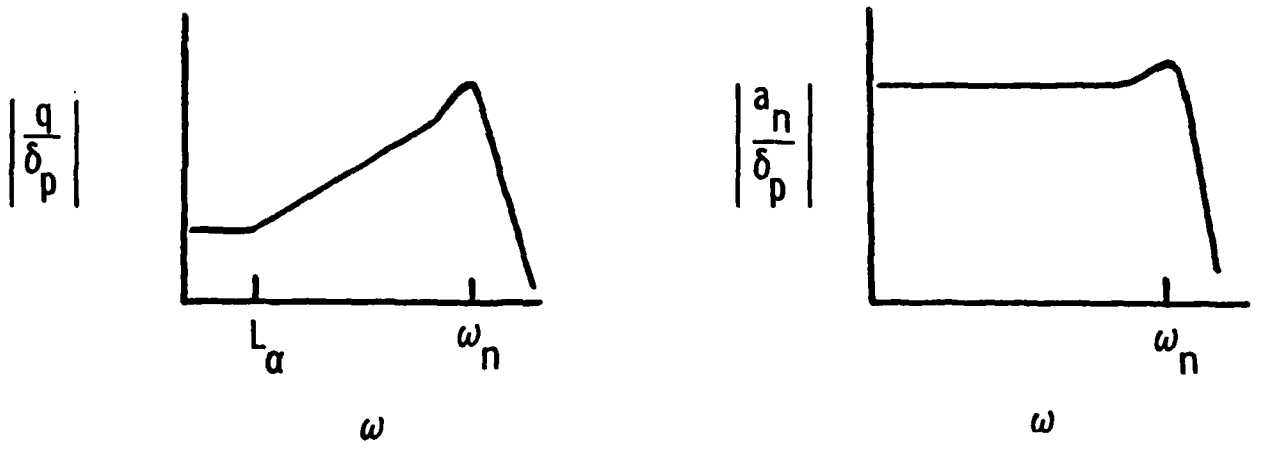


Figure 1

# COMPARISON OF AUGMENTATION EFFECTS
M = 3

CONVENTIONAL



INTEGRAL COMPENSATION
(PITCH RATE COMMAND)

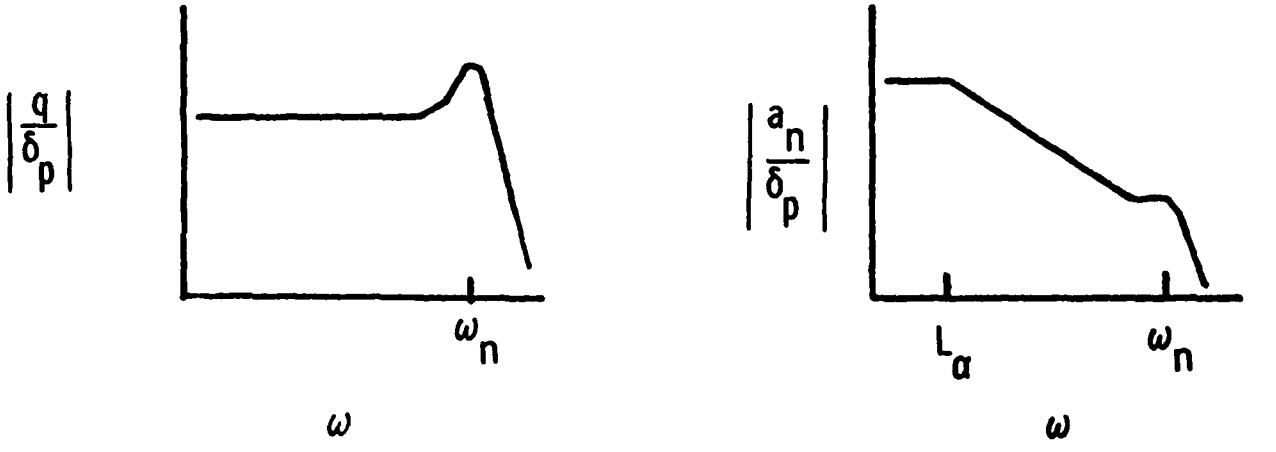


Figure 2
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MALE AND FEMALE STRENGTH CAPABILITIES FOR OPERATING AIRCRAFT CONTROLS

Joe W. McDaniel
Air Force Aerospace Medical Research Laboratory
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AFAMRL is studying the physical characteristics (size and strength) of Air Force men and women to determine their capabilities to operate existing systems and equipment and to provide design criteria for developing specifications for future systems and equipment. One of these studies is to quantify strength and endurance characteristics available to operate aircraft controls. The background and methodology for these pilot strength studies are described in a previous report (3).

The strength capabilities of women in general are less than that of men (1), and a related study by the FAA of female civilian pilots (2) indicated that some would not have sufficient strength to pilot aircraft under some conditions. Since the aircraft and specifications for aircraft are based on the physical size and strength characteristics of male pilots, there is need to investigate the accommodation of future pilots.

The objectives of this study, were (a) to measure the strength characteristics of male and female subjects for operating a stick-type aileron and elevator control and rudder pedals, (b) to determine how much increase in control performance could be achieved by a physical training program, and (c) to determine what type of physical training is most efficient for this purpose.

This study involved a combined effort at two research facilities. The strength testing was performed at AFAMRL by Dr. Joe McDaniel and Lt Col Maureen Lofberg of the Workload and Ergonomics Branch, together with Mr Michael C. Jennings of the University of Dayton Research Institute. The anthropometric measures were performed by Lt Col Lofberg (AFAMRL) and Kathleen Robinette of Anthropology Research Project, Inc. The physical training part of the program was conducted at the Department of Physical Education at the University of Dayton by Dr. Doris Drees, Dr. Robert Boyce, Mr. David Eby, and Ms. Janet Schlabach.

Sixty-one male and 61 female subjects were selected according to the stature and weight criteria for USAF pilots defined in AFR 160-43. With few exceptions, the subjects routinely participated in strenuous physical exercise.

Subjects were tested in a stick-configured cockpit instrumented with electronic force transducers and their scores recorded via a computerized data collection system. Subjects wore Nomex flying gloves and USAF flying boots during the strength tests. The data reported here represent the maximum force applied to a control during a 4-second static exertion. All exertions on the stick were with the right hand only. Endurance measures were also made, but will not be reported here.

Table 1 shows the summary results of the baseline maximum strength data, that is, measurements taken prior to the physical training (122 subjects). The 50th percentile represents the median force value. The median forces for the female were about 60 percent of the male forces. There was little overlap of strength distributions for the stick control, the weaker males (5th percentile) performing similar to the stronger females (95th percentile). The notable exception was that weaker males and weaker females showed similar performance on the rudder controls. There were no meaningfully predictive relationships between strength and anthropometric characteristics (correlations) between 0 0.59).

TABLE 1 - MAXIMUM FORCES EXERTED ON AIRCRAFT CONTROLS (Pounds) BEFORE PHYSICAL TRAINING

Control & Direction	61 MEN Percentile			61 WOMEN Percentile		
	5th	50th	95th	5th	50th	95th
Stick Fwd	93	123	165	46	87	109
Stick Back	64	85	106	38	52	64
Stick Left	35	52	74	17	26	35
Stick Right	22	35	43	14	19	28
Left Rudder	170	450	700	160	260	460
Right Rudder	190	450	755	180	290	530

The stick cockpit used in this study is relevant for not only small aircraft, such as trainers; but also future transport aircraft such as the YC-14, YC-15 and even the CX. Each aircraft has different control resistances and failure modes. In some cases, the actual control resistance exceeds that currently allowable in the worst case forces in MIL-F-8785B, Flying Qualities of Piloted Aircraft. The data from this study suggest that this specification may not be consistent with the capabilities of pilots. Table 2 shows the percentage of subjects in this study falling below the specified maximum control resistance. Aileron right (adbuction) is the most difficult with 50 percent of the male subjects and all of the female subjects failing to exceed the 35-pound specified value.

TABLE 2 - PERCENT OF SUBJECTS WHOSE MAXIMUM FORCE WAS BELOW MIL-F-8782B DESIGN CRITERIA

Control	Criteria (Pounds)	Percent Below Criteria	
		MALES	FEMALES
Stick Fwd	75	0%	28%
Stick Back	50	0%	40%
Stick Left	35	5%	95%
Stick Right	35	50%	100%
Left Rudder	180	7%	11%
Right Rudder	180	0%	5%

After the baseline strength testing, subjects participated in a supervised exercise class three times per week for nine weeks. The subjects were split into two exercise groups: isotonic (31 males and 31 females) and isometric (30 males and 30 females). The isotonic exercise employed handles and pedals for raising weights by levers and cables. The equipment is similar to that commonly found in gyms and spas. The isometric exercises employed handles and pedals made immovable by cables attached to fixed objects. The exercises were defined to meet two criteria: first, the location, range, and direction of force must be similar to those of the aircraft controls; second, the exercise equipment must be readily available. Strength testing in the cockpit simulator was repeated after 3, 6, and 9 weeks of exercise. Of the 122 subjects beginning the study, 110 (55 males and 55 females) reported for the last test session.

Table 3 shows the effects of physical training after 0, 3, 6, and 9 weeks of exercise. Both the isometric and isotonic groups show similar increase in performance indicating one type of exercise is as good as the other. For the directions of left and right for the stick control, there was no increase due to either type of exercise for either sex. For left and right rudder pedals, there was a considerable increase for both sexes with both types of exercise. Although a larger increase was expected, the exercise program must be placed in the context of the subjects routine exercise outside of the program. The majority of these subjects were in good-to-excellent overall physical condition coming into the program. Where there were improvements due to exercise, males and females improved by the same amount. Weaker subjects benefited more from the physical training than stronger subjects.

TABLE 3. MEAN STRENGTH VALUES FOR MALE AND FEMALE SUBJECTS AFTER 0, 3, 6, 9 WEEKS OF ISOTONIC OR ISOMETRIC EXERCISES

		MALE				FEMALE			
	TYPE OF	DURATION OF PHYSICAL TRNG				DURATION OF PHYSICAL TRNG			
CONTROL	EXERCISE	0	3 wks	6 wks	9 wks	0	3 wks	6 wks	9 wks
Stick Fwd	Isometric	119	125	128	135	85	93	96	99
	Isotonic	132	129	135	142	84	88	90	86
Stick Back	Isometric	79	79	80	80	51	53	52	53
	Isotonic	91	87	92	94	52	50	50	51
Stick Left	Isometric	51	49	52	50	26	29	28	27
	Isotonic	56	54	55	56	27	28	28	28
Stick Right	Isometric	33	33	35	34	19	21	20	20
	Isotonic	35	35	36	38	20	21	20	22
Rudder Left	Isometric	402	410	438	450	277	341	363	380
	Isotonic	470	477	467	516	292	320	322	340
Rudder Right	Isometric	426	448	491	503	311	353	395	407
	Isotonic	486	518	489	558	320	327	348	373

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A DESIGN CRITERION FOR HIGHLY AUGMENTED FLY-BY-WIRE AIRCRAFT

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U.S. Naval Air Development Center

Warminster, Pa.

Abstract

The introduction of fly-by-wire aircraft by both the Air Force and Navy has resulted in highly complex flight control systems with full-time augmentation. An immediate consequence is the question of applicability of the existing MIL specifications as design guidelines and assurances that specification compliances will guarantee not only a satisfactory system from the Cooper-Harper viewpoint, but will produce an optimum system in terms of mission performance. The situation is further clouded by the introduction of new flight modes featuring de-coupled systems and direct force, nonlinear flight regimes, integrated control systems, and the need to simultaneously satisfy the pilot with respect to both Cooper-Harper and Pilot Induced Oscillation Ratings. An approach that utilizes the principles of good feedback control systems is suggested.

Introduction

Fly-by-wire control systems have become accepted state-of-the-art in high-performance aircraft since the first flight of the Air Force F-16A on 8 Dec. 1976, the world's first operational fly-by-wire aircraft. On 18 Nov. 1978, the Navy F/A-18 demonstrated the world's first digital fly-by-wire control system. Since then, a British Aerospace GR.MK.1 Jaguar has claimed the first all-digital fly-by-wire (no backup), and Dassault-Brequet, Saab, and Israeli Aircraft Industries are all developing digital fly-by-wire. Although all these systems are extremely complex and sophisticated with four active channels, they are essentially electronic equivalents of mechanical systems with additional features provided by the digital logic capabilities. The full potential of digital control is currently being exploited in the joint Air Force/Navy/NASA Advanced Fighter Technology Integration (AFTI-16) Advanced Development Program. The AFTI-16 program is directed at the development, integration, and flight test evaluation of emerging technologies for improving fighter aircraft mission effectiveness. In December 1978, General Dynamics (Fort Worth Division) was contracted for the design and implementation of the AFTI-16 systems and supporting aircraft modifications. Major development thrusts include a Digital Flight Control System (DFCS), Direct Force and Weapon Line Control, Pilot Vehicle Interface and Automated Maneuvering Attack System (AMAS). Development of an advanced highly reliable DFCS is the core technology building block for accomplishing the overall AFTI-16 objectives.

Application of DFCS technology provides the opportunity to integrate these advanced concepts into a multi-role, high-performance fighter aircraft to achieve operational versatility, improved overall mission effectiveness and decreased cost of ownership without sacrificing system reliability and safety. The DFCS portion of the program encompasses the complete development and integration of a multimode triplex DFCS employing decoupled six DOF flight path control capabilities. Primary flight control modes and associated control laws based on specific mission/weapon delivery requirements also provides the opportunity for enhancing overall mission effectiveness, while at the same time emphasizing the pilot's role as a mission manager rather than a subsystem operator. In consonance with this design philosophy, the following basic mission tailored control modes will be implemented in the AFTI-16 testbed: (a) Conventional Normal (CN) Mode with ancillary functions for take-off/landing, refueling, formation, cruise and pilot relief; (b) Air-to-Air Gunnery (AAG) Mode, (c) Air-to-Surface Gunnery (ASG) Mode, and (d) Air-to-Surface Bombing (ASB) Mode. Control law/sensor reconfiguration schemes will also be employed to provide optimum flight characteristics based on available functioning system elements. In each of these primary modes, the flight control system provides the necessary flight path decoupling, and desired vehicle response characteristics, specifically tailored and optimized for the appropriate mission segment. The numerous control combinations are shown in Figure 1 for the longitudinal control axis. A similar set is also available for the lateral-directional axes.

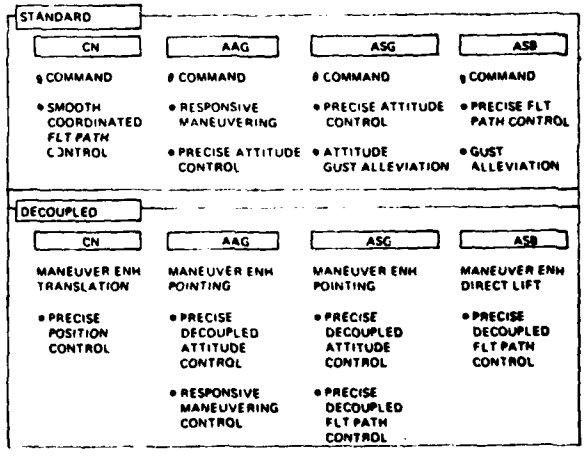


Fig. 1 Longitudinal Control Modes

A more detailed description of the AFTI-16 program and multimode control features is given in (1, 2).

I. Recent Advanced Aircraft Control Law Design Methodology

As previously noted, the AFTI-16 multimode control laws are structured to provide both standard conventional control and decoupled control. The standard control characteristics are tailored for maneuvering flight and target acquisition, and the decoupled control characteristics are tailored to vernier tracking and small-

amplitude weapon delivery error removal. High performance, unique maneuverability, rapid pitch and roll response, neutral speed stability, turn coordination, departure prevention, high angle-of-attack (AOA) performance, and high AOA command limiting are major design considerations in the development of AFTI-16 multimode control laws. Flying quality requirements such as MIL-F-8785B and suggested revisions thereto which have been developed for use in the design of conventional aircraft control systems, were utilized by the AFTI vehicle in the conventional modes. Since, by use of these criteria, deficiencies have been discovered in accurately predicting pilot ratings and tracking characteristics for the high-order systems associated with highly augmented aircraft; additional criteria such as C*, D*, Neal-Smith, and the newly developed step-target tracking techniques were used to compare results. Six DOF simulation results will provide the final test and acceptance criteria for all modes before flight testing.

The four basic task-tailored modes significantly affect the inner-loop design of the flight control system. The modes can also be categorized by the influence on performance of aircraft flight path, as in the CN and ASB Modes, or aircraft attitude as in the AAG and ASG Modes. This influence is manifested in the flight control system design by controlling the normal acceleration and pitch rate responses of the aircraft, respectively.

The analytical method used to derive the longitudinal axis feedback gains for each of the AFTI-16 standard modes is based on optimal control theory and is referred to as Linear Quadratic Synthesis (LQS). In this procedure, weighting parameters in a quadratic cost function are selected to yield systems with desirable performance characteristics. Weighting parameters reflect consideration of gust response, tracking performance, phase and gain margin, short period frequency and damping, transient response characteristics and other relevant performance indices. A simplified longitudinal block diagram of the CN, Mode is shown in Figure 2. In addition to the feedback gain variables, further response tailoring is provided to the system through the command path parameters, pilot gain (K_p) and pilot filter time constant ($1/a$). Optimum L/D flap scheduling is also provided.

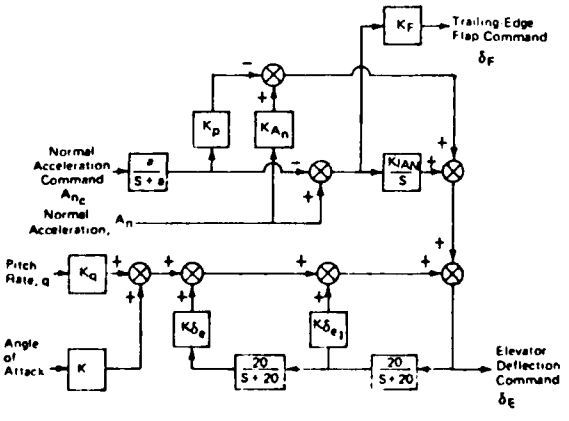


Fig. 2 Longitudinal CN Mode

This multimode design flexibility allows the flight control system designer to establish gains, feedbacks, and compensation parameters not only as a function of flight condition, but also as a function of the mode selected. The system performance can then be tailored to match the desired characteristics of a specific task at hand, e.g., air-to-air combat, air-to-surface bombing, etc. Besides the design flexibility obtained with a multimode system, the AFTI-16 vehicle utilizes the trailing-edge flap as an additional control surface (along with the horizontal tail) in the longitudinal axis to enhance its performance capability. The flap used in conjunction with the horizontal tail can produce changes in the lift vector without the corresponding rotation of the aircraft, characteristic of systems using only the horizontal tail for control. The motions of both flap and tail can be coordinated by proper control system design to provide maneuver enhancement, decoupled motions, and gust alleviation for the aircraft.

While the AFTI-16 program will provide design guidelines for circa 1990 flight control systems, it will not provide definitive criteria to ensure optimum performance for the mission-related flight modes or for highly augmented future aircraft.

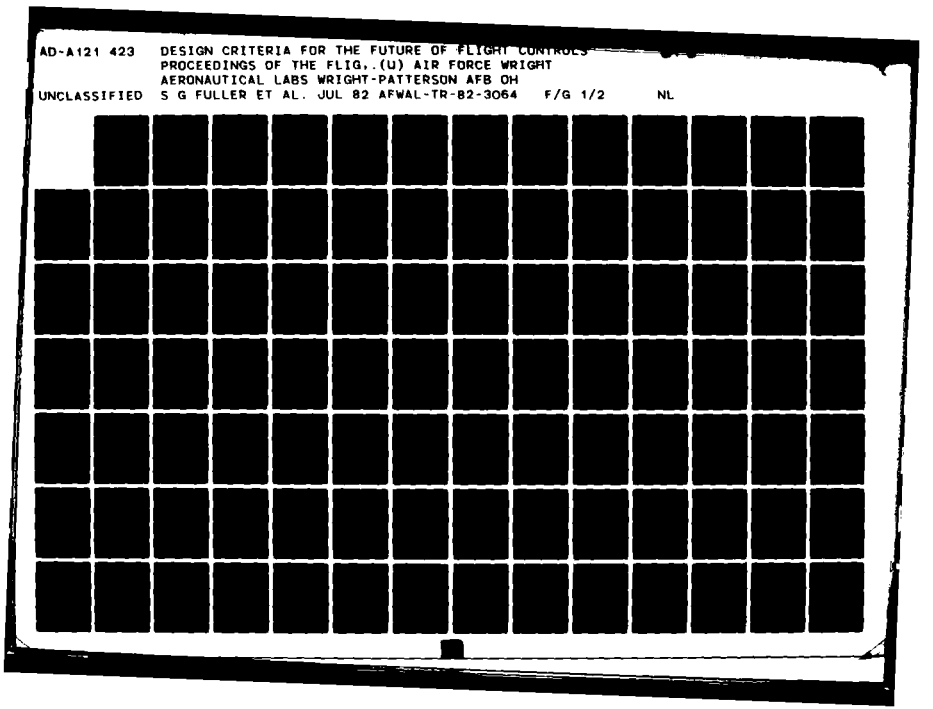
II. Design of Feedback Control Systems

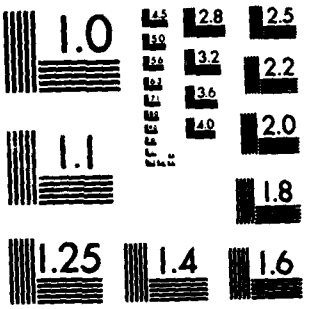
A. Theoretical Feedback Considerations

A flight control system is fundamentally a feedback control system, and is therefore subject to all feedback constraints. The reasons for using feedback are discussed in (3). In general, feedback is used to:

1. Contend with uncertainty of a plant and its environment.
2. Exploit the property that the static and dynamic characteristics of an element are altered by feedback.
3. Reduce the effect of a nonlinear element in the system.
4. Suppress the effects of undesired inputs.

The three basic problems inherent in the design of all feedback control systems are the feedback problem, the filter problem, and the control problem. The feedback problem or design of the loop transmission (L) to realize required insensitivity to variations in the plant and its environment, by linearization of nonlinearities and precision of the output despite estimated bounds of ignorance. The filter problem or design of the closed loop transfer function (C/R); if input (R) and noise (N) signals enter the system at the same point, it is desired that the output respond only to the input and reject the noise. The control problem or the variety of methods available for achieving a desired output (C). Choice of a control law will depend on performance requirements, plant capacity, plant saturation levels, nonlinearities, relations among multiple inputs and outputs, interface with other systems, etc. The satisfactory solution of a particular control problem will relate to an adequate description of the


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types of uncertainties and objectives that may be accommodated by different levels of [illegible], and optimum procedures for achieving the objectives.

B. Specifying Performance of Feedback Control Systems

In the process of synthesizing a feedback control system, the final design will evolve from a set of specifications defining performance in terms of minimum tolerable degree of stability, accuracy of control, transient behavior to both deterministic and stochastic inputs, etc. The nature of the specifications must be such that they are easily applied, readily demonstrated, contain no ambiguities or inconsistencies, serve as effective design guidelines, and do not allow unsafe or improper operation of the plant. Typically, system specifications are formulated in either the time, frequency, S-plane domain, or various combinations. A particular choice depends on the system's function and the nature of the inputs.

1. Time Domain

The ultimate performance of any feedback control system is exhibited in the time domain. All the generalized criteria of stability, accuracy, and transient behavior may be readily observed in this domain. For a second order-zero position error system, the response to a unit step input may be written as

$$c(t) = 1 + \frac{1}{\sqrt{1-\zeta^2}} e^{-\zeta \omega_n t} \sin\left(\sqrt{1-\zeta^2}\,\omega_n t - \theta\right)$$

$$\theta = \tan^{-1}\frac{\sqrt{1-\zeta^2}}{-\zeta}$$

If $c(t)$ is plotted versus $\omega_n t$ the curve shown in Figure 3 results. Note that the shape of the curve is determined solely by the damping ratio (ζ), while the natural frequency (ω_n) stretches or compresses the time scale. From Figure 3, it can be seen that the shape of the curve is described by the non-dimensional response parameters A_1, A_3, t_d', t_r', t_c' and t_s'. Since the shape of the second order response is defined by the single quantity ζ, then the response parameters are not independent, and the specification of one parameter (e.g. overshoot) will determine all five. However, the specification of ω_n will separate the non-dimensional and dimensional parameters, A_1, A_3 - t_d, t_r, t_c, t_s. Evidently, for a given ω_n, a ζ exists that will yield an optimum combination of these parameters. The challenge is to determine a suitable Figure of Merit (FOM) that will define an optimum response in the time domain.

2. Frequency Domain

Frequency domain (Bode) specifications are convenient as a solution to the filter problem where the bandwidth is an important consideration. In filter theory, the bandwidth determines the ability of the system to reproduce the shape of the input signal. For example, if a square pulse is applied as the input to a low-pass filter with a finite cutoff frequency (ω_c), the filter output will not be a square pulse but a distorted waveform depending on ω_c. The bandwidth is also an

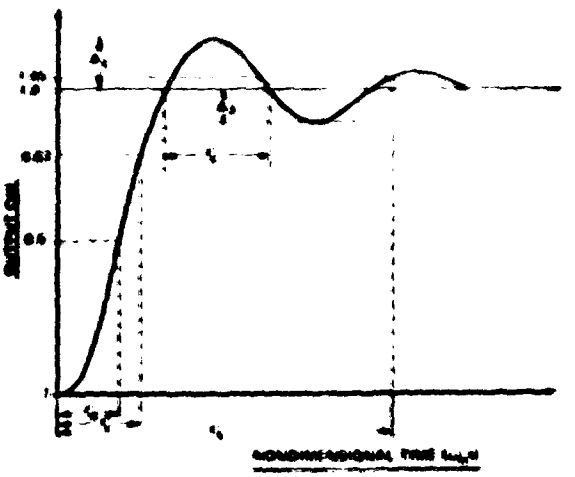


Fig 3 Key Transient Response Parameters

indication of the system's speed of response. In addition to bandwidth, the characteristics of the cutoff (slope) and peak amplitude are important. For control system design where statistical frequency information is available (i.e., structural resonance, turbulence, sensor noise), it may be necessary to design a system which blocks the transmission of signals in a particular frequency region, but transmit both lower and higher frequencies.

For a second order system, the closed loop transfer function may be written as

$$T(S) = \frac{\omega_n^2}{S^2 + 2\zeta\omega_n S + \omega_n^2}$$

For a sinusoidal input, $S = j\omega$

$$T(j\omega) = \frac{\omega_n^2}{-\omega^2 + 2\zeta\omega_n\omega + \omega_n^2} = \frac{\omega_n^2}{(\omega_n^2 - \omega^2) + j2\zeta\omega_n\omega}$$

$$T(ju) = \frac{1}{(1-u^2) + j2\zeta u}, \text{ where } u = \frac{\omega}{\omega_n}$$

$$|T| = \frac{1}{\left[(1-u^2)^2 + (2\zeta u)^2\right]^{1/2}} \quad \text{(Magnitude)}$$

$$\angle T = \tan^{-1} - \frac{2\zeta u}{1-u^2} \quad \text{(Phase Angle)}$$

A plot of the magnitude (amplitude) of T is given in Figure 4. The shape of the amplitude curve is defined by the nondimensional closed loop frequency parameters M, u_p, u_c, u_b, and u_n. Since the shape of the amplitude response is determined solely by ζ, it would be of interest to examine the relationships between time and frequency domain parameters as a function of ζ.

3. Parameter Relationships

From (4), the following relationships were extracted and are tabulated in Table 1.

III. Optimum Transient Response

A. Second Order-Zero Position Error

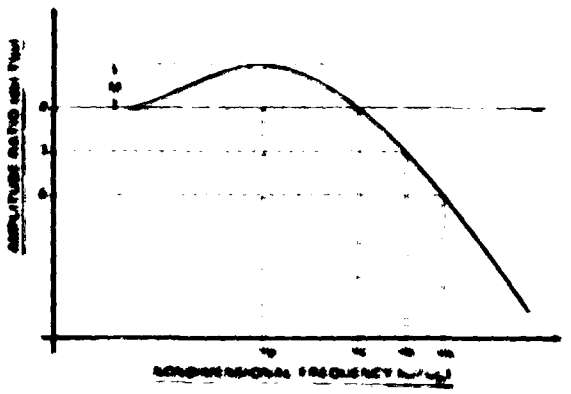


Fig. 4 Key Frequency Response Parameters

Table 1 Time and Frequency Relationships

Parameter	Relationship	Time/Freq. Correlation
M	$\frac{1}{2\zeta\sqrt{1-\zeta^2}}$, $\zeta < 1$	
ω_p	$\omega_n\sqrt{1-2\zeta^2}$	
ω_r	$\omega_n\sqrt{1-\zeta^2}$	
ω_b	$\omega_n\sqrt{1+\sqrt{4\zeta^4-4\zeta^2+2}}$	
ω_b	$\omega_n\sqrt{3+\sqrt{8\zeta^4-4\zeta^2+1}}$	
A_1	$e^{-\sigma t_r}$, $\sigma = \zeta\omega_n/\sqrt{1-\zeta^2}$	$e^{-2\pi\zeta^2/M}$
A_2	$e^{-3\sigma t_r}$	$e^{-2\pi(\zeta^2/M)\sqrt{1-\zeta^2}}$
t_d^*	$0.783\zeta^2 + 0.367\zeta + 1.056$	
t_r^*	$0.5\zeta^2 + 0.429\zeta + 1.287$	
t_s^*	$\ln 20\zeta$, $0 < \zeta < 1$	

*Note: Exact analytical expressions for t_d^*, t_r^*, and t_s^* are not feasible as they require solutions to a transcendental function.

The optimum transient response of a servomechanism which has a zero steady state displacement error for a step input may be characterized by a number of different criteria. In [5], a number of performance indices are suggested. For the second order closed loop transfer function

$$T(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} = \frac{1}{\left(\frac{s}{\omega_n}\right)^2 + 2\zeta\left(\frac{s}{\omega_n}\right) + 1}$$

Let

$$p = \frac{s}{\omega_n}, \text{ then}$$

$$T(\omega_n p) = \frac{1}{p^2 + 2\zeta p + 1}$$

Results of [5] indicate that the performance indices

$$\int_0^\infty |e|dt, \quad \int_0^\infty t|e|dt \text{ will be minimized if } \zeta = 0.707.$$

An additional significant property of $\zeta = 0.707$ may be obtained from the expression for closed loop amplitude

$$M = \frac{1}{2\zeta\sqrt{1-\zeta^2}}$$

If $M = 1$ (0db), then the amplitude response does not peak.

Solving for ζ

$$2\zeta\sqrt{1-\zeta^2} = 1$$

Squaring both sides

$$\zeta^4 - \zeta^2 + \tfrac{1}{4} = 0, \text{ or}$$

$$\zeta^2 = \tfrac{1}{2}$$

$$\zeta = 1/\sqrt{2} = 0.707$$

Therefore, for a second order-zero position error system, the smallest damping ratio that yields no peak in the amplitude response is $\zeta = 0.707$.

The important features of the transient response are A_1, t_d^*, t_r^*, and t_s^*. For improved accuracy, a digital computer program was used to obtain values for these parameters which are listed in Table 2.

Table 2 Key Parameters of a Second Order Transient Response

ζ	A_1	t_d^*	t_r^*	t_s^*	FOM
0.1	0.73	1.09	1.76	29.0	32.07
0.2	0.53	1.14	1.32	13.75	16.74
0.3	0.37	1.19	1.38	10.14	13.08
0.36	0.31	1.21	1.42	7.88	10.82
0.4	0.25	1.24	1.48	7.61	10.56
0.6	0.095	1.36	1.64	5.23	8.33
0.707	0.043	1.44	1.76	2.93	6.17
0.8	0.015	1.51	1.87	3.38	6.79
0.9	0.001	1.58	2.0	4.02	7.61

It has been established that an optimum damping ratio for a second order response is $\zeta = 0.707$. For this value of damping, the integrals $\int_0^\infty |e|dt$ and $\int_0^\infty t|e|dt$ are minimized and the amplitude response (M) does not exceed 0db. It is not clear, however, why these characteristics provide an optimum response. There must be additional criteria that are not so obvious. If Table 2 is used as a data source to determine why $\zeta = 0.707$ is so special, then significant trends may be observed. Since the parameters given in Table 2 completely identify the shape of the transient response, there must be some optimum combination that produces the best overall response. Therefore, assume an arbitrary Figure of Merit that consists of a linear combination of the key parameters. Let

$$\text{FOM} = A_1 + t_d^* + t_r^* + t_s^*$$

If FOM is plotted versus ζ for $\omega_n = 1.0$, the curve shown in Figure 5 results. It is evident that a minimum value occurs at $\zeta = 0.707$. While the meaning of this minimum value is not clear, it is clear that the significance of $\zeta = 0.707$ is that it produces a minimum value for a combination of parameters and not for any single parameter.

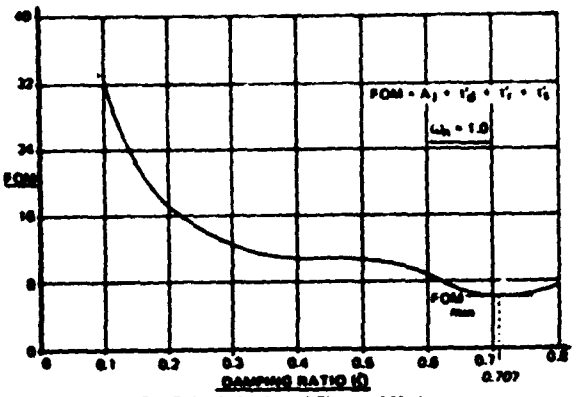


Fig. 5 Minimization of Figure of Merit

IV. Higher Order Effects

A. Third Order-Zero Position Error

A third order-zero position error system may be written as

$$T(S) = \frac{\omega_n^3 b}{a} \frac{(S + a)}{(S + b)\ (S^2 + 2\zeta\omega_n S + \omega_n^2)}$$

Let $a = N_1\ \omega_n$

$b = N_2\ \omega_n$

$$T(S) = \frac{(N_2 / N_1)\ \omega_n^2\ (S + N_1\ \omega_n)}{(S + N_2\ \omega_n)\ (S^2 + 2\zeta\omega_n\ S + \omega_n^2)}$$

Dividing numerator and denominator by ω_n^2

$$T(S) = \frac{N_2/N_1\ (S/\omega_n + N_1)}{(S/\omega_n + N_2)\ [(S/\omega_n)^2 + (S/\omega_n) + 1]}$$

Let $p = \frac{S}{\omega_n}$ then

$$T(\omega_n p) = \frac{(1 + p/n_1)}{(1 + p/N_2)\ (1 + 2\zeta p + p^2)}$$

For a unit step input

$$C(\omega_n p) = \frac{1/\omega_n\ (1 + p/N_1)}{p\ (1 + p/N_2)\ (1 + 2\zeta p + p^2)}$$

The above transfer function was programmed on a digital computer to obtain transient responses for various combinations of ζ, N_1, and N_2. Transient parameters for a value of $N_2 = 0.5$ are listed in Table 3.

The data contained in Table 3 is plotted in Figure 6. Note that the $N_1 = 0.5$ line corresponds to the values for a second order-zero position error system. For low values of $N_1 < 0.55$, increasing the damping ratio to $\zeta = 0.6$ tends to lower the FOM. For high values of $N_1 > 0.65$, a reversal of the trend begins, and for $N_1 > 1.0$, a damping ratio of $\zeta = 0.4$ appears to be optimum. Additional data from the digital program are plotted in Figures 7 and 8. A low-frequency zero ($N_1 = 0.10$) produces a significant variation from the second order FOM for all values of N_2. A

Table 3. Third Order Transient Response Parameters

$N_2 = 0.5$

ζ	N_1	A_1	t'_d	t'_r	t'_s	FOM
0.2	0.1	3.73	0.48	0.56	22.7	27.46
	0.2	1.88	0.70	0.80	19.4	22.58
	0.5	0.63	1.14	1.32	13.8	16.79
	0.7	0.34	1.33	1.55	13.5	16.72
	1	0.22	1.54	1.80	11.0	14.56
	2	0.13	1.90	2.19	11.0	15.22
	5	0.11	2.17	2.48	8.82	13.56
	10	0.11	2.27	2.58	8.90	13.86
0.3	0.1	3.19	0.49	0.56	13.9	18.14
	0.2	1.38	0.72	0.83	11.0	13.93
	0.5	0.37	1.18	1.38	10.14	13.07
	0.7	0.22	1.40	1.64	8.04	11.30
	1	0.12	1.63	1.92	8.13	11.80
	2	0.063	2.02	2.35	8.33	12.75
	5	0.037	2.29	2.65	8.64	13.52
	10	0.036	2.38	2.75	8.63	13.81
0.4	0.1	2.76	0.49	0.57	11.3	15.12
	0.2	1.15	0.74	0.86	9.2	11.96
	0.5	0.26	1.24	1.46	7.61	10.56
	0.7	0.12	1.47	1.76	7.43	10.77
	1	0.047	1.72	2.05	3.13	6.96
	2	0.0026	2.13	2.62	3.96	8.61
	5	0.0019	2.41	2.83	4.40	9.64
	10	0.0018	2.53	2.93	4.53	9.99
0.6	0.1	2.13	0.52	0.60	8.12	11.37
	0.2	0.80	0.78	0.91	6.84	9.33
	0.5	0.095	1.36	1.64	5.25	8.35
	0.7	0.0094	1.64	2.00	3.41	7.06
	1	0	1.92	2.37	4.46	8.75
	2	0	2.39	2.90	5.64	10.93
	5	0	2.69	3.23	6.09	12.01
	10	0	2.79	3.33	6.19	12.31
0.8	0.1	1.70	0.54	0.63	10.25	13.12
	0.2	0.57	0.83	0.98	8.46	10.84
	0.5	0.016	1.51	1.87	3.39	6.79
	0.7	0	1.84	2.31	4.94	9.09
	1	0	2.19	2.75	6.13	11.07
	2	0	2.67	3.33	7.0	13.00
	5	0	2.98	3.68	7.37	14.01
	10	0	3.09	3.76	7.49	14.34

damping ratio of $\zeta = 0.4$ yields a particularly large FOM. A high-frequency zero ($N_1 = 10$) produces excellent correlation with the second order FOM for $N_2 > 2$, but the correlation becomes extremely poor when $N_2 < 0.5$. It is also interesting to note from Figure 6 that at a value of N_1 between 2 and 5, a crossover occurs so that lower values of FOM are obtained for $\zeta = 0.2$ than $\zeta = 0.8$.

It is evident from the above discussion that the concept of damping ratio as defined for a second order-zero position error system becomes abstract when additional pole-zero combinations exist. For a limited range of pole-zero combinations, a correlation with second order damping ratio is realistic, but must be used with caution to ensure good transient response characteristics. A better performance index than damping ratio is the FOM which may be optimized for a particular application.

V. Application of Performance Indices to Manned Aircraft

A. Pilot-Airframe Considerations

The performance index suggested in Section III, that is, FOM = $A_1 + t'_r + t'_s + t'_d$ while

suitable for a positional servo or similar type of system, would not be suitable for specifying manned aircraft maneuvering performance. It does not consider the human performance factors as an element in the loop. In fact, any analytical approach which ignores the human element is doomed to failure, at least in correlating with pilot opinion. The FOM approach would appear to have considerable merit if it could be appropriately modified to reflect piloting factors.

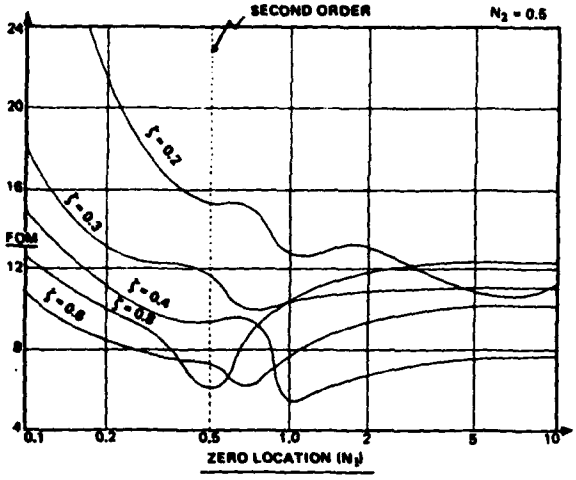


Fig. 6 The Effect of Zero Location and Damping Ratio on FOM

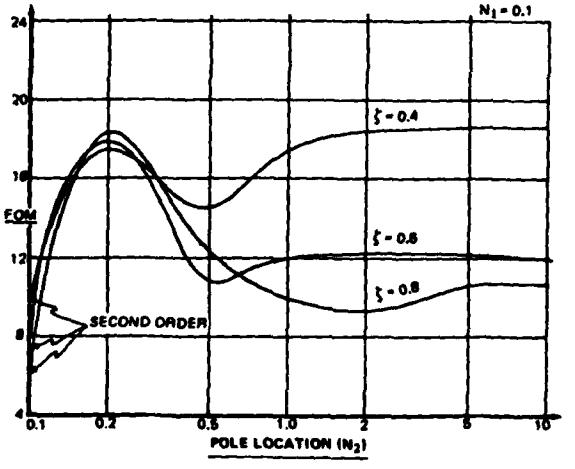


Fig. 7 The Effect of Pole Location and Damping Ratio on FOM

In the selection of a performance index for highly augmented aircraft, the following factors must be considered:

1. The augmented high-performance aircraft does not typically resemble the second order-zero position error system, and the significance of damping ratio and natural frequency is unknown for a system with arbitrary poles and zeros.

2. Artificial feel systems, actuation systems, and augmentation systems are significantly different among aircraft.

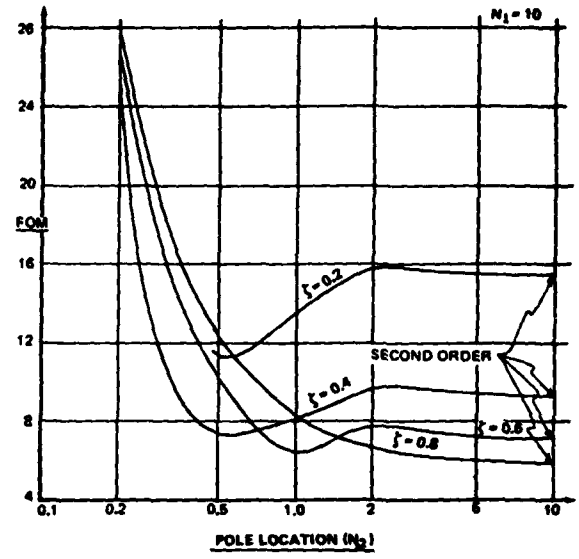


Fig. 8 The Effect of Pole Location and Damping Ratio on FOM

3. Structural modes of high-performance aircraft are decreasing in both frequency and damping, necessitating more complex compensation and further increasing the order of the airframe-SAS loop.

4. The trend toward command augmentation (fly-by-wire) introduces additional feed-forward shaping, increasing the emphasis on closed loop zeros.

5. The increasing flight envelope has placed severe demands on the fixed gain-compensation system, virtually requiring some form of gain switching.

6. Many schemes for self-regulating adaptive systems are nonlinear by nature, and preclude the use of linear-oriented performance indices.

7. A second order response due to its inherent limitations is rarely ever optimum for a given task.

8. The introduction of integrated control systems using two or more simultaneous controls will interject additional dynamic modes into the aircraft's maneuvering response.

The above factors indicate that a performance index similar to the one suggested in Section III, but suitably modified for aircraft use, may be required as a solution to specifying overall aircraft performance. A further complication is the many missions inherent in the role of fighter/attack aircraft, which must be accomplished in both VFR and IFR operation. Pilot tasks would include pitch attitude and altitude tracking, constant attitude and altitude turns, small perturbation maneuvers, high "g" maneuvers, and flight path control. It would be desirable to formulate a single performance index with the ability to distinguish between satisfactory and unsatisfactory flying qualities for all pilot tasks.

B. The Time Response Approach

It has been suggested that the pilot is concerned with the overall response of the airplane which is manifested by the time history of the airplane's variables. A reasonable assumption would be that the pilot's comments are in some manner related to the shape of the transient responses for a particular input. If such is the case, then the problem reduces to a selection of the critical variables and the parameters associated with each variable. For longitudinal control, there is a vast amount of research data indicating the critical nature of the pitch rate response as relating to pilot opinion. It is unlikely that pilot opinion could be correlated with any single parameter, and some are more important than others. While extensive research has shown the pilot is affected by the cyclic nature of the response, the correlation with pilot opinion has been generally poor and confused. Evidently, the cyclic characteristics must act in conjunction with other aspects of the response to be meaningful. It appears reasonable to expect that for a given cyclic characteristic, the pilot's rating will be affected by the delay time, and that for a given delay time the pilot's rating will be affected by the cyclic characteristic.

The major differences between an optimum response for the regulator problem and manned aircraft are in the tolerance that the pilot has in parameters such as overshoot, rise time, etc., and the relative importance (weighting) of these parameters. For the regulator problem an ideal response would be no overshoot, zero delay, and essentially an approximation of a step response. This would be unacceptable for a manned aircraft. If it is assumed that the shape of the transient response can be suitably defined to reflect all the key variables and parameters for a particular mission mode, then a performance index can be constructed. The index should have the following form

Time Response Parameter (TRP) = $(TRP)_{\alpha_1}$ + $(TRP)_{\alpha_2}$ + $(TRP)_{\alpha_n}$, where α_n = a controlled variable.

$$(TRP)_{\alpha_1} = K_{1\alpha_1}(A_{1\alpha_1} - k_{1\alpha_1}) + K_{2\alpha_1}(t_{d\alpha_1} - k_{2\alpha_1}) + K_{3\alpha_1}(t_{c\alpha_1} - k_{3\alpha_1}) + \cdots$$

There should be sufficient terms to adequately define the shape of the transient responses.

C. TRP Example For Longitudinal Control Axis

For the Conventional Normal (CN) mode shown in Figure 2, assume that the angle-of-attack input is not significant and the response is dominated by pitch rate and normal acceleration. Let

$$TRP = (TRP)_{\dot{\theta}} + (TRP)_{n_z}$$

1. Pitch Rate Response

a. Overshoot (A_1)

A certain amount of overshoot in pitch rate can be tolerated by the pilot without significantly affecting his rating. Such a value extracted from flying qualities data is $A_1 \leq 1.0$

Then $k_{1_{\dot{\theta}}} = 1.0$

b. Delay and Cyclic Times (t_d and t_c)

These parameters are defined in Figure 3. Two different responses are plotted in Figure 9. From Figure 9a, it is evident that response (1) will be preferred to response (2) for an input applied at t=0. It is not immediately evident which response will be preferred in Figure 9b if τ is significant, although they will probably both be unsatisfactory. An interesting observation from the above discussion is that the ratio (t_d/t_c) could conceivably serve as a suitable parameter.

Therefore, let $(TRP)_{\dot{\theta}} = K_{1\dot{\theta}}(A_{1\dot{\theta}} - 1.0) + (t_d/t_c)_{\dot{\theta}}$

2. Normal Acceleration Response

a. Overshoot (A_1)

The tolerable normal acceleration overshoot is less than that of pitch rate. A reasonable value suggested by the flying qualities data is $k_{1_{n_z}} = 0.3$

b. Dead and Delay Times (τ and t_d)

For a tail controlled aircraft, the normal acceleration response is typically non-minimum phase; that is, there is a dead time until the response goes toward the commanded direction. Since τ contributes to t_d, let it be included in t_d, and select a value of $t_d = 0.7$.

Therefore, let $(TRP)_{n_z} = K_{1n_z}(A_{1n_z} - 0.3) + K_{2n_z}(t_{d_{n_z}} - 0.7)$

3. Selection of Weighting Factors

The weighting factors $K_{1_{\dot{\theta}}}$, $K_{1_{n_z}}$ and $K_{2_{n_z}}$ must be carefully selected so as to properly weight the influence of each term. From the data given in (6), a set of non-optimum weighting factors was empirically determined.

Let $K_{1_{\dot{\theta}}} = 0.08$

$K_{1_{n_z}} = 0.3$

$K_{2_{n_z}} = 0.5$

Note: (1) $(t_d/t_c) = 0$ if $t_c = \infty$ (no overshoot)
(2) Only positive bracketed terms should be included.

4. Selection of TRP Values

For a high-performance aircraft, the values for the transient response parameters should be kept small so that the response will be rapid and well behaved. Hopefully, a trend will be observed, so that a small enough value for TRP will ensure a Pilot Rating (PR) of at least 2.0. Using the data of (6) as a baseline, a plot of PR versus

RP was constructed and is shown in Figure 10. The data for two pilots and two flight conditions shows a PR range of 2-10. The trend of PR with TRP is clearly evident. An exponential least mean squares curve fit of the data yields the following relationship.

$$PR = 10 - 12.19e^{-3.18\ TRP}$$

From these data, a suitable value for TRP is determined to be ≤ 0.23.

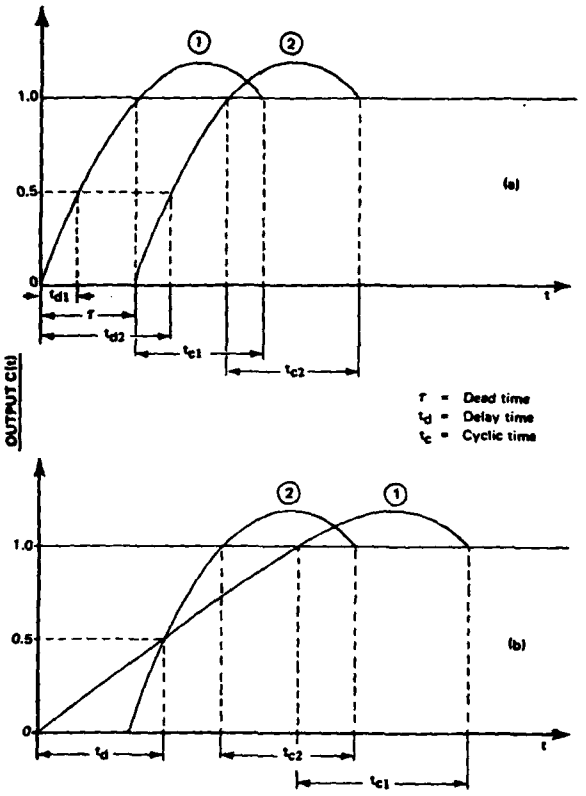


Fig. 9 Initial Pitch Rate Response Parameters

VI. Evaluation of TRP

A. F-15 Control System Development Simulator

An evaluation of several control criteria applicable to highly augmented aircraft was conducted on an F-15 simulator and reported in (7) and (8). The results were averaged for two different longitudinal control systems and shows excellent correlation of the TRP with PR.

The data however, suggests a linear fit rather than exponential as indicated in Figure 10. Since the only region of interest is that of TRP<0.23, the data of (6) and (7) is consistent with that of (5), as both produce PR<3.5. An analysis was also performed to determine the Pilot Induced Oscillation (PIO) trend with the TRP. The results are shown in Figure 12, and indicate a definite trend of increasing PIO tendencies with increasing TRP. From these data, a selected value would be $(TRP)_{pio} < 0.3$.

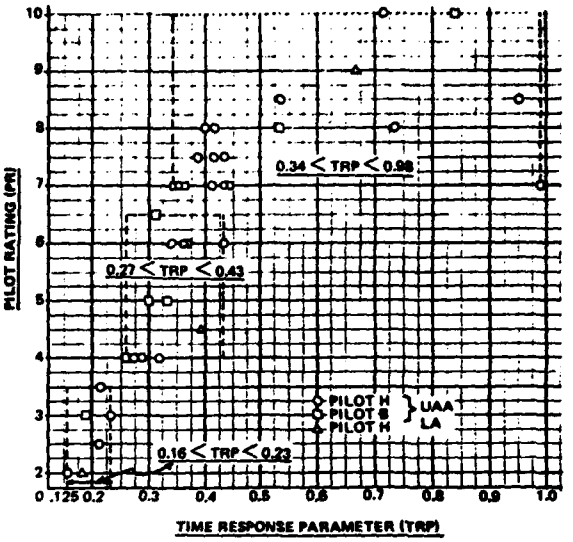


Fig. 10 Correlation of Pilot Rating With Time Response Parameter

B. Correlation With Other Criteria

A correlation was attempted with another proposed longitudinal time history specification, the well known C* whose boundaries are shown in Figure 13.

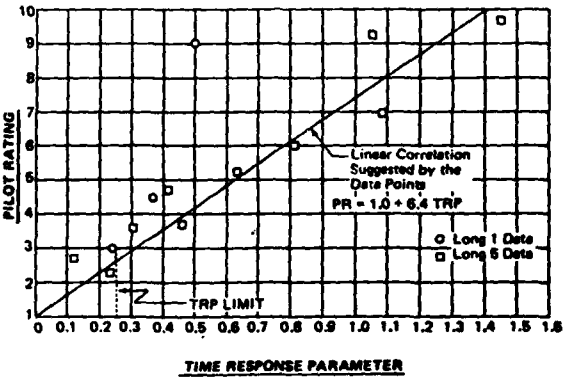


Fig. 11 F-15 Data Evaluation of TRP

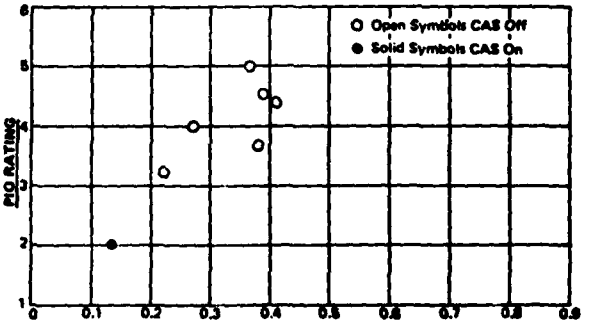


Fig. 12 PIO Rating Variation with TRP

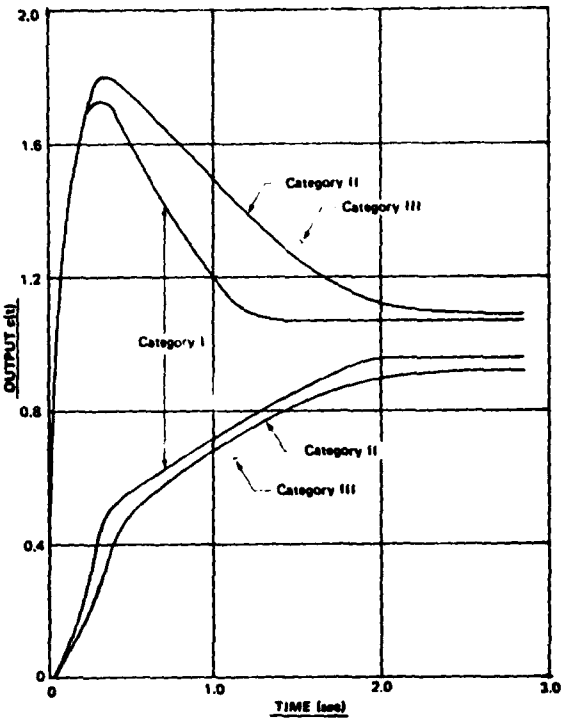


Fig. 13 C* Response Criterion

The categories are defined as follows:

Category	Applicable Tasks
I	Air-to-Air and Air-to-Ground Attack
II	Cruise and Refueling
III	Loiter

A hypothetical high-performance fighter was simulated for three flight conditions with TRP values ranging from 0 to 0.207. The results are shown in Figure 14, and all the responses lie well within the Category II boundaries. The responses are also very close to meeting the Category I boundaries. Referring to Figure 1, Category I is equivalent to the air combat modes and Category II is equivalent to the Conventional Normal (CN) Mode. The significance is that TRP correlates very well with C*, and with slight modification can probably be used to specify all the Standard Modes listed in Figure 1.

VII. Suggested Further Research

There are certain difficulties with the TRP in its present form which may be alleviated by further research. The following improvement areas should produce a criterion that will yield optimum control system designs for highly augmented aircraft.

1. Optimize weighting factors - perhaps variable factors as a function of dynamic pressure.

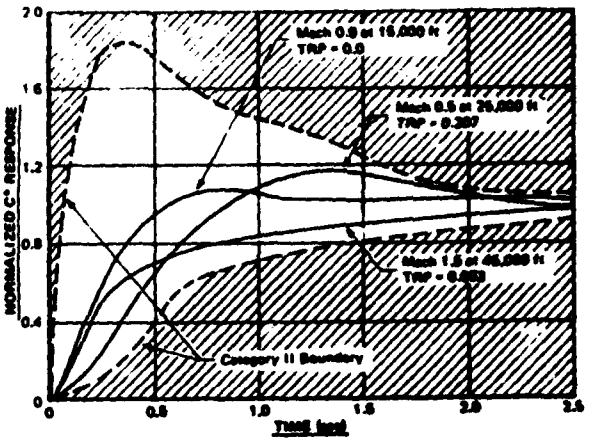


Fig. 14 Correlation of C* With TRP

2. Investigate TRP criteria for decoupled, direct force modes with deadbeat response.

3. Investigate the effect of high-frequency oscillations superimposed on a low-frequency response.

4. Investigate the sensitivity of TRP due to t_c being referenced to the final value.

5. Develop multivariable criteria for the lateral-directional modes.

6. Develop TRP criteria for specialized phases such as carrier landings. Example, TRP = $(TRP)_v + (TRP)_\alpha + (TRP)_\gamma$.

VIII. Conclusions

A versatile control criterion for highly augmented fly-by-wire aircraft has been proposed that can provide optimized mission-oriented performance. Based on an optimization process for a second order system, a Time Response Parameter has evolved that can be adapted to a variety of mission phases and new flight modes. The TRP approach has demonstrated definite trends with both Pilot Ratings and Pilot Induced Oscillation Ratings, and is also compatible with other transient response criteria. The TRP criterion can be readily applied to high order, nonlinear, and multivariable control systems, and is easily computerized for continuous evaluation of control system design. The use of such criteria will promote the utilization of military aircraft as a weapons platform through more effective flight control design.

References

1. Ramage, J. K. and Watson, J. M., Design Considerations For AFTI/F-16 Digital Flight Control System, presented at Meeting No. 46 of SAE Aerospace Control and Guidance Systems Committee, 13 November 1980, Ft. Worth, Texas.

2. Ramage, J. K., Abrams, C. R. and Watson, J. M., AFTI/F-16 Digital Flight Control System Development Status, presented at the 4th

AIAA IEEE Digital Avionics Systems Conference, 17-19 November 1981, St. Louis, Missouri.

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5. Kolnovitch, J., et al, Performance Criteria For Linear Constant-Coefficient Systems With Deterministic Inputs, Report No. ASD-TR-61-501, December 1961.

6. Di Franco, D. A., In-Flight Investigation Of The Effects Of Higher-Order Control System Dynamics On Longitudinal Handling Qualities, Report No. AFFDL-TR-66-90, August 1966.

7. Brulle, R. V. and Moran, W. A., Dynamic Flying Qualities Criteria Evaluation, Report No. AFFDL-TR-74-143, January 1975.

8. Brulle, R. V., Flying Qualities Evaluation Using F-15 Control System Development Flight Test Data, presented at SAE Aerospace Control and Guidance Systems Committee, 24-26 September 1975, Atlanta, Georgia

- COMMENTS RE PARA 3.1.2.6 Ride Smoothing OF FLIGHT CONTROLS MIL PRIME - (9490)

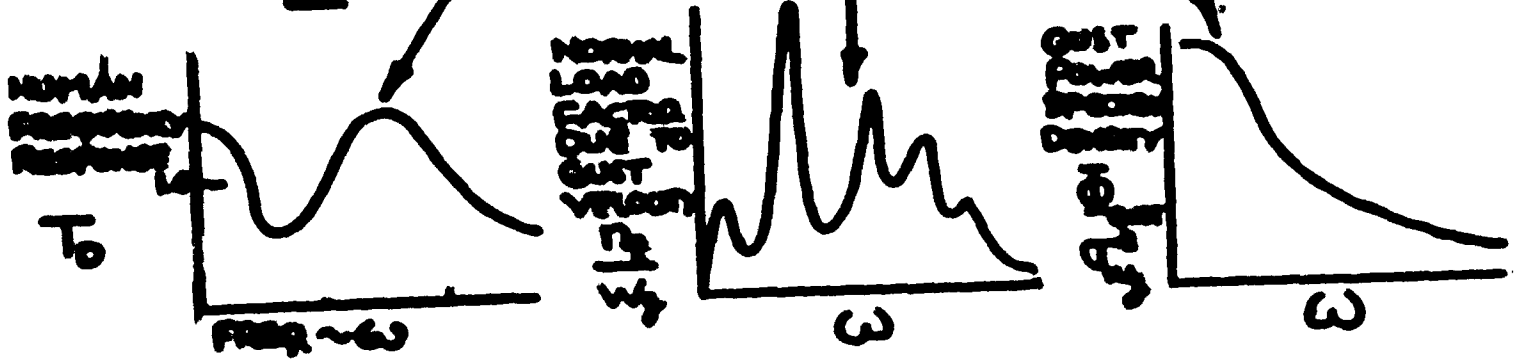
- APPENDIX A SUGGESTS $\bar{n}_z$ CRITERION BE USED

- B-1 RIDE QUALITIES STRUCTURAL MODE CONTROL SYSTEM BASED ON $\bar{n}_z$ CRITERION

C. A. Crothers
Rockwell International

CREW SENSITIVITY INDEX FOR RIDE QUALITY

$$\bar{H}_z = \left[\int_0^{\omega_{co}} |T_{D_z}|^2 \left| \frac{n_{z_{RIGID}}}{w_g} \right|^2 \frac{\Phi_{GUST}}{\sigma_{w_g}^2} d\omega \right]^{\frac{1}{2}} \frac{1}{FT/SEC}$$



$\bar{H}_y$, LATERAL CREW SENSITIVITY INDEX ASSEMBLED SIMILARLY WITH T_{D_y}, $\frac{n_y}{\sigma_{w_g}}$.

MIL-F-9490D RIDE QUALITY SPECIFICATION

$$D_{i_2} = \left[\int_{\omega=0}^{\omega=\infty} |W|^2 \left| \frac{n_z}{w_g} \right|^2 \frac{\Phi_{gust}}{\sigma_{w_g}^2} \sigma_{w_g}^2 \, d\omega \right]^{\frac{1}{2}}$$

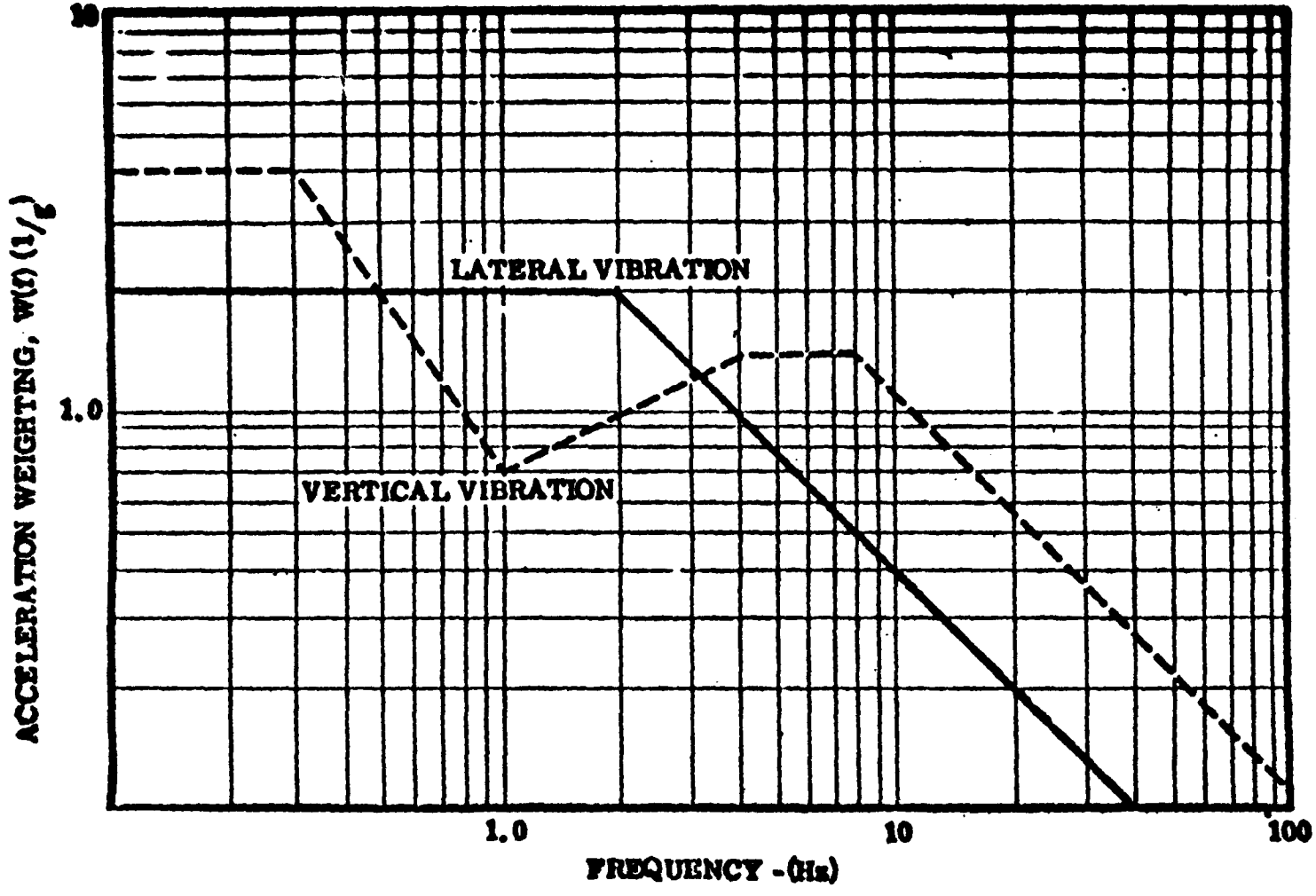
WEIGHTING FUNCTIONS

FROM TABLE IV

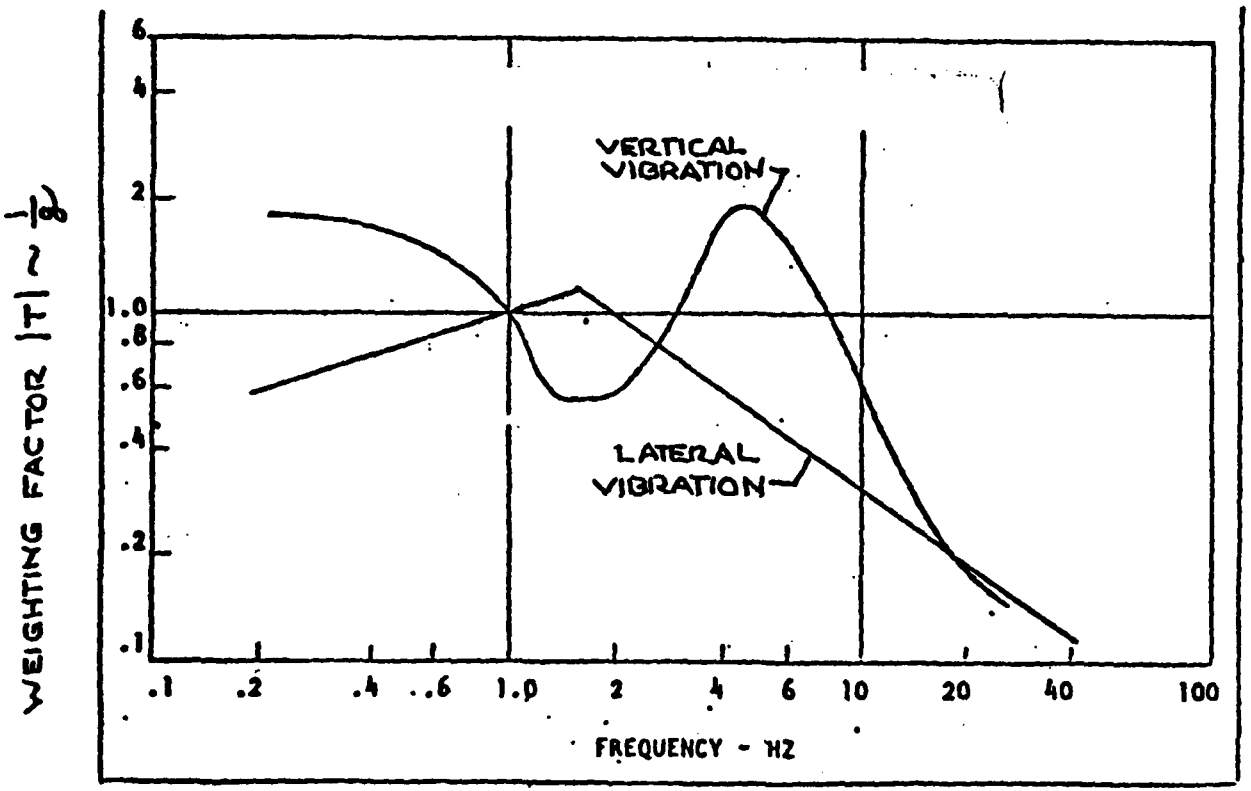
TABLE II
RIDE DISCOMFORT INDEX LIMITS

Ride Discomfort Index, D_i		Flight Phase Duration (Exposure Time)	Probability of Exceeding RMS Turbulence Intensity
Long Term Requirement	0.10	Over 3 Hours	0.20
	0.13	From 1.5 to 3 Hours	0.20
	0.20	From 0.5 to 1.5 Hours	0.20
Short Term Requirement	0.26	Less than 0.5 Hour	0.01

HUMAN TRANSFER FUNCTIONS (WEIGHTING FUNCTIONS)
D_i CRITERIA



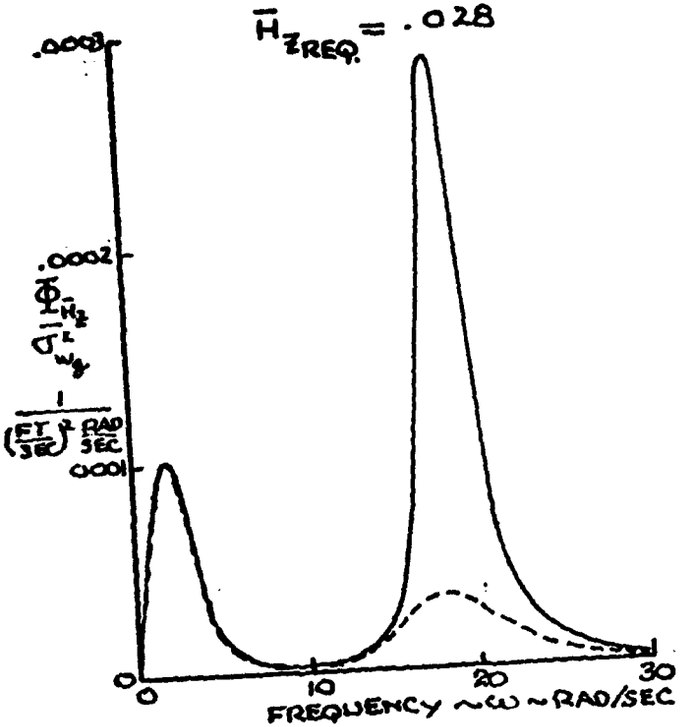
HUMAN TRANSFER FUNCTIONS (WEIGHTING FUNCTIONS)
$\bar{H}$ CRITERIA



B-1 RIDE QUALITY IN $\bar{H}$ AND D_i FORMATS

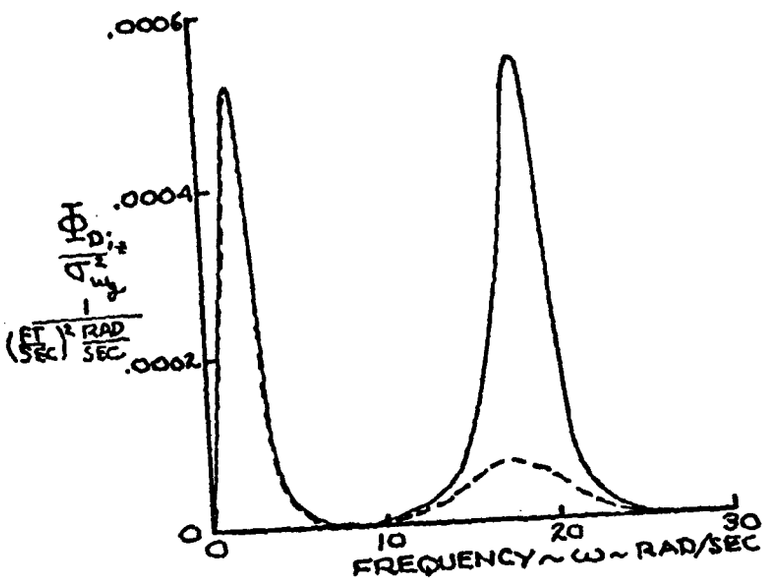
—— SCAS , $\bar{H}_z = .0395$
--- SCAS + SMCS, $\bar{H}_z = .0267$

$\bar{H}_{z_{REQ.}} = .028$



—— SCAS , $D_{i_z} = .187$
--- SCAS + SMCS $D_{i_z} = .132$

$D_{i_{Z\,REQ.}} = .100$



M = .85, S.L.
WT. = 263,000 LBS, $\Lambda = 65°$

CREW COMMENTS ON SMCS EFFECTIVENESS

RIDE QUALITIES

"SMCS IS VERY EFFECTIVE AND REQUIRED IN B-1 TO AID THE FLIGHT CREW IN PERFORMANCE OF THE TF TASK" (PILOT).

"ESSENTIAL FOR EFFECTIVE B-1 MTF, DESIRED FOR EFFECTIVE B-1 ATF" (PILOT)

"I CONSIDER SMCS ESSENTIAL FOR LONG TERM TF FLIGHT" (OFFENSIVE SYSTEMS OPERATOR)

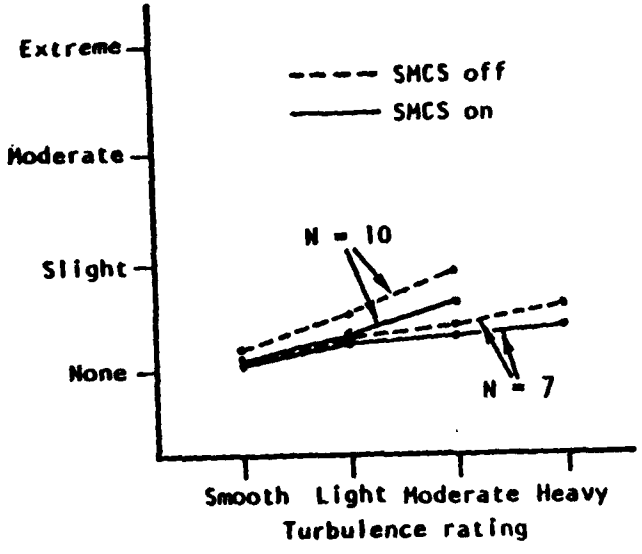
HANDLING QUALITIES

"AIRCRAFT RIDE IS SMOOTHER WITH SMCS ON AND THEREFORE CONTROL IS EASIER" (PILOT)

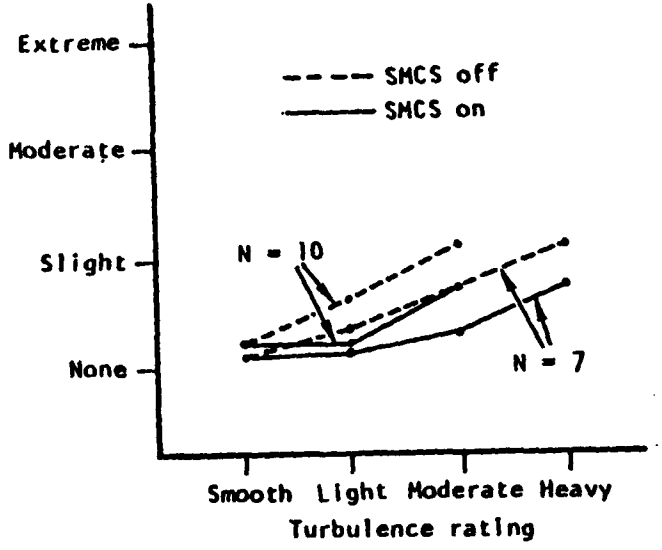
LOW FREQUENCY MOTION EFFECTS
B-1 FLIGHT TEST DATA

N=NUMBER OF TEST PARTICIPANTS

MOTION SICKNESS EFFECT RATING



PHYSICAL DISCOMFORT EFFECT RATING



MIL-PRIME - (9490D)

PARA 3.1.2.6 RIDE SMOOTHING

- THE RECOMMENDED D_1 CRITERION IS TOO SEVERE AND WILL PENALIZE FUTURE AIRCRAFT UNDULY

- THE $\bar{H}$ CRITERION USED ON THE B-1 PRODUCED A SATISFACTORY AIRCRAFT

- THE DIFFERENCE IS TRACEABLE TO THE ACCELERATION WEIGHTING FACTOR IN THE LOW FREQUENCY (MOTION SICKNESS) REGION

CONCLUSIONS AND RECOMMENDATIONS OF THE WORKSHOP ON FLIGHT TESTING TO IDENTIFY PILOT WORKLOAD AND PILOT DYNAMICS

by

Robert B. Crombie, Captain, USAF
Flight Dynamics Laboratory

Michael L. Frazier
Air Force Flight Test Center

SPONSORS. The Workshop on Flight Testing to Identify Pilot Workload and Pilot Dynamics was held at the Edwards AFB Officer's Club 19-21 January 1982. The workshop was sponsored by the Air Force Flight Test Center in conjunction with the Flight Dynamics Laboratory, NASA-Dryden, the American Institute of Aeronautics and Astronautics, and the Human Factors Society.

NEED. This paragraph outlines the need that motivated this workshop. Advances in avionics and control systems have increased the mission capability of military and civil, fixed- and rotary-winged aircraft. The challenge to designers of advanced aircraft systems now is to make the crewmember's job easier, i.e., to allow him to precisely control the aircraft and successfully perform the mission while maintaining adequate mental and physical reserve capacity to handle emergencies. This design problem calls for all parties involved in the research, development, test, and evaluation of advanced aircraft to understand the elements that influence the efficient interaction between the pilot and aircraft. Fundamental to this understanding are quantitative measures of pilot workload and performance, and descriptive models of the pilots's dynamics. Currently such measures and models are not mature enough for reliable use in the testing and development of advanced aircraft. A forum is needed to gather the proper expertise in the areas of flight testing, workload measurement, pilot-in-the-loop dynamics, and applications so that the state-of-the-art in these areas can be understood and approaches can be recommended that will develop flight-worthy measures of pilot workload and flight-validated models of pilot dynamics. The present workshop, the fourth in an annual series exploring specialized areas of flight testing, was structured to meet this need.

OBJECTIVE. The objective of this workship was to bring together technical experts working with various measures of pilot workload and performance and with various models of pilot dynamics to meet face-to-face with the flight test and applications community and together to define:

1. The need for and applications of flight-worthy measures of pilot workload and flight-validated models of pilot dynamics,

2. The state-of-the-art and current problems to be overcome in order to measure pilot workload or task performance in flight or to tailor flight tests to identify pilot dynamics, and

3. Recommended ways to solve these technical problems.

AGENDA. More than 150 people from over 50 organizations attended the workshop. The participants were involved in various segments of aircraft research, development, test and evaluation and represented several technical disciplines including human factors, pilot dynamics, pilot modeling and flying qualities. The three-day agenda of workshop presentations is given in the Appendix. The first day had overview papers on the subjects of pilot workload, pilot dynamics, and flight test requirements. Presentations that day also described the various mission environments encountered by advanced aircraft and design procedures used to improve pilot-vehicle performance capability. The second day addressed the quantification of pilot workload using measures of spare mental capacity, subjective ratings and pilot physiology. The final day covered the identification of pilot dynamics and task performance including the measurement of pilot performance, the modeling of pilot dynamics and the collection of flight test data. The following conclusions and recommendations are extracted from the proceedings.

FLIGHT TESTING TO IDENTIFY PILOT WORKLOAD. Workload is a multidimensional concept in which the pilot (physiology, perceptions, technique, training), the vehicle (dynamics, controls, displays, subsystems), the tasks (number, difficulty, relative importance) and the environment (stress, disturbances) all play significant and interrelating roles. Each aspect must be carefully considered in order to effectively assess pilot workload in flight. One or several of these aspects of pilot workload have been objectively measured in flight by Schiflett, Van de Graaff, Roscoe, the Navy Pacific Missile Test Center and the Air Force School Aerospace Medicine. Important measures that show near-term promise for assessing pilot workload in flight are pilot subjective ratings, rate of pilot control activity, heart rate, and secondary task performance. Several other measures were proposed in the proceedings. The most promising of these for further development appears to be the event-related brain potential described by Donchin and Biferno.

Workload should be specifically addressed throughout the systems acquisition process. Workload technology promises to become as useful in the design, development, test and evaluation of new systems as flying qualities technology is today. Resources should continue to be allocated to measuring pilot workload because increasingly complex mission demands continue to be made of pilots and their aircraft.

FLIGHT TESTING TO IDENTIFY PILOT DYNAMICS AND TASK PERFORMANCE. These areas are complementary to the evaluation of pilot workload and thus deserve careful attention. Van de Graaff has successfully combined measures of pilot dynamics, pilot workload, and task performance on a helicopter in-flight experiment. Complementary measures for each of these areas are listed in an annotated bibliography of "Pilot Performance" measures authored by Mixon and Moroney.

Models of pilot dynamics are presently being used to design dynamic characteristics of flight controls and displays. However, the usefulness of the models has been hampered by the lack of validating flight test data. Methods for identifying pilot dynamics have been successfully used during simulation, but in-flight experience is lacking. Often the cues the pilot is sensing are difficult to instrument or measure. However,

it is still important to determine the strategy and dynamics used by pilots during critical flying tasks to validate simulator fidelity and aid in vehicle design.

Task performance or mission effectiveness measures are important in the design and evaluation of aircraft. They are quite sensitive to variations in the task and initial conditions and must be applied and interpreted very carefully.

RECOMMENDATIONS. Two primary technical recommendations for the research and development community resulted from the workshop.

1. Define and introduce into common use a standardized set of objective and subjective workload and task performance measures and procedures. Such a set will encourage those conducting experiments to plan and report findings that will be meaningful throughout the pilot workload, pilot dynamics, and task performance disciplines. Flight test engineers could then adapt the measurement set to particular experimental circumstances. Not all the elements of the set would need to be measured in every experiment.

2. Hold periodic conferences to stimulate the exchange of technical results among the disciplines involved in the measurement of pilot workload, pilot dynamics and mission effectiveness. These conferences will allow the lessons learned in the present workshop to be applied, extended, and distributed widely. Perhaps next year's Annual Conference on Manual Control could be expanded to meet this need.

In addition, flight research projects should be undertaken to validate pilot workload measurement techniques and models of pilot dynamics. This is needed to develop confidence in those measurement techniques and models so that they may be effectively used by designers of advanced aircraft.

PROCEEDINGS. The "Proceedings Of The Workshop On Flight Testing To Identify Pilot Workload And Pilot Dynamics" is being published as AFFTC-TR-82-5. The proceedings are unclassified and cleared for public release. The controlling office is AFFTC/ENAH, Stop 239, Edwards AFB, CA 93523. The volume is approximately 780 pages long. Copies may be obtained from the National Technical Information Service or the Defense Documentation Center.

APPENDIX - WORKSHOP AGENDA

OVERVIEW OF PILOT WORKLOAD, PILOT DYNAMICS, AND FLIGHT TEST REQUIREMENTS
Tuesday, 19 January 1982

I. PRELIMINARIES

II. OVERVIEW OF VARIOUS MISSION ENVIRONMENTS AND THE PROBLEM OF PILOT WORKLOAD

"Pilot Workload in Single-Seat Fighters: Past, Present, and Future" - Lt Col D. Milam (AF Flight Test Center)

"Task Demands and Pilot Workload in Army Helicopter Missions" - R. Dunn (Army Research and Technical Lab)

"Workload Requirements of a Helicopter Anti-Submarine Warfare Mission" - CDR R. Sigrey (Naval Air Test Center)

"Civil Aviation Airman Performance Enhancement and Error Reduction" - P. Ruschinsky (Federal Aviation Administration)

III. GENERAL BACKGROUND

"History of Pilot Workload Measurement" - Lt Col R. O'Donnell (AF Aerospace Medical Research Lab)

"Present and Future Workload and Fatigue Measurement Development Programs" - J. Courtright (AF School of Aerospace Medicine)

"A Brief History of Applications of Pilot Dynamical Models, the State of the Art and Needs for Flight Testing" - R. Anderson (AF Flight Dynamics Lab)

IV. PILOT/VEHICLE/ENVIRONMENT INTERRELATIONSHIPS AND THEIR INFLUENCE ON PILOT WORKLOAD AND PERFORMANCE

"Restraint Considerations in Dynamic Environments" - D. Rogers (AF Aerospace Medical Research Lab)

"The Effects of Acceleration, Turbulence, and Control Loop Dynamics on Pilot Ratings and Performance" - A. Piranian (Naval Air Development Center)

V. PILOT/VEHICLE/TASK INTERRELATIONSHIPS IN THE DESIGN OF ADVANCED AIRCRAFT

"Automated Aircraft and Flight Control System Design" - M. Ostgaard (AF Flight Dynamics Lab)

"Cockpit for the Future and Challenges to Workload Measurement" - L. Butterbaugh (AF Flight Dynamics Lab)

"Flying Qualities Specification Related to Task Performance" - F. George (AF Flight Dynamics Lab)

"Development of Controller Requirements for Uncoupled Aircraft Motion" - J. Stolpinann, K. Citurs (McDonnell Aircraft), R. Rish (Systems Technology, Inc.), T. Card (AF Flight Dynamics Lab)

VI. FLIGHT TEST NEEDS AND REQUIREMENTS

"An Army Aviation Viewpoint" - R. Dunn (Army Research and Technical Lab)

"A Naval Aviation Viewpoint" - S. Schiflett (Naval Air Test Center)

"The Flight Research Viewpoint" - D. Barry (NASA Dryden)

"AFTTC Needs and Requirements" - C. Jones (AF Flight Test Center)

TAILORING FLIGHT TESTS TO IDENTIFY PILOT WORKLOAD
Wednesday, 29 January 1992

I. INTRODUCTION

"Measuring Airborne Workload: Problems, Progress, and Promises" - R. Jex (Systems Technology Inc.)

II. SPARE MENTAL CAPACITY

"Evaluation of a Pilot Workload Assessment Device to Test Alternate Flagship Formats and Control Handling Qualities" - S. Schiflett (Naval Air Test Center), P. Linton (Naval Air Development Center), R. Eggleston (Systems Research Labs)

"Quantification of Pilot Workload via Instrument Scan" - J. Tole (Stevenson Polytechnic Institute), A. Stephens (Boeing Company), R. Harris (NASA Langley), A. Ephrath (Dell Labs)

"Helicopter Pilot Performance and Workload as a Function of Night Vision Systems" - E. Merrell (Army Aeromedical Lab)

"An Investigation of the Effects of an Isometric Side Stick Controller on Pilot Workload for Helicopter Terrain Flight" - J. Hindsperry (NASA Ames)

"The Elusive Goal of Measuring Pilot Workload in General Aviation" - E. Stein, J. Perry, D. Rosenberg (Federal Aviation Administration Technical Center)

III. SUBJECTIVE RATINGS AND OPINION

"Subjective Workload Assessment Technique" - C. Reid (DF Aerospace Medical Research Lab)

"Assessment of Reliability and Validity of the Subjective Operability Technique, SOFT" - K. Williams, S. Hargenstein (Naval Pacific Missile Test Center)

"Validation of Pilot Workload Subjective Utility In-Flight Data" - R. Galish (Douglas Aircraft Company)

IV. PHYSIOLOGICAL MEASURES

"New Tools for Assessing Aircraft/Pilot Performance" - L. York (SRI International)

"A Self-Contained, Non-Invasive Biomedical Instrumentation System in the Flight Testing of Naval Weapons Systems" - CDR D. Call, LCDR D. Kelly, D. Robertson (Naval Pacific Missile Test Center)

"Physiological and Performance Parameters as Indices of Pilot Workload: An Analysis of Data from the AFTI/F-16 Project" - MAJ CDR D. Raabe (AF School of Aerospace Medicine)

"Heart Rate as an In-Flight Measure of Pilot Workload" - A. Roscoe (Royal Aerospace Establishment)

"Some Physiological Changes in Lateral (Gy) Acceleration" - Karl J. Poppen (AF Aerospace Medical Research Lab)

"Event Related Potentials as Indices of Workload" - E. Donchin, C. Wickens (University of Illinois at Urbana - Champaign)

V. MULTIPLE MEASURES

"Human Factors in Night Attack - Test Methodology" - Lt(s) P. Long (AF Test and Evaluation Center)

"Theoretical Basis for NASA Ames Workload Research" - S. Hart (NASA Ames)

"Determination of Sensitive Measures of Pilot Workload as a Function of the Type of Piloting Task" - W. Wierwille (Virginia Polytechnic Institute)

TAILORING FLIGHT TESTS TO IDENTIFY PILOT DYNAMICS AND TASK PERFORMANCE
Thursday, 21 January 1982

I. PILOT PERFORMANCE MEASUREMENT

"Objective Pilot Performance Measures" - W. Moroney, T. Nixon (Naval Postgraduate School)

"A Study of Task Difficulty with a Subjective Rating Scale" - D. Rapperger, D. Rogers, R. VanPatten, J. Frazier (AF Aerospace Medical Research Lab)

II. CLASSICAL MODELS OF PILOT DYNAMICS

"Overview of Work in Progress on Non-Intrusive Pilot Workload Assessment" - R. Heffley, W. Jewell, W. Clement (Systems Technology Inc.)

III. OPTIMAL CONTROL MODELS OF PILOT DYNAMICS AND TASK PERFORMANCE

"The Optimal Control Model for the Human Operator: Theory, Validation and Application" - W. Levison (Bolt Beranek and Newman Inc.)

"Time Domain Identification of the Optimal Control Pilot Model with Emphasis on the Objective Function" - D. Schmidt (Purdue University)

"Information Requirements, Display Evaluation and Workload Assessment in a Simulated Terrain Following Task" - D. Kleinman, S. Gully, J. Korn (Alphatech Inc.)

IV. OTHER MODELS OF PILOT DYNAMICS AND TASK PERFORMANCE

"Development of a Pilot Model for Helicopter VMC Flight-Task Segments" - A. Phatak, M. Karmali (Analytical Mechanics Associates), E. Hartzell (Army Aeromechanics Lab)

V. FLIGHT TESTING TO IDENTIFY PILOT DYNAMICS AND TASK PERFORMANCE

"Pilot Model Determination Using Parameter Identification Methods on Hovering VTOL Flight Data" - D. Andrisani II, S. Bourne, C. Gau (Purdue University)

"Flight Measurements of Pilot Performance and Workload for UH-60 Simulation Validation Assessment" - W. Cleveland (NASA-Ames), R. Heffly (STI), D. Key (Army Aeromechanics Lab)

"Methods for Identifying Pilot Dynamics" - W. Levison (Bolt Beranek and Newman Inc.)

"The AFTI/F-16 Flight Test Program and Opportunities to Identify Pilot Dynamics and Workload" - Capt R. Crombie (AF Flight Dynamics Lab), M. Frazier (AF Flight Test Center)

RECENT FLIGHT TEST RESULTS PERTAINING TO LONGITUDINAL FLYING QUALITIES CRITERIA

Robert F. Stengel
Princeton University
Flight Research Laboratory
Department of Mechanical and Aerospace Engineering
Princeton, N.J. 08544

The Flight Research Laboratory (FRL) at Princeton University is conducting experiments to determine the flying qualities of aircraft equipped with high-order control systems, to investigate the effects of modelling the high-order dynamics with low-order equivalent systems, and to correlate flight test results with candidate flying qualities criteria. These tests make use of Princeton's Variable-Response Research Aircraft (VRA), which is equipped with a Microprocessor-based Digital Flight Control System (Micro-DFCS). Particular attention is directed at aircraft carrier approach and landing, with flight paths extending through touchdown. Test pilots from the U.S. Naval Air Test Center, Patuxent River, MD, perform the flight evaluations, which currently concentrate on the aircraft's longitudinal modes.

This is a presentation of work in progress. The research is sponsored by the U.S. Naval Air Development Center, Warminster, PA.

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* Presented at "Design Criteria for the Future of Flight Controls", AFFDL Flying Qualities Symposium, Dayton, March 2-5, 1982.

AVAILABLE COPY

RECENT FLIGHT TEST RESULTS
PERTAINING TO LONGITUDINAL FLYING QUALITIES CRITERIA*

- EXPERIMENTAL OBJECTIVES
- FLIGHT TEST AIRCRAFT AND SYSTEMS
- CONFIGURATIONS AND RESPONSE
- PILOT OPINION RATINGS FOR FCLP THROUGH TOUCHDOWN
- TASK DEPENDENCE OF PILOT RATINGS

---

* CONTRACT NO. N62269-80-C-0720 FOR NAVAL AIR DEVELOPMENT CENTER, WARMINSTER, PA.

EXPERIMENTAL OBJECTIVES

Twenty-nine response configurations have been defined for flight test; to date, twenty of these have been evaluated by two Navy pilots and FRL's chief test pilot. They have compared the response of high-order systems to that of low-order equivalent systems defined using two matching assumptions. They have evaluated the effects of pure time delay for aircraft characterized by slow and moderately fast response. They will evaluate the effects of the distance between the pilot and the aircraft's center of gravity in future flights. All of the pilot opinion results will be correlated with several flying qualities metrics to determine which of the latter is the best indicator of pilot opinion.

EXPERIMENTAL OBJECTIVES

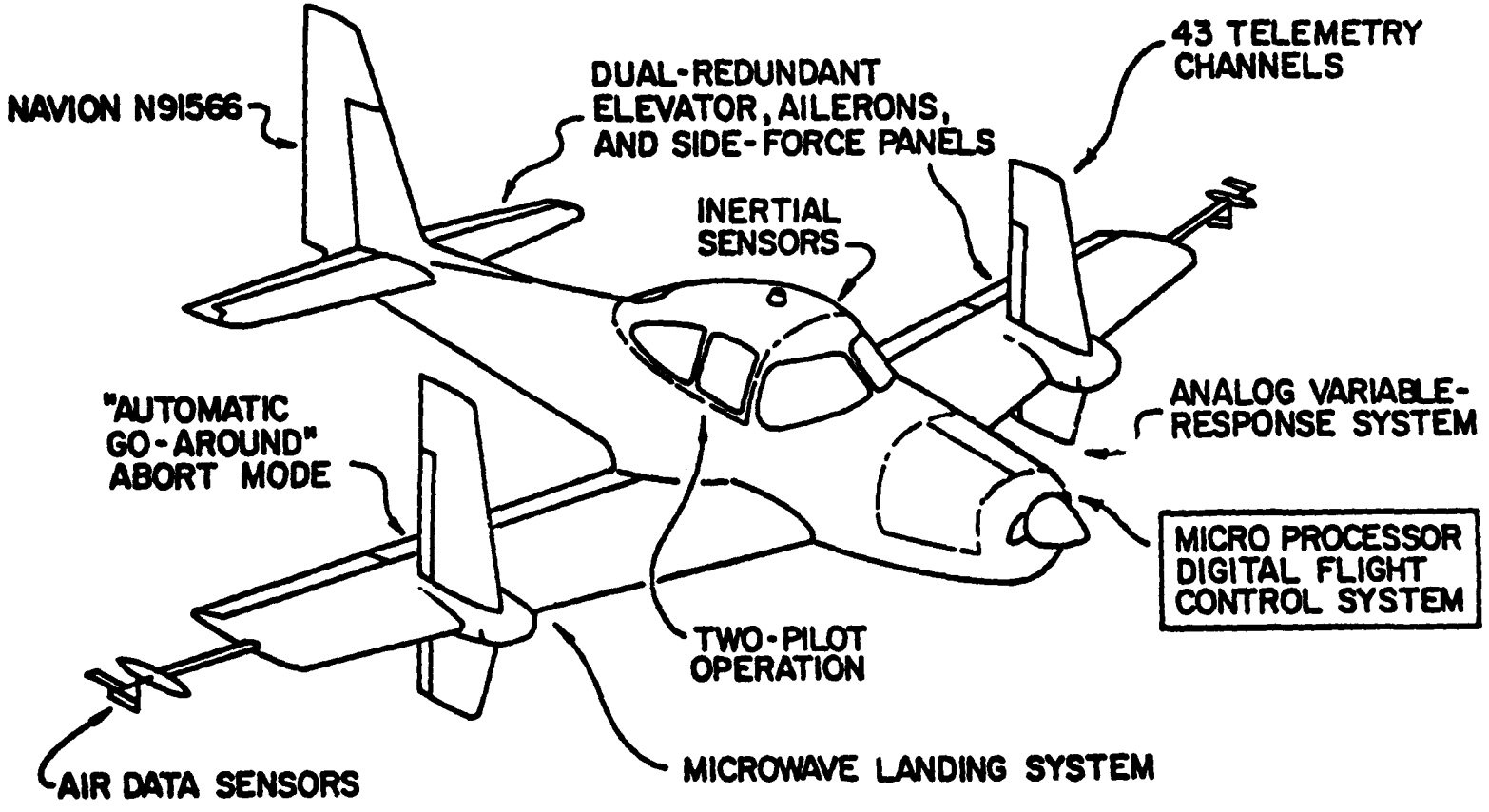
- LONGITUDINAL FLYING QUALITIES DATA FOR CARRIER APPROACH THROUGH TOUCHDOWN
- EVALUATION OF EQUIVALENT SYSTEM MATCHING ASSUMPTIONS (FIXED L_α VS. FREE L_α)
- EVALUATION OF PURE DELAY EFFECTS WITH TWO (L_α, $\omega_{n_{sp}}$) PAIRS
- EVALUATION OF PILOT/CENTER-OF-GRAVITY OFFSET EFFECTS
- COMPARISON OF FLYING QUALITIES CRITERIA

VARIABLE-RESPONSE RESEARCH AIRCRAFT (VRA)

The VRA is a six-degree-of-freedom in-flight simulator that has been used in flying qualities research for more than 20 years in programs sponsored by the USN, USAF, NASA, FAA, and ONERA. The VRA is equipped to conduct flight experiments of contemporary significance. In addition to its basic analog fly-by-wire system, it contains a flexible digital flight control system that is programmed using the PASCAL high-order language. Its direct-force control surfaces (lift and side force) support experimentation with advanced control concepts, including decoupled response and CCV modes. The VRA's two-pilot operation allows the evaluation pilot to concentrate on experimental configurations, controlling the aircraft through its digital/analog electronic system. Princeton's safety pilot controls the VRA using a conventional mechanical system, and he sets up and monitors the operation of the fly-by-wire system.

VARIABLE-RESPONSE RESEARCH AIRCRAFT (VRA)

- INDEPENDENT CONTROL OF LIFT, SIDEFORCE, THRUST, PITCH, YAW, AND ROLL



- FULLY OPERATIONAL AIRCRAFT

VRA VARIABLE-STABILITY ELECTRONICS

All digital control algorithms can be coded in the Micro-DFCS using 32-bit floating-point arithmetic (64-bit floating point and 16-bit fixed-point operations also are available). Well over 95 percent of the coding for the present program used the PASCAL language; compilers for C, FORTRAN, and ADA currently exist and may be used in future programs. The Micro-DFCS supports multiprocessor configurations and has been used recently in a demonstration of fiber-optic data transmission.

The analog system provides an input-output interface between the Micro-DFCS and the VRA, and it can be used alone for in-flight simulation.

VRA VARIABLE-STABILITY ELECTRONICS

- MICROPROCESSOR-BASED DIGITAL FLIGHT CONTROL SYSTEM (MICRO-DFCS, MODEL 2)
  - MULTIBUS™ ARCHITECTURE
  - Z-80A CENTRAL PROCESSING UNIT
  - AM9511 ARITHMETIC PROCESSING UNIT
  - 32-BIT FLOATING-POINT OPERATIONS
  - PASCAL HIGH-ORDER PROGRAMMING LANGUAGE
  - 32K RAM, 12K EPROM
  - 32 ANALOG INPUTS, 6 ANALOG OUTPUTS

- ANALOG FLY-BY-WIRE SYSTEM (AFBW)
  - 6-DOF IMPLICIT MODEL-FOLLOWING CAPABILITY
  - 10 Hz MOMENT ACTUATION
  - 3 Hz DIRECT LIFT AND SIDE FORCE ACTUATION

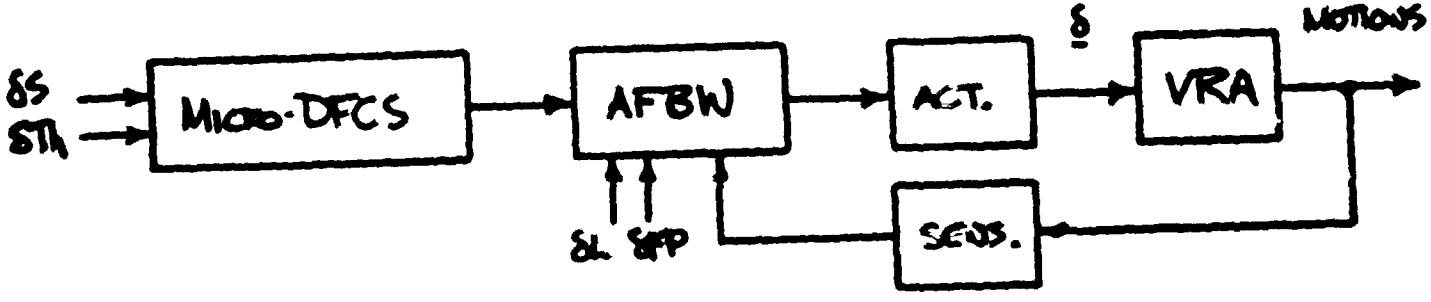
FUNCTIONS OF DIGITAL & ANALOG SYSTEMS IN THE CURRENT STUDY

In the present study, the evaluation pilot's longitudinal control commands are processed by the Micro-DFCS, and his lateral-directional commands are fed directly to the analog system. The digital system is used to add pure delay (for experimentation) and control stick prefiltering. A sampling rate of 20 per sec has been used for all flights. The longitudinal control computations require 16 msec, although the transport lag between stick input and elevator output is only 9 msec. Closed-loop dynamics of the VRA are modified using the analog system. Examples of digital closed-loop control are reported in (1) to (4).

FUNCTIONS OF DIGITAL & ANALOG SYSTEMS IN THE CURRENT STUDY

- MICRO-DFCS
  - LONGITUDINAL PILOT INPUTS & STICK GEARING ($\delta_E, \delta T_4$)
  - SAMPLING RATE = 20 PER SEC; COMPUTATION DELAY = 16 MSEC
  - PURE DELAY & 1ST-ORDER PREFILTER ($\delta_S \rightarrow \delta_E$)

- ANALOG FLY-BY-WIRE SYSTEM
  - LONGITUDINAL MODEL FOLLOWING
  - LATERAL-DIRECTIONAL CONTROL (UNAUGMENTED)



SHORT-PERIOD MODELS OF TEST CONFIGURATIONS

For comparative purposes, the phugoid mode can be neglected, and the elevator-to-pitch rate transfer functions of the base, equivalent system, and time delay configurations can be modelled by a second-order denominator, first-order numerator, and pure time delay. The relationship to stability-and-control derivatives is made apparent in the corresponding state equation. A first-order prefilter is added for three test configurations, as identified in the next figure. These are approximated by six reduced-order equivalent system configurations, also identified in the next figure.

SHORT-PERIOD MODELS OF TEST CONFIGURATIONS

- BASE, EQUIVALENT, AND TIME DELAY CONFIGURATIONS

$$\frac{\Delta q(s)}{\Delta \delta_E(s)} = \frac{K_q e^{-\tau_D s}(s + 1/T_{\theta_2})}{(s^2 + 2\zeta\omega_n s + \omega_n^2)_{sp}}$$

$$\begin{bmatrix} \Delta \dot{q}(t) \\ \Delta \dot{\alpha}(t) \end{bmatrix} = \begin{bmatrix} M_q & M_\alpha \\ 1 & -L_\alpha/V_0 \end{bmatrix} \begin{bmatrix} \Delta q(t) \\ \Delta \alpha(t) \end{bmatrix} + \begin{bmatrix} M_{\delta_E} \\ -L_{\delta_E}/V_0 \end{bmatrix} \delta_E(t)$$

$$\Delta \delta_E(t) = \Delta \delta_S(t - \tau_D)$$

- BASE CONFIGURATION PLUS FIRST-ORDER PREFILTER

$$\frac{\Delta q(s)}{\Delta \delta_S(s)} = \frac{-K_q \lambda_{PF} e^{-\tau_D s}(s + 1/T_{\theta_2})}{(s - \lambda_{PF})(s^2 + 2\zeta\omega_n s + \omega_n^2)_{sp}}$$

$$\begin{bmatrix} \Delta \dot{q}(t) \\ \Delta \dot{\alpha}(t) \\ \Delta \dot{\delta}_E(t) \end{bmatrix} = \begin{bmatrix} M_q & M_\alpha & M_{\delta_E} \\ 1 & -L_\alpha/V_0 & -L_{\delta_E}/V_0 \\ 0 & 0 & \lambda_{PF} \end{bmatrix} \begin{bmatrix} \Delta q(t) \\ \Delta \alpha(t) \\ \Delta \delta_E(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ -\lambda_{PF} \end{bmatrix} \delta_S(t - \tau_D)$$

- NORMAL ACCELERATION (AT PILOT'S STATION, x_p)

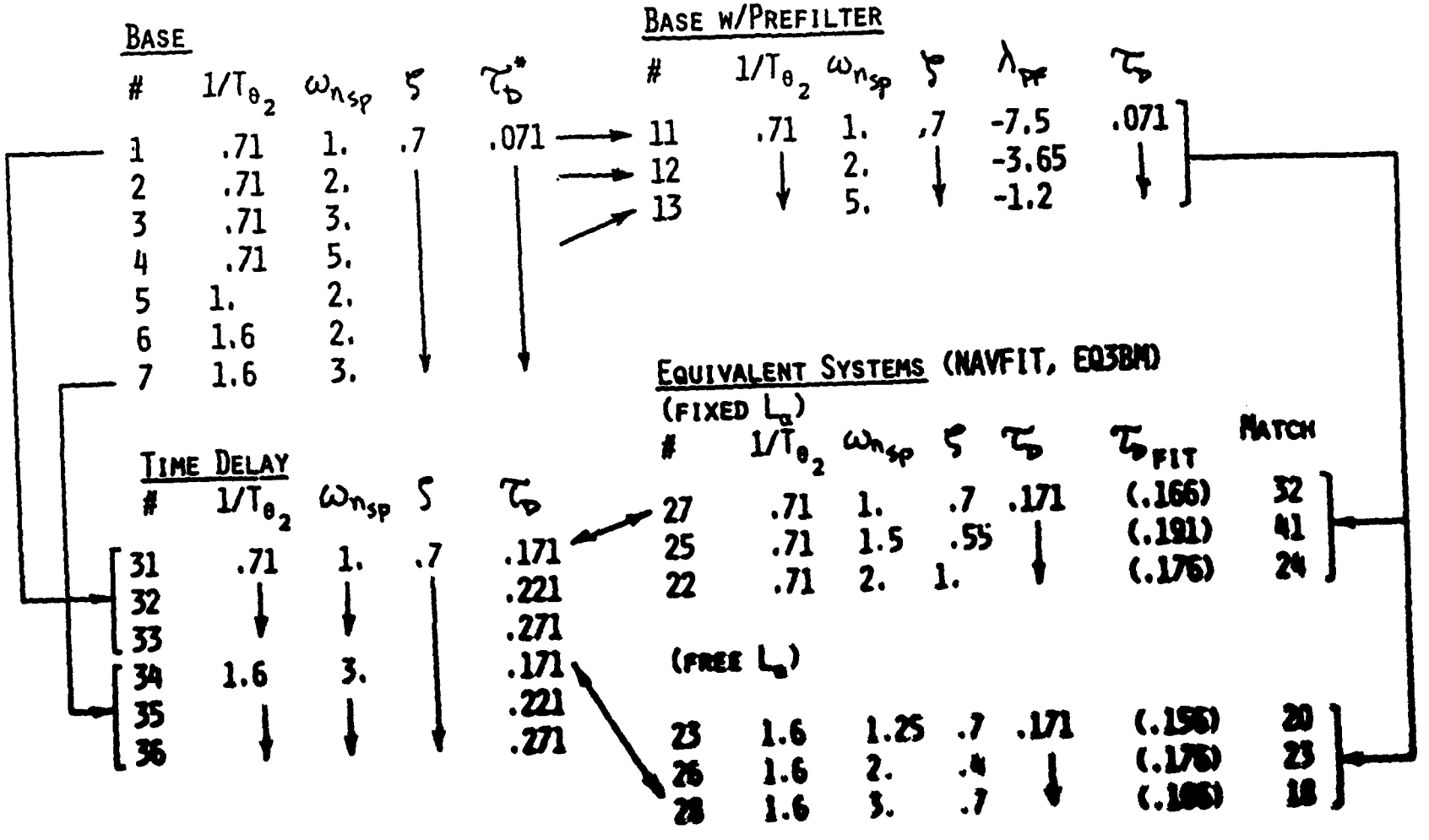
$$\Delta n_{z_p} = \left(\frac{1}{g}\right)\left[x_p M_q \Delta \dot{q} + (L_\alpha + x_p M_\alpha)\Delta\alpha + (L_{\delta_E} + x_p M_{\delta_E})\Delta\delta_E\right]$$

RELATIONSHIP OF CASES TESTED TO DATE

Four families of configurations have been tested, and each is related to the other configurations as shown in the figure. The base configurations provide a range of natural frequencies and lift slope sensitivities (through $1/T_{\theta_2}$). Pure time delays are added to low-frequency, low-lift and moderate-frequency, high-lift configurations. First-order prefilters are added to three configurations with varying $\omega_{n_{sp}}$ and fixed $1/T_{\theta_2}$ and ζ. These three prefiltered configurations then are modelled by two sets of equivalent systems. In the first set, the value of L_α/V is fixed, thereby fixing $1/T_{\theta_2}$, and the NAVFIT equivalent systems program is used to find the values of $\omega_{n_{sp}}$, ζ, and τ_D in a second-order model that best fits the prefiltered (third-order) model. The elevator-to-pitch rate frequency response, $\Delta q(j\omega)/\Delta\delta E(j\omega)$, for $0.1 \leq \omega \leq 10$ rad/sec is used as the basis for matching, i.e., the squared-error between second-order and third-order frequency responses is minimized using parameter optimization.

The matching process is repeated with "free" L_α, i.e., with $1/T_{\theta_2}$ considered to be a variable parameter. To provide a common basis for comparison, it was desired that all "free" L_α cases actually have identical vaues of $1/T_{\theta_2}$; therefore, the prefilter break frequencies, λ_{pf}, were chosen iteratively to yield this result. Note that matching errors are reduced in the "free" L_α cases. All nine cases were simulated in the VRA to allow the evaluation pilots to compare the actual prefiltered versions with the equivalent systems. Time delays were added in integral sampling intervals. Consequently, all six equivalent systems used the same time delay.

RELATIONSHIP OF CASES TESTED TO DATE



• τ_D = Computation Delay (.016) + Sampling Lag (.025) + Servo Lag (.030)
+ Added Delay (Variable), see

PILOT COMMENT CARD

All evaluations were conducted in Field Carrier Landing Practice (FCLP) at FRL's Forrestal Airfield using a Navy carrier approach mirror for guidance. Nominal approach speed was 75 KIAS, and glide slope was -2.8 deg, resulting in a no-flare sink rate at touchdown of 6 fps. Pilot A (Princeton's chief test pilot) performed a standard carrier approach through loss of "meatball" image in the mirror, followed by a flared landing. The latter procedure is not normally used in carrier landing, but it provided a high-stress task for flying qualities evaluation. Pilot B (U.S. Navy test pilot) performed conventional carrier approach and no-flare landings. Nevertheless, he chose not to rate flight path response, basing his opinions solely on pitch attitude response. Pilot C (U.S. Navy test pilot) performed the same tasks and rated flight path response. Although indicated on the card, numerical PIO ratings were not consistently collected in the flights due to lack of familiarity with the PIO rating scale.

PILOT COMMENT CARD

Pilot: Date: Config.:

1. PITCH ATTITUDE RESPONSE
   - initial response (delays?)
   - predictability of final response
   - special pilot techniques?
   - PIO tendency? (hi/lo frequency?)

2. FLIGHT PATH RESPONSE
   - response time
   - predictability of flight path
   - meatball tracking
   - flare/landing

3. AIRSPEED CONTROL

4. PERFORMANCE ASSESSMENT
   - meatball
   - flare/landing
   - special techniques?

5. CONTROL FEEL
   - forces, displacements
   - pitch sensitivity, trim?

6. TURBULENCE/WIND A FACTOR?

7. LATERAL-DIRECTIONAL CHARACTERISTICS A FACTOR?

8. MAJOR PROBLEMS

9. PIO RATING

10. APPROACH/MEATBALL RATING

11. FLARE/LANDING RATING

12. ADDITIONAL COMMENTS

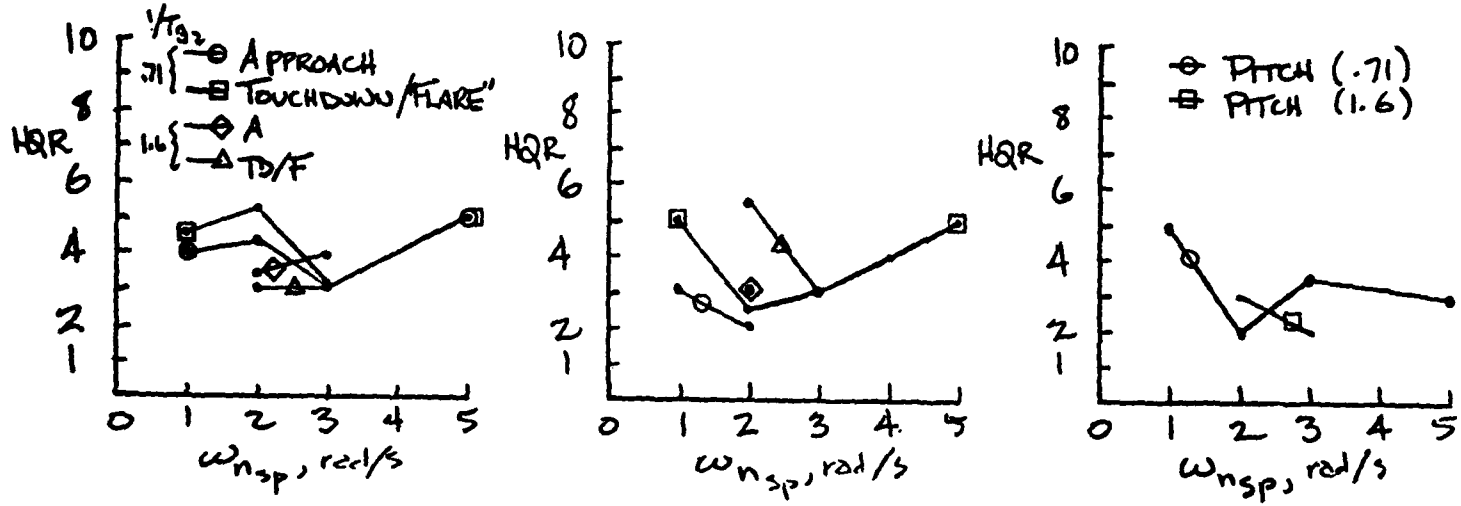
PILOT OPINIONS OF BASE CONFIGURATIONS

The separate effects of lift slope and short-period natural frequency can be deduced from pilot handling qualities ratings (HQR) of the base configurations. These ratings are expressed in terms of the Cooper-Harper Scale [5], in which better configurations are indicated by lower numbers. The numbers represent averages of at least two and as many as six replications. Best values of $\omega_{n_{sp}}$ lie in the region from 2 to 3 rad/sec. Pilot A, whose recent flying experience centers on light aircraft, preferred increasing $1/T_{\theta_2}$ and, therefore, increasing lift slope. The Navy pilots (B and C), whose recent experience has been gained with heavier aircraft, preferred low values of $1/T_{\theta_2}$. Ratings during the touchdown or flare (from 3 sec before touchdown to touchdown) typically are higher than the approach ratings (from 10 sec to 3 sec) due to the increased difficulty of the task.

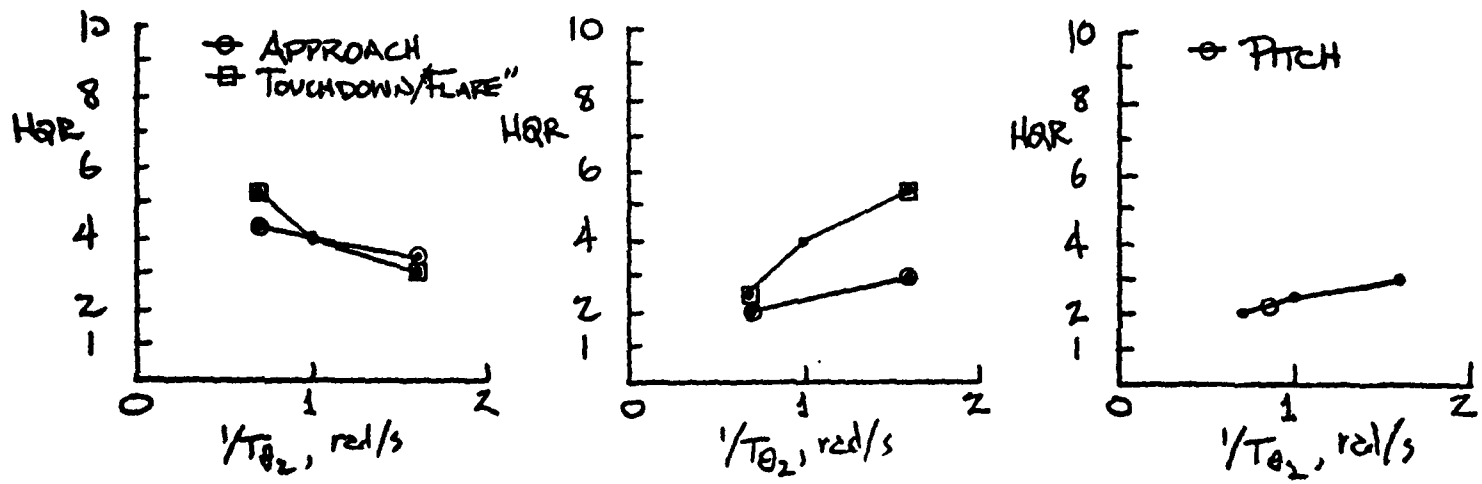
PILOT OPINIONS OF BASE CONFIGURATIONS

PILOT A | PILOT C | PILOT B

SHORT PERIOD NATURAL FREQUENCY VARIATION



PITCH-RATE TRANSFER FUNCTION ZERO VARIATION ($\omega_{n_{SP}}$ = 2 RAD/S)



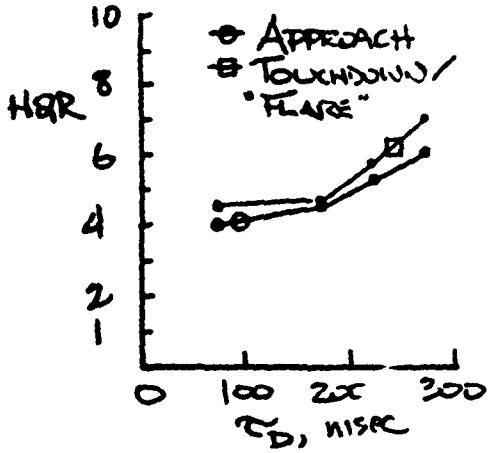
PILOT OPINIONS OF TIME DELAY, τ_D

Pilot ratings of pure time delay are somewhat different for configurations whose basic pitch response could be characterized as "slow" and "moderately fast". In the first case, with a pitch rate rise time (to 100% of the "steady-state" value) of 1.11 sec, there is a sharp degradation of ratings for τ_D = 0.171 sec. For the second case, with 0.25-sec pitch rate rise time, the ratings of Pilots A and B degrade more slowly and do not evidence the sharp break seen in the first case. Pilot C's poor rating of the 0.171-sec delay does not fit the trend and may be anomalous.

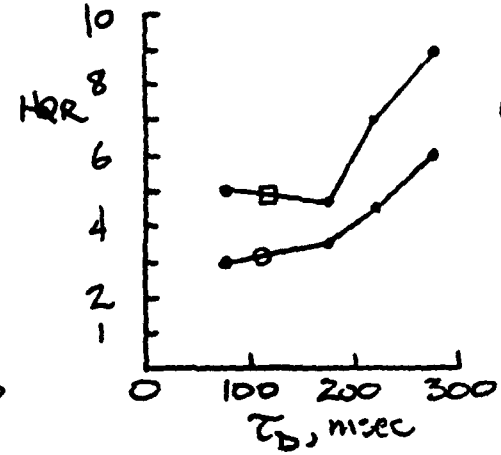
PILOT OPINIONS OF TIME DELAY, τ_D

PILOT A

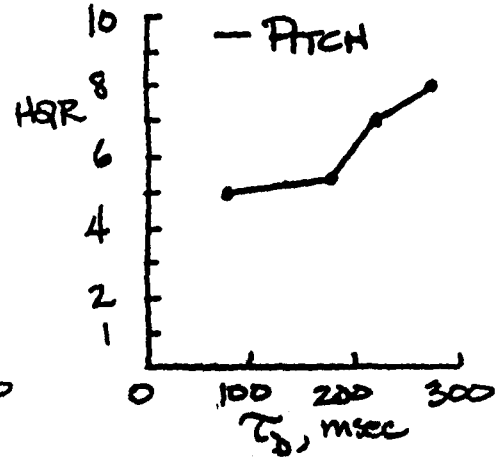
$1/T_{\theta_2} = .71$, $\omega_{n_{sp}} = 1.$



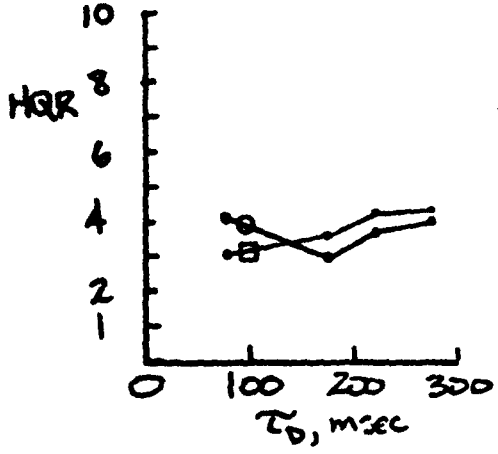
PILOT C

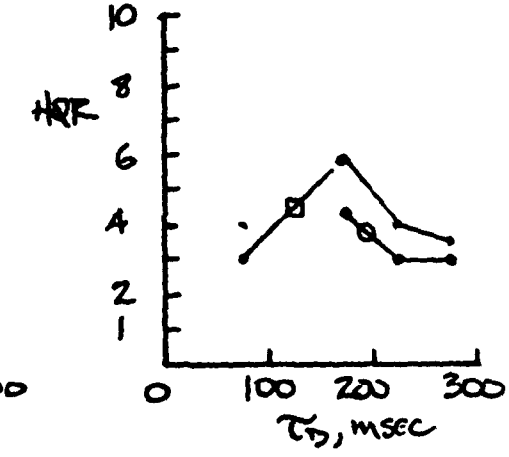


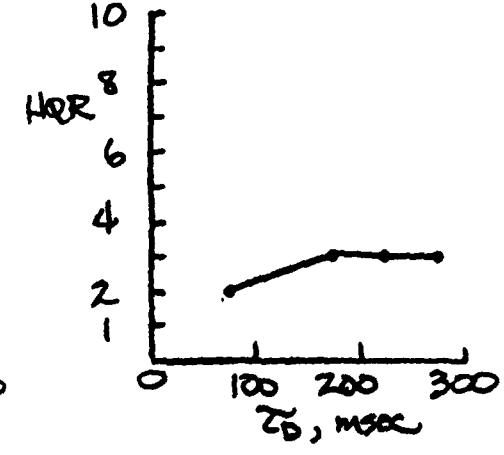
PILOT B



$1/T_{\theta_2} = 1.6$, $\omega_{n_{sp}} = 3.$







PILOT OPINIONS OF PREFILTER EFFECTS

The three high-order configurations are compared to the base configurations in this figure. The prefilter generally degrades pilot ratings, although there are several examples of negligible effect. The ratings of Pilots A and C pertain to approach and touchdown, while those of Pilot B refer to pitch attitude response.

PILOT OPINIONS OF PREFILTER EFFECTS

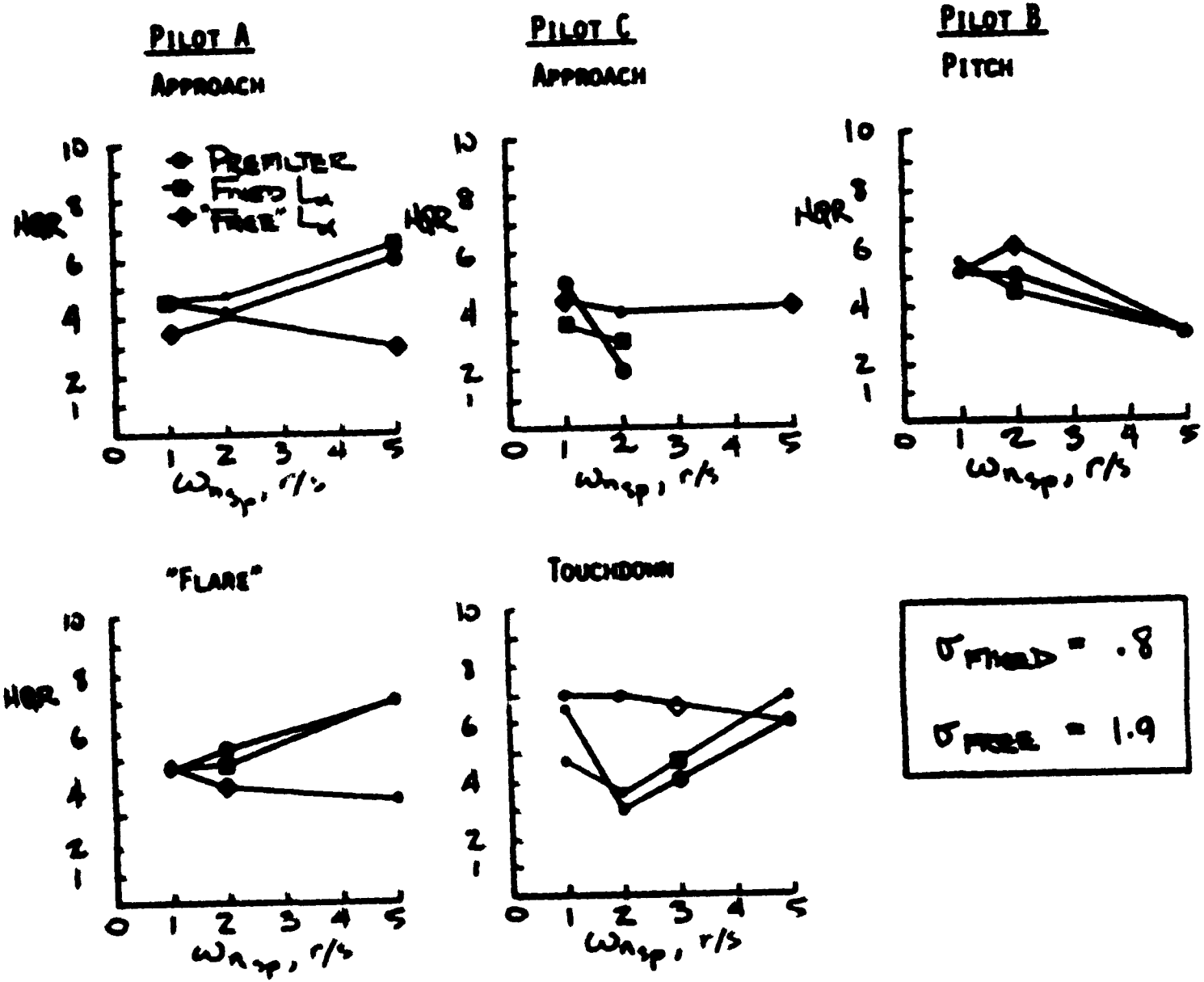
	Pilot A		Pilot C		Pilot B	
	Base	Filter	Base	Filter	Base	Filter
$1/T_{\theta_2} = .71,\ \omega_{n_{sp}} = 1.,\ \lambda_{PF} = -7.5$						
Approach (Pitch)	4.	4.5	3.	5.	5.	5.
Touchdown/Flare	4.5	4.75	5.	6.5	-	-
$1/T_{\theta_2} = .71,\ \omega_{n_{sp}} = 2.,\ \lambda_{PF} = -3.65$						
Approach (Pitch)	4.25	4.25	2.	2.	2.	5.
Touchdown/Flare	5.25	5.25	2.5	3.	-	-
$1/T_{\theta_2} = .71,\ \omega_{n_{sp}} = 5.,\ \lambda_{PF} = -1.2$						
Approach (Pitch)	5.	6.	-	-	3.	3.
Touchdown/Flare	5.	7.	5.	6.	-	-

PILOT OPINIONS OF EQUIVALENT SYSTEMS

Pilots A, B, and C flew the three prefilter configurations (#11 to 13) and the six equivalent systems (#22 to 28) in the approach and landing. The VRA's digital and analog systems provided in-flight simulation of each of the nine configurations identified earlier. The lift slope and $1/T_{\theta_2}$ were equal for the prefilter and fixed L_α cases; direct lift control was used to change L_α in the remaining three cases. Attention is directed to the "goodness of fit" of the ratings obtained by flying the equivalent systems, as compared to the prefilter ratings. Sample standard deviations indicate that the fixed-L_α equivalent systems tend to get ratings more like those of the original (prefilter) systems than do the free-L_α equivalent systems.

The deviations occur principally in the approach and touchdown ratings of Pilots A and C, while Pilot B sees little variation in the acceptability of the pitch attitude response characteristics. Although not shown here, simultaneous matching of pitch rate and normal acceleration frequency responses with free L_α tends to give results that are similar to matching pitch rate response alone with fixed L_α (6). As both responses are important in flight path control, this could explain the smaller deviations experienced with fixed L_α matching. For Pilot C's pitch attitude evaluation, the normal acceleration response may be less significant, because fixed L_α and free L_α matching results in similar ratings.

PILOT OPINIONS OF EQUIVALENT SYSTEMS



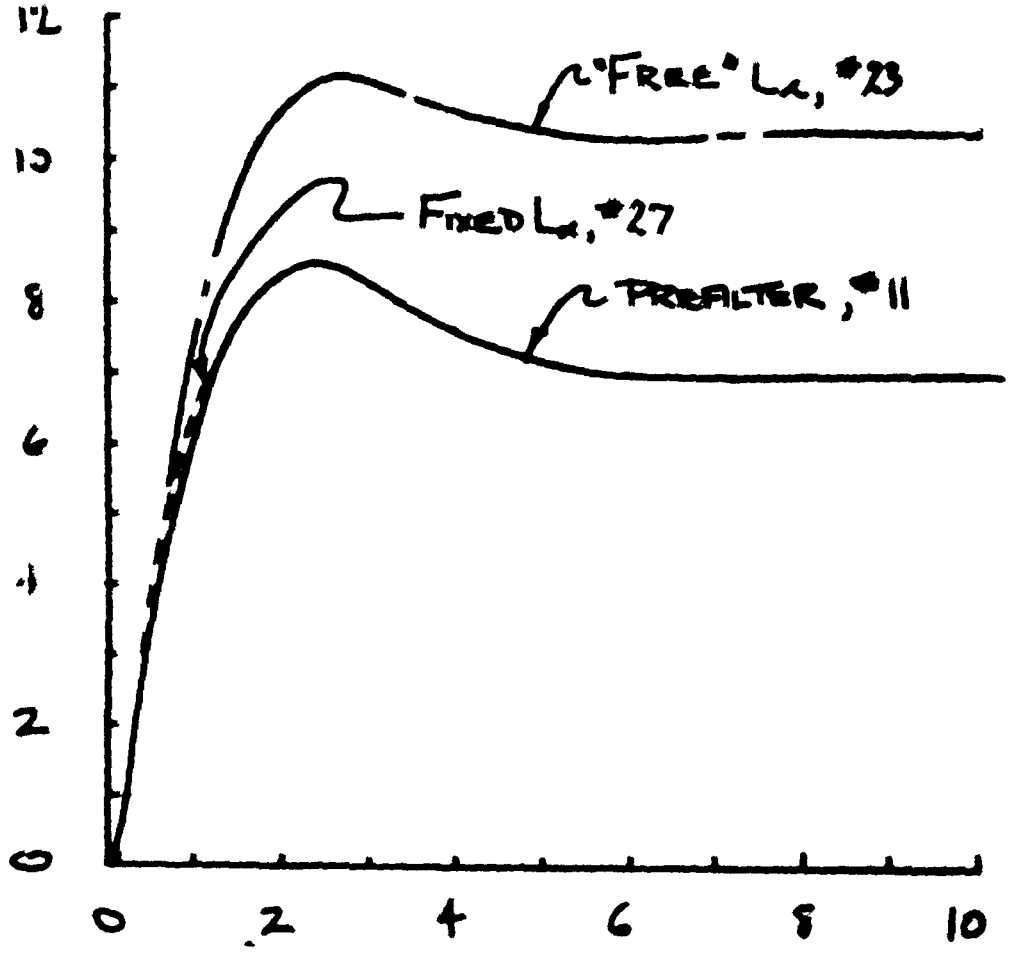
COMPARISON OF PREFILTER AND EQUIVALENT SYSTEM RESPONSE

A qualitative comparison of the prefilter and equivalent systems can be made using step responses. In matching, the high-order and equivalent systems are normalized by the transfer function gain; hence, a difference in steady-state step response can be expected. The step responses shown here are not normalized, principally to illustrate the amount of gain adjustment that could be required in modelling high-order systems with equivalent systems. In all cases, the 0.071-sec time lag felt by all systems is not plotted.

For $\omega_{n_{sp}} = 1$ rad/sec, the prefilter and fixed L_α traces are nearly identical; the principal difference occurs in the first second, and the state-state responses are the same. The initial response of the free-L_α case is very similar to the fixed-L_α case (each has a 100-msec delay and identical slope), but the steady-state response is affected by differing values of $1/T_{\theta_2}$ and $\omega_{n_{sp}}$. The prefilter's break frequency of 7.5 rad/sec is well above $\omega_{n_{sp}}$, so the prefilter output approaches steady-state before the aircraft pitch rate.

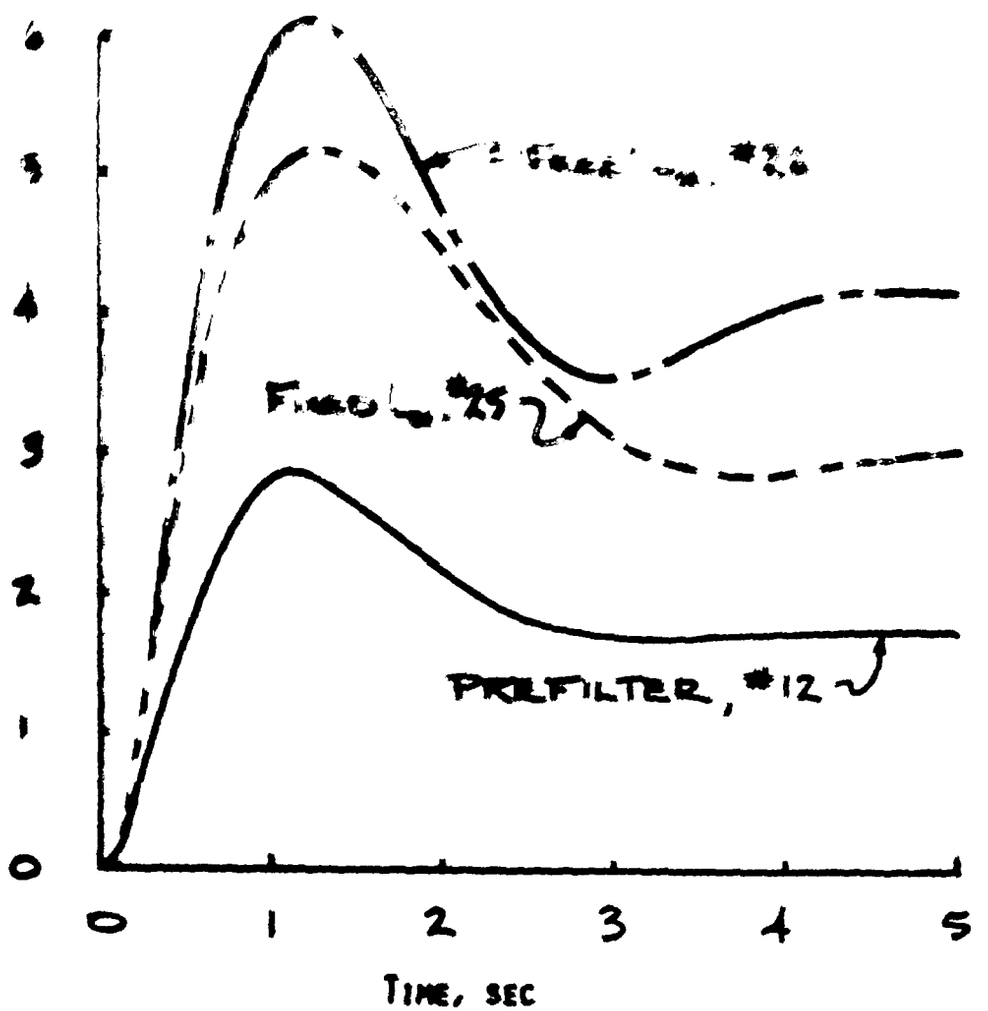
COMPARISON OF PREFILTER AND EQUIVALENT SYSTEM RESPONSE

PREFILTER: $\omega_{n_{sp}} = 1$ RAD/SEC, $1/T_{\theta_2} = .72$ RAD/SEC, $\lambda_{pf} = -7.5$ RAD/SEC



COMPARISON OF PREFILTER AND EQUIVALENT SYSTEM RESPONSES

For $\omega_{n_{sp}} = 2$ rad/sec, the λ_{pf} which provides the fixed/free comparison has a similar time scale, and neither of the equivalent system responses is very close to the prefilter system response. Nevertheless, the shape of the fixed-L_α transient response is quite similar to the prefilter response, and normalizing would provide a reasonable fit. The free-L_α case possesses less damping, and while it might not be objectionable in itself, it does not represent the original system step response as well.

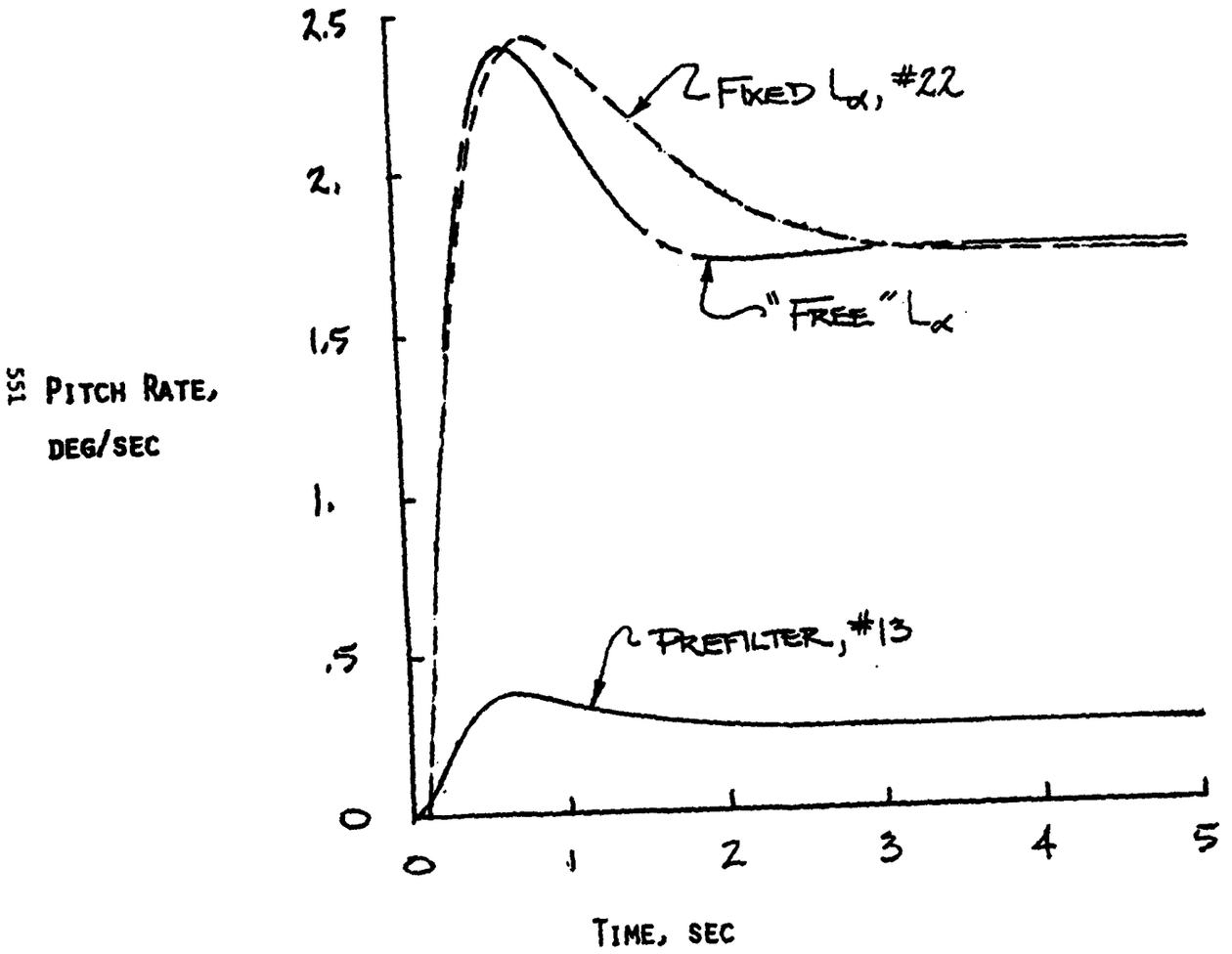

PITCH RATE, DEG/SEC
0
1
2
3
4
5
6
0
1
2
3
4
5
TIME, SEC
PREFILTER, #12

COMPARISON OF PREFILTER AND EQUIVALENT SYSTEM RESPONSES

For $\omega_{n_{sp}}$ = 5 rad/sec, the λ_{pf} required for fixed/free comparison occurs at lower frequency (1.2 rad/sec); hence, the aircraft pitch response is faster than the prefilter's response. Once again, the shape of the fixed-L_α transient is more like the original transient, and there is a substantial difference in steady-state responses. Stick gearing was doubled for VRA flights with configuration #13; this leaves a factor of three difference in steady-state responses.

COMPARISON OF PREFILTER AND EQUIVALENT SYSTEM RESPONSES

PREFILTER: ωn_{sp} = 5 RAD/SEC, $1/T_{\theta_2}$ = .71 RAD/SEC, λ_{PF} = - 1.2 RAD/SEC



TASK DEPENDENCE OF PILOT RATINGS

Field Carrier Landing Practice

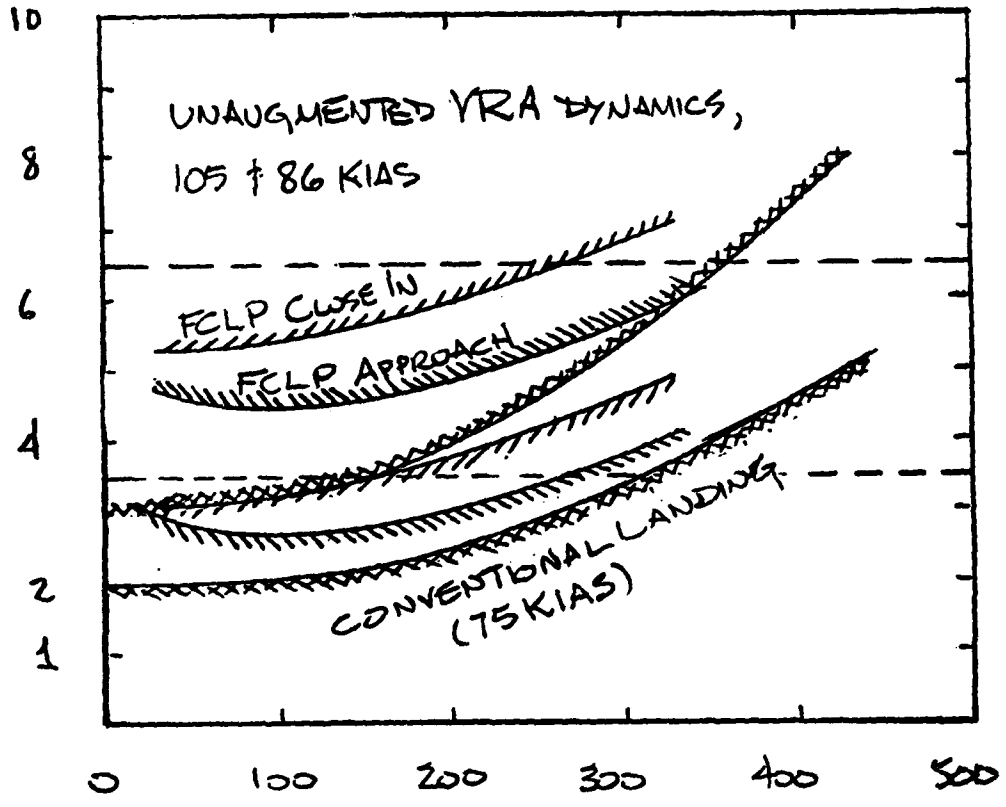
Earlier flight tests to determine the effects of pure time delay on pilot opinions illustrate the task dependence of pilot ratings {3}. These tests used the Micro-DFCS to produce an equivalent delay (defined here to be the pure delay plus half the digital sampling interval) in longitudinal stick commands. The VRA's unaugmented dynamics provided the following short-period characteristics:

V, KIAS	ω_n, rad/sec	ζ,-	$1/T_{\theta_2}$, rad/sec
75	2.60	0.77	1.28
86	2.95	0.75	1.64
105	3.54	0.71	2.00

The conventional (nonprecision) flared landings at 75 KIAS yielded satisfactory ratings for delays up to about 200 msec, and the rate of HQR degradation increased with increasing delay. The rates of HQR degradation were lower for FCLP approach and "close-in" tracking of the "meatball", but they were biased up by the increased difficulty of the task. It should be noted that airframe dynamics are "moderate" to "fast", in comparison with the results shown earlier.

TASK DEPENDENCE OF PILOT RATINGS*

FIELD CARRIER LANDING PRACTICE



* JGC, Nov-Dec 1980

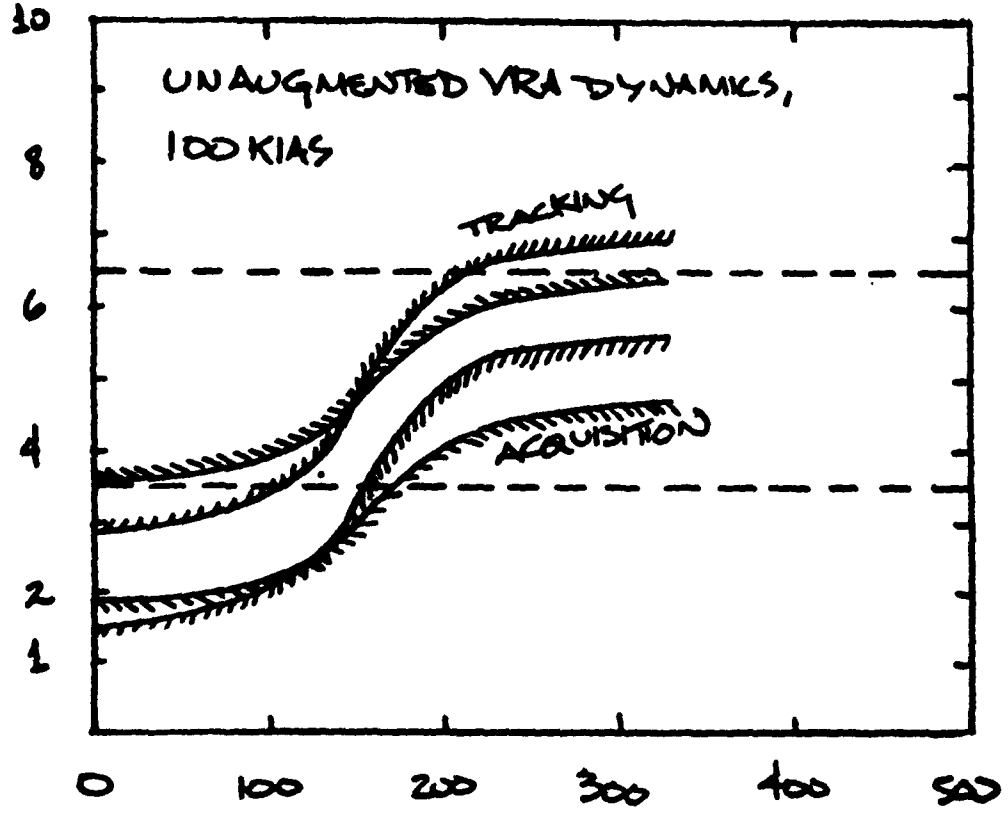
TASK DEPENDENCE OF PILOT RATINGS

Tracking at Altitude

The tracking task at altitude--which consisted of identification of an arbitrary object on the ground, roll and dive to acquire, and 15 to 20 sec of tracking--also used equivalent pure delay in longitudinal stick command and unaugmented VRA dynamics {3}. There was a sharp degradation of pilot ratings at an equivalent delay of 150 msec, with a plateau beyond 200 msec.

TASK DEPENDENCE OF PILOT RATINGS*

TRACKING AT ALTITUDE



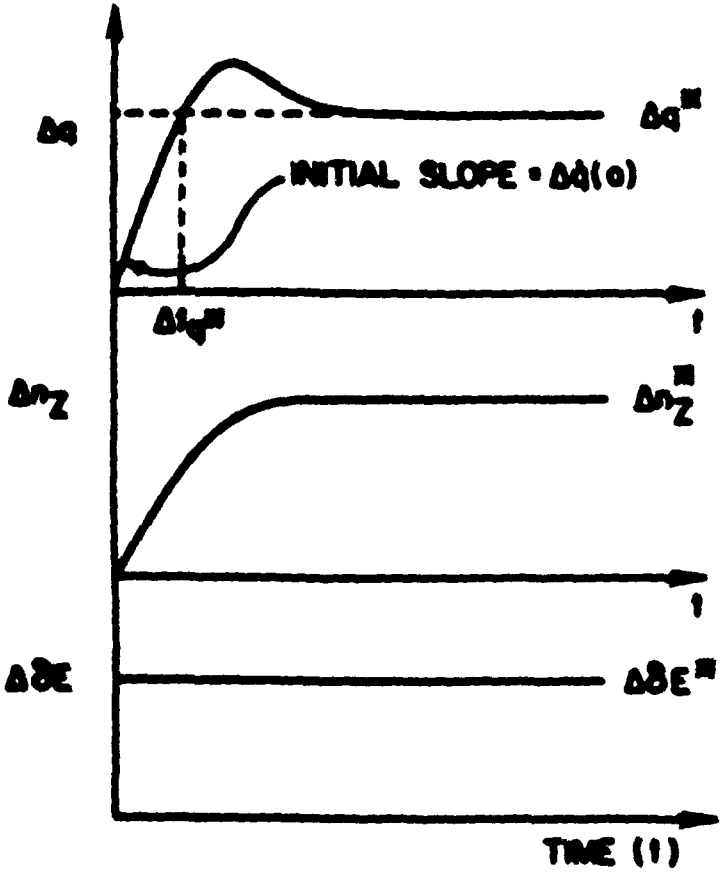
* JGC, Nov-Dec 1980

CONTROL ANTICIPATION PARAMETER (CAP)

The control anticipation parameter, originally defined in (7), provides the principal short-period flying qualities criterion. The CAP hypothesis is that the initial pitching acceleration ($\Delta\dot{q}(o)$) sensed by the pilot's inner ear should be a "harmonious" predictor of the aircraft's steady-state normal acceleration (Δn_z^*). Constant values of CAP should be equally acceptable to the pilot over a wide range of pitch accelerations and normal accelerations. A parameter-centered definition of CAP, based upon simplifying assumptions, is used in MIL-F-8785C. This definition gives rise to the independent consideration of short-period natural frequency ($\omega_{n_{sp}}$) and normal acceleration sensitivity to angle of attack (n_z/α) as flying qualities parameters which may or may not be related to the original values of CAP.

CONTROL ANTICIPATION PARAMETER (CAP)

TRUNCATED SHORT PERIOD STEP RESPONSE



- ORIGINAL DEFINITION OF CAP

$$CAP = \Delta\dot{q}(0)/\Delta n_{Z_A}^{ss}$$

- INITIAL PITCH ACCELERATION

$$\Delta\dot{q}(0) = M_{\delta_E}\Delta\delta_E^{ss}$$

- STEADY-STATE NORMAL ACCELERATION

$(A = c.g.,\ L_{\delta_E} = \gamma_0 = \alpha_0 = 0)$

$$\Delta n_{Z_A}^{ss} = \frac{-(L_\alpha/g)M_{\delta_E}\Delta\delta_E^{ss}}{(M_\alpha + M_q L_\alpha/V_0)}$$

- PARAMETER-CENTERED DEFINITION OF CAP

$$CAP = \frac{-(M_\alpha + M_q L_\alpha/V_0)}{(L_\alpha/g)}$$

$$\triangleq \frac{\omega_{n_{sp}}^2}{n_Z/\alpha}$$

SHORT-PERIOD FREQUENCY REQUIREMENTS

Category C Flight Phases

This example from MIL-F-8785C illustrates the use of $\omega_{n_{sp}}$ and n_z/α as flying qualities parameters. Constant values of CAP ($\omega^2_{n_{sp}}/n_z/\alpha$) are noted. It can be seen that there are deviations from constant CAP values in the low $\omega_{n_{sp}}$ - n_z/α boundaries.

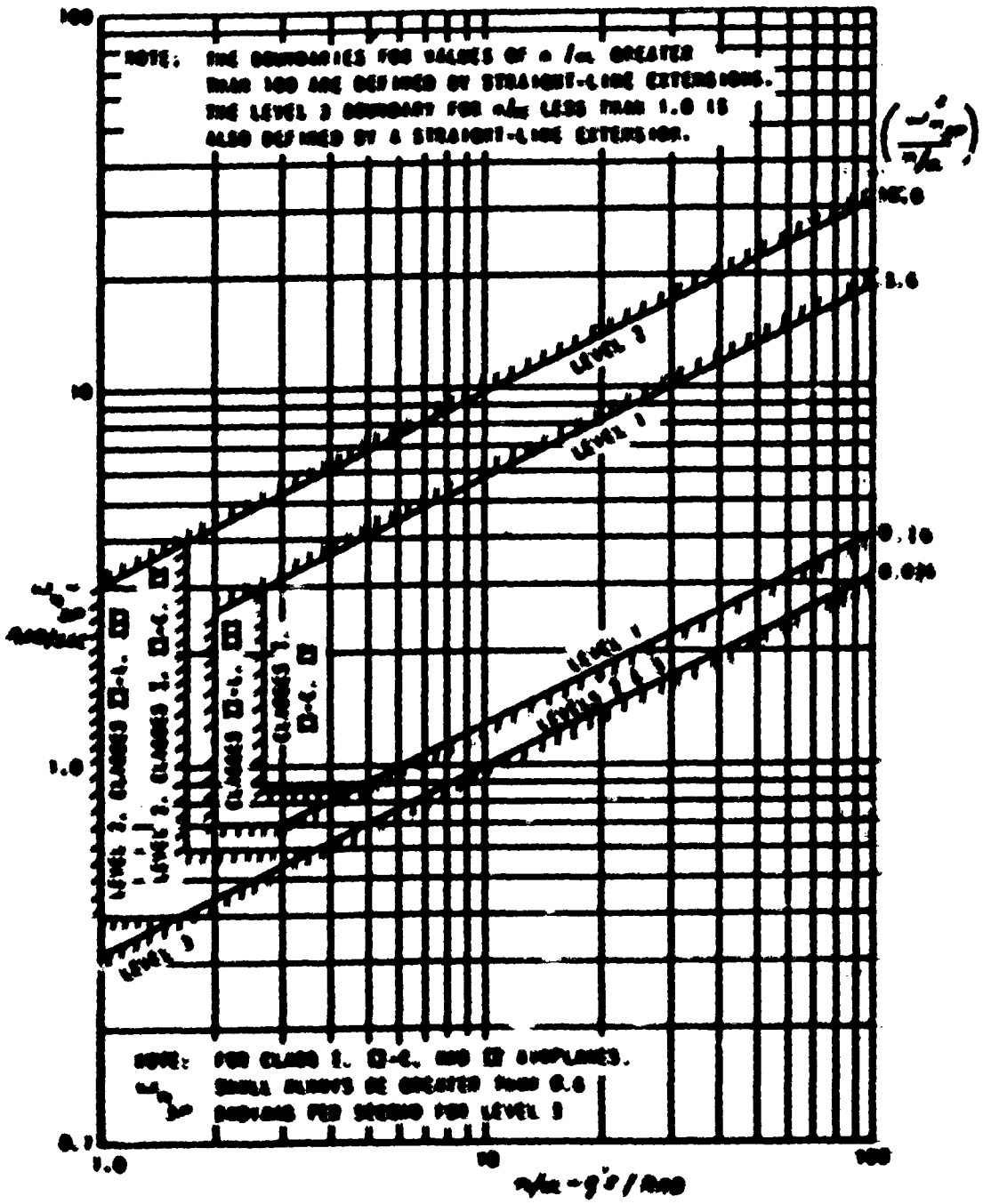


FIGURE 3. Short-period frequency requirements.

PITCH RATE RISE TIME AND CAP

An alternate response-centered definition of CAP can be based upon pitch rate rise time (to 100%). CAP then is expressed in terms of the rise time (Δt_{q^*}), the steady-state pitch rate (Δq^*), and the steady-state normal acceleration (Δn_z^*). Using the same assumptions that are used in MIL-F-8785C to transform CAP into $\omega_{n_{sp}} - n_z/\alpha$ boundaries, constant CAP is provided by a pitch rate rise time that is inversely proportional to airspeed. This relationship is presented in [8] and [9], with minor differences in the definition of rise time.

PITCH RATE RISE TIME AND CAP

- PITCH ACCELERATION APPROXIMATION

$$\Delta\dot{q}(0) \approx \Delta\dot{q}^{ss}/\Delta t_q^{ss}$$

- RESPONSE-CENTERED DEFINITION OF CAP

$$CAP' = \left(\frac{1}{\Delta t_q^{ss}}\right)\left(\frac{\Delta q^{ss}}{\Delta n_z^{ss}}\right)$$

- STEADY-STATE PITCH RATE RESPONSE ($L_{\delta_E} \neq 0$)

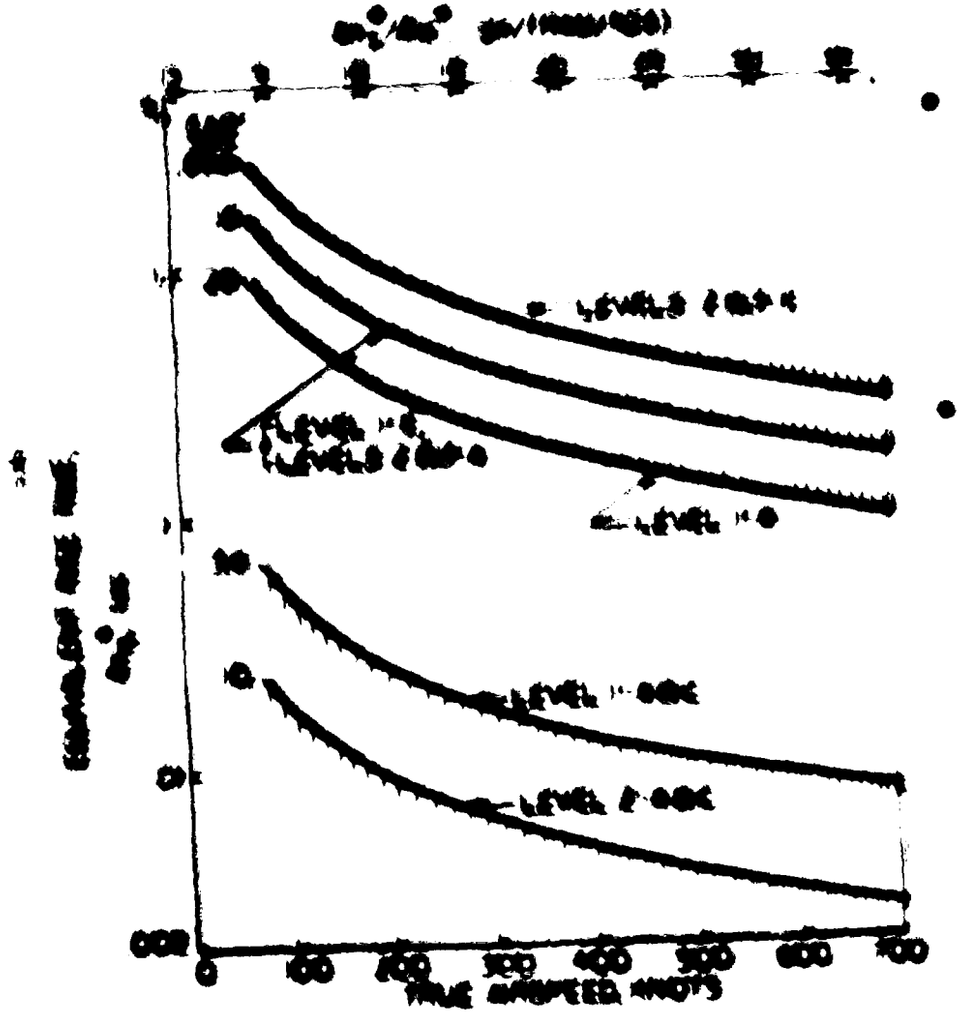
$$\Delta q^{ss} = \frac{-M_{\delta_E} L_\alpha / V_0}{(M_q + M_{\dot{\alpha}} L_\alpha / V_0)} \cdot \left(\frac{g}{V_0}\right) \Delta n_z^{ss}$$

- EQUIVALENT DEFINITION OF CAP

$$CAP' = \left(\frac{1}{\Delta t_q^{ss}}\right)\left(\frac{g}{V_0}\right)$$

PITCH RATE RISE TIME HANDLING QUALITIES CRITERION

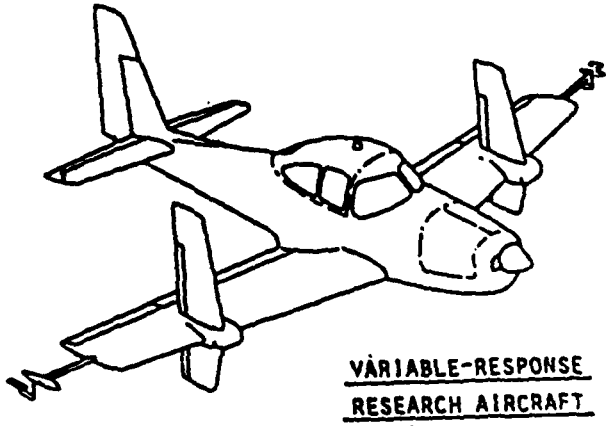
The CAP boundaries of MIL-F-8785C are elegantly and simply expressed in terms of pitch rate rise time [9]. For a conventional long-tailed aircraft, Δt_{q_θ} is merely a function of airspeed. For aircraft with significant lift-due-to-elevator, high angle of attack, direct lift control, or significant pilot - c.g. offset, Δt_{q_θ} is presented as a function of the ratio of steady-state normal acceleration and pitch rate responses.



APPLICATION OF Δt_{q_θ} CRITERION TO DIGITAL FLIGHT CONTROL

Because delay <u>times</u> are of particular concern for aircraft with digital control systems, the Δt_{q_θ} criterion appears well-suited to the analysis of these aircraft's flying qualities. Although simply adding the various delays as shown here is probably <u>not</u> the best use of the criterion, the result does tend to provide a consistent trend in pilot ratings of 3.5 (the <u>de facto</u> Level 1 - Level 2 boundary) for the data presented in [3] and [9]. Further evidence for the use of pitch rate rise time as a good correlator of pilot opinions is offered in [10].

APPLICATION OF Δt_q^* CRITERION TO DIGITAL FLIGHT CONTROL



VARIABLE-RESPONSE RESEARCH AIRCRAFT (VRA)

- AGGREGATE EQUIVALENT RISE TIME (PRELIMINARY)

$$\Delta t_q^* = \Delta t_{AIRCRAFT} + \Delta t_{\substack{CONTROL \\ EFFECTORS}} + \tau_{COMPUTATION} + \underbrace{T/2}_{SAMPLING\ DELAY}$$

- VRA/MICRO-DFCS LONGITUDINAL FLIGHT TESTS

FLIGHT PHASE	V, KIAS	Δt_q^* (msec) FOR HQR = 3.5
A	105	380
B	105	440
C (PRECISION LANDING)	86	290
C (PRECISION LANDING)	105	275
C (CONVENTIONAL LANDING)	75	485

CONCLUSION

After briefly describing experimental systems, the results of flight testing were presented. Proceeding to touchdown in the landing task is found to produce a more challenging task than pulling up at 10 to 20 feet above the runway; however, the distinction between requirements on the pilot in "flare" and "no-flare" landings is significant. When flying a mirror-guided approach, the pilot normally does not flare, keeping the "meatball" in his scan pattern as long as possible in order to touch down at the optimum position between second and third arresting wires. Forcing the pilot to break his attention from the "meatball" to flare the aircraft causes him to fly the aircraft in an unnatural fashion. It is a general conclusion of the Navy test pilots who have flown this program that actually touching the ground is not a factor in their ratings.

Pure delay effects on pilot ratings are functions of basic airframe dynamics and piloting task. The opinion degradation with increasing time delay is more pronounced for slow airframes than fast, although the latter configurations (long delay, fast aircraft) may be more PIO-prone.

For the approach and landing, equivalent systems based on fixed-L_α matching of pitch rate response provide pilot opinions that are closer to those for the original high-order system than are the ratings of equivalent systems based on free L_α. This is true even though the free-L_α frequency responses have a better fit to the original frequency response. This tends to confirm the previous finding that fitting both pitch rate and normal acceleration is more realistic for tasks requiring path control, as dual matching tends to fix the modelled L_α at original aircraft values. The difference in matching assumptions appears negligible for a pitch control task.

Future work includes the replication of test flights with the configurations described above, plus testing of nine configurations in which pilot-c.g. offsets of -10 to +30 feet are simulated using direct-lift control. All of these results will be analyzed using existing and new flying qualities criteria.

CONCLUSION

- FLIGHT TESTING TECHNIQUES AND EQUIPMENT
- TOUCHDOWN VS. NO TOUCHDOWN,
  FLARE VS. NO FLARE
- EFFECTS OF PURE DELAY
- EQUIVALENT SYSTEMS
- FUTURE FLIGHTS
  - ADDITIONAL PILOTS
  - PILOT-C.G. EFFECTS
- NEW CRITERIA

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2. J. C. Seat, G. E. Miller, and R. F. Stengel, "A Microprocessor Control System for Flight Control Research", Proceedings of the 1979 National Aerospace & Electronics Conference, Dayton, May 1979.

3. R. F. Stengel and G. E. Miller, "Flight Tests of a Microprocessor Control System", AIAA Journal of Guidance and Control, Vol. 3, No. 6, Nov-Dec 1980, pp. 494-500.

4. D. Atzhorn and R. F. Stengel, "Design and Flight Test of a Lateral-Directional Command Augmentation System", AIAA/IEEE 4th Digital Avionics Conference, AIAA Paper No. 81-2331, Nov 1981.

5. G. E. Cooper and R. P. Harper, Jr., "The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities", NASA TN D-5153, Apr 1969.

6. D. Bischoff, "Longitudinal Equivalent Systems Analysis of Navy Tactical Aircraft", AIAA 1981 Guidance and Control Conference, AIAA Paper No. 81-1775, Aug 1981.

7. W. Bihrle, Jr., "A Handling Qualities Theory for Precise Flight Control", AFFDL-TR-65-198, June 1966.

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9. R. F. Stengel, "A Unifying Framework for Longitudinal Flying Qualities Criteria", AIAA 1981 Atmospheric Flight Mechanics Conference, AIAA Paper No. 81-1889, Aug 1981.

10. H. A. Mooij, W. P. de Boer, and M. F. C. van Gool, "Determination of Low-Speed Longitudinal Maneuvering Criteria for Transport Aircraft with Advanced Flight Control Systems", NLR TR 79127U, Dec 1979.

FAILURES IN ADVANCED FLIGHT CONTROL SYSTEMS

BY M.F.C. VAN GOOL
NATIONAL AEROSPACE LABORATORY NLR
ANTHONY FOKKERWEG 2
1059CM AMSTERDAM, THE NETHERLANDS

THE NATIONAL AEROSPACE LABORATORY NLR IS PREPARING AN EXPERIMENT ON A MOVING-BASE FLIGHT SIMULATOR DIRECTED AT FLYING QUALITIES OF TRANSPORT AIRCRAFT EQUIPPED WITH ADVANCED FLIGHT CONTROL SYSTEMS OF THE RATE-COMMAND/ATTITUDE-HOLD TYPE. SEVERAL ASPECTS OF FAILURES IN THE PRIMARY FLIGHT CONTROL SYSTEM ON PILOT OPINION WILL BE STUDIED. THE PILOTING TASK WILL CONSIST OF TERMINAL MANOEUVRING (TAKE-OFF, IFR APPROACH, LANDING).
THE BASELINE AIRCRAFT HAS REDUCED STATIC STABILITY AND SITUATIONS WITH UNSTABLE PITCH CONTROL AFTER FAILURE WILL BE INVESTIGATED.
ASPECTS THAT WILL BE INCORPORATED IN THE INVESTIGATION INCLUDE:
1. TIME TO DOUBLE PITCH ATTITUDE
2. THE MOMENT OF THE FAILURE
3. AUTOTHROTTLE ON OR OFF
4. TURBULENCE INTENSITY
5. CROSSWIND LANDINGS
6. FAILURE TRANSIENTS

THE RATIONALE BEHIND THE CONFIGURATION SELECTION WILL BE DESCRIBED AND COMMENTARY IS REQUESTED FROM THE AUDIENCE ON THE EXPERIMENT DESIGN. VALUABLE SUGGESTIONS CAN BE IMPLEMENTED IN THE EXPERIMENTS YET.

FIGURES:

1. BLOCK DIAGRAM OF THE AIRCRAFT/FLIGHT CONTROL SYSTEM
2. FAILURE INTRODUCTION
3. PILOTING TASK
4. ROOT LOCUS PITCH ATTITUDE FEEDBACK
5. ROOT LOCUS PITCH ATTITUDE+PITCH RATE FEEDBACK
6. ROOT LOCUS PITCH RATE FEEDBACK (FAILURE)
7. EQUIVALENT SYSTEM BEFORE FAILURE
8. EQUIVALENT SYSTEM AFTER FAILURE
9. RESPONSE TO BLOCK-TYPE PITCH INPUT BEFORE FAILURE
10. RESPONSE TO BLOCK-TYPE PITCH INPUT AFTER FAILURE
11. RESPONSE TO ANGLE OF ATTACK OFFSET BEFORE FAILURE
12. RESPONSE TO ANGLE OF ATTACK OFFSET AFTER FAILURE

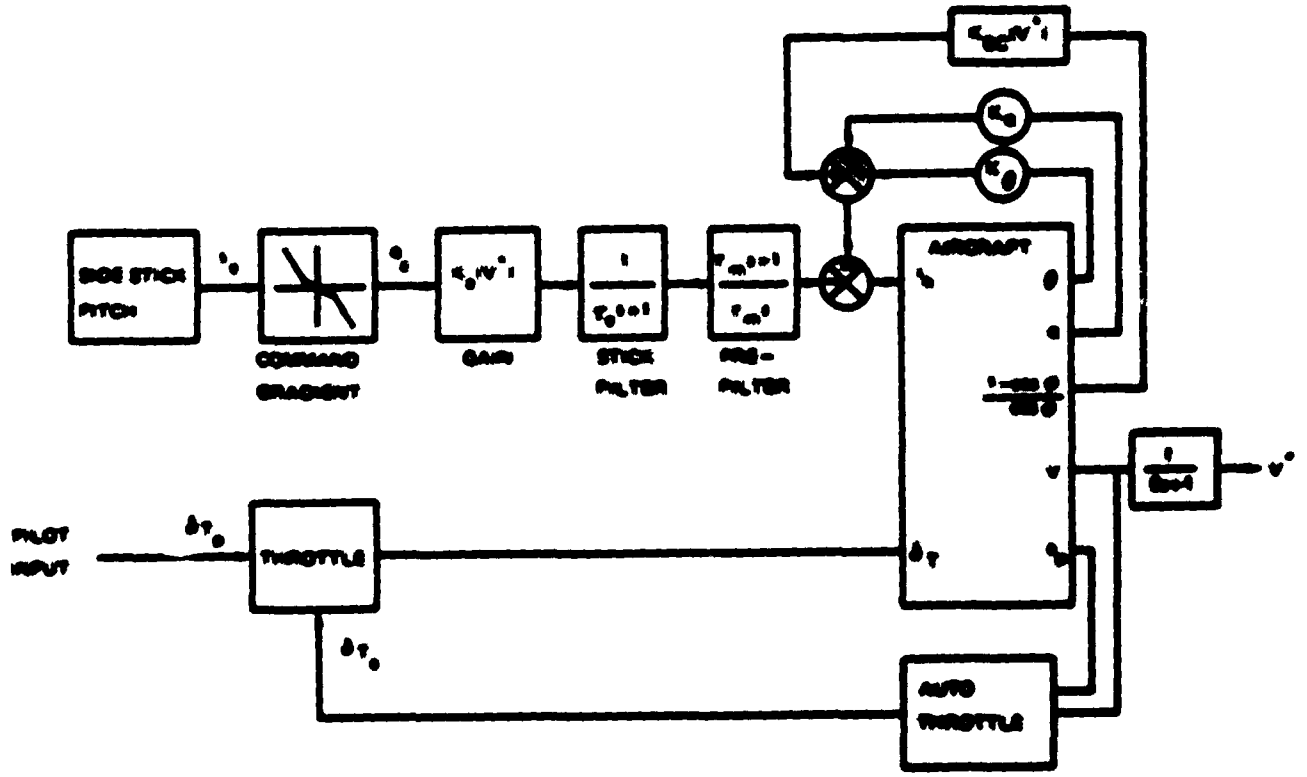


Fig. 1 Block diagram of the aircraft/flight control system

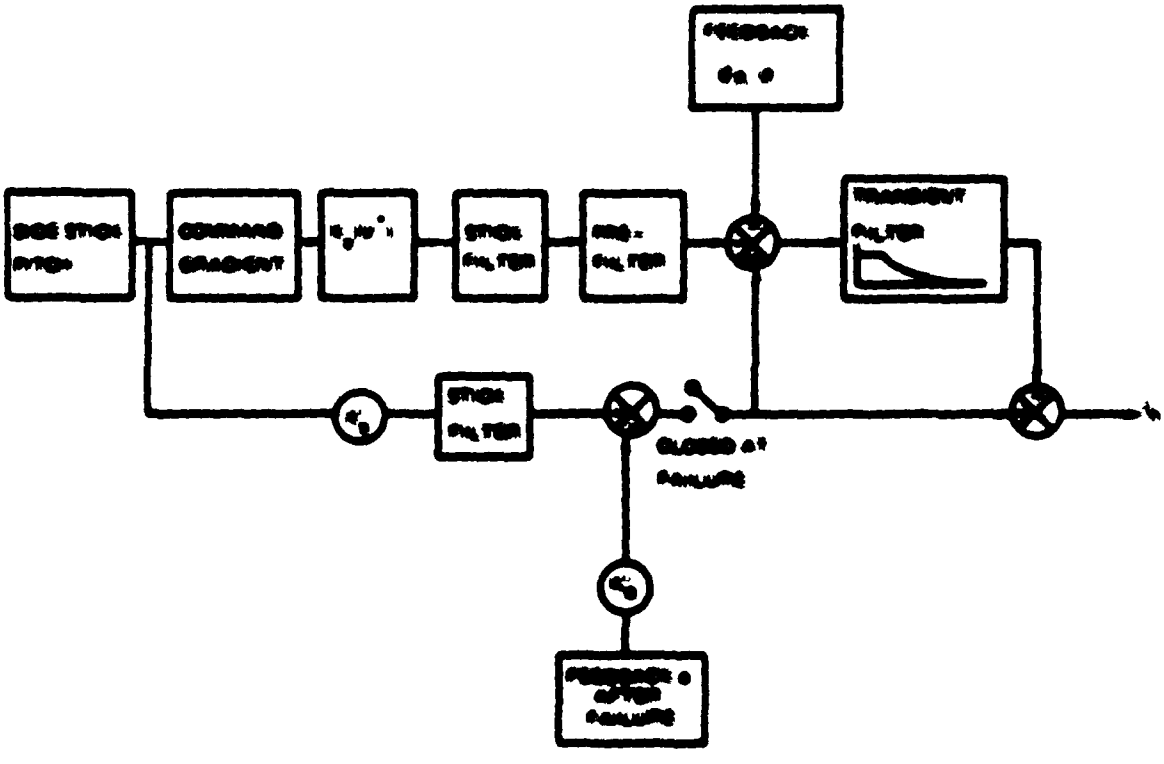


Fig. 2 Failure introduction

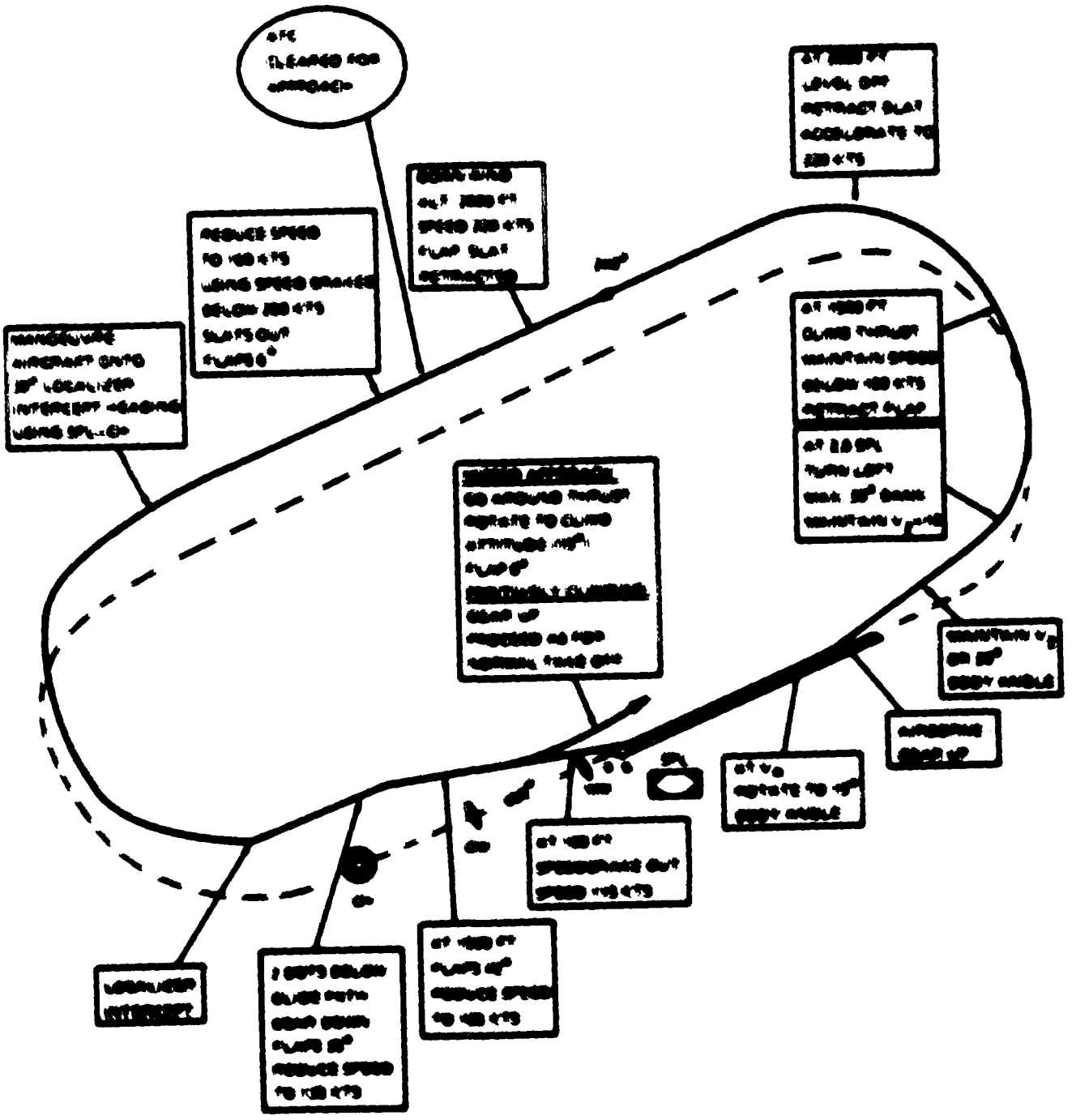


Fig. 3 Piloting task

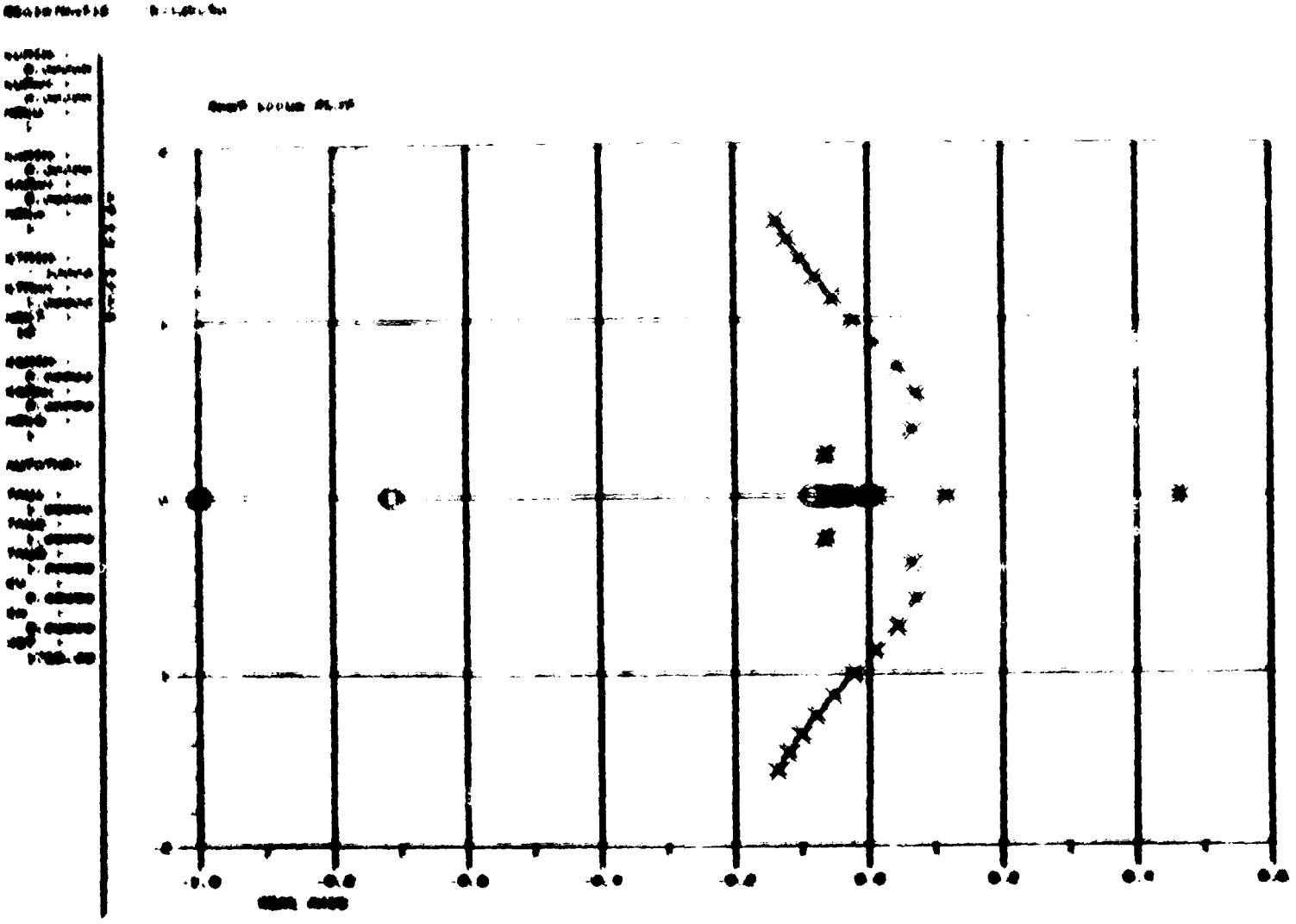


Fig. 4 Root locus pitch attitude feedback

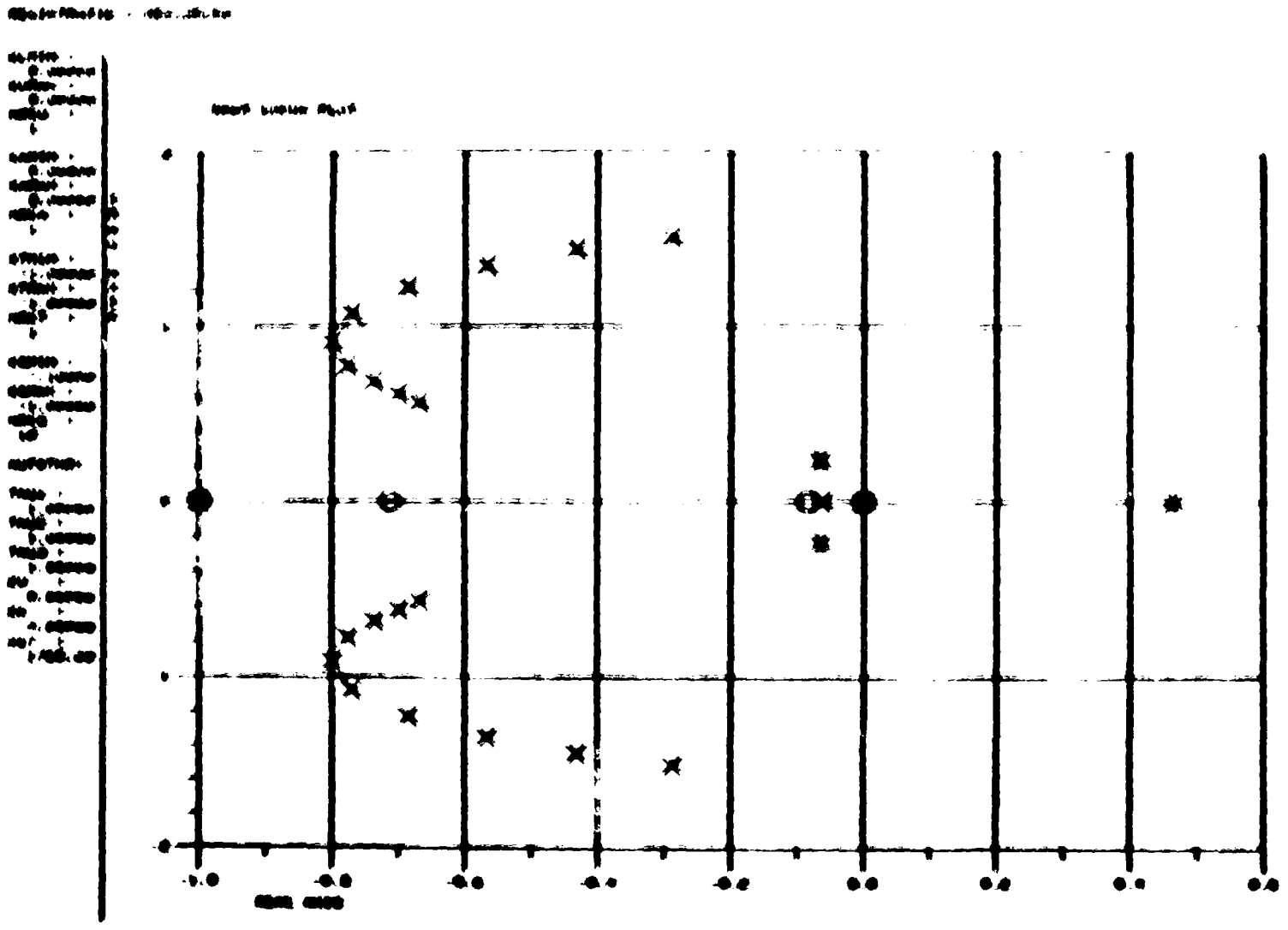


Fig. 8 Short tosque pitch attitude - pitch rate feedback

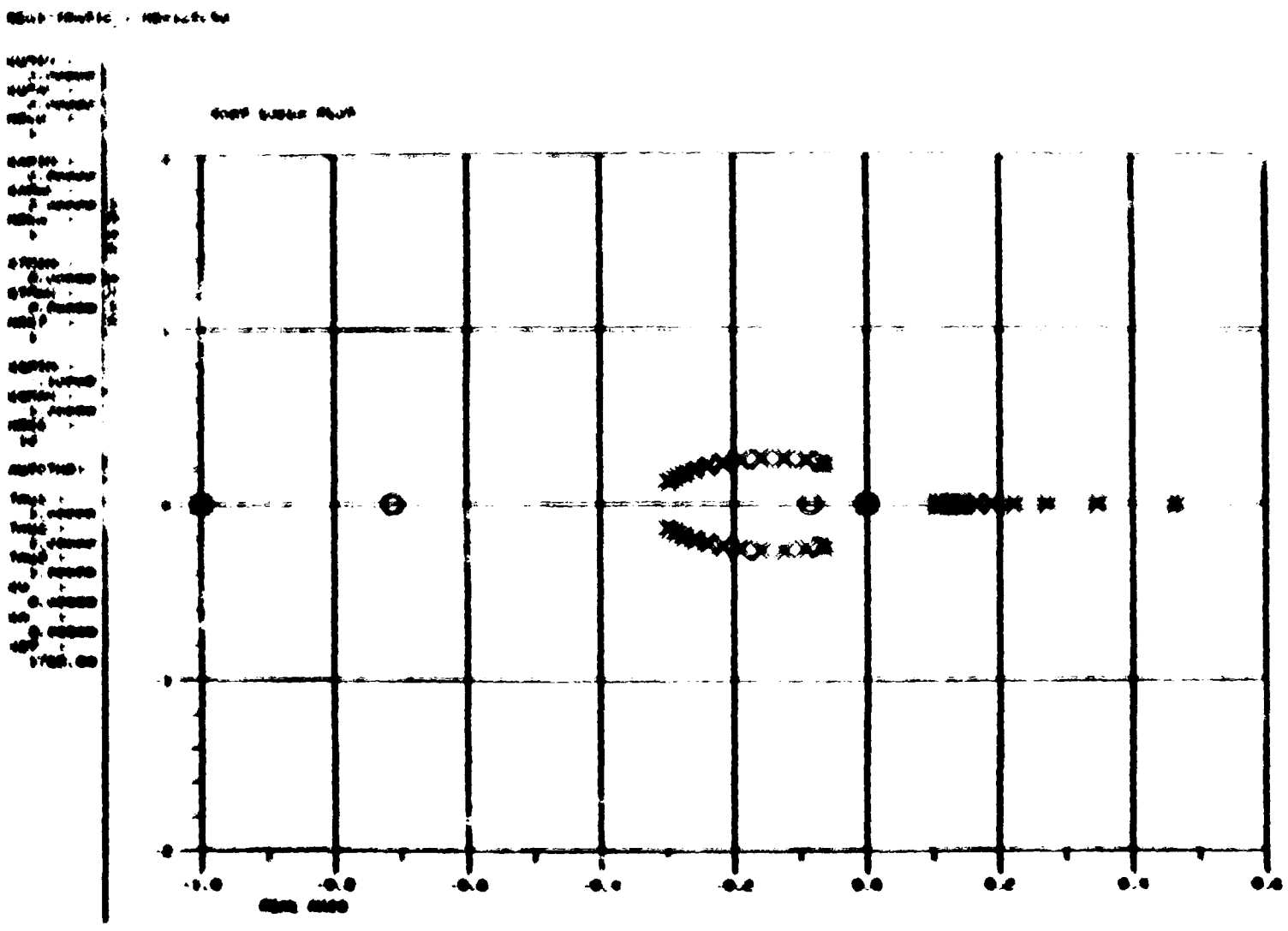


Fig. 8 Root Locus pitch rate feedback (failure)

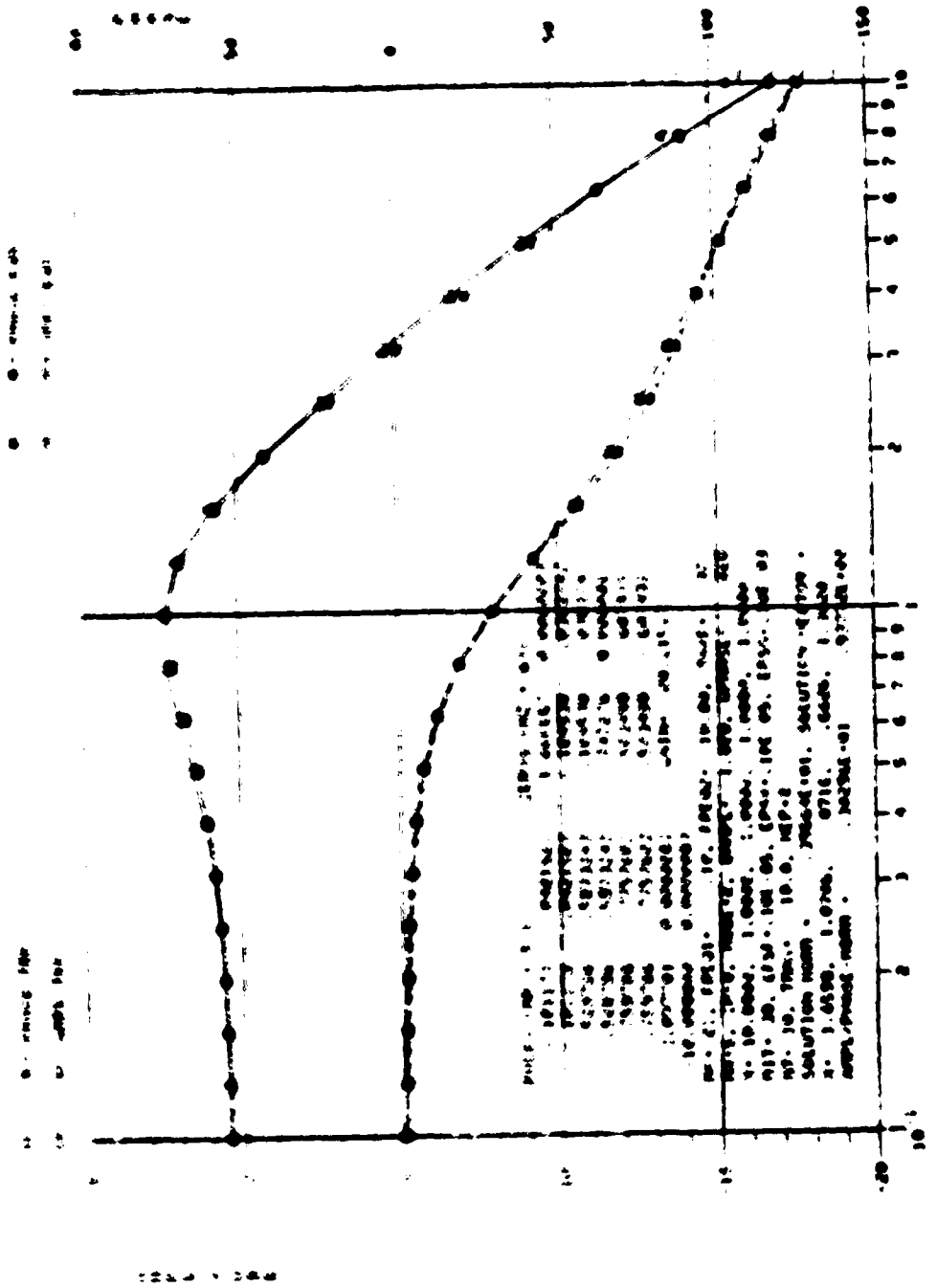
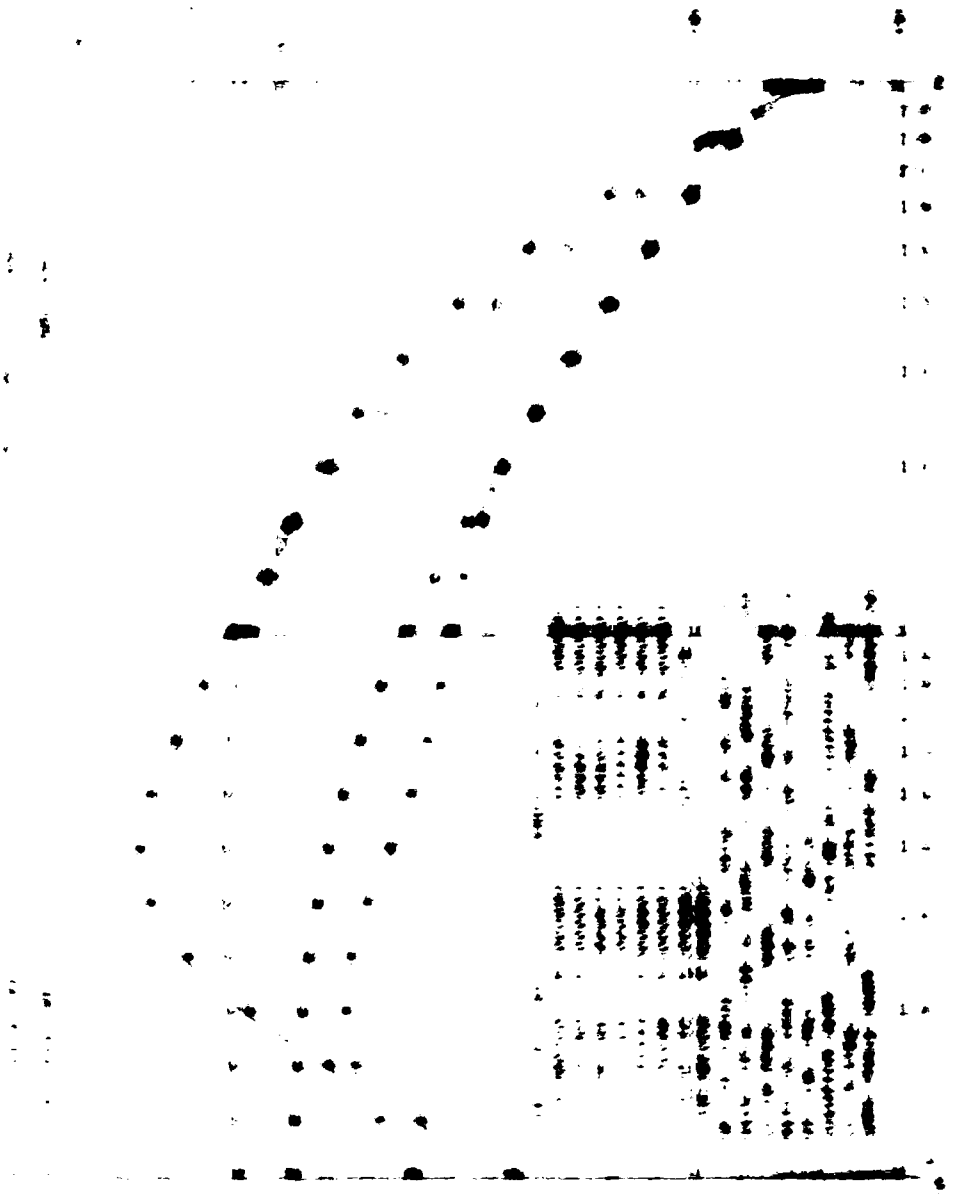


Fig. 7 Equivalent system before failure



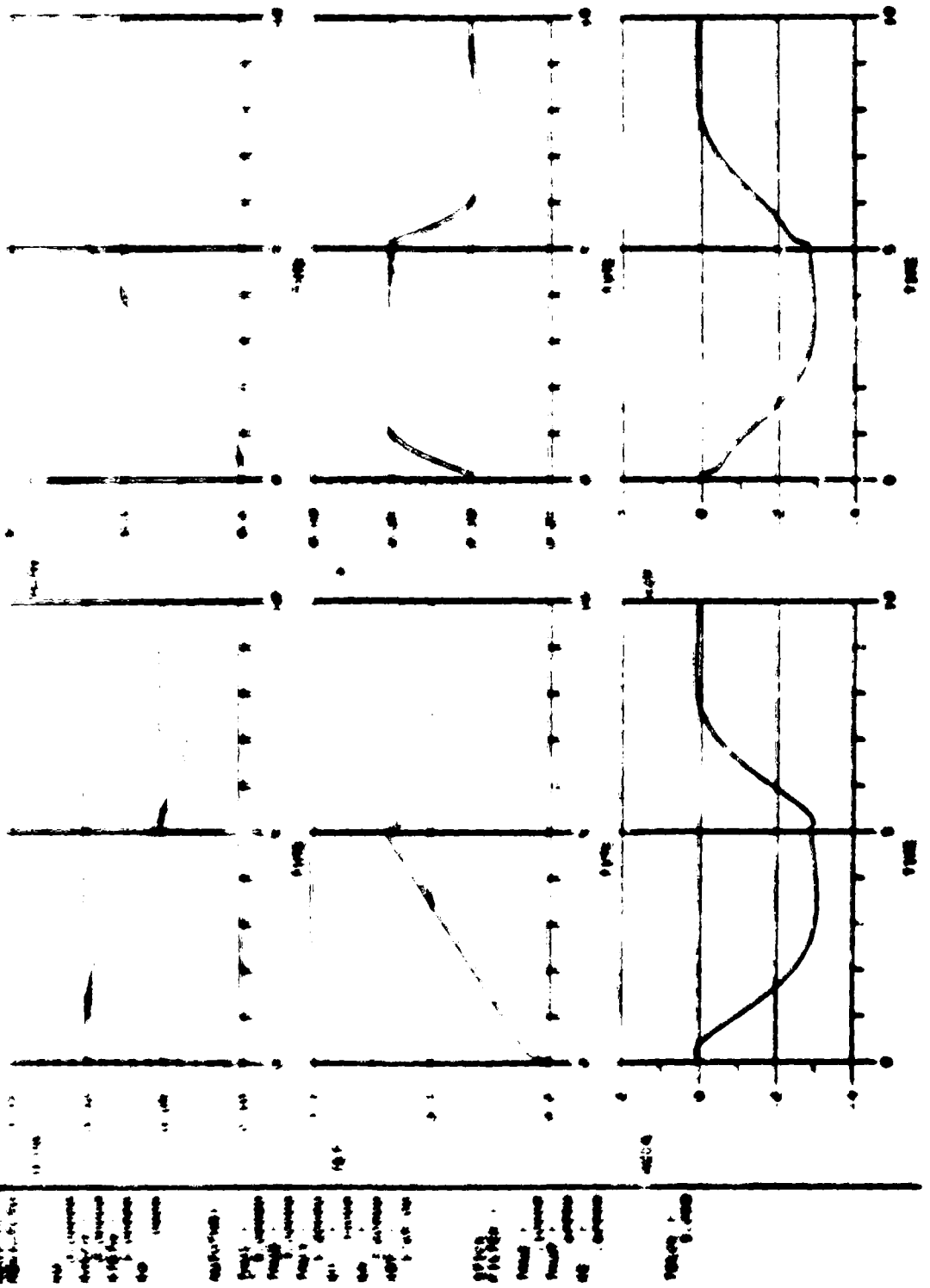


Fig. 9 Response to block-type pitch input before failure

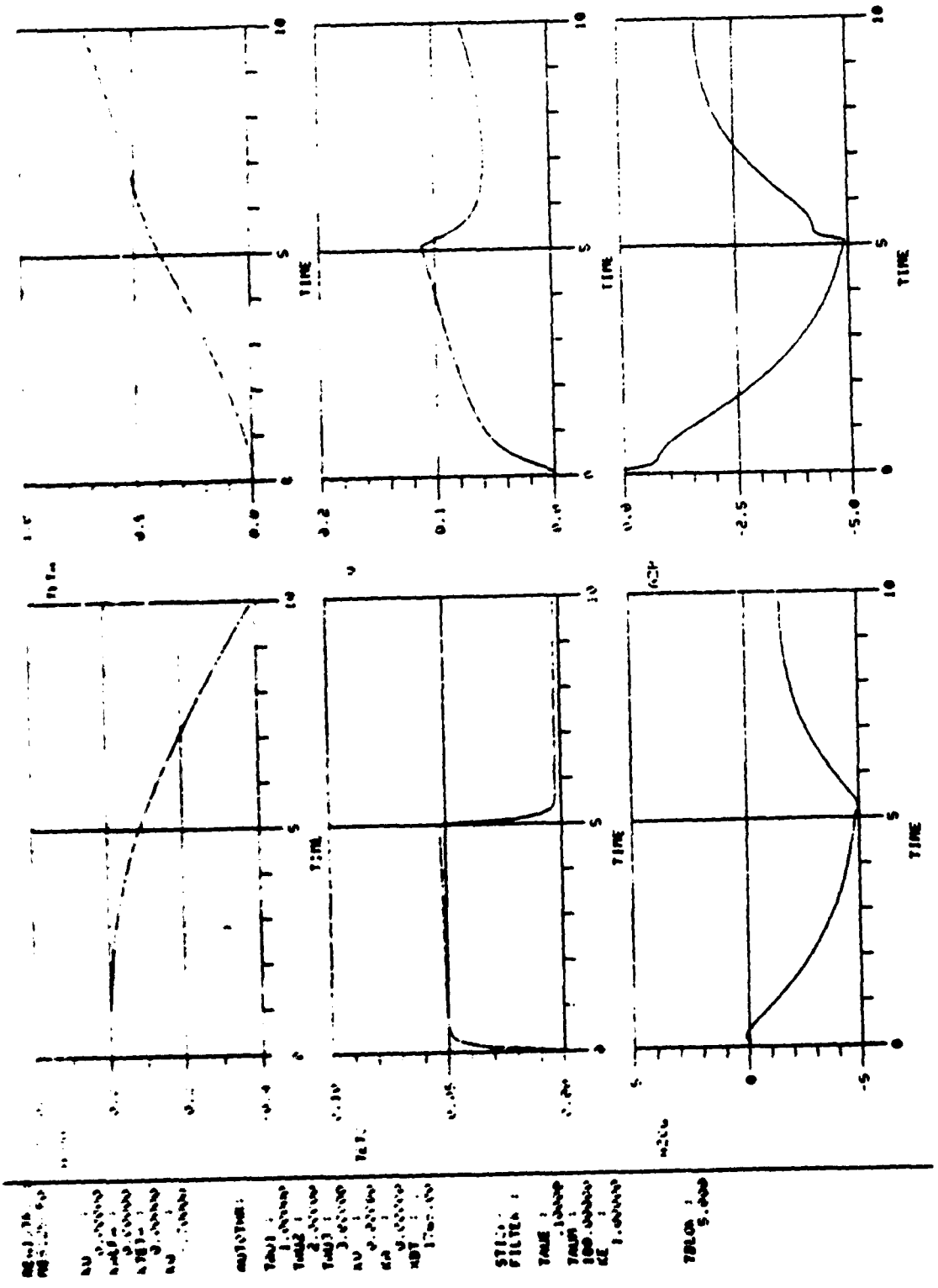


Fig. 10 Response to block-type pitch input after failure

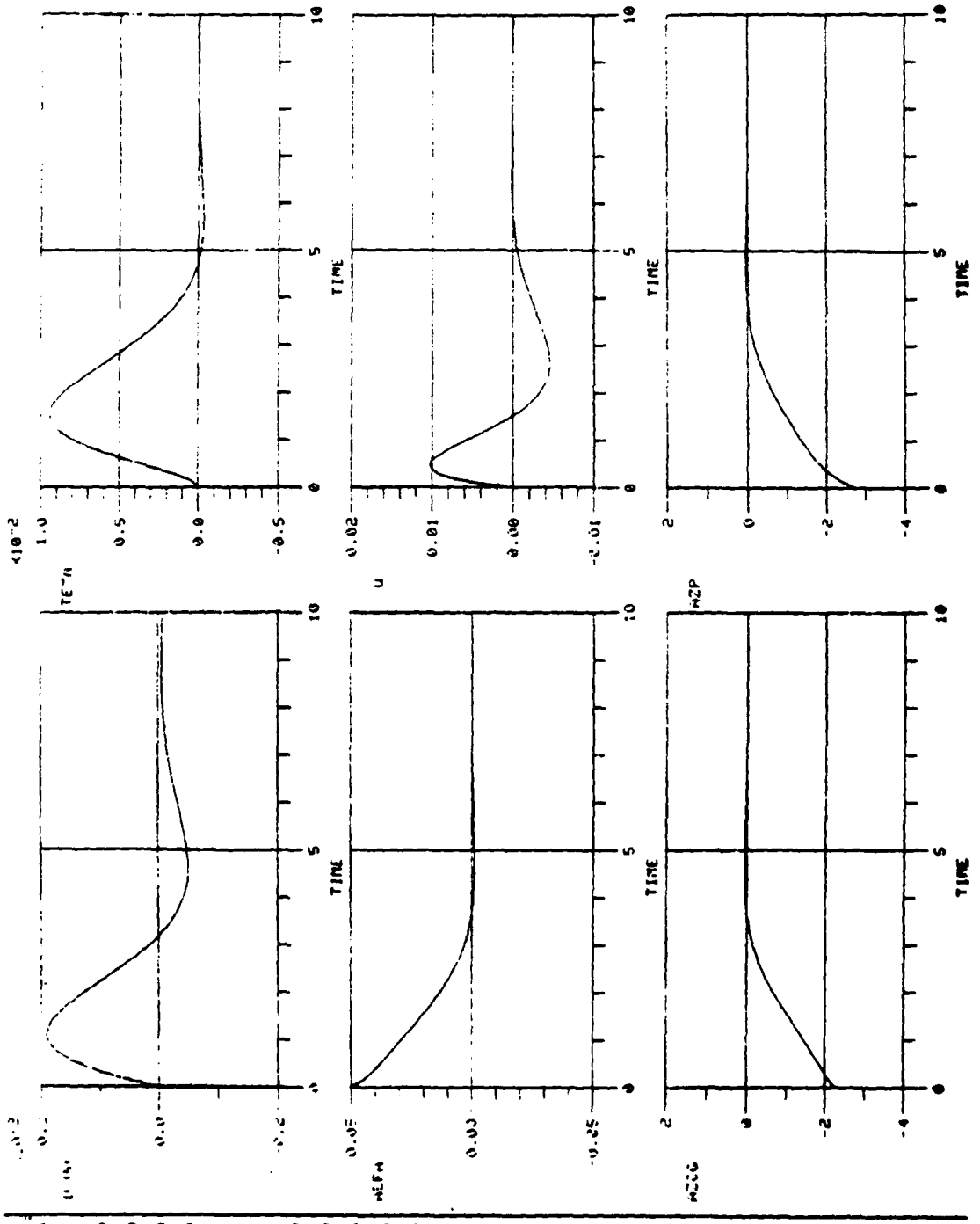


Fig. 11 Response to angle of attack offset before failure

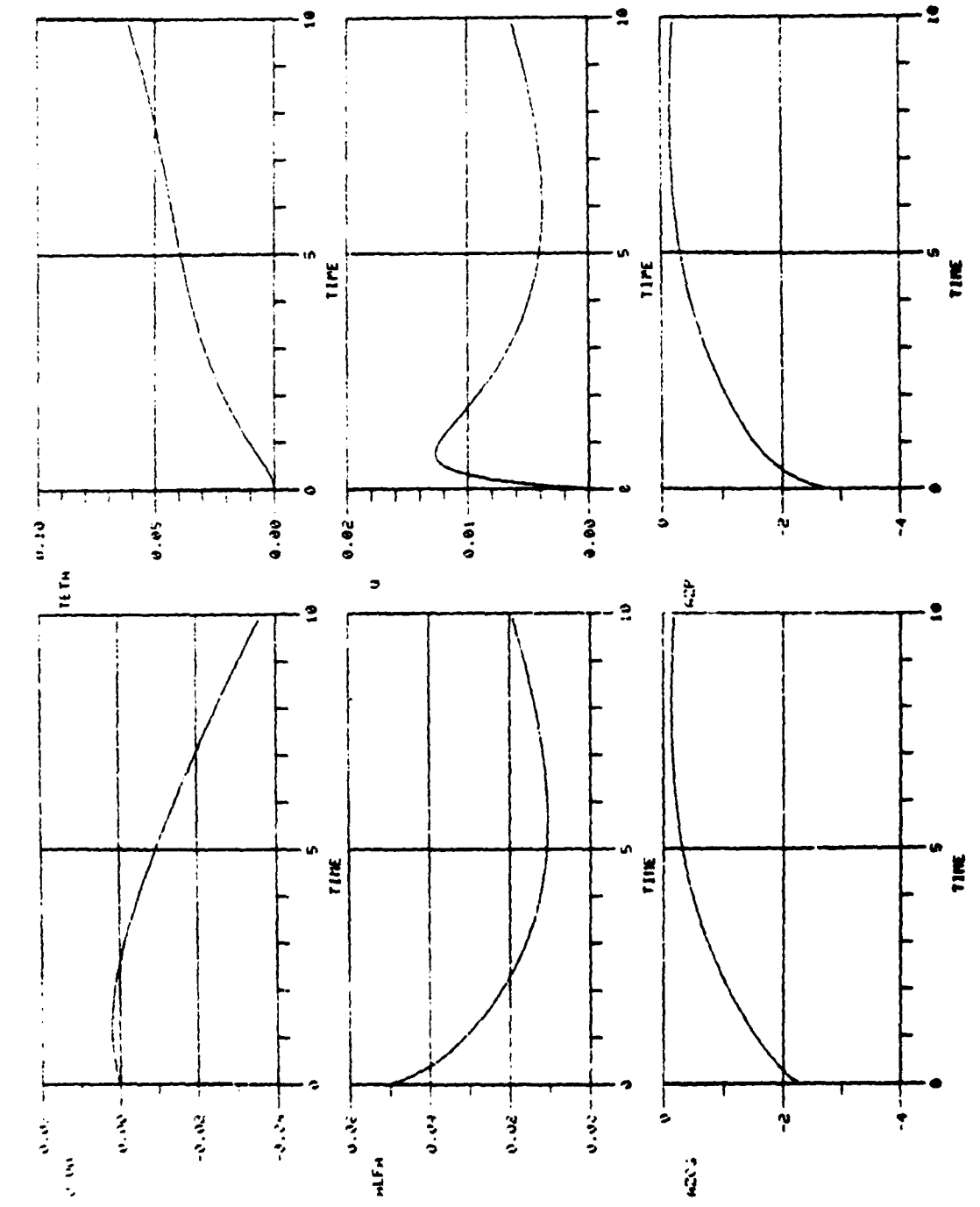


Fig. 12 Response to angle of attack offset after failure

MODERN APPROACHES TO HANDLING QUALITIES RESEARCH

David K. Schmidt
Purdue University

MODERN APPROACHES TO HANDLING QUALITIES RESEARCH

BY

DAVID K. SCHMIDT
SCHOOL OF AERONAUTICS & ASTRONAUTICS
PURDUE UNIVERSITY
WEST LAFAYETTE, IN

USAF FLYING QUALITIES SYMPOSIUM
WPAFB, OHIO
MARCH 2-5, 1982

SUPPORTED UNDER NASA
GRANT NAG4-1
DRYDEN FLIGHT RESEARCH FACILITY

TOWARDS BRIDGING THE GAP

FREQUENCY DOMAIN

LEAD/LAG

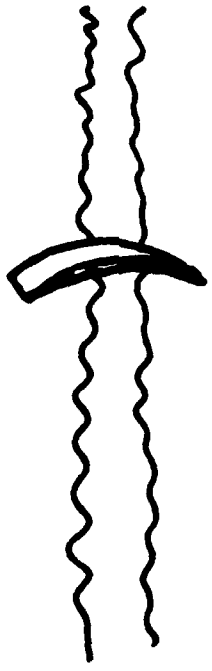
BANDWIDTH
ω_{SP}

EFFECTIVE TIME DELAY

"DROOP"

RESONANCE PEAK

•
•
•



TIME DOMAIN

TRACKING ERROR

NEUROMUSCULAR TIME CONSTANT

OBJECTIVE FUNCTION

Q R

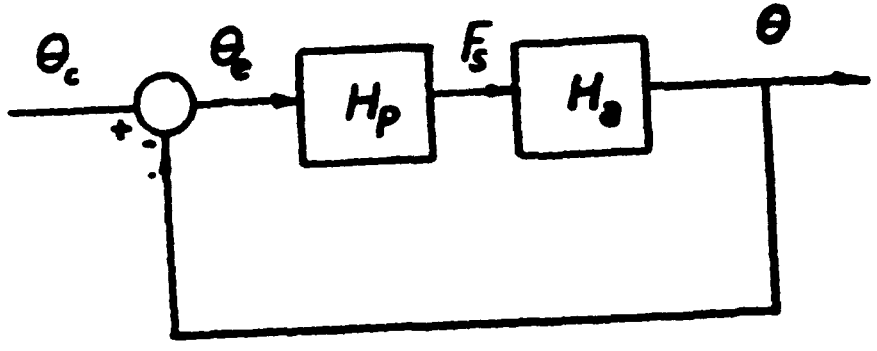
MARKOV PROCESS

•
•
•

TOPIC

- NEAL-SMITH CRITERIA VIA OPTIMAL CONTROL

NEAL SMITH MODEL



NEAL SMITH APPROACH

SET PILOT MODEL FORM

$$\frac{F_s}{\theta_e} = K_p e^{-0.3s} \left| \frac{T_{D_1} s + 1}{T_{P_2} s + 1} \right|$$

FIND K_p, T_{P_1}, T_{P_2} SUCH THAT

① BANDWIDTH EQUALS 3.5 RAD/SEC

② $|\theta/\theta_c| > -3$ DB FOR $\omega \leq BW$

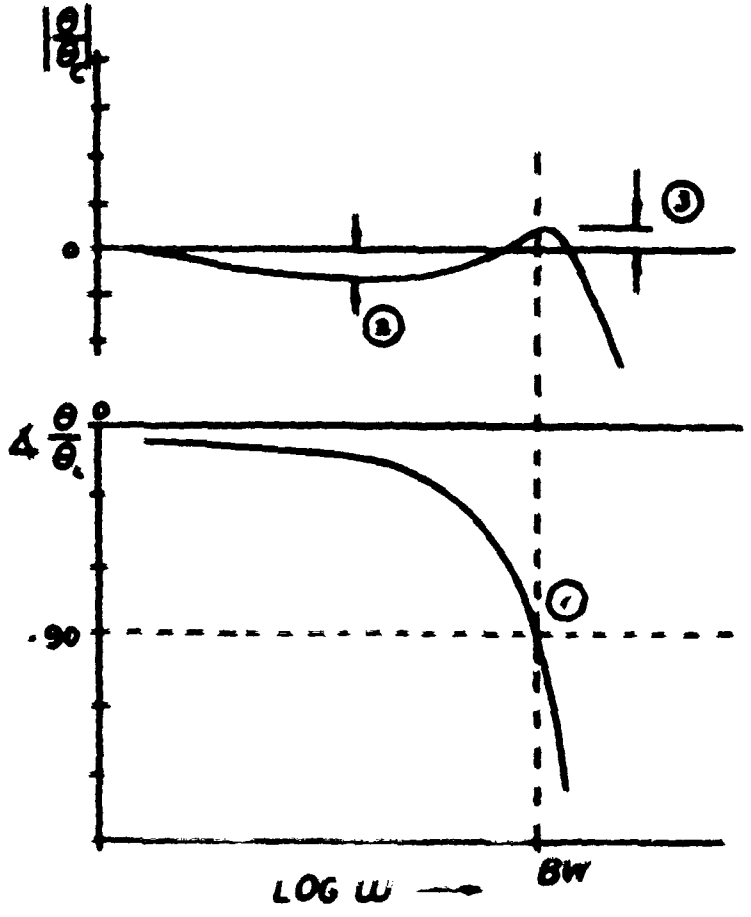
IN THE <u>CLOSED-LOOP</u> ANALYSIS.

NEAL SMITH CRITERIA

① A REASONABLE BANDWIDTH

② A MINIMUM OF LOW-FREQUENCY DROOP

③ GOOD HIGH-FREQUENCY STABILITY

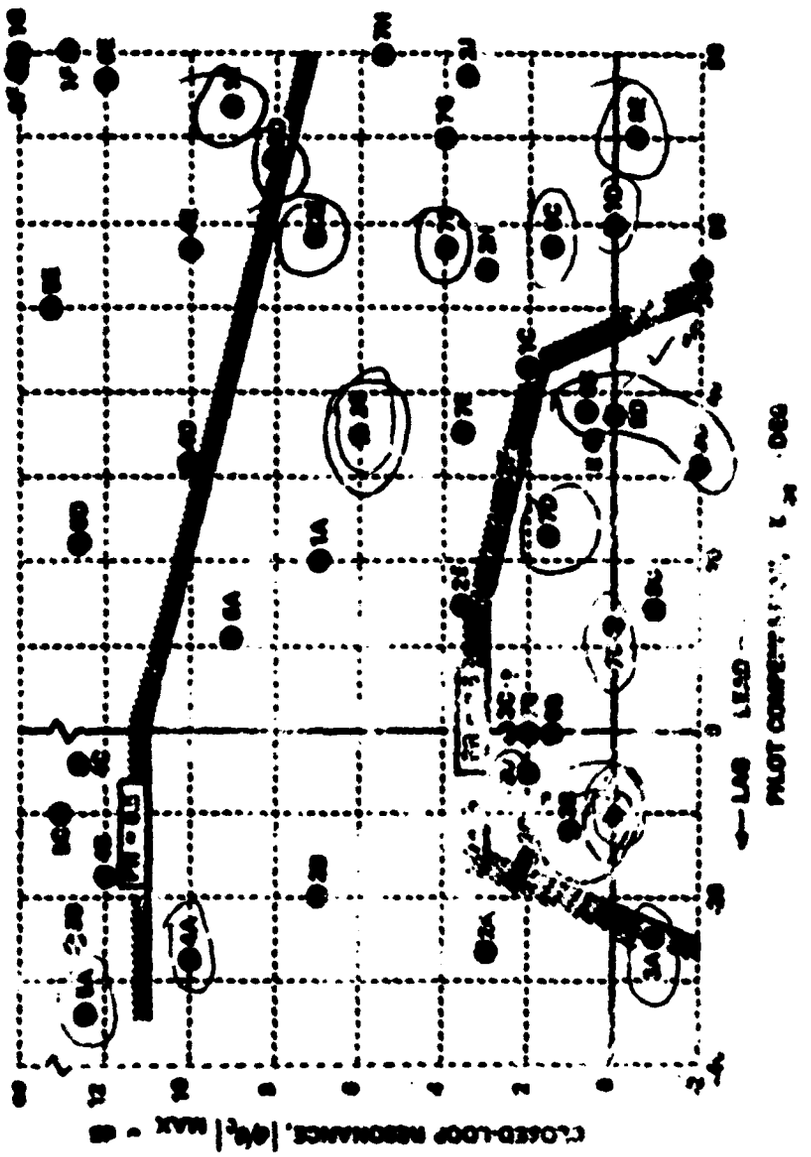


NEAL SMITH RESULTS

① PILOT COMPENSATION (i.e. LAG, LEAD)

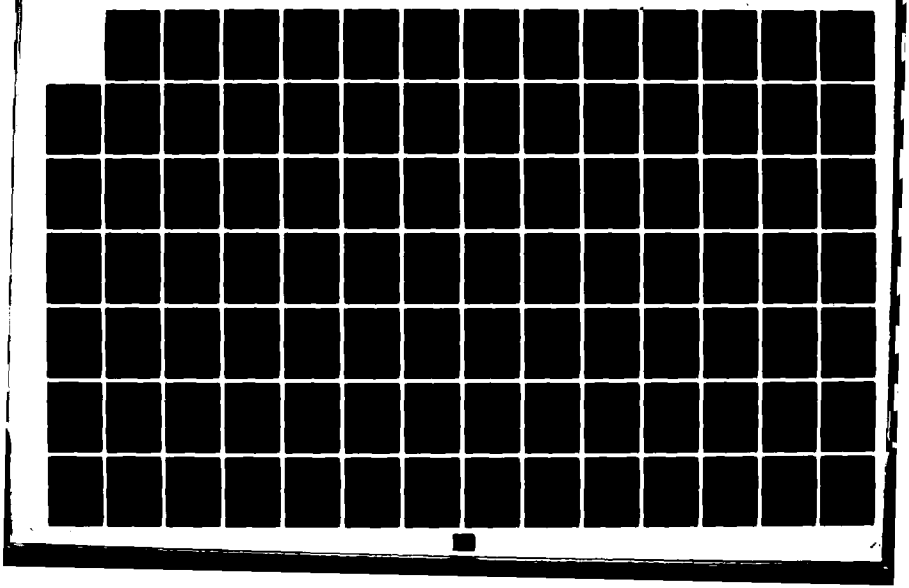
② $|\theta/\theta_c|_{max}$

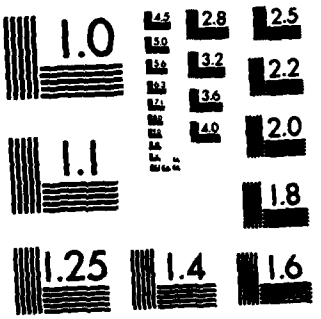
THESE PARAMETERS YIELD PILOT RATING PREDICTIONS!


CLOSED-LOOP RESONANCE, $|\phi/\phi_c|_{MAX}$ = dB
PILOT COMPENSATION, K_p, DEG
LAG
LEAD

AD-A121 423 DESIGN CRITERIA FOR THE FUTURE OF FLIGHT CONTROLS PROCEEDINGS OF THE FLIG..(U) AIR FORCE WRIGHT AERONAUTICAL LABS WRIGHT-PATTERSON AFB OH

UNCLASSIFIED S G FULLER ET AL. JUL 82 AFWAL-TR-82-3064 F/G 1/2 NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

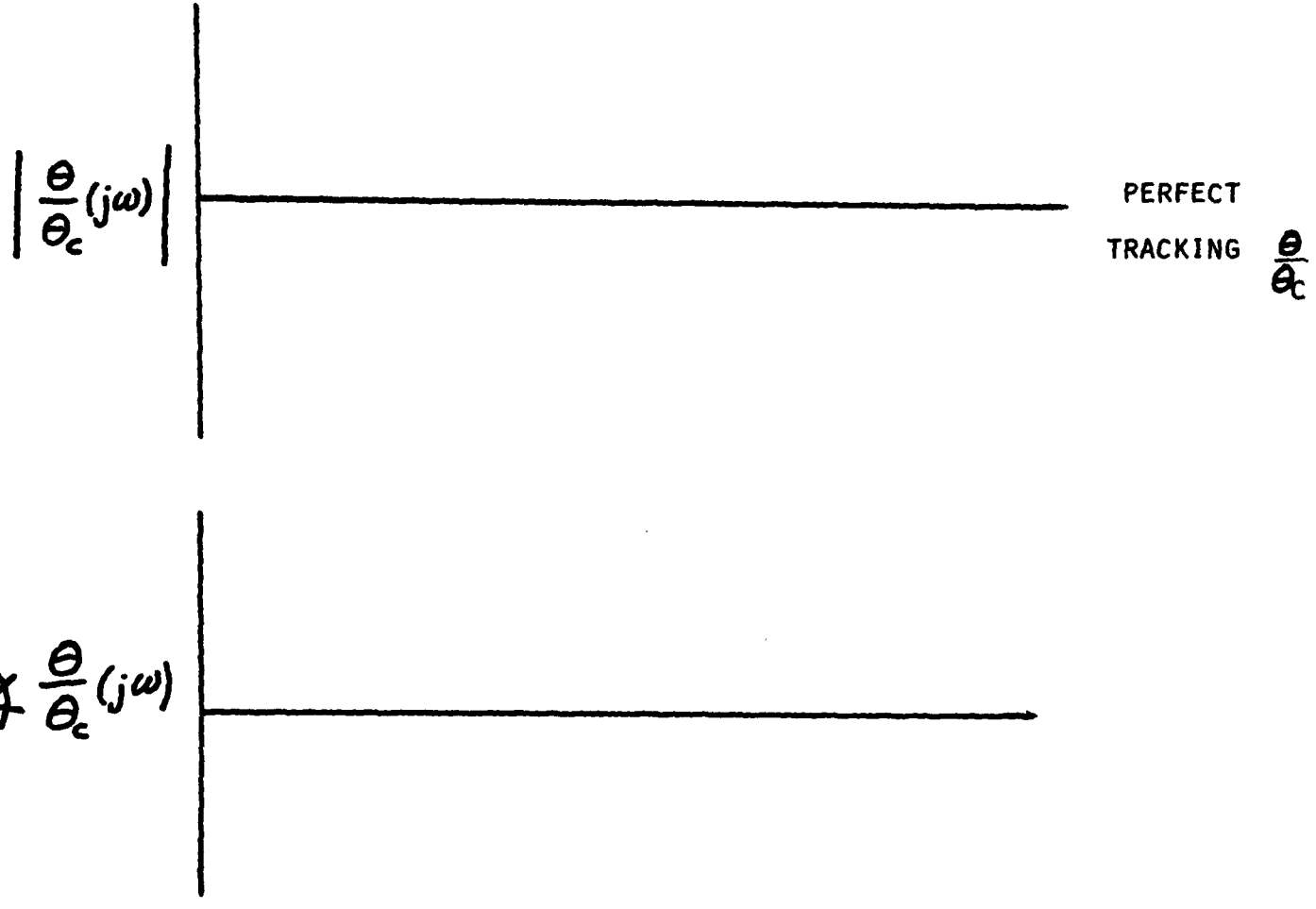
THE KEY RELATION

IF $E = \theta - \theta_{\text{COMMAND}}$

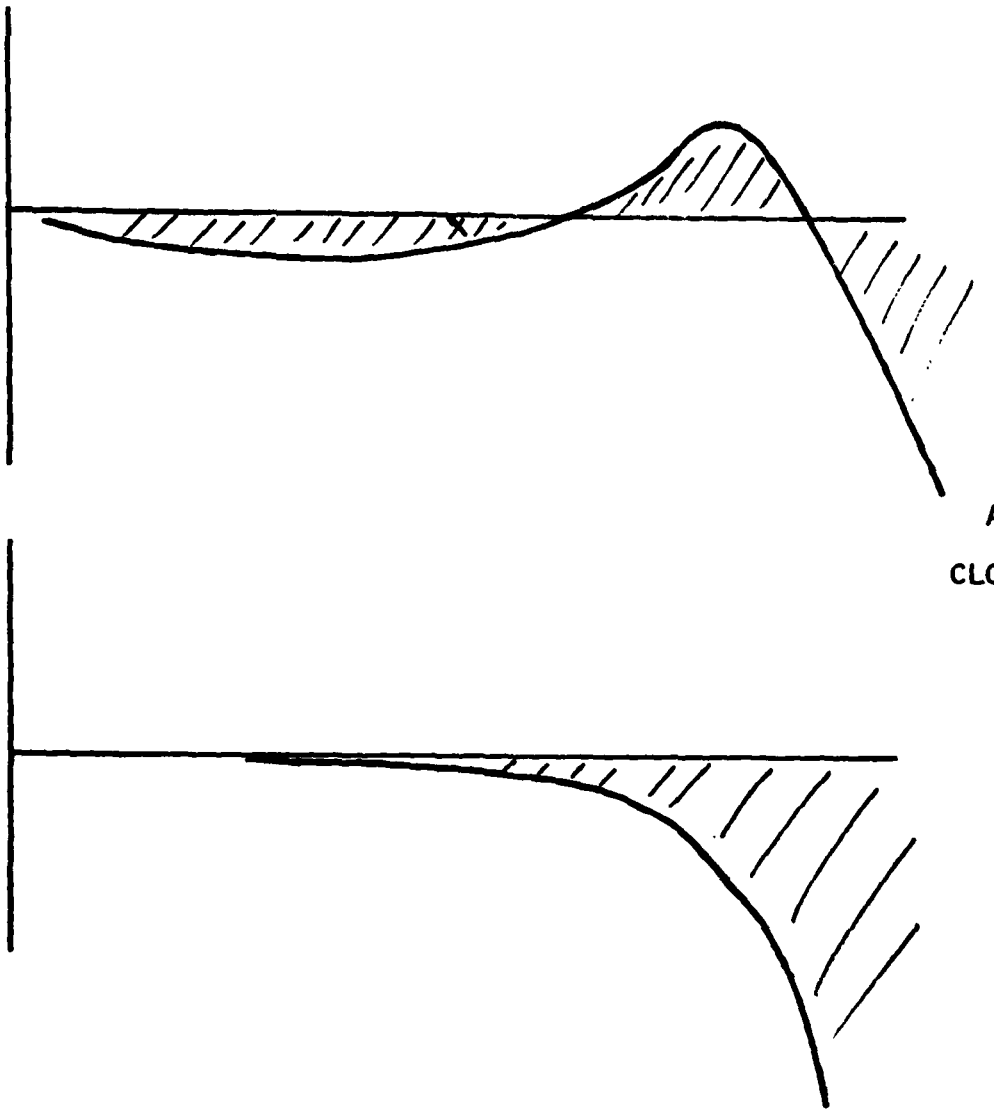
$$\sigma_E^2 = \frac{1}{\pi}\int_0^\infty \left|\frac{E}{\theta_c}(j\omega)\right|^2 S_{\theta_c}(\omega)\, D\omega$$

WHERE $$\frac{E(s)}{\theta_c(s)} = 1 - \frac{\theta(s)}{\theta_c(s)}$$

FREQUENCY DOMAIN INTERPRETATION



(A)

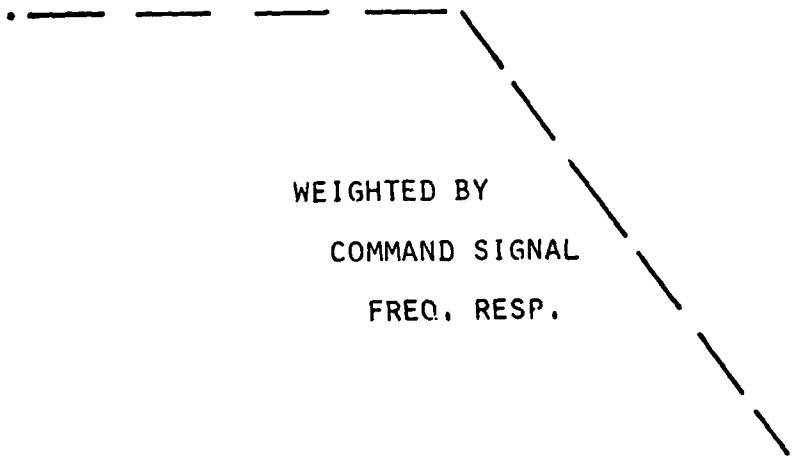


ACTUAL

CLOSED-LOOP

θ/θ_c

Overlay on (A)



595

Overlay on (A)

INTERMEDIATE RESULT

IF OPTIMAL CONTROL PILOT MODEL = MIN σ_E^2

(SUBJECT TO HUMAN LIMITATIONS, τ_N, τ_{DELAY}, ETC)

THE Y_P FROM OCM MINIMIZES DROOP

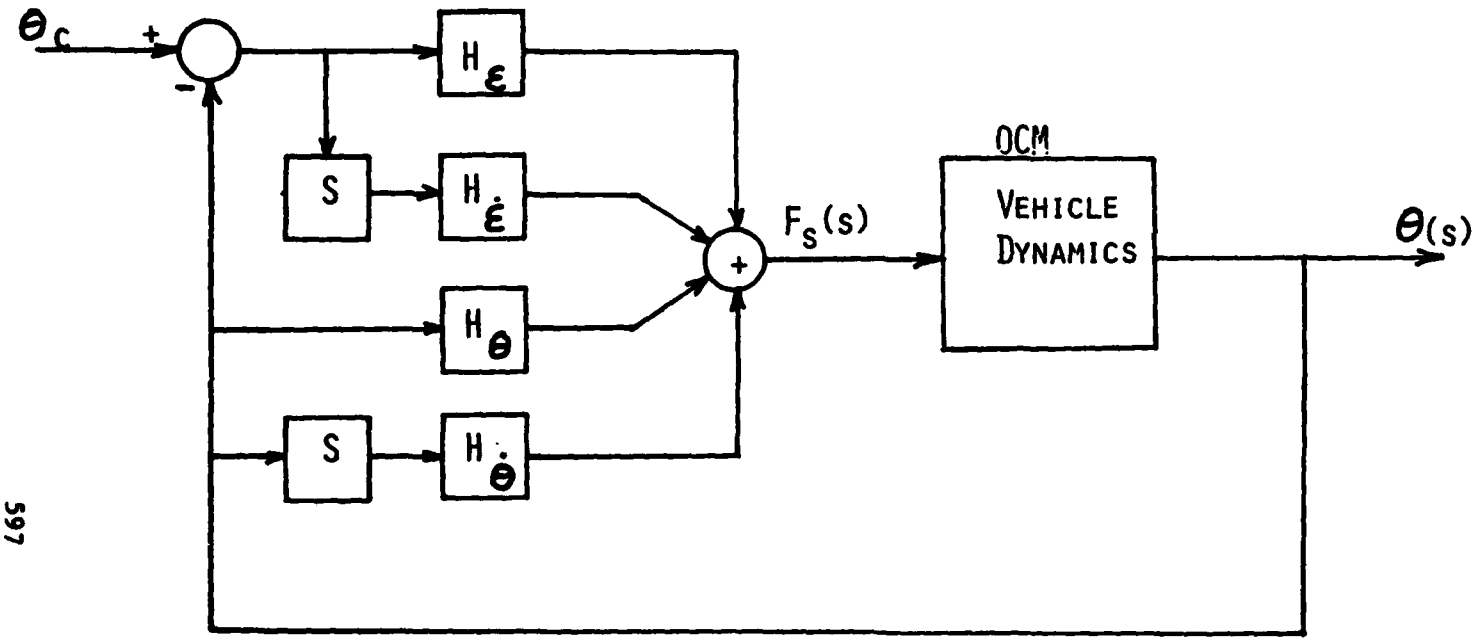
MINIMIZES RESONANT PEAK !

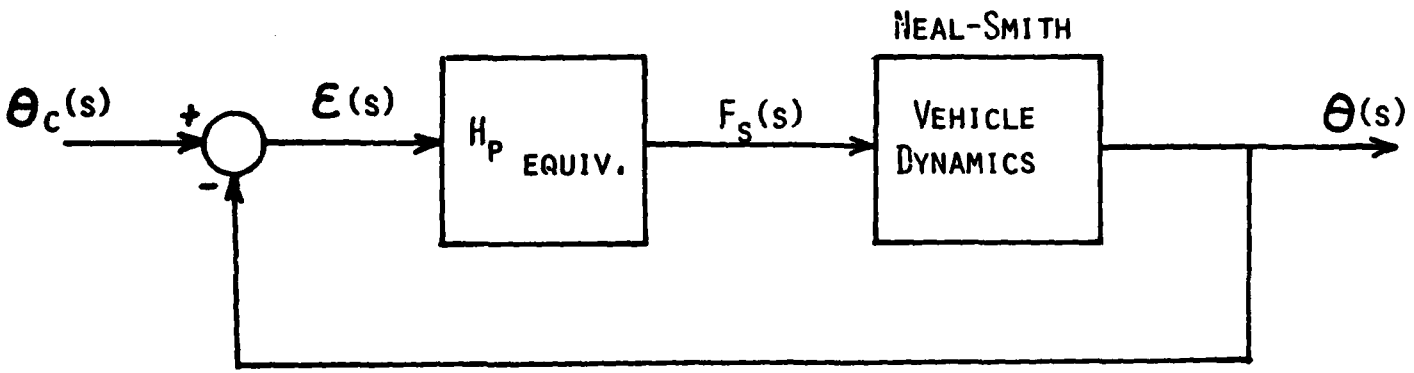
REMARKS

1. AMOUNT OF DROOP DEPENDS ON
   COMMAND SIGNAL FREQUENCY RESPONSE

2. FOR SELECTED τ_N - BANDWIDTH VARIES AND DEPENDS ON
   VEHICLE DYNAMICS

PILOT VEHICLE SCHEMATICS





$$S_w(\omega) = \sigma_w^2$$

$$S_{\theta_c}(\omega) = |H_1(j\omega)|^2 S_w(\omega) \longrightarrow \sigma_{\theta_c}^2$$

$$S_{\theta_e}(\omega) = \left|\frac{\theta_e}{\theta_c}(j\omega)\right|^2 S_{\theta_c}(\omega) \longrightarrow \sigma_{\theta_e}^2$$

$$S_{F_s}(\omega) = \left|\frac{F_s}{\theta_e}(j\omega)\right|^2 S_{\theta_e}(\omega) \longrightarrow \sigma_{F_s}^2$$

$$S_{\theta}(\omega) = \left|\frac{\theta}{F_s}(j\omega)\right|^2 S_{F_s}(\omega) \longrightarrow \sigma_{\theta}^2$$

		ACTUAL
σ_{θ_c}	3.939	4.000
σ_{θ_e}	.9745	1.116
σ_{F_s}	2.498	2.598
σ_{θ}	3.6946	3.775

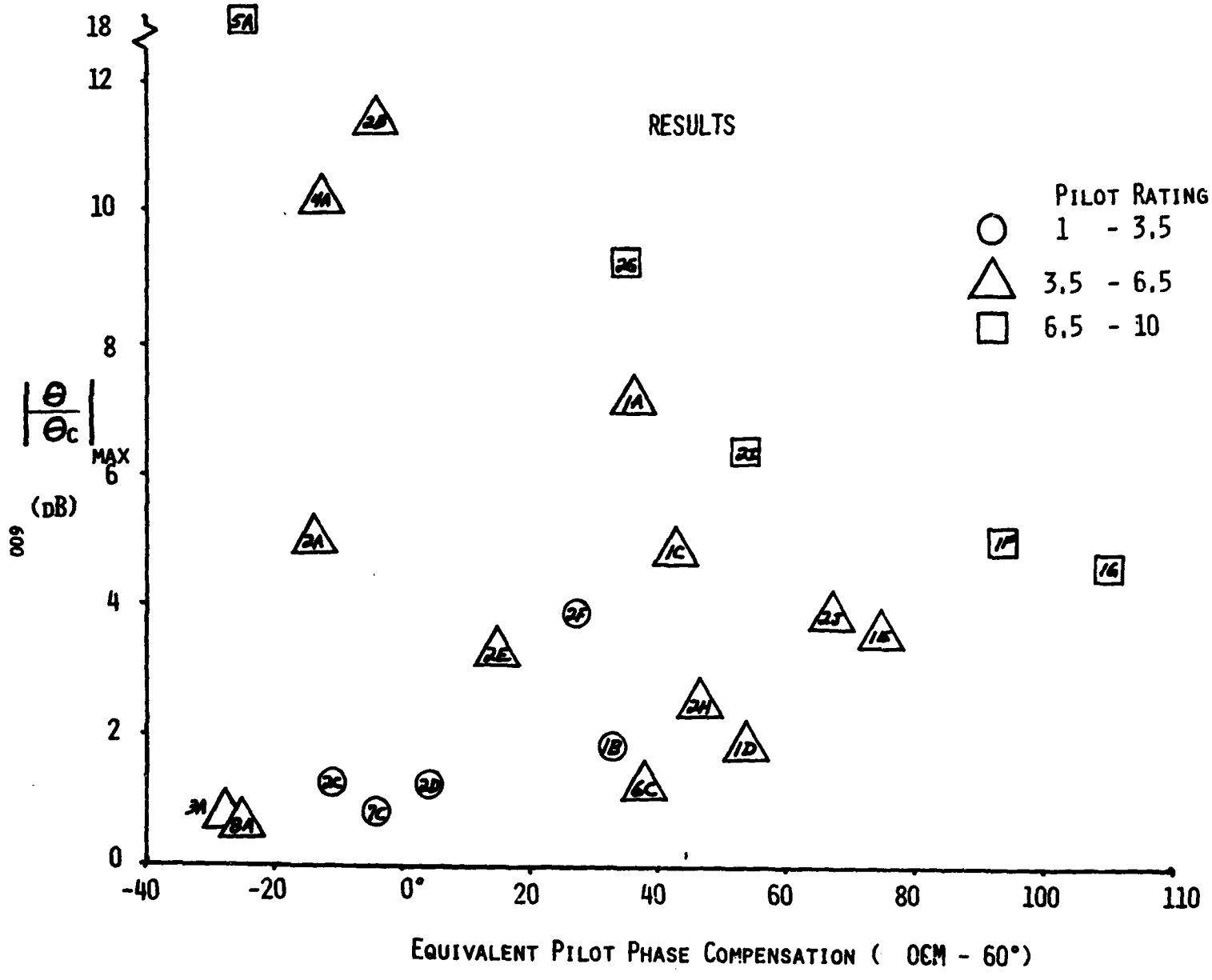
NEW APPROACH (OCM)

SET OCM TO TRACK A SIGNAL OF SAME STATISTICS AS USED IN FLIGHT TEST.

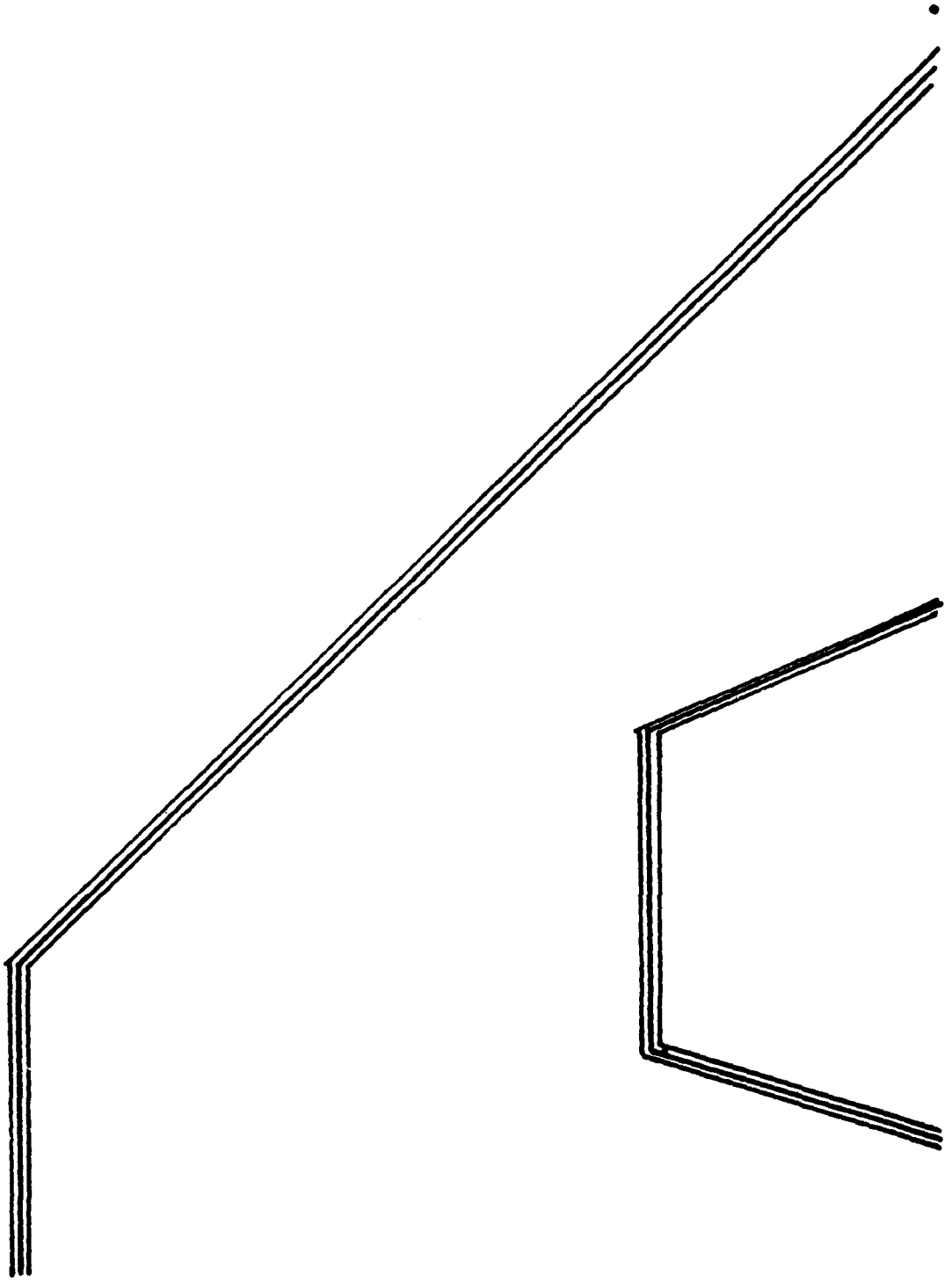
SELECT AN OBJECTIVE FUNCTION WHICH REPRESENTS ACTUAL EXPERIMENTAL CONDITIONS.

$$J(F_S) = \frac{1}{T}\int_0^T \left(16(\theta_c - \theta)^2 + (\dot{\theta}_c - \dot{\theta})^2 + q(\dot{F}_S)^2\right) dt$$

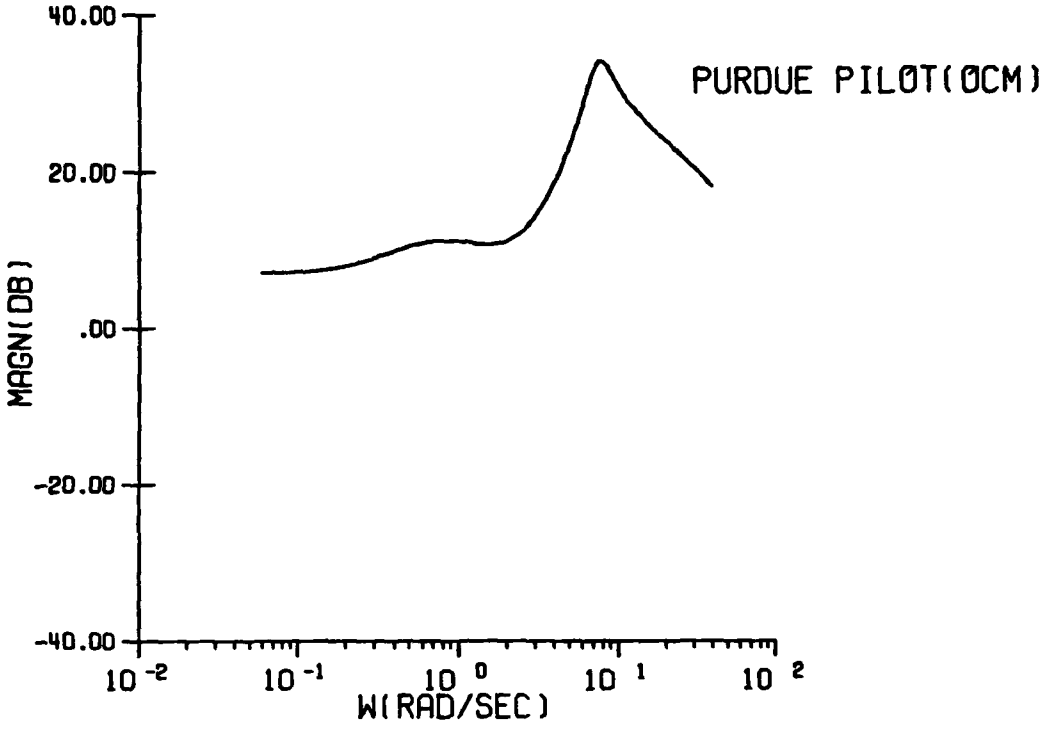
USE THE OCM'S PILOT FREQUENCY DATA TO MAKE AN ANALYSIS COMPARABLE WITH NS.

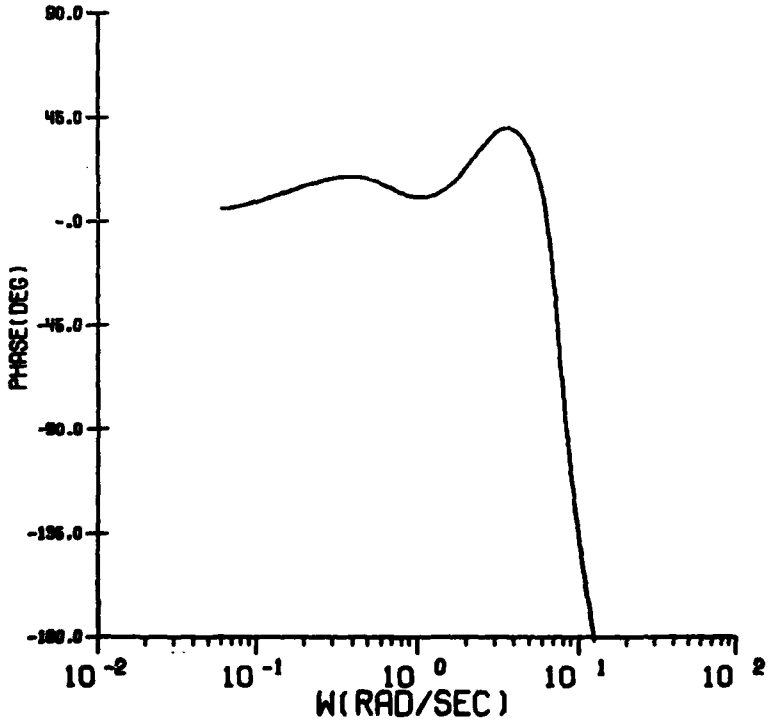

RESULTS
PILOT RATING
1 - 3.5
3.5 - 6.5
6.5 - 10
18
12
10
8
6
4
2
0
MAX
(DB)
-40
-20
0°
20
40
60
80
100
110
EQUIVALENT PILOT PHASE COMPENSATION (OCM - 60°)

Overlay on (6)

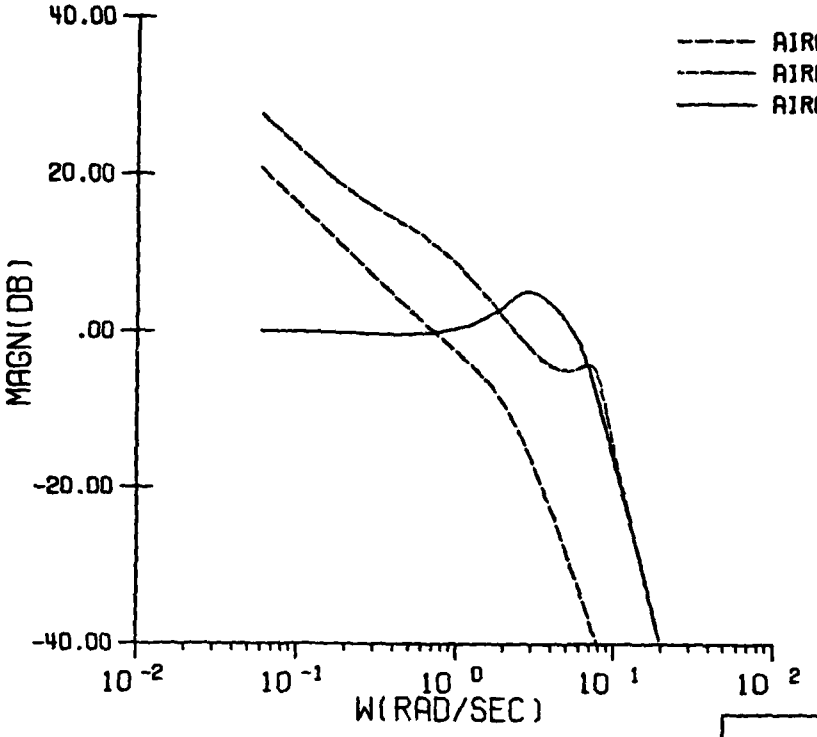


CONFIGURATION 1F

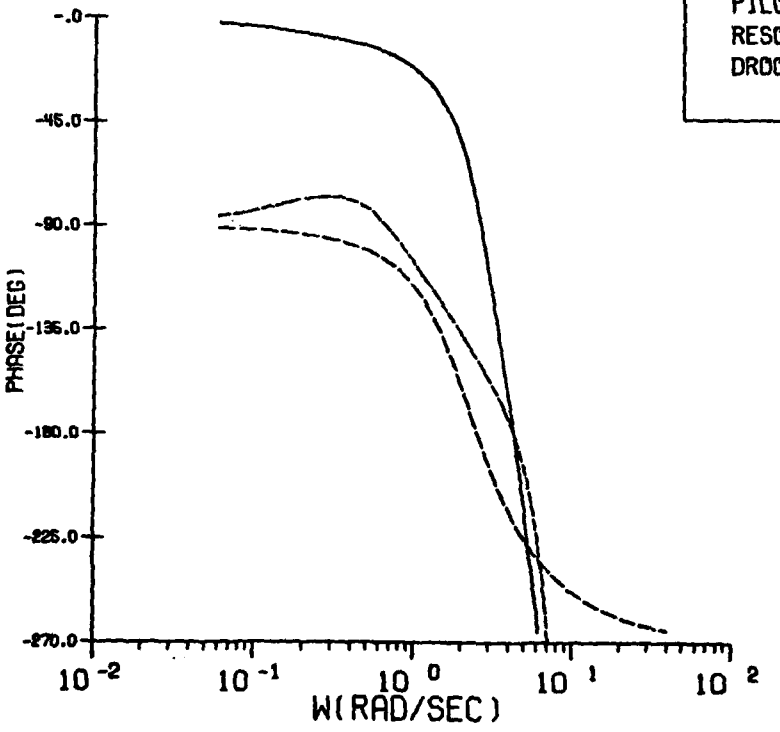




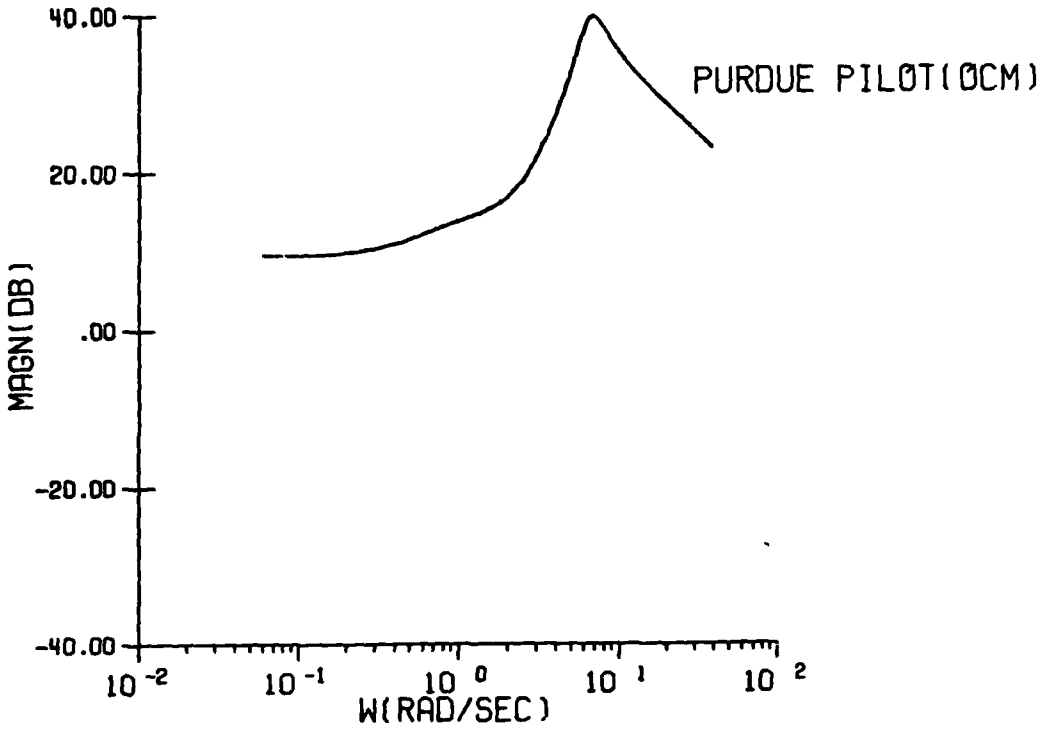
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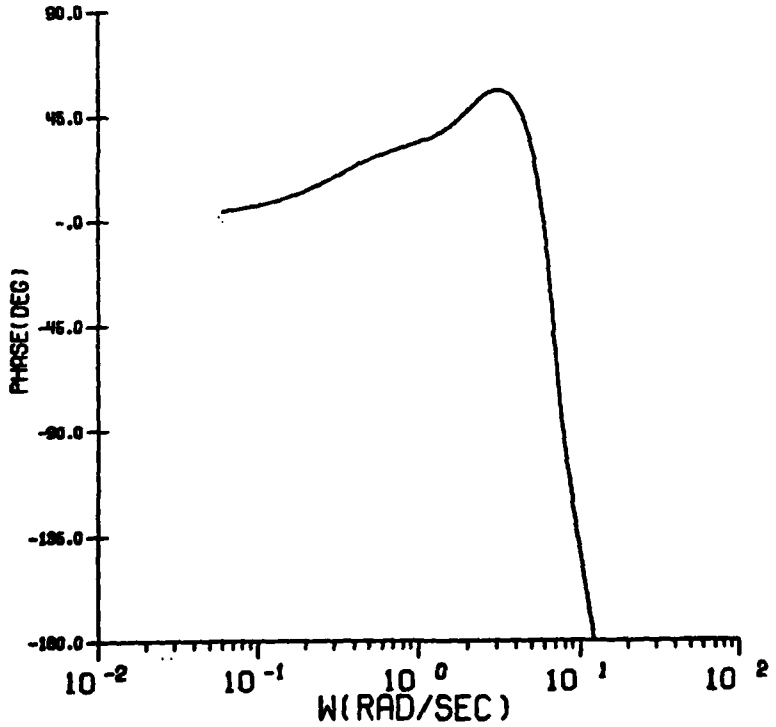


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DROOP -.47 DB

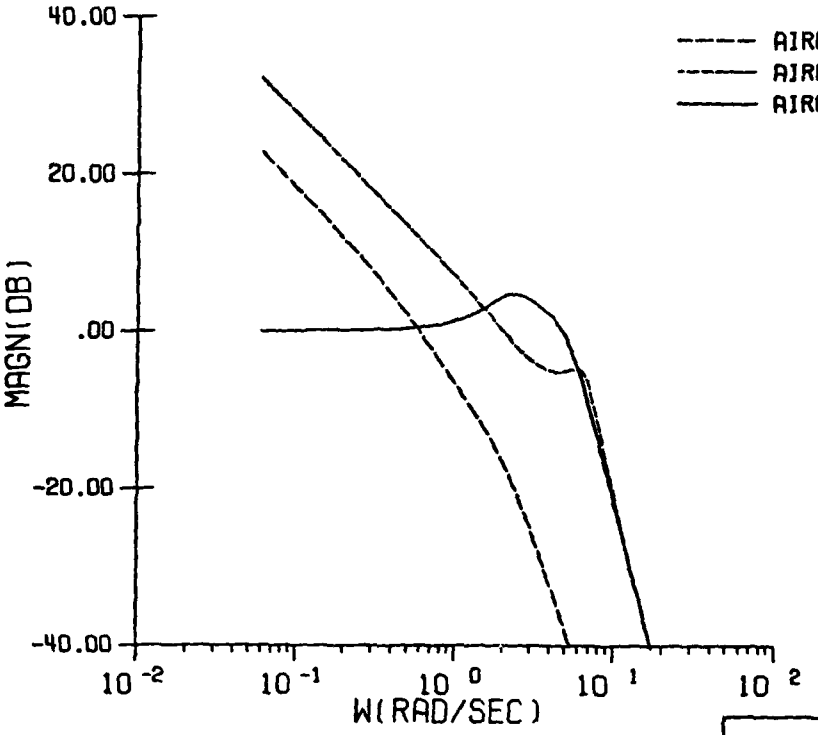


CONFIGURATION 1G

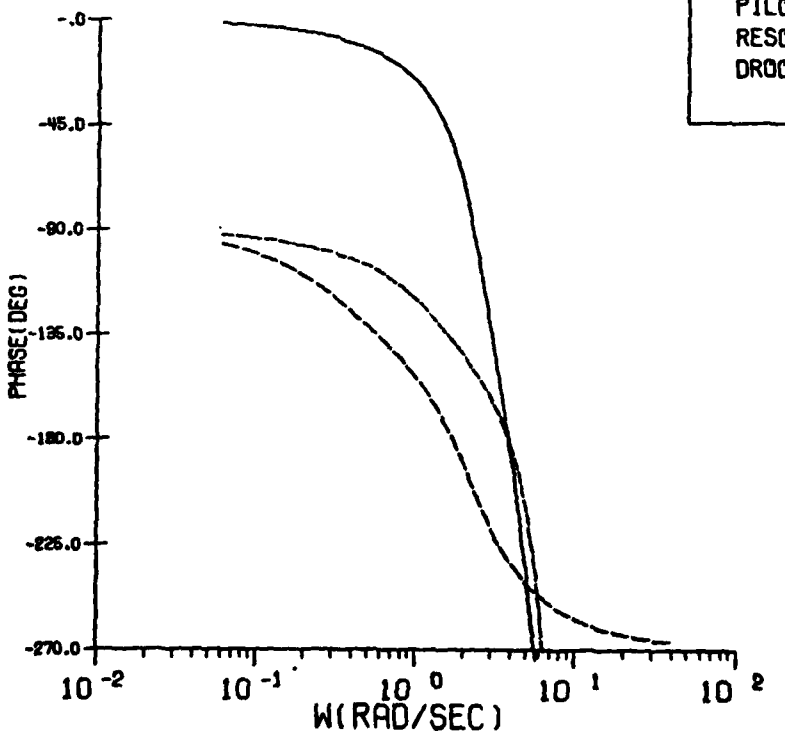




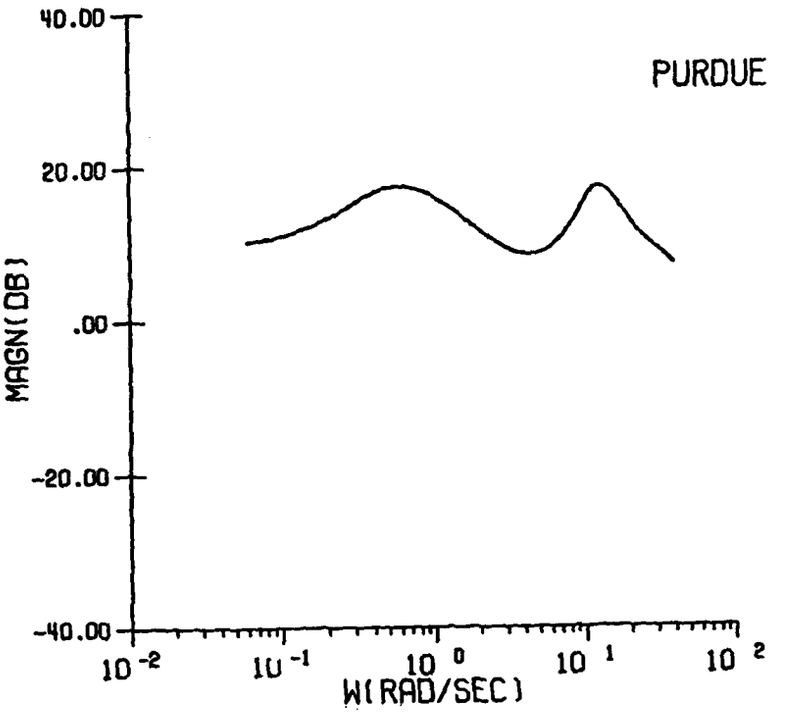
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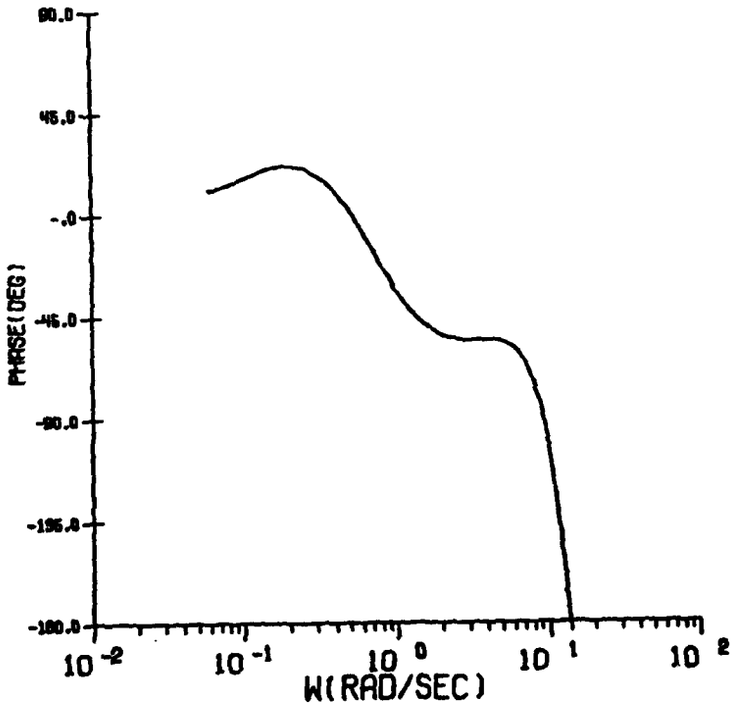


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PILOT COMPENSATION= 50.51 DEG
RESONANCE PEAK 4.69 DB
DROOP .01 DB

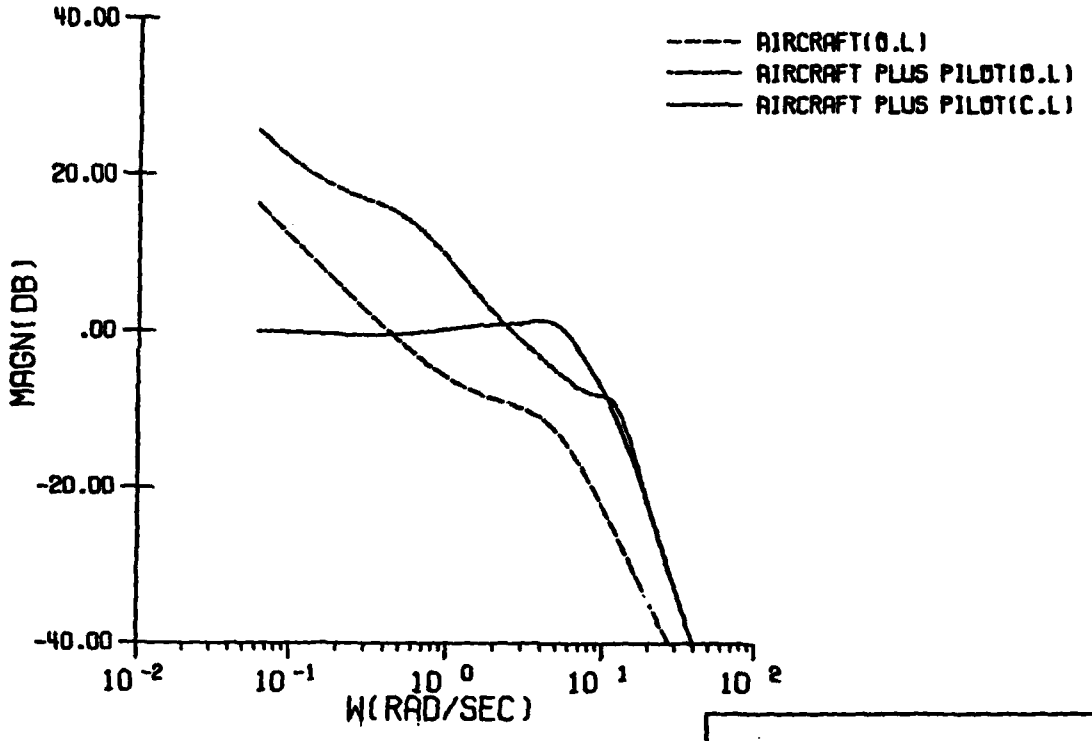


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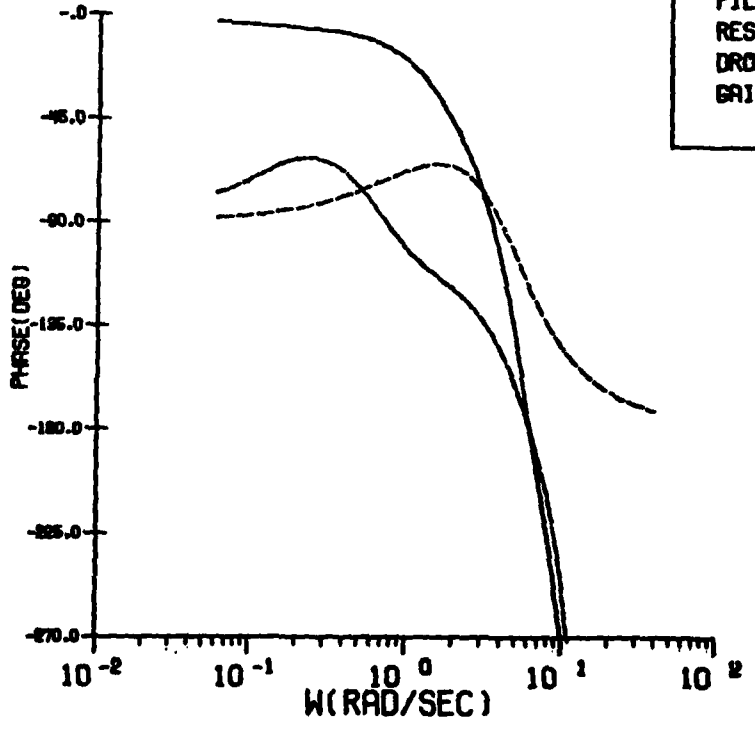




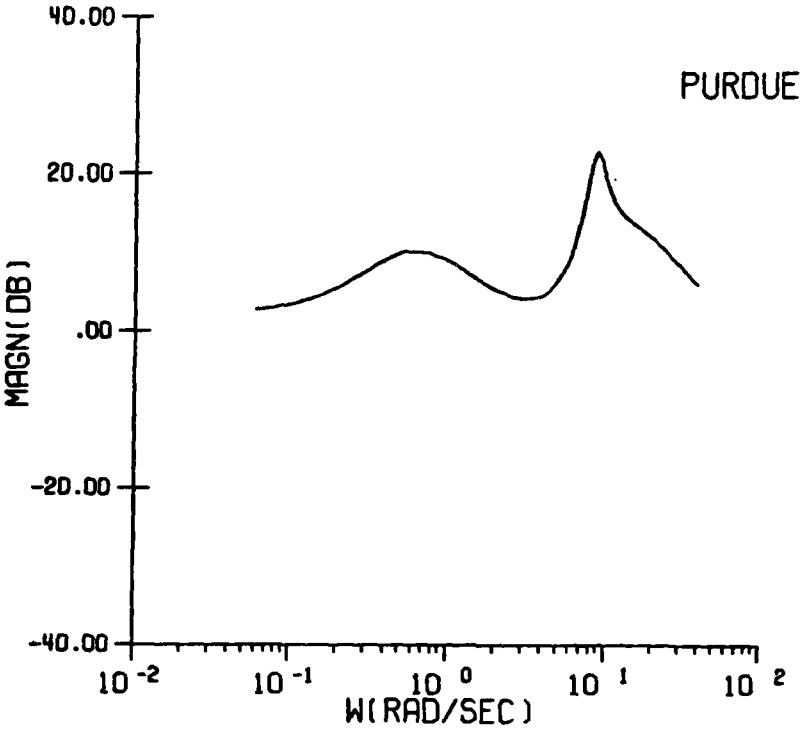
CONFIGURATION 2D



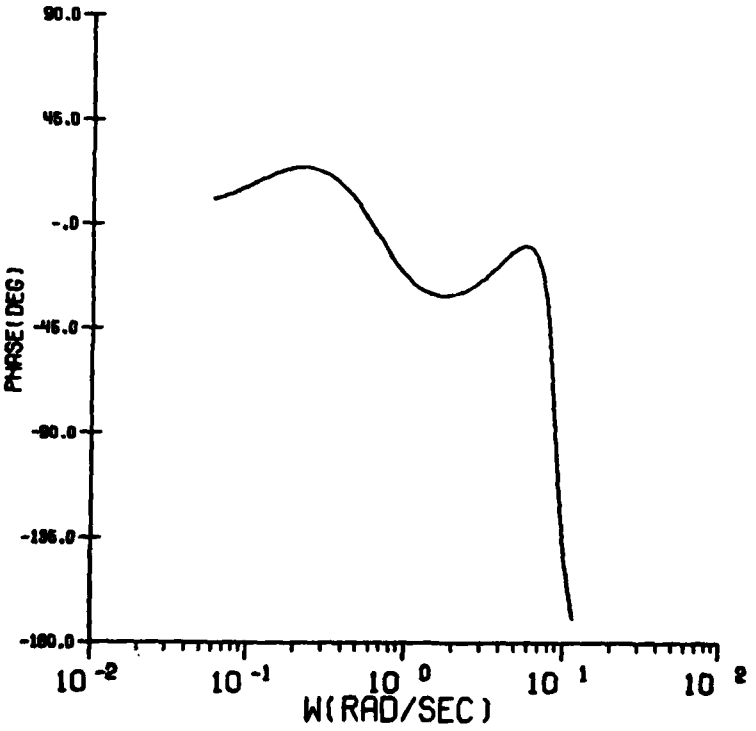
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DROOP -.60 DB
GAIN= -.83 DB



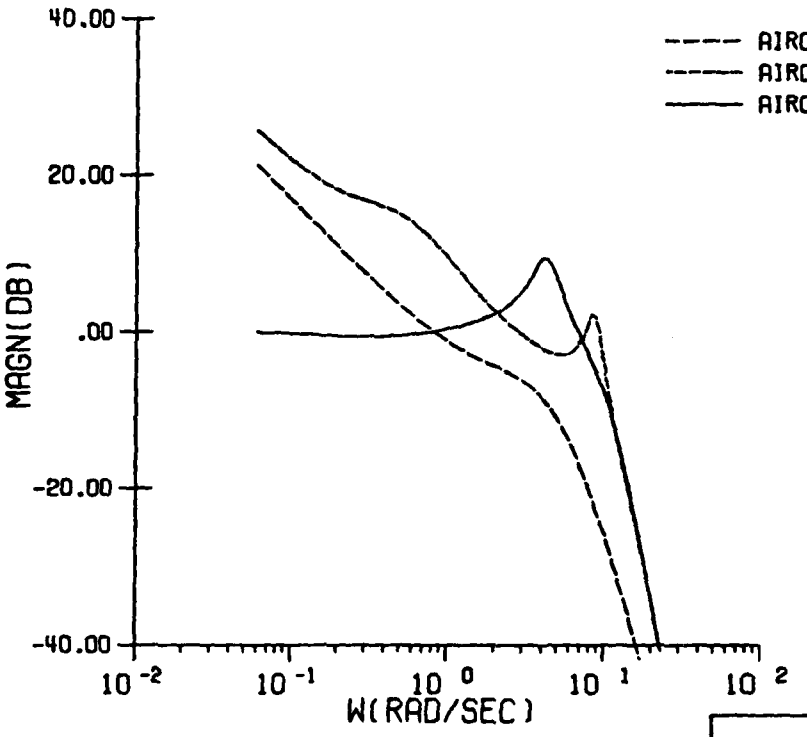
CONFIGURATION 2G



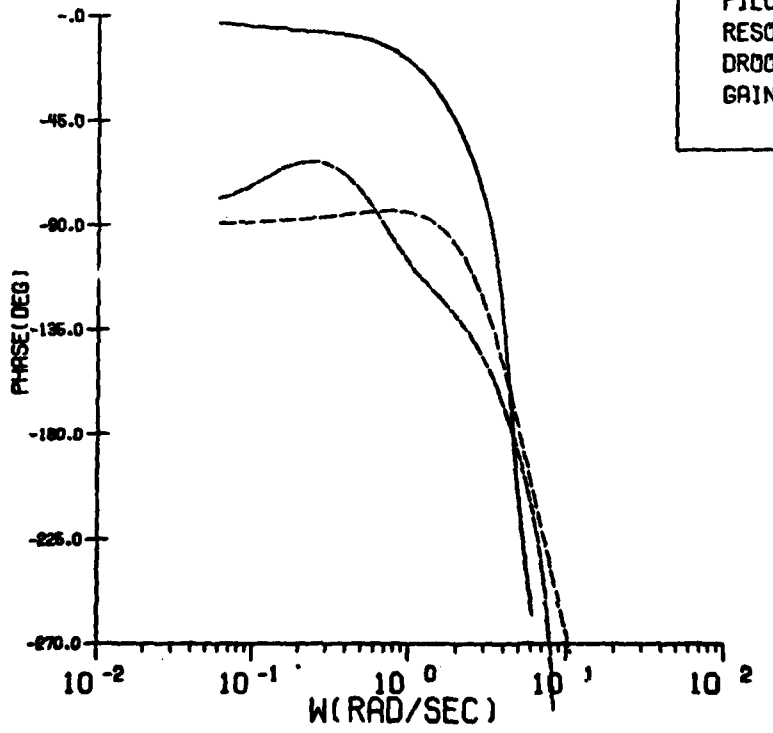
PURDUE PILOT(0CM)



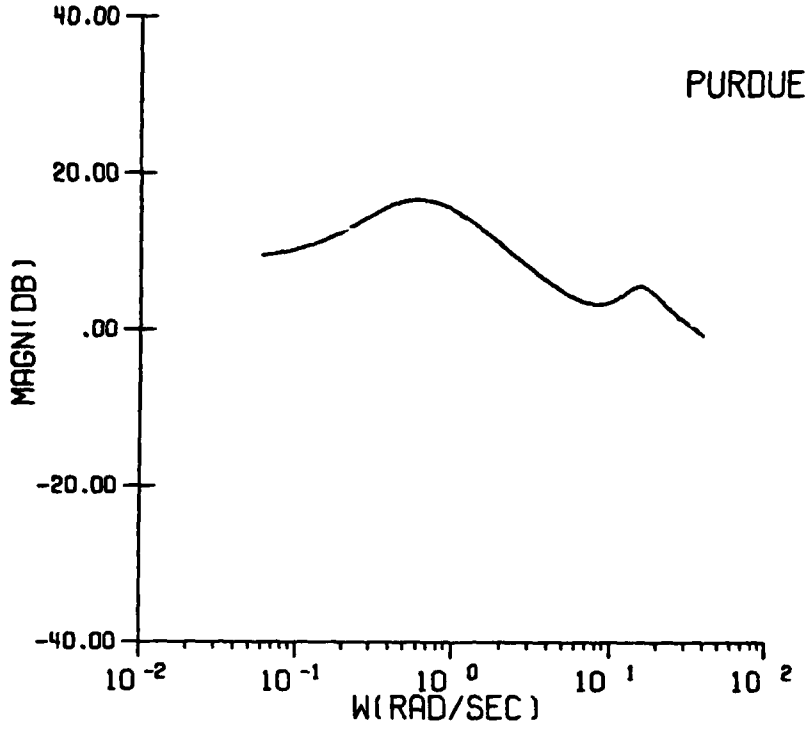
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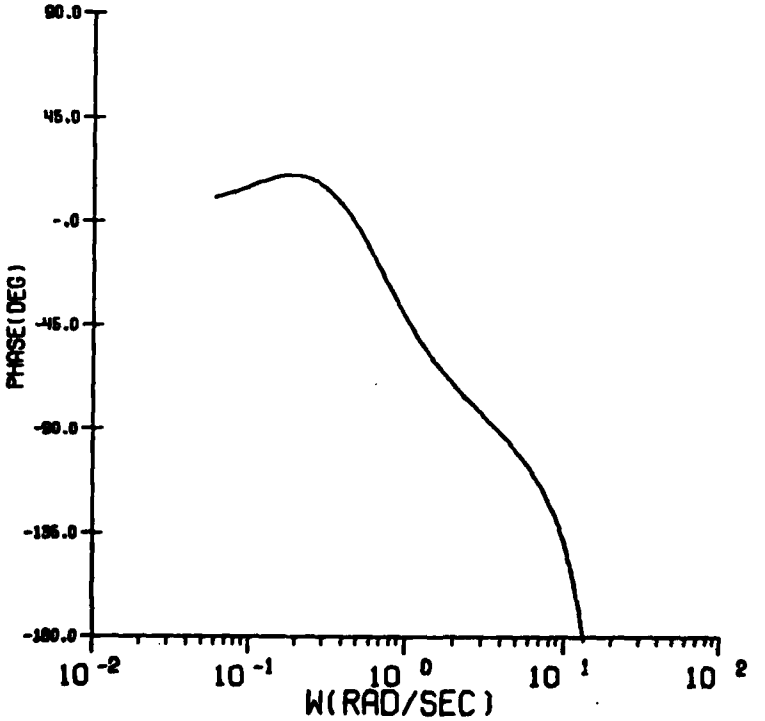


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RESONANCE PEAK 9.25 DB
DROOP -.60 DB
GAIN= 1.73 DB

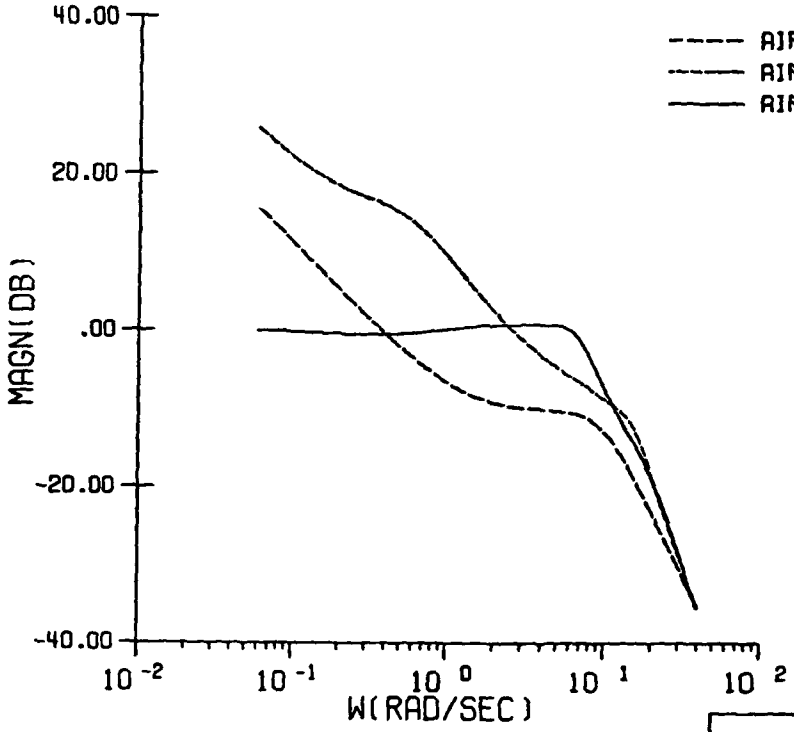


CONFIGURATION 3A

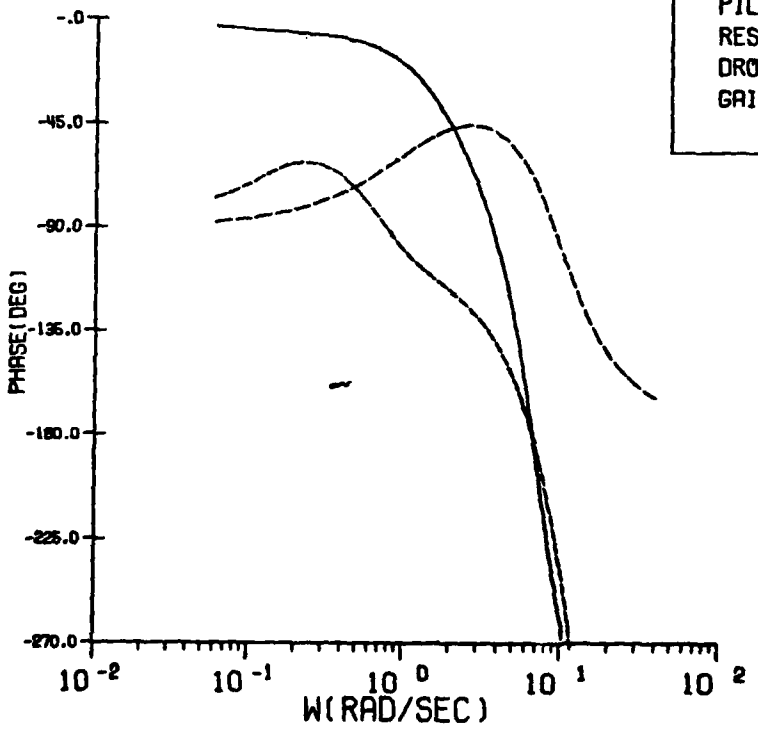




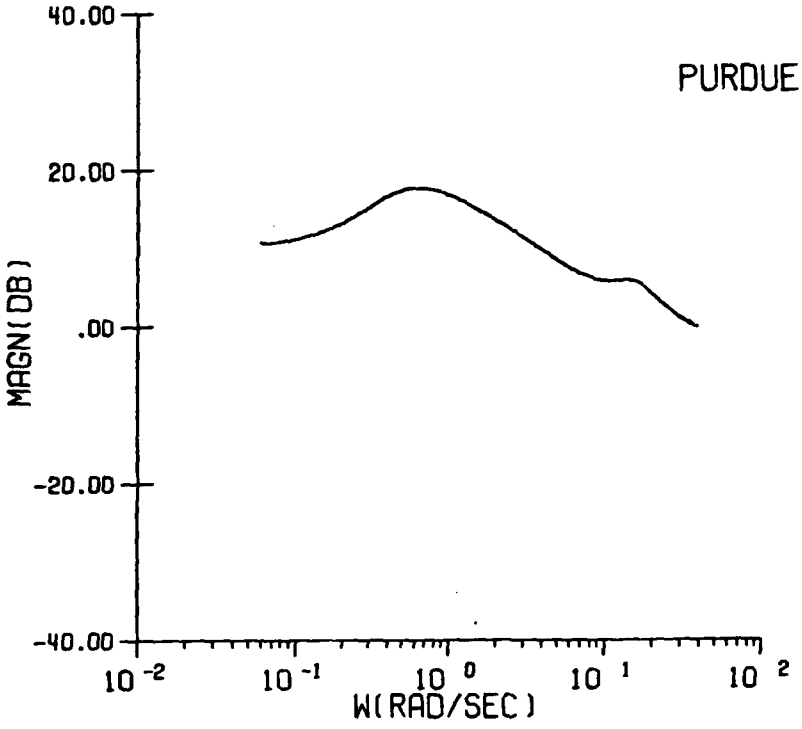
CONFIGURATION 3A

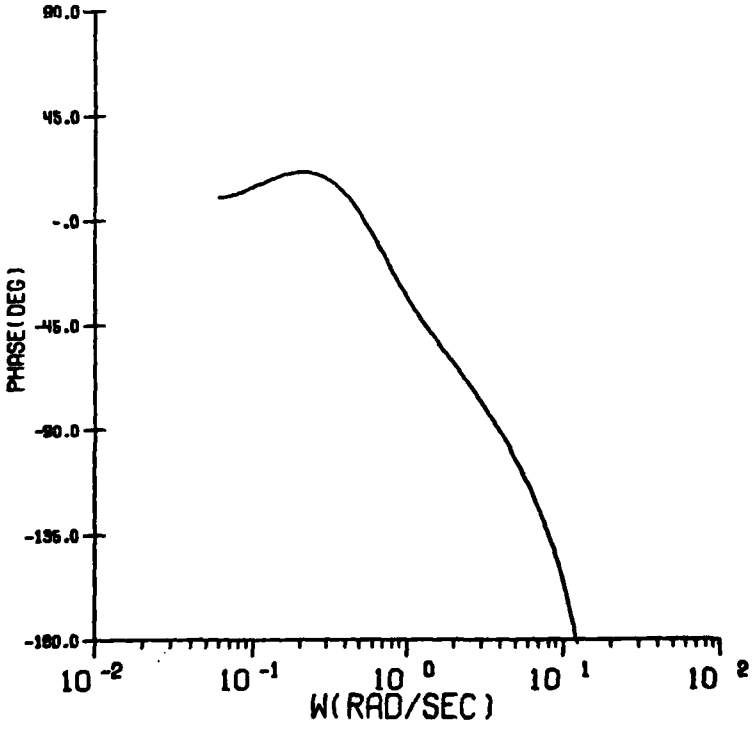


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PILOT COMPENSATION= -89.29 DEG
RESONANCE PEAK .68 DB
DROOP -.60 DB
GAIN= .70 DB

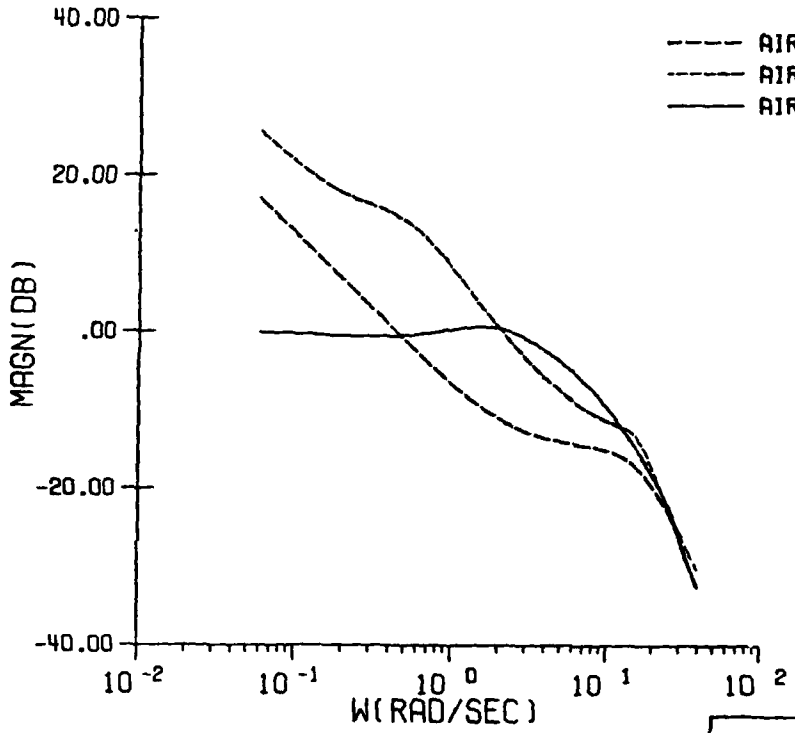


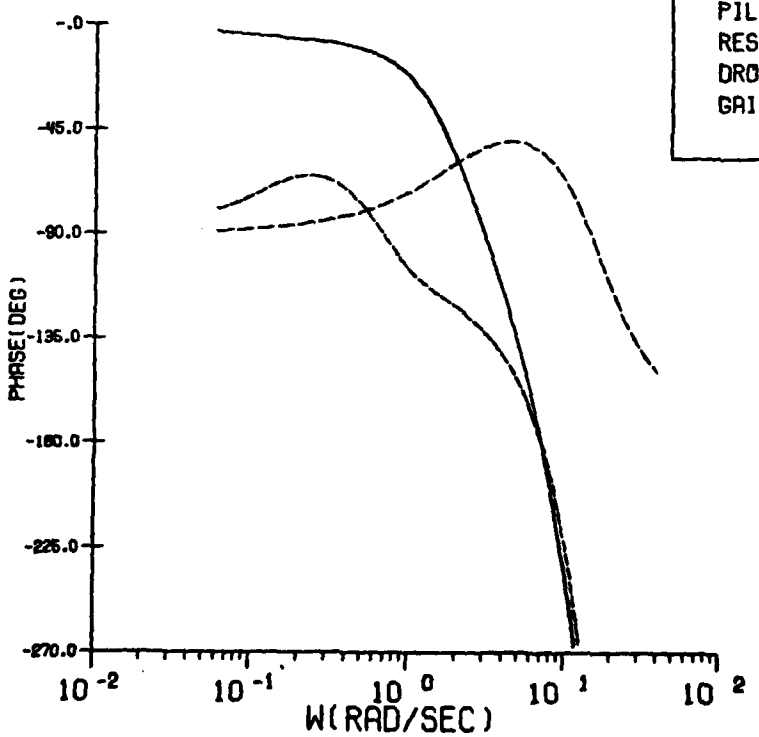
CONFIGURATION 8A





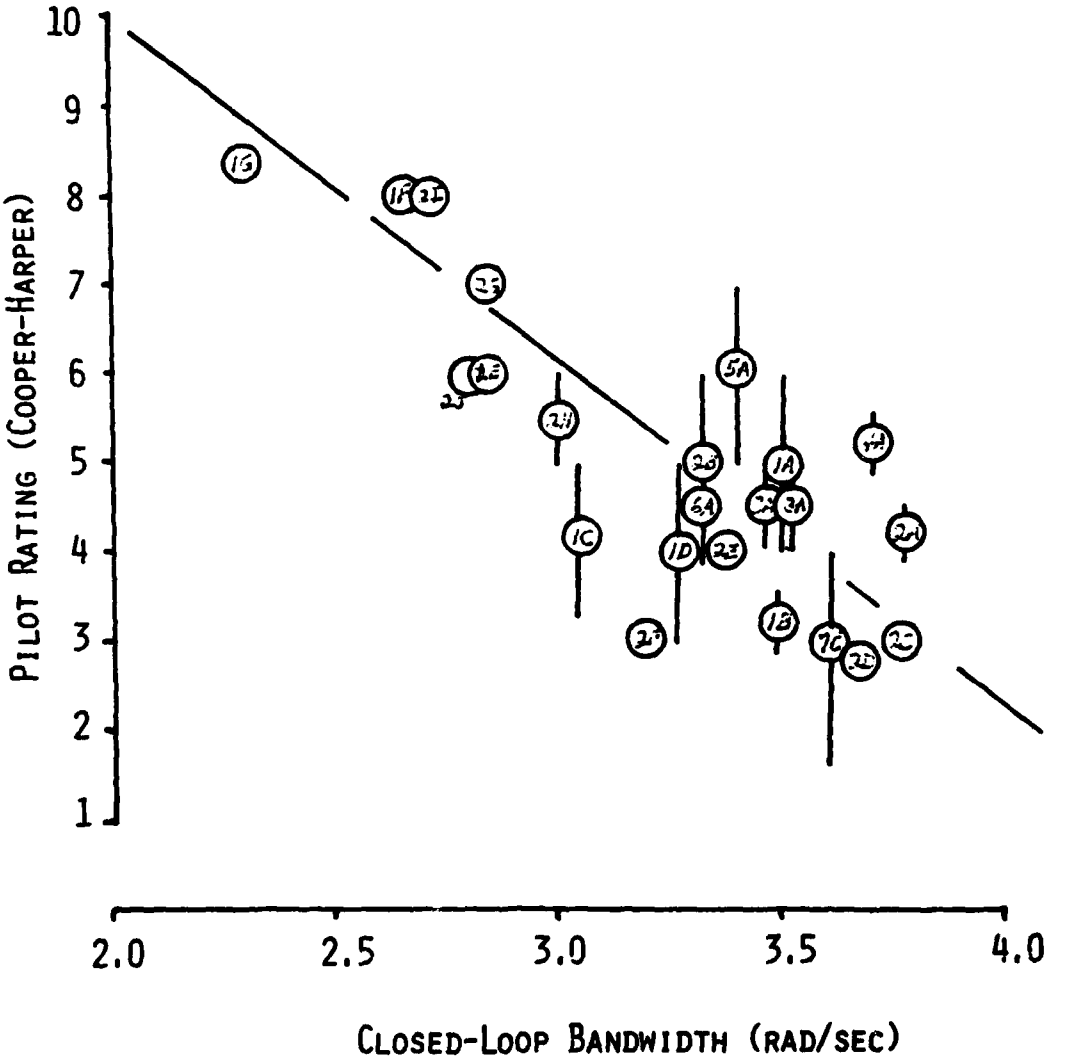
CONFIGURATION 8A





BANDWIDTH= 3.05 RAD/SEC
PILOT COMPENSATION= -78.93 DEG
RESONANCE PEAK .65 DB
DROOP -.60 DB
GAIN= -1.98DB

RATING/BANDWIDTH CORRELATION



SUMMARY

- METHOD IS CONSISTENT WITH NEAL-SMITH
- PILOT COMPENSATION IS OBTAINED VIA OCM
  - ACTUAL PURSUIT TASK
  - BEST PILOT REPRESENTATION
  - MUCH EASIER TO OBTAIN
- TRUELY APPLICABLE TO HIGHER-ORDER SYSTEMS
- "ALMOST AUTOMATIC"

A MODERN APPROACH TO PILOT/VEHICLE ANALYSIS AND THE NEAL-SMITH CRITERIA

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Purdue University
West Lafayette, Indiana 47907

Abstract

In 1970, Neal and Smith presented a pilot-in-the-loop analysis technique for evaluating the attitude dynamics of highly augmented aircraft. Unfortunately, the methodology requires a priori selection of system bandwidth, and suffers the inherent problem of selecting the appropriate pilot model parameters. The goal of this paper is to merge the approach of Neal and Smith with the advances in pilot modelling via optimal control techniques. While confirming the findings of Neal and Smith, this paper develops a methodology that explicitly includes the pilot's objective in attitude tracking. More importantly, the method yields the required system bandwidth along with a better pilot model directly applicable to closed-loop analysis of systems in any order.

Introduction

In the past, the longitudinal handling qualities of an aircraft were determined almost entirely by the modal characteristics of the classical rigid body modes (short period and phugoid). These modes dominate the conventional aircraft's dynamics and their modal parameters (i.e. damping and natural frequency) exhibit a definite correlation with pilot opinion ratings. Unfortunately, beyond the realm of conventional aircraft, criteria based on these parameters alone are inadequate. The addition of other modes, whether they be due to structural dynamics or to augmentation has been shown to seriously affect pilot opinion rating.

In the early 70's, Neal and Smith [1] hypothesized that "pilot rating is a strong function of the pilot's compensation required to achieve good low frequency performance and the pilot/vehicle oscillatory tendencies that resulted." Equating good tracking performance with closed-loop Bode characteristics, they devised a "pilot-in-the-loop" analysis capable of pinpointing pilot problem areas in pitch attitude tracking. Unfortunately, the method has one drawback centered on selecting the appropriate parameters for their pilot model structure.

The goal of this paper, then, is a better pilot modelling technique via optimal control theory, and still conceptually approach the pilot rating problem in a manner similar to the Neal and Smith method. This paper is structured such that we first review the Neal and Smith method, focusing on the possibility of implementing the optimal control pilot model (OCM) in the analysis. We next address synthesizing the tracking task using the OCM. Finally, we present the proposed OCM analysis and discuss the results of re-evaluating some of the Neal and Smith aircraft configurations.

The Neal Smith Methodology

The Neal and Smith's investigation of the early 70's had a two-fold objective: to provide data on the effects of Flight Control System (FCS) dynamics and to develop a design criterion capable of pinpointing pilot problem areas encountered in performing a given task.

To meet the first objective, a total of 51 basic FCS/short period configurations were flight tested. An overall pilot rating (Cooper-Harper) representing a numerical summary of an aircraft's suitability to perform a given task was assigned to each configuration. Preliminary results concluded that the addition of FCS dynamics "can drastically alter the airplane's short period response."

Moreover, difficulties of using existing open-loop criterion to explain all the results of this experiment lead to the development of an alternate approach: the "pilot-in-the-loop" analysis. Based on the assumption that most of the pilot's rating is determined on how precisely the pilot could control pitch attitude, the analysis was conducted using the compensatory tracking model of Figure [1].

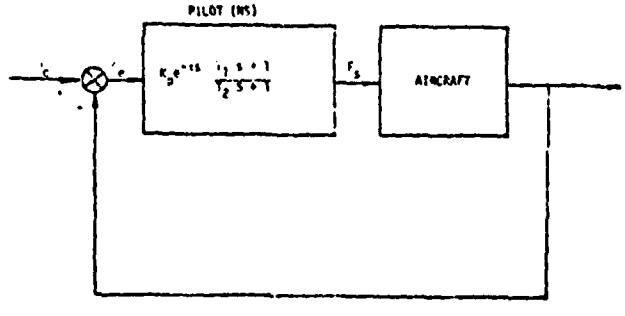


Figure 1 Classical model structure.

This diagram represents a compensatory tracking task where the pilot operates on the difference between the aircraft's attitude and the commanded attitude. The pilot is modelled as a simple lead-lag filter with a time delay and gain. The pilot's time delay (0.3 sec) includes the effects of perceptual delays and neuromuscular lags associated with most manual control systems.

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To aid in the coming discussion the following terminology should be noted:

(1) $\frac{\theta}{F_s}$ is the open-loop transfer function of the aircraft plus FCS.

(2) $\frac{\theta}{\theta_e}$ is the open-loop transfer function of the aircraft plus FCS plus pilot.

(3) $\frac{\theta}{\theta_c}$ is the closed-loop transfer function of the aircraft plus FCS plus pilot, which is related to $\frac{\theta}{\theta_e}$ by

$$\frac{\theta}{\theta_c} = \frac{\frac{\theta}{\theta_e}}{1 + \frac{\theta}{\theta_e}}$$

With the ultimate goal of evaluating the pilot and the aircraft engaged in a tracking task, Neal and Smith translated the pilot's objective of tracking into closed-loop, frequency response specifications. (see Fig. 2).

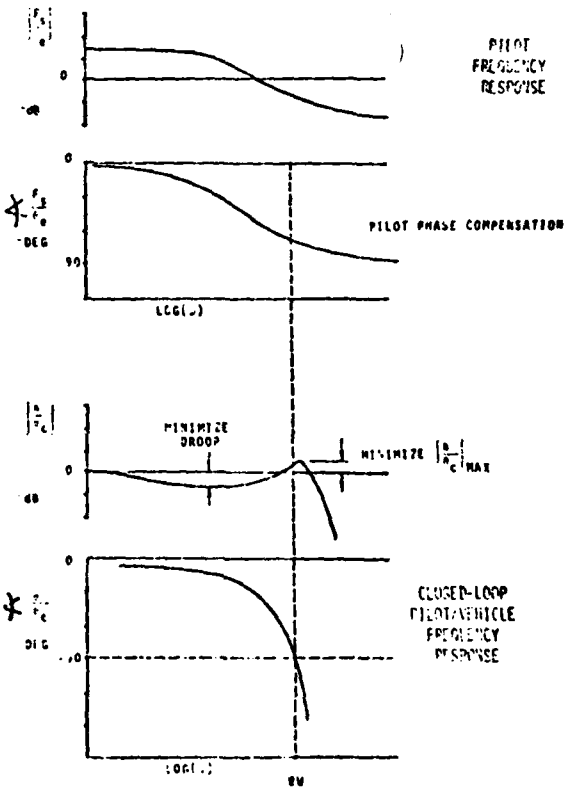


Figure 2 Neal-Smith Analysis

Clearly, the pilot wants to acquire the target quickly and predictably, with a minimum of overshoot and oscillation. The analysis interpreted the phrase "To acquire the target quickly and predictably" as meaning the pilot wants to attain a certain bandwidth, and below this frequency, keep the magnitude of $(\frac{\theta}{\theta_c})$ relatively close to 0dB. Bandwidth (Bw) is defined as the frequency at which the closed-loop phase angle of $(\frac{\theta}{\theta_c})$ is -90 degrees. Neal and Smith continued the interpretation of this phrase by correlating the desire "to minimize oscillation" with minimizing the closed loop resonant peak $|\frac{\theta}{\theta_c}|_{max}$ They noted typically that pilot strategy was a trade-off between striving for acceptable low frequency performance and eliminating the accompanying oscillations.

The Neal-Smith investigation concluded that "pilot rating is a function of the compensation required to achieve good low frequency performance and the oscillatory tendencies that result." Pilot compensation was taken as

$$\angle_{pc} = \angle \left(\frac{T_{p_1} s + 1}{T_{p_2} s + 1} \right)_{\omega = Bw}$$

from their pilot model. It is frequently interpreted as the pilot's physical and mental "workload" required.

Therefore, the objective of the analysis was to determine the pilot model parameters (K_p, T_{p_1}, T_{p_2}) such that the following enumerated performance standards were met

(1) Bandwidth was set at 3.5 rad/sec.

$$\angle (\theta/\theta_c) \geq -90° \text{ at } \omega = 3.5$$

(2) A maximum low-frequency droop of -3dB

$$|\frac{\theta}{\theta_c}| \geq -3dB \text{ for } \omega \leq Bw$$

and the form of the compensation (or the ratio of T_{p_1}/T_{p_2}) related to a minimum value of resonant peak $\left|\frac{\theta}{\theta_c}\right|_{max}$.

In Figure [3], Neal and Smith correlated pilot rating with the resulting pilot compensation

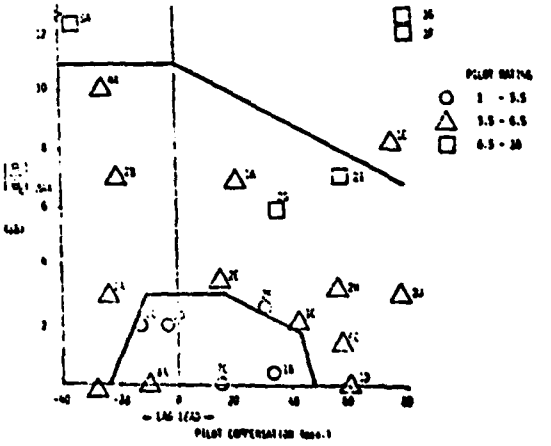


Figure 3 Neal-Smith results

and magnitude of resonance peak. The diagram divides the pilot ratings into the three levels of handling qualities

	Cooper-Harper Rating	
Level 1	1.0 - 3.5	good
Level 2	3.5 - 6.5	fair
Level 3	6.5 -10.0	poor

The following transfer function represents the vehicle dynamics of selected aircraft analyzed. (More were evaluated in Ref. 1).

$$\frac{\theta(s)}{F_s(s)} = \frac{K_0(\tau_1 s+1)(\tau_{\theta_2} s+1)}{s(\tau_2 s+1)(\frac{s^2}{\omega_3^2} + \frac{2\zeta_3}{\omega_3} s+1)(\frac{s^2}{\omega_{sp}^2} + \frac{2\zeta_{sp}}{\omega_{sp}} s+1)}$$

Parameters classified according to the configuration number are listed in Table 1.

Conf.	$1/\tau_1$	$1/\tau_{\theta_2}$	$1/\tau_2$	ω_{sp}/ζ_{sp}	ω_3/ζ_3
1A	0.5	1.25	2	2.2/.69	
1B	2.0		5.0		
1C	2.0		5.0		16./.75
1D	∞		∞		
1E			5.0		
1F			2.0		
1G			0.5		
2A	2.0		5.0	4.9/.70	
2B	2.0		5.0		16./.75
2C	5.0		12.0		
2D	∞		∞		
2E			12.0		
2F			5.0		
2G			5.0		
2H			2.0		
2I			2.0		16./.75
2J			0.5		16./.75
3A			∞	9.7/.63	
4A				5.0/.28	
5A				5.1/.18	
6C		2.4		3.4/.67	
7C				7.3/.73	
8A				16.5/.69	

Table 1 Configuration summary

Overall, the results of this analysis were encouraging, however, problems inherent to pilot parameter identification made this method cumbersome.

One of the biggest problems centered on bandwidth selection. Bandwidth is dependent on task, flight conditions and how aggressive the pilot feels he must be to satisfy the task's objectives. In their analysis, Neal and Smith said, "BW was determined by trying a few values of BW in the evaluation of a cross-section of configurations until the resulting values of $\left|\frac{\theta}{\theta_c}\right|_{max}$ correlated qualitatively with pilot comments concerning PIO tendencies." This fact makes the analysis somewhat impractical as a predictive tool. In addition, the determination of the pilot representation has always been difficult. Thus an alternate method is desired. We will accomplish this via an optimal-control pilot model.

The Optimal Control Model (OCM)

In 1970, Kleinman, Baron and Levinson[2] published a mathematical model of human response using optimal-control and estimation theory. This optimal-control model (OCM) of the pilot assumes that the well-trained, well motivated human operator chooses his control input u_p subject to human limitations such that the following objective function is minimized

$$J_p = E\{\lim_{T\to\infty} \frac{1}{T}\int_0^T (\bar{y}' Q\bar{y} + ru_p^2 + g\dot{u}_p^2)dt\}$$

where g is selected to obtain a chosen neuromuscular lag time constant τ_N. The pilot's output is expressed as

$$\tau_N \dot{u}_p = -K_x \hat{\bar{x}} - u_p + v_m$$

Figure [4] gives a qualitative representation of the overall pilot model. A detailed discussion of the model can be found in Reference [2].

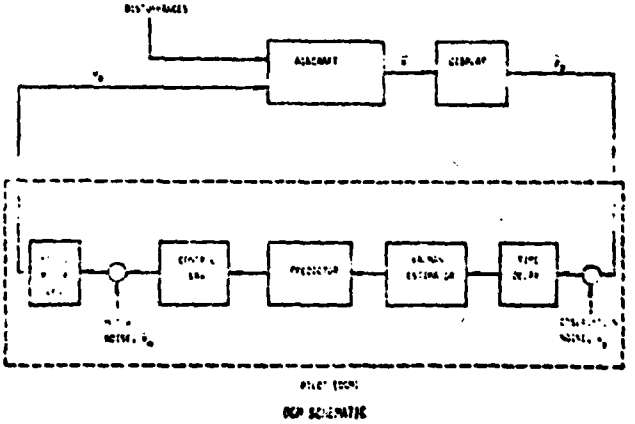


Figure 4 Optimal control model

As a simple review, the pilot model considers the pilot's observations $\bar{y}(t)$, to consist of delayed state observations corrupted by white measurement noise, or

$$\bar{y}_p(t) = C_p \bar{x}\,(t-\tau) + v_p\,(t-\tau)$$

The state estimation is accomplished via a Kalman Filter cascaded with a least-mean-square predictor. The optimal control gains are determined from the minimization of the cost function J_p, which represents the pilots strategy. As stated before, the first order lag $(\tau_N s+1)^{-1}$ associated with the pilots neuromotor dynamics results naturally from including control rate $\dot{u}_p$ in the cost function J_p.

Consider now the minimization of tracking error $(\theta_c - \theta)$ in J_p as a preview of the following sections. This would result in a control strategy that would minimize the mean squared value of error, which can be expressed as

$$\sigma_E^2 = \frac{1}{\pi}\int_0^\infty \left|1 - \frac{\theta}{\theta_c}(j\omega)\right|^2 S_{\theta_c}(\omega)\, d\omega$$

where S_{θ_c} is the spectral density of the commanded signal. Minimizing the above expression forces the closed-loop frequency response $(\frac{\theta}{\theta_c})$ to tend to unity over the frequency range of the command θ_c, with the lowest bound being attained by the perfect tracker with $|\frac{\theta}{\theta_c}| = 0dB$ and $\not\propto(\frac{\theta}{\theta_c}) = 0°$ across all (weighted) frequencies. Thus, the OCM can be considered to be "automatically" minimizing the droop and resonance peak of the frequency response of θ/θ_c. More importantly, it will automatically determine the bandwidth required to achieve the pilot's objective within the abilities of the vehicle!

The realization of the perfect tracker is unrealistic since it implies an instantaneous transfer of energy between input and output. But, a tracker that attempts to be ideal across the frequency band of the commanded signal is realizable. This, in fact, is a product of optimal-control theory, the basis for the alternate approach.

In the terms of Neal-Smith, the pilot is trying to achieve good low frequency performance (a reasonable bandwidth with a minimum of low frequency droop) plus good high frequency stability ($|\theta/\theta_c|_{max}$ as small as possible). This statement is in fact a frequency domain representation of the pilot's objective to minimize the error between the commanded attitude and the aircraft's attitude.

In the next sections we will develop and apply the optimal control model as an alternate to the "pilot-in-the-loop" analysis of Neal and Smith.

Synthesis of the Tracking Task via OCM

Three key elements concerning application of the pilot model must be established:

(1) The pilot's observations and objective function to be minimized.

(2) The system's representation in a tracking task.

(3) A definition of the command signal to be tracked.

In this discussion, specific attention will be given to adapting the OCM transfer functions to the simplified compensatory tracking task model of Neal and Smith. But first, the appropriate objective function must be selected.

The optimal control model's control input is selected to minimize the following objective function

$$J_p = E\left(\lim_{T\to\infty}\frac{1}{T}\int_0^T (\bar{y}'\,Q\bar{y} + r u_p^2 + g\dot{u}_p^2)dt\right),$$

subject to human limitations. The weighting matrix, $Q = \text{diag}\,[q_1, q_2, \ldots q_m] \geq 0$, where m is the dimension of the observation vector $\bar{y}$; the weightings on control and control rate, (scalars in this analysis) $r \geq 0$ and $g > 0$; plus the elements of $\bar{y}$ must all be determined to quantify the task.

Obviously, the most critical parameter is the tracking error ε; the difference between the commanded attitude θ_c and the aircraft's attitude θ. Observation of attitude itself is also required if the task is one of pursuit rather than compensatory in nature. (A compensatory task is defined such that only error is observed). In addition to ε and θ, studies [2] have shown that the human controller can also extract rate as well as position from a single display, thereby expanding $\bar{y}$ we have

$$\bar{y}^T = (\varepsilon, \dot{\varepsilon}, \theta, \dot{\theta})$$

The next step in quantifying the pilot's control objective is selecting the cost function weightings. Fortunately, research has begun to shed some light on the critical task of weight selection. One study [3] attempted to identify the weighting matrix Q by correlating pilot opinion ratings, the objective cost J_p, and performance statistics with simulation results. The investigation concluded that over a wide range of tracking tasks and flight conditions the following weights on ε, $\dot{\varepsilon}$ and F_{stick}

$$q_{\varepsilon} = 16\,,\quad q_{\dot{\varepsilon}} = 1\,,\quad q_{F_s} = 0$$

would accurately reflect the pilot's control objectives. The weighting, along with zero weighting on θ and $\dot{\theta}$ defines Q and r in the following analysis. It should be noted that this Q emphasizes the pilots primary goal of minimizing error with some constraint on how fast the error may fluctuate. To complete the definition of J_p, the weightings on control rate must be set.

The weighting g on the control rate $\dot{u}_p$ is constrained by physiological limits. These limits are linked with the neuromuscular dynamics associated with the human controller, modelled as a

first order lag. The associated lag time constant τ_N is expressed in the context of the pilot (model) control law,

$$\tau_N \dot{u}_p = -K_x \hat{\bar{x}} - u_p + v_m$$

For a given set of weights on $\bar{y}$ and u_p ($r = 0$ usually), adjusting g in the cost function determines τ_N. Finally, for aggressive control action, the lower limit on τ_N has been determined to be near 0.1 seconds, based on experimental, man-machine data.

The vehicle dynamics to be controlled must be represented by the linear time-invariant equations of motion:

$$\dot{x}(t) = Ax(t) + Bu(t) + N(t)$$

To model the tracking task, the vehicle states must be augmented with the command signal states. The augmented system is structured as follows:

$$\begin{bmatrix} \dot{\bar{x}}_c \\ \dot{\bar{x}} \end{bmatrix} = \left[\begin{array}{c|c} A_c & 0 \\ \hline 0 & A_{veh} \end{array}\right] \begin{bmatrix} \bar{x}_c \\ \bar{x} \end{bmatrix} + \left[\begin{array}{c} o \\ \hline b_{veh} \end{array}\right] u + \left[\begin{array}{c} e_c \\ \hline o \end{array}\right] w$$

$$\bar{y} = \left[\begin{array}{c|c|c} I_2 & -I_2 & \\ \hline 0 & I_2 & 0 \end{array}\right] \begin{bmatrix} \bar{x}_c \\ \bar{x} \end{bmatrix} + \bar{v}$$

where the vehicle states are defined as $\bar{x}^T = [\theta, \dot{\theta}, u, \alpha$, etc.], the command signal states $\bar{x}^T = [\theta_c, \dot{\theta}_c]$, and $I_{(\cdot)}$ indicates the identity matrix of appropriate dimension.

In our analysis the commanded attitude is generated by a second order filter driven with white noise, or

$$\ddot{\theta}_c + .25\dot{\theta}_c + .5\theta_c = .25w(t)$$

where $w \sim N(0, 64)$. This commanded signal approximates the tracking experiment performed in the Neal and Smith investigation. The statistics on θ_c and $\dot{\theta}_c$:

$$\sigma_{\theta_c}^2 = 16\text{deg}^2 \ , \ \sigma_{\dot{\theta}_c}^2 = 4\text{deg}^2/\text{sec}^2$$

indicate a reasonable, yet sufficiently challenging task to test pitch attitude tracking. Defining the commanded signal completes the objectives of this section. Table [2] summarizes the resulting pilot model parameters.

The Methodology

We turn now to the acquisition of those parameters required for the analysis technique. The ability to obtain the pilot's transfer function matrix $\bar{H}_p(j\omega)$ and vehicle transfer function $H_a(j\omega)$ in the frequency domain from the OCM is the key to this method.

Observation Vector, $\bar{y}^T = [\varepsilon, \dot{\varepsilon}, \theta, \dot{\theta}]$

Objective Function Weights, $Q_{y_{ii}} = [16, 1, 0, 0]$

$R_{F_s} = 0$

Observation Thresholds, $T_\varepsilon = T_\theta = 0.05$ deg.

$T_{\dot{\varepsilon}} = T_{\dot{\theta}} = 0.18$ deg./sec.

Observation Noise Ratio, = -20 db

Fractional Attention, f_i = 0.5 all observed variables

Observation Delay, T = 0.2 sec.

Neuromuscular Lag, $\tau_N = 0.1$ sec.

Motor Noise Variances, -25 dB

Control Input, F_s(stick force)

Table 2 Baseline pilot model

To obtain the closed-loop frequency response, we expand the coherent part of the pilot's control in the frequency domain:

$$u_p(s) = H_\varepsilon(s)\varepsilon(s) + H_{\dot{\varepsilon}}(s)\dot{\varepsilon}(s) + H_\theta(s)\theta(s) + H_{\dot{\theta}}(s)\dot{\theta}(s)$$

where

$$\bar{H}_p(s) = [H_\varepsilon(s), H_{\dot{\varepsilon}}(s), H_\theta(s), H_{\dot{\theta}}(s)]$$

is obtained from the relation [2]

$$\bar{H}_p(s) = \frac{-\ell_e^*}{\tau_N s+1}\left[(sI-\hat{A}) \int_0^{t_{delay}} \exp(sI-A_1)\,\sigma d\sigma \cdot (sI-A_1 + b_1\ell_e^*) + sI-\hat{A} + b_1\ell_e^*\right]^{-1} \cdot \Sigma_1 C_1^T V_y^{-1}$$

with $\ell_e^* = [K_x \,\vdots\, 0]$; pilot gains

$b_1 = \text{col}\,[0, \cdots 0, 1/\tau_N]$,

$A_1 = \left[\begin{array}{c|c} A & B \\ \hline 0 & -\frac{1}{\tau_N} \end{array}\right]$; system matrices

and

$C_1 = [C_p \,\vdots\, 0]$ observation matrix.

The steady-state estimation error covariance Σ_1 is that for the Kalman Filter, V_y is the covariance associated with the pilot's observation noise, and $\hat{A}$ is defined as

$$\hat{A} \triangleq A_1 - \Sigma_1 C_1' V_y^{-1} C_1$$

all defined in the OCM modeling approach. The previous expression for the pilot's control input may be rewritten as

$$u_p(s) = (H_c(s) + sH_c'(s))\epsilon(s) + (H_\theta(s) + sH_{\dot\theta}'(s))\theta(s)$$

where the bracketed terms are the true transfer functions relating tracking error and attitude angle to pilot input, respectively. Given the aircraft attitude transfer function as

$$\theta(s) = H_a(s)\, u_p(s)$$

and $$\epsilon(s) \triangleq \theta_c(s) - \theta(s) \quad ,$$

the desired closed loop transfer function is simply

$$\frac{\theta(s)}{\theta_c(s)} = \frac{H_a(s)[H_c + sH_c']}{1 + H_a(s)[(H_\epsilon + sH_\epsilon') - (H_\theta + sH_{\dot\theta}')]}$$

A block diagram of this $\frac{\theta}{\theta_c}$ transfer function is presented in Figure [5].

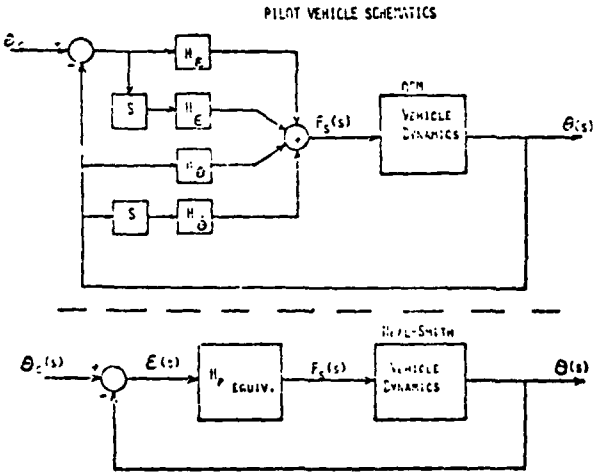


Figure 5 Model schematic comparison

In the compensatory tracking model used by Neal and Smith, however, the inner loop $(H_\theta + H_{\dot\theta})$ is not considered. The contribution to the pilot's compensation is thereby assumed small. (Since the task was actually one of pursuit, this is clearly an approximation.) If then the pilot transfer function is taken simply as $H_p(s) = H_c + sH_c'$, the approximate closed loop transfer function is, of course

$$\frac{\theta(s)}{\theta_c(s)} \doteq \frac{H_a(s)H_p(s)}{1 + H_a(s)H_p(s)}$$

identical to the Neal and Smith's compensatory tracking model.

Also, one final difference is to be noted. In addition to the command process θ_c, the motor noise and observation noises, ignored by Neal and Smith by not including any pilot remnant, are also included in the calculation of $H(s)$ of the OCM. However, this caused no problem in application as we will see.

So now the closed loop frequency response $(s = j\omega)$ is reduced to algebraically manipulating the elements of $H_p(j\omega)$, along with the vehicle's $H_a(j\omega)$.

One approach to validate the model in question is to construct the spectral densities of the system's variables θ_c, ϵ, u_p, and θ using the simpler model structure. The area under the spectral density is related to the respective mean squared value by the relation

$$\sigma_x^2 = \frac{1}{\pi}\int_0^\infty S_X(\omega)d\omega$$

if x is zero mean process. Since θ_c, ϵ, u_p, and θ are zero mean processes, the above integration will yield the system variances $\sigma_{\theta_c}^2$, σ_ϵ^2, $\sigma_{u_p}^2$, and σ_θ^2. These variances may then be compared to their counterparts obtained from the OCM's state covariance matrix. A comparison of the two results should indicate the agreement between the modelling approaches.

One method of calculating the needed spectral densities, assuming θ_c as the only source (i.e. ignoring remnant), proceeds as follows:

$$S_w(\omega) = \sigma_w^2$$

$$S_{\theta_c}(\omega) = |H_1(j\omega)|^2 S_w(\omega)$$

$$S_\epsilon(\omega) = \left|\frac{\epsilon}{\theta_c}(j\omega)\right|^2 S_{\theta_c}(\omega)$$

$$S_{u_p}(\omega) = \left|\frac{u_p}{\epsilon}(j\omega)\right|^2 S_\epsilon(\omega)$$

$$S_\theta(\omega) = \left|\frac{\theta}{u_p}(j\omega)\right|^2 S_{u_p}(\omega)$$

where σ_w^2 is the intensity of the white noise driving the θ_c process with $H_1(s)$ the shaping filter's transfer function. Once the spectral densities are evaluated over a sufficient band (ω), the integration can be performed numerically to obtain the desired variances. A sample of these variances and their OCM-derived counterparts are presented in Table [3].

Surprisingly, the effect of cancelling the inner attitude loop, and neglecting the controller noises made little impact on the system's variances here. Thus, the simpler closed-loop structure is a close approximation to this part of

	Reduced System	Actual (OCM)
σ_{θ_c} (deg)	3.943	4.000
σ_{θ_e} (deg)	0.824	0.8081
σ_{F_s} (lbs)	2.289	2.496
σ_{θ} (deg)	3.670	3.840

Table 3 RMS Comparison for configuration 2A

the OCM. Conversely, the OCM's format is now a valid model for the Neal and Smith's "pilot-in-the-loop" analysis. It remains to identify those required parameters deemed critical to pilot vehicle analysis.

Since the Bode characteristics of both the open-loop OCM pilot and the closed-loop OCM pilot/vehicle system are available, the following measures are obtained directly from their frequency response plots: bandwidth, pilot phase compensation, resonance peak. As an example, consider Figures [6 and 7], results obtained from analysis of Neal-Smith's configuration 2D.

Bandwidth, recall, is defined as the frequency at which the closed-loop phase $\angle \theta/\theta_c$ is -90°. Unlike the Neal and Smith study, bandwidth is now a variable, dependent on task, vehicle, and human factors. Clearly, neuromuscular lag τ_N effects all four elements of the pilot transfer vector $\bar{H}_p(s)$: $H_c(s)$, $H_{\dot{c}}(s)$, $H_\theta(s)$, and $H_{\dot{\theta}}(s)$. Although τ_N's effect on the pilot's characteristics is self-evident, it is the not-so-self-evident effect on closed-loop bandwidth (speed of response) that is of interest. As τ_N increases, the closed-loop bandwidth decreases. Therefore, "relaxed" pilot behavior, or large τ_N, is associated with a closed-loop system exhibiting slow response characteristics. Conversely, aggressive pilot behavior, or a low τ_N, produces a higher bandwidth, producing a more responsive and more aggressive pilot/aircraft combination. Since, then, the minimum τ_N is usually accepted to be 0.1 sec for aggressive tracking, setting this value in the OCM determines the maximum achievable bandwidth for the system.

The second measure is the pilot phase compensation. The total pilot phase compensation from the OCM is the phase angle of the pilot's frequency response evaluated at the system bandwidth frequency (ω = Bw). This compensation, however, includes the effects of neuromuscular lag τ_N and the perceptual time delay t_{delay}. These effects may be corrected for via the following expression

$$\angle_{pc} = \angle OCM + 57.3\, t_{delay} \cdot Bw + \tan^{-1}(\tau_N \cdot Bw)$$
$$\omega = Bw$$

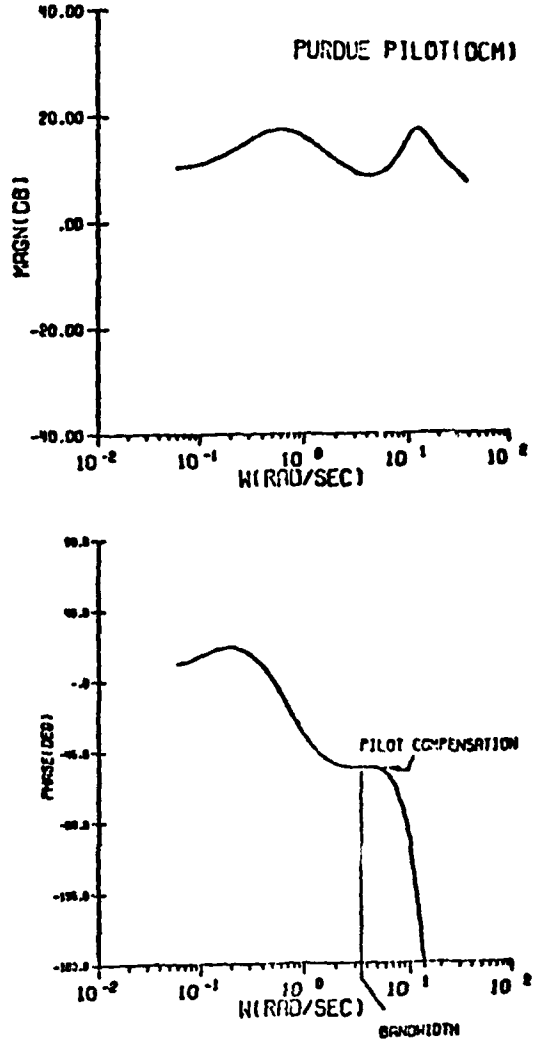


Figure 6 Pilot frequency response

where $\angle_{pc}$ corresponds to the Neal and Smith's interpretation of pilot compensation. For the purpose of correlation, Neal and Smith could have included their (constant) effective time delay as part of the pilot compensation. And since their bandwidth was fixed, this would simply slide the phase compensation scale (see Fig. 3) lower by a fixed angle for all aircraft configurations.

The last measure, magnitude of resonance peak, $|\frac{\theta}{\theta_c}|$ is available from the closed-loop Bode plot, and we'll discuss this further below. Hence all the quantities are obtainable through the OCM modeling process presented in this section.

Results

Application of the method to several aircraft configurations evaluated by Neal and Smith resulted in the bandwidth/pilot rating results shown

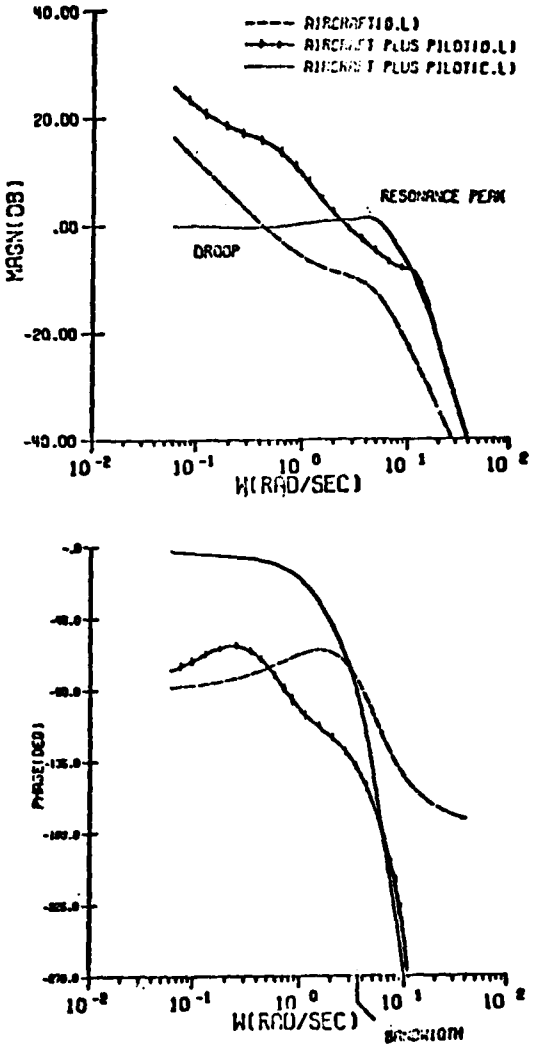


Figure 7 System frequency responses

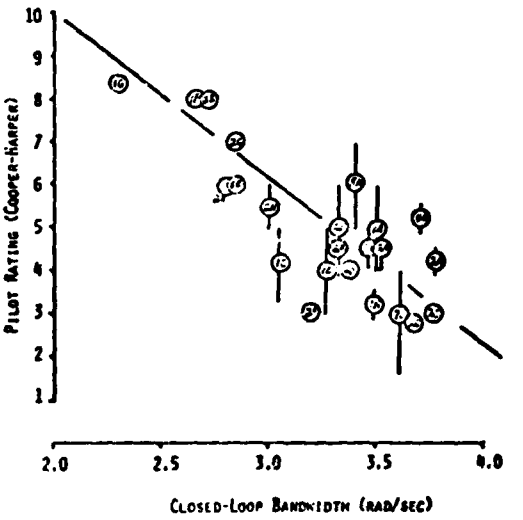


Figure 8 Rating/bandwidth correlation

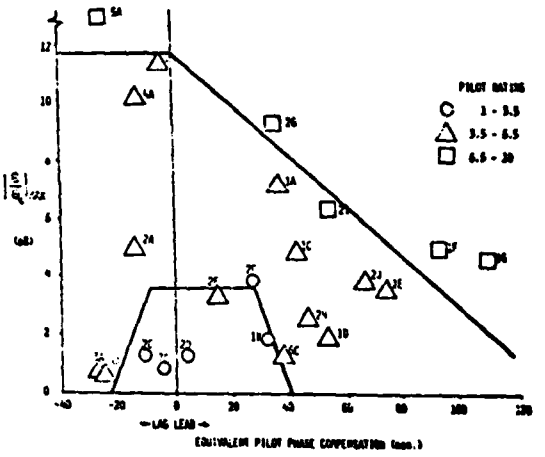


Figure 9 Results of optimal control analysis

in Figure [8]. These results reveal a trend of degraded pilot opinion with decreased closed-loop bandwidth, particularly where Bw $\leq$ 3 rad/sec in this task. Pilot comments mention an inability to track without several PIO problems in configurations 1G, 1F, 2I, and 2G, in support of the above results. Pilots also complained that these aircraft were "real sleepers", that is, they had large initial response delays, another indication of insufficient bandwidth.

The question of how to expose poor handling when a sufficient bandwidth is present is answered by the results shown in Figure [9], in which pilot rating is shown to depend on closed-loop resonance and pilot's phase compensation. With sufficient closed-loop bandwidth, large time delays of the initial responses are no longer the problem. The problem, which appears in the rms tracking errors, is rooted in the trade between errors due to low-frequency versus high frequency performance. The pilot appears to "back off" and sacrifice low frequency performance to minimize rms error due to any excessive resonance in the system. This statement is justified by correlating maximum low-frequency "droop" with the pilot's comments. The cases found to exhibit a lower droop automatically had higher error rms value and pilot comments indicating some overshoot and PIO problems. This "delicate" strategy of avoiding highly damped oscillation (or PIO's) will always be the results obtained from the OCM due to the guaranteed stability of this optimal solution -- or it will always use the "best" piloting strategy. Alternatively, one could argue that PIO's are a result of a sub-optimal piloting strategy, and in particular, this usually means that the pilot's "gain" is too high (above the "optimal").

On the hypothesis that the optimal (OCM) pilot is sacrificing low frequency performance, suppose an additional gain is added in the "forward path" for example, to raise the closed-loop droop to try to achieve a higher level of tracking performance. Typically, the droop of the

configurations analyzed, ranged from -.3 to -1.0 dB. Adjusting the additional forward path gain to achieve

$$\left|\frac{\theta}{\theta_c}\right| > -.6 \text{ dB} \quad \text{for } \omega \leq Bw$$

produced resonant peaks comparable to those in Neal-Smith and therefore exposed those PIO prone configurations with this parameter. This procedure may sound reminiscent of the original approach, but only one degree of freedom exists -- that of "DC" gain adjustment. This was accomplished as an integral part of the computer-based analysis in the following way.

1) Scan the magnitude of the closed-loop droop in min $\left|\frac{\theta}{\theta_c}\right|_{\omega=\omega_m}$; $0 < \omega_m < Bw$ for ω_{min} (frequency at the droop)

2) At ω_{min} record the open loop $\frac{\theta}{\epsilon}$ (s) pilot frequency response as the complex number $\alpha + i\beta$

3) Find additional pilot gain K to produce -.6dB droop at ω_{min}

4) Add K to the open loop frequency response $\frac{\theta}{\epsilon}$ (s) and re-evaluate the closed loop frequency response

$$\frac{\theta}{\theta_c}(s) = \frac{\frac{\theta}{\epsilon}(s)}{1 + \frac{\theta}{\epsilon}(s)} \qquad s = j\omega$$

5) Check droop and scan for the corrected $\left|\frac{\theta}{\theta_c}\right|_{max}$.

Some of the benefits of using the OCM model are evident in the results of Figure [9]. Of particular interest are those vehicles the Neal and Smith approach failed to place in the correct "areas". In one instance, Configuration 8A appeared in the level one area, although it received a level 2 rating. We were able to not only identify it properly as level 2, but placed the aircraft next to another configuration (3A) with different short period characteristics, but sharing the same pilot comments and pilot ratings (4-5). Other examples, such as level-3 - configuration 2G were incorrectly placed in the level 2 area by Neal-Smith. Once again, the OCM approach predicted a PIO problem serious enough to warrant a level 3 rating. In cases correctly rated by Neal and Smith, agreement was almost always attained by the OCM approach. Configurations 2C, 7C, and 2D were all given high marks in acquiring the target, which exemplifies the level 1 rating predicted by both methods. In only two cases evaluated (2E, 2F) did the OCM method yield marginal results. These configurations are on the level 1 - level 2 boundary, and only one rating data point was obtained for each configuration.

Conclusion

Thus we have shown that the optimal control model not only provides a viable alternative to the classic Neal and Smith "pilot-in-the-loop-analysis", but actually offers some distinct advantages. Among these, the OCM has the capacity to better represent complex pilot compensation likely to be present in the control of high-order dynamics, in contrast to being restricted to only lead-lag compensation. Also, use of the OCM reflects more correctly the actual experimental situation, incorporating important effects of human factors in actually modeling the tracking task. More importantly, the method eliminates the critical task of pre-selecting important limitations, such as bandwidth, in favor of selecting the more fundamental physiological limitations such as neuromotor lag. Finally, the method eliminates the task of graphically determining pilot model parameters (K_p, T_{p_1}, T_{p_2}), yet yielding what is considered a better pilot model.

Acknowledgment

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Helicopter Handling Qualities Specifications Status and Plans

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The paper provides an assessment of current helicopter specifications and describes the plans that the US Army AVRADCOM has for a major effort to develop a new specification providing mission-oriented re-requirements.

The current specification MIL-H-8501A, Helicopter and Ground Handling Qualities' is a 1961 revision of a 1952 document. It gave good guidance in its early years, but by the late 1960's had many obvious deficiencies. MIL-H-8501A is still used by AEFA, to some extent, as a yardstick for flight-test evaluation, but for procurement of the UTTAS and AAH, the Army Aviation Research and Development Command (AVRADCOM) developed a new set of handling qualities specifications and incorporated them into the Prime Item Development Specification (PIDS). The Navy used essentially the same requirements for the LAMPS-III. For the Army Helicopter Improvement Program (AHIP) the handling quality requirements referred to MIL-H-8501A and provided some guidance on control sensitivity and rate damping.

There have been several formal attempts to revise MIL-H-8501A - a B version was proposed in 1968 but never developed and adopted. The V/STOL specification MIL-F-83300 was the culmination of a major effort by Cornell Aeronautical Laboratory under the sponsorship of the Air Force Flight Dynamics Laboratory. It incorporated all the data available at the time and followed closely the structure and format of the

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recently revised specification for conventional aircraft - MIL-F-8785B. The data and rationale for the requirements were presented in a background information and users guide (BIUG) which were modeled after the equivalent BUIG for MIL-F-8785B. MIL-F-83300 attempted to include helicopters and, in fact, was adopted for helicopter application by the USAF. However, the U.S. Navy and Army chose not to adopt it for helicopter application. In an attempt to overcome the perceived shortcomings of MIL-F-83300, the Army and Navy jointly sponsored Pacer Systems, Inc., to draft a revision to MIL-H-8501A. This effort adopted some of the concepts and structure used in MIL-F-8785B and 83300 and many of the new requirements were innovative, though they lacked data for substantiation. The preliminary report of this effort was submitted in March 1973, it had limited distribution, and was never finally published.

Experience in previous efforts to revise MIL-H-8501A showed that the primary obstacle to developing new requirements was a lack of systematic data from which new criteria could be developed and used for substantiation. In the last ten years several sources have contributed towards enlarging this technical data base: significant experience has been gained in procurement of three Army projects the UTTAS (UH-60A Blackhawk), the AAH (AH-64 Apache), and the AHIP Near-Term Scout Helicopter (NTSH); the Navy has procured the LAMPS III (Seahawk), which is based on the Blackhawk; experimental research work specifically oriented at building the flying qualities data base has been underway by the Army and NASA at the Ames Research Center; significant strides have been made by the fixed-wing community towards developing techniques for analysis and understanding of flying qualities, particularly techniques to handle fly-by-wire digital control systems, and tailored responses for the integration of flight control and weapon delivery maneuver exploiting features such as direct force control. This body of experience will form a reasonable basis for mounting a major revision effort.

With this in mind, the Army and Navy have initiated a systematic effort to develop a new general specification for the handling qualities of military rotorcraft. The effort will build upon the ideas, techniques and technology developed by the fixed-wing community as well as utilize the available experience with current helicopter specifications and V/STOL criteria. The existing data base will be used to the maximum extent possible, and supplemented by new data obtained under the auspices of this and related projects. Specific programs developing new data base for this purpose are being performed by the Army Aeromechanics Laboratory and by NASA at the Ames Research Center and by the Navy at NADC Warminster. The primary effort of developing the specification revision will be performed under contract. The RFP has been issued and a contract award is planned for September 1982.

Rotorcraft to be covered must include conventional single and tandum rotor-helicopters and, to the maximum extent possible, high speed rotorcraft such as compound (e.g., Lockheed AH-56A) and novel configurations such as the Bell XV-15 Tilt Rotor and the Sikorsky XH-59A ABC. This is a joint Army/Navy program the resulting specification must address the mission requirements of both services. The contracted effort will be directed by the Army Aviation Research and Development Command (AVRADCOM), technical responsibility being shared between the Aeromechanics (AL) (Research and Technology Laboratories) and the Directorate for Development and Qualification (D and Q). Contributions to the program will also be made by NASA, the USAF and, the FAA, and a Technical Committee has been formed to coordinate all these inputs.

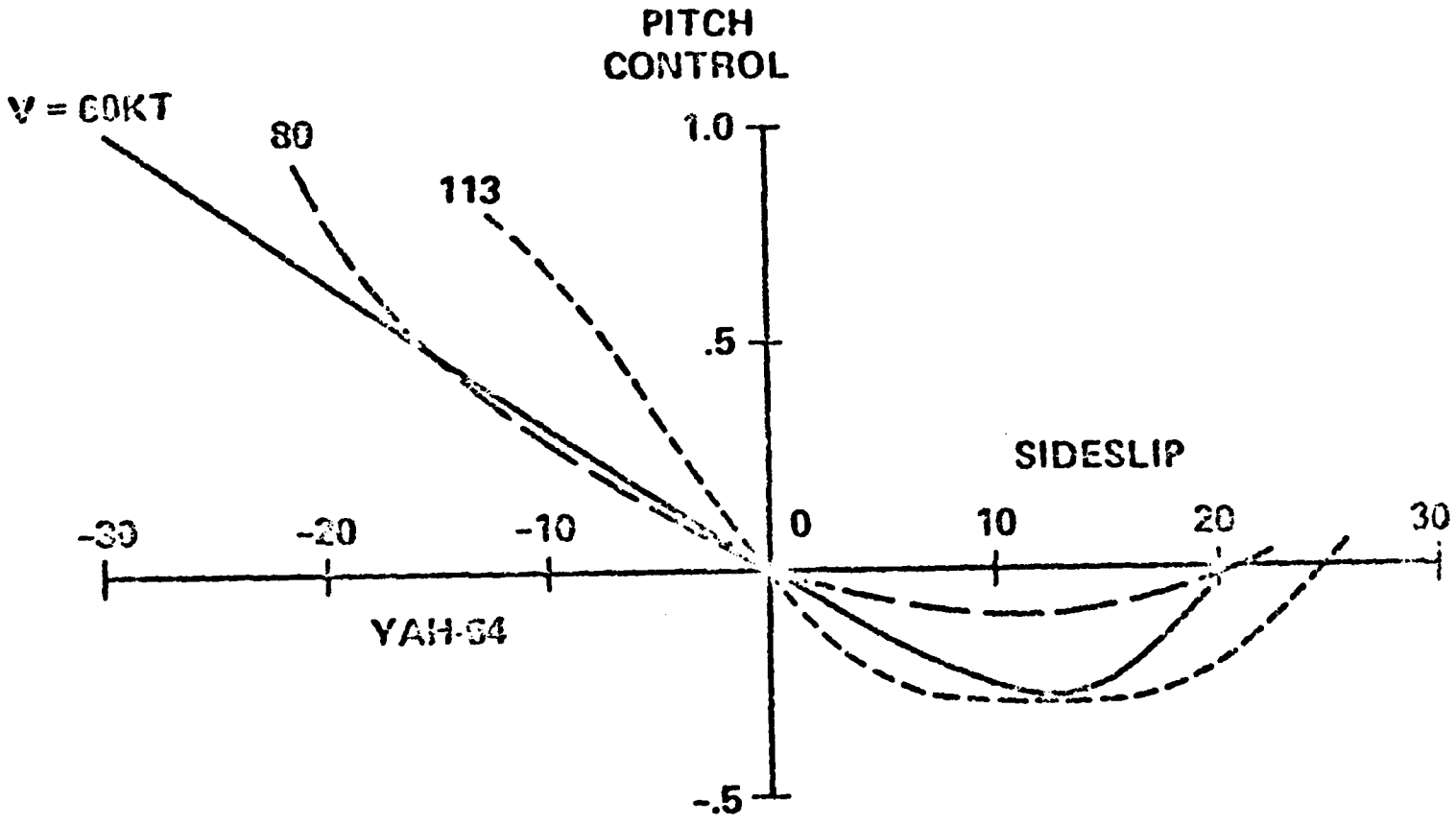
Contractor efforts will consist of analysis and evaluation. Access will be provided to Army/Navy (Marine) aviation users for mission task analysis and possibly flight test and simulation demonstration and evaluation.

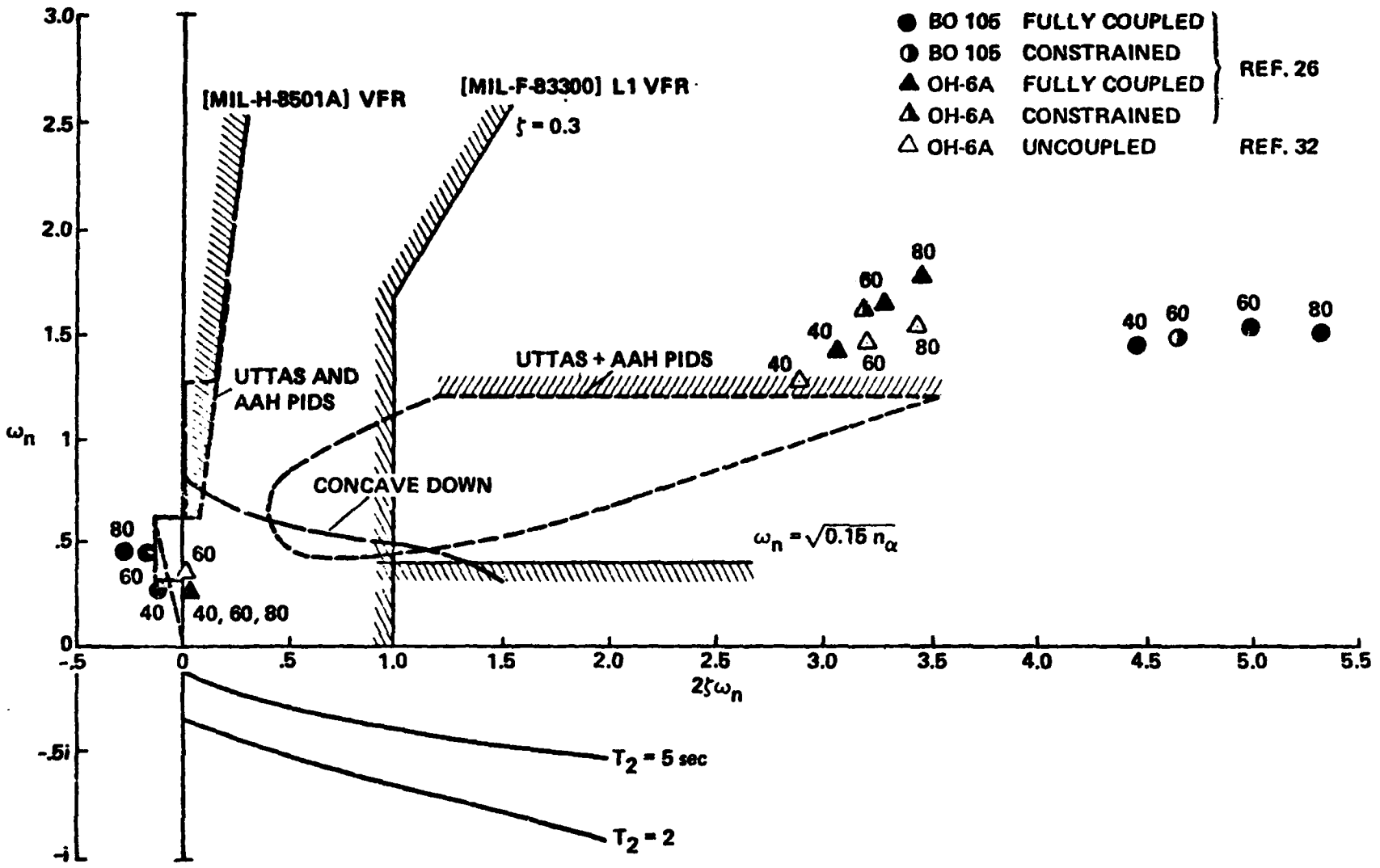
The contracted effort will be divided into two Phases:
Phase 1 will involve developing a specification structure, incorporating

existing data base/criteria into that structure and defining critical gaps and possible ways for addressing these gaps.

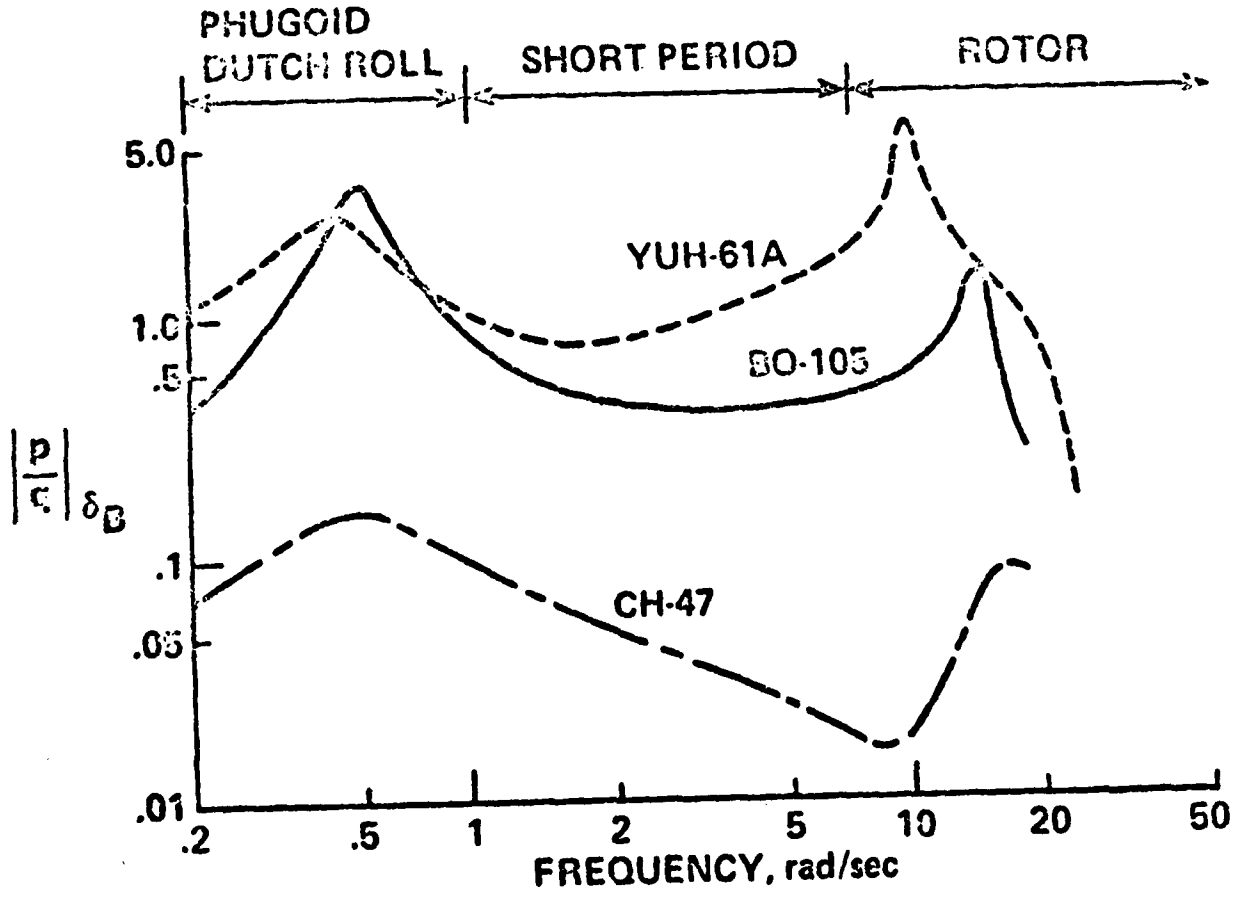
Phase 2 will extend the effort by finalizing the structure, incorporating any new data and criteria, and producing a proposed specification and background document. This will then be distributed for government and industry review, and the comments will be reworked into a final MIL-SPEC and BIUG that can be submitted for adoption.

STATIC NONLINEARITIES




● BO 105 FULLY COUPLED
◑ BO 105 CONSTRAINED
▲ OH-6A FULLY COUPLED
▲ OH-6A CONSTRAINED
△ OH-6A UNCOUPLED
REF. 26
REF. 32
[MIL-H-8501A] VFR
[MIL-F-83300] L1 VFR
ζ = 0.3
UTTAS AND AAH PIDS
UTTAS + AAH PIDS
CONCAVE DOWN
$\omega_n = \sqrt{0.15\, n_\alpha}$
T_2 = 5 sec
T_2 = 2
ω_n
$2\zeta\omega_n$
40, 60, 80

COUPLING VARIATION WITH FREQUENCY



HELICOPTER AND V/STOL SPECIFICATIONS

SPECIFICATION	DATE	APPLICATION	COMMENTS
MIL-H-8501	1952	HELICOPTERS	SPECIFICALLY HELICOPTERS
MIL-H-8501A	1961	MINOR REVISION	SPARSE COVERAGE CRITERIA INADEQUATE FOR ARMY MISSIONS LACKS TREATMENT OF ENVELOPES & FAILURES BASICALLY FOR VMC
AGARD 408	1962	V/STOL	
MIL-F-83300	1970	V/STOL (AND HELICOPTERS USAF ONLY)	BROAD COVERAGE SYSTEMATIC STRUCTURE CRITERIA INADEQUATE FOR ARMY MISSIONS BASED ON V/STOL DATA BASICALLY FOR VMC
UTTAS PIDS	1971	UTTAS	BASED ON 8501A
AAH PIDS	1973	AAH	MANEUVERING CRITERIA ADDED
AGARD 577	1973	V/STOL	
8501B (PROPOSED)	1973	HELICOPTERS	MANY NEW UNSUBSTANTIATED REQUIREMENTS
AHIP SPEC	1981	INTERIM SCOUT	BASICALLY 8501A

HELICOPTER HQ SPEC UPDATE

MODERN MISSIONS REQUIRE:

- MORE STRINGENT CRITERIA FOR STABILITY AND CONTROLLABILITY
- INTEGRATED TREATMENT OF:
  - HELICOPTER DYNAMICS
  - FLIGHT CONTROL SYSTEM CHARACTERISTICS
  - COCKPIT CONTROLLERS
  - DISPLAYS/VISION AIDS
  - MISSION EQUIPMENT AND TASKS

HELICOPTER HQ SPEC UPDATE

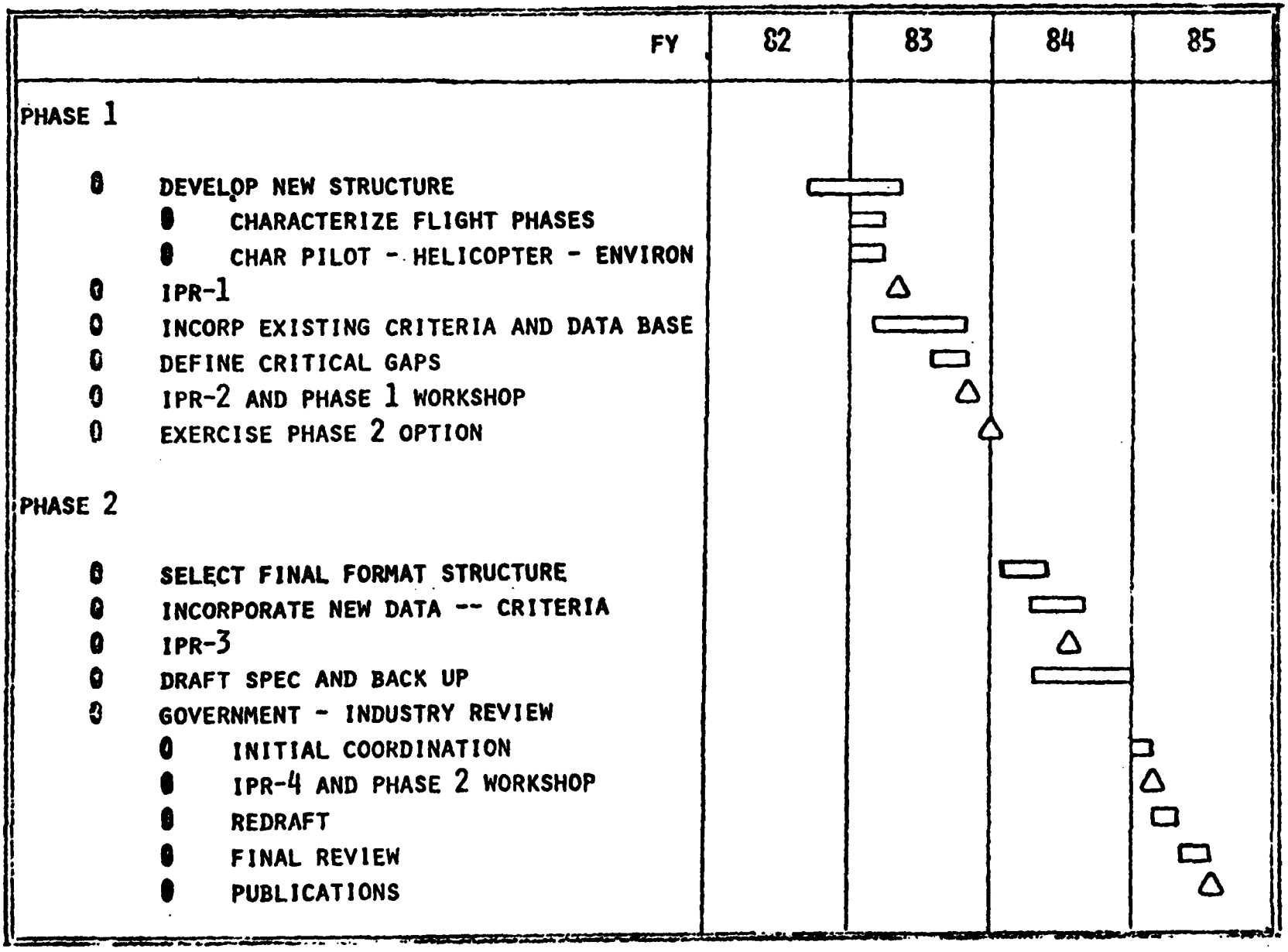
OBJECTIVES

- NEW STRUCTURE TO ACCOMMODATE INTERACTIONS
- INCORPORATE EXISTING CRITERIA INTO NEW STRUCTURE (WHERE SUBSTANTIATED)
- DEFINE CRITICAL GAPS
- ASSESS SELECTED CRITICAL GAPS
- PREPARE DRAFT SPEC AND DIDS
- COORDINATE DRAFT WITH GOVT & INDUSTRY
- CONTINUE DEVELOPING DATA BASE & CRITERIA

TECHNICAL COMMITTEE

US ARMY AVRADCOM	D AND Q
	R & T LABS
	DAS
	AEFA
AVIATION CENTER	
US NAVY	NADC
USAF	AFWAL
NASA	AMES
FAA	SW REGION

SCHEDULE FOR "UPDATE 8501"



SECTION V.
SUMMARY COMMENTS

SUMMARY COMMENTS
FLYING QUALITIES REVISION

DAVID J. MOORHOUSE
FLIGHT DYNAMICS LABORATORY

These summary comments are taken primarily from the last working session of the symposium devoted to the flying qualities discussions. It was chaired by David Moorhouse of the Flight Dynamics Laboratory and Roger Hoh of Systems Technology, Incorporated.

This last session was devoted to a quick review of the major differences between the proposed MIL-Standard and MIL-F-8785C. The intent was to uncover any potential major objections to material in the Standard or Handbook. The discussion centered on few topics, as follows.

Format: Sam Craig stated that partitioning of modes complicates its use as a design guide, e.g. the optimum ω_{sp} and T_{θ_2} could be different for the heave and pitch axes. Chick Chalk felt that both by-axis and by-controller organizations are awkward for conventional aircraft. He suggested that we should organize the requirements to facilitate their use for 90% of aircraft, which are conventional. Tom Cord said that about 20 questionnaires had been received so far - split about even between MIL-F-8785C and axis formats, with one suggestion to provide a cross-reference to other formats. As indicated elsewhere in the proceedings, the final tally includes votes for the by-controller format as well, but still no clear preference. Taken with the discussion in other sessions, we interpret this to indicate that the format is of less importance than the content and no effort will be expended to reformat the draft Standard and Handbook.

Levels/Cooper-Harper Scale: John Schuler felt that Level definitions include a landing requirement, while a Cooper-Harper rating applies only to one specified task. This comment is also related to the results presented in Schuler's paper elsewhere in the proceedings. Sam Craig suggested checking the legal consequenses of use of the Cooper-Harper scale as a requirement. This refers to a long-standing discussion as to whether a subjective opinion could form a contractual requirement. Moorhouse pointed out the factors

that went into the organization of the MIL-F-8785C with both "Levels of flying qualities" and "Qualitative degrees of suitability" in order to differentiate between numerical design requirements and factors that influence pilot rating. In particuler, the STI proposal is very similar to the original Air Force proposal for MIL-F-8785C. This proposal received a lot more objections at the 1978 symposium that the current proposal is apparently generating.

Pitch Response to Pitch Controller: Bill Rickard stated the need for more options, especially the Neal-Smith criterion. Ed Rynaski suggested the need for a time domain criterion since he felt that most airplanes are designed to one. Sam Craig stated that all forms of requirement are related, ideally, and suggested including a discussion showing their equivalence. It is noted that all these comments reflect the direction that we are taking - the Handbook was intended to present alternative criteria stressing the similarities rather than any competing aspects.

PIO Requirements: John Gibson, Randy Bailey and Chick Chalk all expressed doubt about Ralph Smith's PIO requirement, stating that it has correlated PIOs in the past (especially for the LAHOS configurations). Bill Rickard considered the criterion OK for design guidance, but a qualitative requirement was preferred. Dave Bischoff said that the Navy did not want a quantitative PIO criterion. These comments are in line with MIL-F-8785C, where the requirement is qualitative but the numerical criterion is discussed in the Background Information and User Guide.

Control Forces/Deflections: Bill Rickard suggested developing a requirement on minimum force to reach n_L (there is only an indirect requirement now, through F_s/n). John Gibson stated that the British specification used to specify force to reach n_L but now used F_s/n as in MIL-F-8785C.

Lateral/Directional Requirements: There were no comments.

Departures/Spins: Ed Rynaski suggested the need to address control power more. Roger Burton stated that the F-18 is an example of a very maneuverable, departure-resistant airplane. NASA has also developed an F-14 FCS for similar results. He also stated that many Navy airplanes are lost due to asymmetric thrust and believes

it has more severe consequences than whatever the pilot does.

Atmospheric Disturbances: Sam Craig stated that wind shear requirements can have a big influence on design. He cited a trainer design that failed the Navy specification on one-engine-out climb because of drag. Bill Rickard stated that transport designers would ignore wind shear requirements assuming the pilot would always go around (even though this certainly does not happen in commercial airline operations). Both of these comments seem to indicate the need to enforce the requirements, rather than the reverse. Ed Rynaski stated that the intent of the requirement looks useful, i.e. study a corner of the flight envelope and expose critical areas. This last comment does reflect our philosophy with MIL-F-8785C - use the disturbance requirements to identify critical failures and critical flight conditions. Dave Schmidt added that there is a need to add task and performance definitions as well.

This discussion (taken as a whole with discussions in other sessions) indicated that the draft MIL-Standard and Handbook does not contain anything that is completely unacceptable. There were many personal opinions stated, but also the feeling that the development of the material from MIL-F-8785C is reasonable, in general. We have every expectation, therefore, that when the MIL-Standard is finalized, it will be used, misused, abused and ignored in the same way that the previous documents have been.

SUMMARY COMMENTS

Evard H. Flinn, Branch Chief
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In our sessions we had concerning MIL-F-9490, basically, we covered several topics and had good discussions on many of them. I think our areas of concern were very similar to what was discussed in the MIL-F-8785 workshops. Trying to summarize any one topic and gain a consensus was next to impossible because many different ideas and thoughts surfaced.

Generally, the MIL-Prime format is accepted as far as MIL-F-9490D is concerned. The biggest concern was over the loss of critical detail design items and we tossed this issue around substantially. They'll appear in an appendix to the Handbook, but that appendix will be limited as far as time goes. These items could eventually disappear so we looked at some other way to get these items incorporated so that people could use them. Maybe the design handbooks would be a useful location. However, no definitive conclusions were reached.

The next area was the concern over present dated material which really wouldn't address anything in a future system. How are we going to include that in the specification? Again, this is a concern expressed and we in the Air Force will take it under advisement and see how we can get it incorporated. Personally, I feel that this is an excellent document to put new technology out and get it into the transition process.

We couldn't arrive at any consensus on combining the flying qualities with the flight control specification as far as the flight control system community is concerned, I think most of us felt that we still need both specifications, though different in character, and we'll leave it at that point. It was felt, however, that the flight control system specification could become a tri-service specification. The Air Force has MIL-F-9490, the Navy has their specification, and are trying to revise it after about 15 years since it was issued. The Army needs to go back and see if it wants to put the rotary wing details into MIL-F-9490. There are a lot of things in 9490 which apply to rotary wing aircraft as opposed to "fixed-wing" aircraft; no wing is 100% fixed anymore. We'll have to discuss this. I feel that this summer the services will get together and take a look at this issue. I think from the Air Force/Navy standpoint, we could combine the specifications together pretty easily and make it a lot easier for us to keep the combined

document up to date. If we had all three services behind us, we could probably use that weight to go up the chain and get the necessary funding to keep this a more active document than we have in the past.

The next area was the "lessons learned" area. I think most people, when they first hear about this area, picture it as trying to document all the horror stories and all the problems. There may be a problem doing that, but my own view on this matter is that we need to think positive. We need to look at all the good things and try to put as much of that together as deals with lessons learned across the board. There is an Air Force Regulation that governs the information and they now have a data base that has all this information in it. So, when you want to get lessons learned, just write to AFALD/PTL, Wright-Patterson AFB, Ohio and request the lessons learned for your particular subject area and they'll send the information they have. This applies to industry requests as well as military requests. We in the Control Systems Development Branch are going to go down soon and try to get a much better interface with them established so that we can at lease make sure that the lessons learned in the Flight Control Systems area get transitioned into their data base and are then accessible. I think that this specification (the draft) will be a useful tool to help accomplish this.

Updating the specification. The big thing here is that we need to be more consistent then we have been in the past. I really don't see any problem in conducting research aimed at trying to improve the specification. The beggest problem we've always had in the past is trying to get the funding for doing the actual specification work and getting the manpower set aside to do it. We're always faced with people setting priorities on us and it turns out this work is a pretty low priority in the minds of some of the research managers in the Laboratory Structure, the Air Force System Command Structure and the Air Force in general. I think the other services face the same thing. If all the services can get together, we may be able to be a little bit more active in this area. Hopefully, the products division people can lend some emphasis to the research community with regard to the importance of keeping specification work active. I'm not sure the Laboratory management understands this fully yet.

We discussed the organization of the material in the specification and there was some concern over it. We've taken down those details and will work those problems. I mentioned the rotary wing problem and I think that when we talk with Dave Key and the other Army people, this can be worked. It's

just going to take some time and we are planning to start on it this summer.

A general conclusion has been that the specification has had very little effect on some contractors. They deal with the prime contractors and this specification is between the procuring activity and the prime contractor. Still, I think that this has been a very productive meeting. Just getting together the flight control systems people and the flying qualities people, having them sit down and listen to each other and start communicating is a monumental effort. I don't really ever remember having a session like this before where we've brought all of these communities together. In gereral, it was either the 9490 community or the 8785 people but not a mix. I would like to see this activity continue. I don't believe the conferences need to be institutionalized, but they should continue on a fairly frequent basis.

I think that it is very important to have this type of interaction if we are going to make these documents usable from both the Air Force standpoint and the standpoint of the contractor. They have to be living documents. They can't be done, put on the shelf and forgotten. My own philosophy is that these specifications are the primary transition tools of technology from the laboratories into the product divisions which buy new hardware for the services. The laboratories are constantly being pushed to be innovative and go way out in the future. Yet the details of today's problems keep coming back and we have to put emphasis on that. It appears to me now that today's problems are overwhelming, especially when looking at the resources that we have to look out in the future.

My history points out that when I look at the research that is going on, it takes about 15 years from the time when we first start doing research in a particular area until you see something get into a product that is being fielded. That's an awfully long time. If you keep the activity going that you have to market, at least in the research laboratory area, it would help. Characteristically, we have not been good marketers, so we have had a lot of stops and starts. My career has been primarily an aerodynamic background associated with STOL and VSTOL since about 1953 and it's been starting and stopping all along the way. VSTOL comes up and people get hot about it. It goes on for about 4 or 5 years and then it cools off and something else becomes hot. As a consequence, I think we can see the impact on at least the specifications. It is only during the time period when the activity was real high that we had any work done. Sometimes it got incorporated, sometimes it didn't. And when the work died off, well the work in the

specification died off too. It was just stagneted at that point. The new guy who comes on to develop a new weapon system is struck with how far the specification was developed. I think it is up to us to try to take and keep the activity a little more constant. We need to try to overcome the yo-yo effect that you see in the funding and emphasis which we've had in the past.

FLYING QUALITIES
SUMMARY COMMENTS

Ronald O. Anderson
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The following is a slightly edited transcript of a verbal summary that was presented on a semi-impromptu basis at the workshop.

I've been asked to provide a general summary of the flying qualities aspects of the workshop. After three and a half days, to summarize it all in a few words is not easy. Figure 1 contains a general outline of my summary. It will have a heavy personal bias, I'm sure, but hopefully will represent the general tone of the workshop.

As far as the specification going to a Standard form, I think from the flying qualities standpoint, that the format per se had some opposition. Ray Siewert, as you remember, said that he wasn't too fond of the Standard-Handbook combination and expressed this in a comment about 25 pages of specifications on "white shorts." He stated that the Handbook could become a huge compendium, getting ever bigger and ever bigger to cover all situations. As a result we might have a nightmare. This came up a little bit this morning. I don't know whether Roger Hoh recognized it or not, but he said, "We can throw in some alternates, whichever ones we want. We just toss them in and let somebody else pick them out of the Handbook." I think that is exactly what Ray was concerned about. Therefore, as a warning, I think we have to consider this possibility as we are conducting the second round of revisions and evaluation. Maybe industry should give this some serious thought also.

From another negative side, our ASD friends tell me that the Standard-Handbook format forces them into the position of picking the right values out of the Handbook for a specific research and development package. Now normally that's great if they have a year and a half or so to do it. In some cases they do; the CX is a good case in point. But many times they're told to "do it this afternoon for such-and-such a mission." In turn, many times they have to hand the job to a relatively junior engineer, and he's got

to take it from there. In fact, this happens to be one of the reasons why the current specification, MIL-F-8785C, has ALL blanks filled in. I argued vigorously, back in the "B" days, not to fill in some of the "blanks", but rather to leave them up to the procuring agency. I was more or less shot down with heavy inputs from ASD, which I respect for just the above reasons. So, in reality, we may have two Standards. One Standard, which has the values already filled in, will be for quick reaction. Warning: it could be 8785C!

During the proposed format discussions, on an axis-by-axis basis, I didn't catch anything super serious. It sounded to me like the problems that were brought up are those of deficiencies in 8785C and not necessarily deficiencies in the revision per se. I heard several comments that people felt STI did a good job, for the most part, in putting it together.

The next item "Problems," (Figure 1) is the topic that had the most activity and it's not related to today's specification. It is related to the specifications of the future. The first of these was the problem of higher-order systems which is a popular subject to kick around. In fact, things finally got to the point where Dave Moorhouse said, "We won't talk about equivalent systems anymore as a flying qualities topic and that's the end of that." Ed Rynaski made the point, "Why do we have higher-order systems in the first place?". That was a good one and should be the practice here. I'll talk about that a little bit more later on. But, number one is to get rid of the high-order effects. In fact, if you love optimal control theory, you can prove that a lower-order system gives better dynamic performance tendencies with just about any performance index you pick. So why high-order? However, if the system has to be high-order, then the question is how to handle the situation and equivalent systems are, of course, the method most discussed. I think that you have to put a little historic perspective on this also. Our good ol' specification is based on airplanes flying like Orville and Wilbur's, and of course the new ones don't. So the equivalent systems approach is simply a way of trying to use our old data base and extrapolate it to new airplanes. As also brought out by John Hodgkinson, it was also a quick way to point out some of the problems that we see

with our modern systems. One sideline aspect that I didn't know before the workshop. It turns out that John Hodgkinson sells his McFits to everybody but he really has good, better and best programs just like Sears Roebuck. However, only the "best" one works.

Another approach is to look at a step response which is, I guess, epitomized by C*. If you go back to C*, the original report by Tobie from Boeing said "Boy wouldn't it be great if we had something like this", and everybody picked it up and used it. The Cooper ratings came to us the same way, incidentally. There has been some successes in this area and some failures. Colonel Moore, whom you've heard before, headed our AFTI office before he went to Washington. When he left I gave him a badge that said "AFTI is a C*C*V". That was because AFTI was partially evaluated using C* even though the flying qualities people don't like it very well.

Another approach to the higher order problem is pilot modeling. This morning we covered it a little in the pilot modeling application area. It is unfortunate but we seem to spend a great deal of time picking on one form or another of the pilot models when they are basically the same. It turns out that it's the similarities that you really ought to think about, and not the differences. That goes for Neal-Smith, the crossover models, the optimal control model you heard about today (Dave Schmidt is getting close -- paper pilot will ride again). The point is, basically, they're all a family of the same thing and we do a great deal of nit-picking, I'm afraid. To the casual observer, and I think this was also brought out by Ed Rynaski, it sounds like there is more confusion in the local community than anywhere else. Well, it turns out, that's just from watching a group of people very much involved in that field have at it. About two or three years ago, at an AIAA meeting, I spent one whole day listening to the parameter identification people. When I got out of there, I said to myself "Forget it!" So the same thing holds. In short we have to get our act in order in terms of similarities and not differences.

The bottom line to all of the above is why not all of the above? There are are a bunch of different ways to skin a cat, and we talked about that just briefly this morning. But I think the nicest example was John Gibson's presentation yesterday when, on one figure, he showed us a number of criteria and how they fit together. I think that's really what we're talking about. Dave Moorhouse has said the same words in terms of intent -- "don't play with the numbers. Get at what you're really trying to do." And I think we all need some jabbing in that direction.

As far as multiple approaches, I certainly won't recommend anybody use just the stochastic representation of gusts and forget the discrete, especially if you're applying that type of thing to terrain-following. The stochastic approach will handle the up-and-down terrain, but it sure doesn't recognize a water tower. I think of some of Ray Siewert's comments on the same point. Remember when he said, "Judgement -- judgement is the bottom line?" I think many are saying the same thing - put it all together and keep it as simple as we can.

Our next problem area was disturbances, and I'm not going to get into this in any great depth at all. We've had probably more discussion and arguments on the disturbance section of the specification, both the C and the B version, than any other area. One thought came to me last night as I was trying to put some of this summary together. I don't know if the disturbance problem is due to a lack of data or a problem of a <u>firm definition</u> of required <u>task performance</u>. I'll let that one sink in for a little while, because I <u>think</u> this may be the case where the performance aspects are really starting to catch up with us, and we <u>are not</u> ready for it like we should be.

The next problem I brought up, and even though it still doesn't seem to bother anybody but me, I'll bring it up again. The problem is the application, or misapplication, of the Level concept in the specification. For example, you heard about the F-15 from Bob Kisslinger. It was designed <u>by intent</u> so that the unaugmented aircraft would meet Level 2. The result was a fair amount of complexity in the control system. On the other hand,

with the B-1, as Carl Crothers mentioned it in his ride control paper, the assumption was made that it would be Level 1 with all systems operating. With everything out, it will be Level 3. I don't know if they have every had "everything out" and been down to Level 3, but I hope not! The data in the specification are essentially partial derivatives. That is, everything "good" but one parameter. With everything at Level 3, I don't know what you've got. Be careful with this one.

The next problem (Figure 1) is a very interesting one indeed. That's the challenge that MIL-F-8785 is not task, performance, or mission-oriented. Well, like many challenges, this one has no single answer. The challenge is wrong to a certain extent. Colonel Moore brought the subject up initially in respect to overall weapon system performance. Pilot opinion rating is the heart of the specification. However, the specification doesn't handle this directly and pilot opinion rating is very much task-dependent. So we are talking about very specific tasks and very specific performance associated with those tasks. But we, the flying qualities community, have trouble remembering that once in a while, and I'll say more about that later. Mission flight phases are defined (e.g. Category B, C) in the specification, again very much task - and mission-dependent.

Finally, what constitutes a good system from a control standpoint? From a pilot modeling-like approach many, many requirements in the specification are really closed-loop-oriented and that means performance-oriented in terms of minimum RMS tracking error, etc. So in terms of both basic control theory and performance measures (that's all the way from rise time to whatever) it's all in there. But it's not in there very explicitly. So in some respects, that challenge is wrong.

In some respects, that challenge is "maybe." For example, Ray Siewert asked the question, "Do we have the criteria to handle the six-degree-of-freedom mode-type operation?" Well, the answer is "maybe." We did finish a contract with STI and the report is out. In fact, a part of the bandwidth activity came from that effort. Their work showed that if you again define the task (which is pipper error to stick deflection, for example, not pitch,

not attitude, not angle-of-attack), to keep the sight on the target and make the effective dynamics K/s-like, you probably have a good airplane. But again, you have to define the task, and I really think we need more data in this area. Maybe our AFTI airplane will provide some. AFTI, unfortunately, does not have the flexibility of a variable stability airplane to do the kinds of things I'd like to have done. So in some respects the challenge is "maybe."

In many other respects, I think the challenge is "right." For example, take "super-augmented" aircraft (I think McRuer coined that word). An example of super-augmented is the forward swept wing aircraft with a 35% static instability. I still don't know exactly what is going to happen with that beast, but it's a whole new region for us and there are some strange dynamic modes with this aircraft, and I'm not sure that we are ready to handle them. But you can carry this problem across to STOL, reduced radar cross-section aircraft, that were mentioned this morning,etc. I don't think we've prepared in this area at all. Also, what about semi-automatic-type modes? Bob Kisslinger mentioned this problem to me, and it's a good one in the IFFC. Here's the case where the pilot handles the low frequency activities in closed-loop fashion, and the high-frequency activities are taken over by the airplane. What do we do as far as -8785 "X" is concerned for this one? I don't know. There's a whole family of these problems in terms of night-all-weather, incidently. When TAC decided to fly a two-seat A-10, the SPO came to us and said, "OK, we are going to fly at night with an A-10. We're going to do everything that we do during the day. What do we do to the flying qualities specification to take care of this situation." And of course our response was, "Damned if I know."

Other sub-systems were mentioned in several cases. Colonel Moore and Jerry Lockenour, both made a hard point that when we talk about dynamics, we ought to be thinking a little bigger. Maybe the dynamics in the equivalent systems, or however else you want to play it, should include the fire control system, the propulsion system, and the flight control system. If we can do it

(apply equivalent systems) on one, I think we can do it on all. I think that theme was a good one and we should listen to it. But there's other systems involved. We mentioned fire control and propulsion. I guess we should also consider a category of "other important aspects" (which gets back to Sam Craig's wings). When all is said and done, maybe a little stability and control in all of this, and a little preliminary design at an early date are pretty nice things to have! Finally, probability of kill is the name of the game for sales these days in the Department of Defense. I don't think we're doing a very good job of "sales" in this respect at all.

A feedback comment from Jack McAllister concerned yesterday's challenge of preliminary design aspects of flight control. That is, we're not doing it very well. One of his comments was that he knows some of the operations analysis people already assume the flight control per se is perfect. Of course the simplest example is the point mass consideration of the vehicle for air-to-air, angle-of-attack analysis, etc. So we are already logged in as "perfect." The bottom line of all this, in the area of performance orientation, is education and sales. The people in flying qualities who are really intimate with the area have to get across to everyone else exactly what is in the specification and what's not.

This brings us to the next point, and that's the -8785/9490 relationship. The general consensus of opinion in the groups that I have been in, was that putting the specifications together (i.e. stapling them together with a great big staple) is, "Who cares?!" No further comment is needed in this regard.

What is interesting, though, is an apparent communication problem and that was brought up pretty well by both flying quality people and control system types. In fact if was mentioned a couple of times already this morning that everybody in this room is a flight control person so our division into flying qualities and flight control is really wrong in the first place. This triggered back on some comments that were made yesterday in terms of the deficiencies in current aircraft. There are two points to this. One, I don't think that we want to stand around and slash our wrists about how bad things are with existing airplanes because they are

not all that bad. We've really made some big strides in flight control in the past few years and we've got some good airplanes. On the other hand, in respect to the experts that we have here, I think that we are all dedicated to locating problems and solving them, to produce the best aircraft we can. The bad news side is that those problems do exist. An open challenge came to the flying qualities discipline from the flight control system people. It was a coffee break comment to the people who have indicated that there <u>are</u> problems with existing systems. In short, the flight control gang would like to know what they are. They were very up-tight about the whole thing. So that's telling me something very dramatic, and that is that we're not talking to each other. What we as flying qualities people <u>think</u> we know is not known, in a practical way, by the hardware guys and vice versa. So this supports Ev Flinn's comment and adds an even more important reason, in my mind, to have all of us get together with more of these types of meetings. You may want to comment further on this later on.

Communications seem to be the "biggee" in this area. As for some quick examples, I already mentioned the comments that 8785 was not mission-oriented. I said that was wrong, and the myth is partly my fault. On the other side of the fence, we heard some words from the flying qualities people saying that digital, by definition, is "damn-digital", but we also heard several times that this is not true. In fact, system time delays are not due to "digital aspects", but rather to higher-order effects and I'm not sure where they come from.

In regard to more joint activity, it was suggested last night that a "joint math model" may be of value -- something that would be put together by the hardware as well as the flying qualities community and could be used for the design of systems. We actually tried that some years back with a contract with Honeywell. We came up with what turns out to be a meat grinder-like approach that led to synthesizing control systems that give you good flying qualities. It's been used by Honeywell ever since. Bob Woodcock has the document over there. We're selling these for a buck and a half, John Hodgkinson, if you want one. We can take a look at that again. When was that, Bob, about ten years ago? (February, 1972)

So my memory is not too bad. So if anyone wants to take a look at it, there it is. One thing, however, it did not have higher-order effects. It was airplanes flying like airplanes. As a result, it may not have been picked up, since there were other ways to look at these systems.

Another suggestion which is now becoming obvious to me. Ev Flinn doesn't know this but he'll help pay for this next suggestion, so we're open for ideas. "Why did we get to where we are?" Given that there are some flying qualities deficiencies in some of our modern aircraft, how did they get there? We heard everybody yesterday talking about prefilters. In fact, years ago I remember the Navy finding a prefilter in their F-8 airplane which implies somebody lost the thing. Why do we have prefilters? Why do we have these higher-order effects? Back to Ed Rynaski -- why are those things there in the first place? I, for one, don't know! I got involved in our AFTI-F-16, which has a prefilter that had a quarter of a radian break and said, "My God, what are you doing?" Later on, it came back that we gave you the wrong information. That's supposed to be 4 radians (One over t versus t kind of thing). I don't know. There is a challenge for people looking for money.

I think we need a joint look at the user/buyer/seller combination a little bit heavier. I don't know if there is any more we can do in the 8785 area. We have sponsored workshops, etc, aimed at bringing the flying qualities community together, and this has been going on for years. I hope it's a big help. I think the flying qualities community has attempted to contribute data to the pool hoping they will get back more than they put in. I'm very grateful for that. I think we have had a very good relationship with all of them. I'm not too sure that's happened heavily in the 9490 area. Maybe that's because of the basic hardware nature.

Which leads to one quick story. On December 6th, 1941, there was a paper presented at a conference the day before Pearl Harbor and it described a new control system called "Pre-act." Pre-act was a patented device,and some results were shown on how wonderful this system was in certain cases, for certain particular control elements. It was also shown how utterly terrible it was in other situations. It turns out that Pre-act was rate feedback around an

attitude control loop. That was patented in 1941. But the interesting part is, one of the authors of that paper was Nichols, of James, Nichols and Phillips, authors of a famous book after the war. His name remains on the "Nichols charts" which we've been talking about all through the workshop. So the hardware/analysis side can be bridged. Maybe that patentable aspect (i.e. that the hardware is sellable) means the hardware side will always play their cards close to the table. I don't know.

Quickly, on the nitty-gritty aspect. I don't have much. I just want to give a couple warnings there again. Back to the flying qualities people. Don't forget history. I was very pleased, again with John Gibson. He went back as far as Ian Hall. There's a lot back there; let's use it. Secondly, don't forget the task aspect. Boy, we preach the Cooper-Harper ratings and task-dependency and yet we get up there in the air and do dumb things that have no relation to task at all. In fact, for Dave Key's benefit and 83300, another quick story. I got involved in the 83300 committee when the Army, Navy and the Air Force got together and sat around the table with the final document in front of them and voted as to whether it should apply to helicopters. Just think about that. Now that's flat task-dependency!

Overall, that's the summary. I've tried to give credit where credit is due. If I've missed a few people and their comments, I'm sorry. The bottom line of it all, I think its been a great workshop. Maybe we can talk about some of the joint activities a little more this afternoon. As far as 8785 goes and the new format, STI has done a good job. We welcome any further comments you may have.

FLYING QUALITIES SUMMARY

I. SPECIFICATION TO STANDARD

II. PROBLEMS
- A. HIGH-ORDER SYSTEMS
- B. DISTURBANCES
- C. ALL LEVEL II OR III
- D. TASK/MISSION/PERFORMANCE ORIENTED

III. MIL-F-8785C and -9490D
- A. CURRENT FLYING QUALITIES PROBLEMS
- B. COMBINE FLIGHT CONTROL/FLYING QUALITIES
  1. SPECIFICATIONS
  2. PEOPLE (COMMUNICATIONS)

IV. NITTY-GRITTY

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FIG 1

TRIP REPORT SUMMARY

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1 INTRODUCTION

The Air Force Flight Dynamics Laboratory has organized a symposium entitled "Design Criteria for the Future of Flight Controls". The symposium was conducted to offer government agencies, contractors, industry personnel, foreign government representatives and Flight Dynamics personal a forum for the discussion of new formats of the Military Specification for the flying qualities of piloted airplanes and of the Air Force flight controls specification.
The existing specification MIL-F-8785 C for flying qualities has been reformatted under contract by Systems Technology Inc. and McDonnell Aircraft Co into a proposed MIL STANDARD and a MIL HANDBOOK for Handling Qualities of Piloted Airplanes.
Likewise the existing specification MIL-F-9490 D for flight controls has been revised under contract by the Northrop Corporation.

The reason for a joint symposium was to promote exchange of views between individuals representing the flying qualities community and the flight controls community which is important,considering the implication of the characteristics of flight control systems on the handling qualities of many current and certainly of most future aircraft designs.
NLR has carried out a great deal of work in this area and the invitation to attend the symposium was therefore appreciated very much. Mr. M.F.C. van Gool has attended the symposium and he has presented an informal paper in the flying qualities workshop under the title "Failures in Advanced Flight Control Systems".
The NLR participation in the workshop was sponsored partly by the United States Air Force Office of Scientific Research (AFSC).

2 ORGANIZATION

A large number of organizations responded to the invitation resulting in a participant list of 200 individuals. (See Appendix 1).
The European participation was limited to England (British Aerospace), Germany (DFVLR) and the Netherlands (NLR).

The symposium was organized in the form of joint sessions in which formal papers were presented directed at subjects related to both flying qualities- and flight control systems spec.revisions. In addition workshops were held, mostly seperately for flying qualities and flight controls, in which more informal presentations were given and more time was reserved for discussion.
This set-up proved to be very efficient, the formal and informal papers in many cases raised controversial issues that could be discussed extensively in the workshops.

Being interested mostly in the flying qualities spec. revision, the NLR representative has concentrated on the Flying Qualities workshop sessions which implicates that the discussion in the separate Flight Controls workshop is not covered in this memorandum and only the final conclusions,as presented in the joint meeting on the last day,are presented.
The presentations and a summary of the discussions will be published by the Air Force Flight Dynamics Laboratory within a reasonable period of time.

3 FORMAL PRESENTATIONS

3.1 Specification revision and validation

New directions in flight control requirements
Merle Hewett, Northrop Corporation

An overview of the proposed MIL-STANDARD and HANDBOOK
Roger Hoh, Systems Technology, Inc.
An assessment of military flying qualities: A look at design criteria for the future .
Stanley G. Fuller, Captain, USAF, Flight Dynamics Laboratory

Flight control to satisfy flying qualities
Edward Rynaski, Calspan Advanced Research Center

The authors of the proposed revisions (M. Hewett and R. Hoh) explained the nature of the change of the existing specifications MIL-F-9490 D and MIL-F8785C

into the format of a STANDARD, containing the specifications with blanks at positions where contractors are supposed to fill in numbers for a specific airplane/flight control system design, and an accompanying HANDBOOK, containing background information to be used as guidance for selecting the numbers for the blanks.
The proposed STANDARD for flight controls basically uses the same sections as MIL-F-9490D. The proposed STANDARD for Flying Qualities has a different organization than MIL-F-8785C in that specifications are presented by axis rather than by control mode.
In both cases one of the reasons for the revision is that the specifications become more simple to use and that they should give design guidance for highly augmented aircraft. Both authors of the proposed revisions made it clear that the information they would get out of this symposium would be incorporated where appropriate in the final documents.

S. Fuller, as Air Force representative, indicated that he had high expectations of the results of this symposium. He urged the participants to see the criteria as complementary rather than competitive. An Air Force initiated handling qualities evaluation program will be started for criteria evaluation in the near future.

E. Rynasky urged control system designers to avoid increasing the system order and to place poles and zeros directly linked to the flying qualities criteria. In his views time domain parameter identification is preferable over frequency domain identification because transport lags are better defined and in his opinion the equivalent systems approach, which is defined in the frequency domain, is not the final solution.

3.2 High technology interface with the specifications

Equivalent systems criteria for the MIL-STANDARD
John Hodgkinson, McDonnell Aircraft Company

How design criteria have caused poor flying qualities for landing - C* and pitch rate envelope criteria applied to the space shuttle
Charles R. Chalk, Calspan Advanced Research Center

Guidance for use of equivalent systems with MIL-F-8785C
Thomas A. Gentry, Flight Dynamics Laboratory

New flying qualities criteria for relaxed static stability
John Schuler, Boeing Military Airplane Company

Correlation of longitudinal flying quality criteria
Dave Bischoff, Naval Air Development Center

Experience in applying lateral-directional equivalent systems
Bob Palmer, Naval Air Development Center
Dave Bischoff, Naval Air Development Center

A large part of the papers and the following discussions were directed at the use of criteria for so called "equivalent systems" which are low-order approximations of high-order systems.
The concept is generally accepted now.

J. Hodgkinson, the originator of the idea, proposed a number of refinements that may even increase the validity. The discussions concentrated on the need to free or fix the numerator parameter of the low-order pitch rate transfer function in the matching proces. No consensus could be reached, indications are that when simultaneously fitting the pitch rate and normal acceleration transfer functions, both methods lead to the same results.

C. Chalk showed that in the Space Shuttle design the wish to reduce pitch rate overshoot, as required by criteria using the pitch rate response and the C* response, caused time delays that resulted in handling qualities problems.

T. Gentry indicated that in applying the equivalent systems approach it is important to exclude the phugoid mode from the computation by selecting the lower bound of the frequency region of fit at an appropriate value. He emphasized that it is important to take into account all filters (even the structual filters) when determining the equivalent system.

J. Schuler reported an investigation on relaxed static stability that is of the utmost importance for the design of the current handling qualities experiments on the NLR flight simulator. It indicated that in unstable

aircraft time to double pitch attitude is not the dominant parameter for handling qualities, and that the relative position of the other roots are equally important. A copy of the paper was obtained and the author promised to send NLR an extended version of the paper shortly.

D. Bischoff compared the criteria for equivalent systems and bandwidth for the F-14 pitch response in category A flight phases. He indicated once again that fixing or freeing the numerator parameter leads to a different value of n_α and thus to a different value of the control anticipation parameter (CAP). Using a modified definition of CAP, he showed that there are inconsistencies in the boundaries defined in the proposed handbook.

B. Palmer used the equivalent systems approach to compare the handling qualities of the A-6 with a stability augmentation system on and off. By simultaneously matching the ϕ and β transfer functions it was possible to get good results, however, it proved to be necessary to fix parameters and he indicated a need for further research in this area.

3.3 Flight testing and related experience

Lateral-directional flying qualities of highly augmented fighter aircraft
Rogers Smith, Calspan Advanced Research Center

In-flight investigation of large airplane flying qualities for approach and landing
Charles R. Chalk, Calspan Advanced Research Center

F-18 Flight control system development and test and equivalent systems analysis
Roger Burton, Naval Air Training Command
James Vincent, Systems Control Technology, Inc.

Impact of military specifications on design of the F-15 flight control system
Bob Kisslinger, McDonnell Aircraft Company

Application of MIL-F-8785C in development and flight test of a pitch augmentation system for a relaxed stability L-1011
Jerry Rising, Lockheed-California Company

R. Bailey represented R. Smith in a presentation of the LATHOS (Lateral High-Order Systems) program on the USAF/Calspan variable stability NT33. Parameters varied included roll mode time constant, roll control authority and roll time delay. The task consisted of tracking, air refuelling, approach and landing and HUD tracking of heading and bank angle.
The results indicate that the sensitivity for time delays was the lowest when roll mode time constant was close to 0.6s. For very low values of roll mode time constant a phenomenon described as roll ratcheting (low amplitude high frequency pilot induced oscillation) was observed. A full report on these experiments will be published shortly.

C. Chalk presented a report on the large airplane flying qualities experiments performed in the USAF/Calspan Total In-Flight Simulator (TIFS) shortly before the NLR experiments were carried out on this aircraft.
In this investigation a statically unstable million pound airplane was simulated and parameters varied included:
- level of augmentation using pitch rate or angle of attack feedback
- pilot location relative to the center of gravity
- lags and time delays in the command path

The results indicated that low equivalent short period frequencies and relatively long time delays can be tolerated . In analyzing the ratings for pilot position shift, the altitude loop bandwidth showed good correlation with pilot opinion.
A complete preliminary report of these experiments, which are of very high importance for the NLR investigations in this area, was obtained through AFFDL.

A report on the development of the F-18 flight control system was given by R. Burton.
This digital full-authority fly-by-wire system has gone through a number of stages and they succeeded in getting equivalent time delays to very low levels of 0.05s.
The system identification is carried out in the time domain and an equivalent system is determined. Good agreement with frequency domain methods were obtained, however it was necessary to free the pitch rate numerator term to fit the effect of the high lift surfaces.
It is planned to repeat the analysis for another aircraft, possibly the AFTI-F-16.

It was emphasized that MIL-F-8785 B had given good guidance in system development.

B. Kisslinger presented the development of the F-15 flight control system.
The system was designed such that the augmented performance was within level 1 limits of MIL-F-8785 A and the mechanical back-up control was level 2 in MIL-F-8785 A terms.
He described the piloting task in such a control system as the low frequency task whereas the automatic system takes care of the high frequency part of the task. Guidance was solicited for the break frequency between these two areas.

J. Rising presented the application of MIL-F-8785 B in the development of the relaxed-stability L 1011.
Using a reduced horizontal tail surface area and specific c.g. locations, the static margin was reduced from 10 % to 5 %.
Interesting to note is that the stick force per g reverses sign in the transonic flight regime which is considered unacceptable. He mentioned that this probably is the case for all wide body aircraft in which weight and thrust have been increased without paying sufficient attention to the column forces.
Simulations both ground-based and in-flight indicated that it was necessary to increase the short period frequency using the augmentation system, to improve the pilot ratings for aft c.g. positions.
He indicated that these results will probably be the last for the time being since the NASA Energy Efficiency program has come to an end.

4 WORKSHOPS

4.1 Informal papers

Definition of levels that include turbulence environment & task performance standards.
Charles R. Chalk, Calspan Advanced Research Center

Development of controller requirements for uncoupled aircraft motion
Kevin Citurs, McDonnell Aircraft Company

Roll-ratchet phenomena and k/s controlled element
Charles R. Chalk, Calspan Advanced Research Center

Douglas position paper on the proposed MIL-F-8785C revision
William W. Rickard, Douglas Aircraft Company

Review of high angle-of-attack requirements for the MIL-handbook
David Mitchell, Systems Technology, Inc.

Some special concerns for the future of flight control
Ernest F. Moore, Colonel, USAF, Flight Dynamics Laboratory

Evaluating todays fighter aircraft
Rogers E. Smith, Calspan Advanced Research Center

Use of equivalent systems with high-speed, highly augmented aircraft
Joe Gera, NASA-Ames Research Center
Bruce Powers, NASA-Ames Research Center

Integrating a pilot into a crewstation
Joe McDaniel, Aerospace Medical Research Laboratory

Design criteria for highly augmented fly-by-wire aircraft
Charles Abrams, Naval Air Development Center

B-1 ride qualities
Carl Crothers, Rockwell International

Flight testing to identify pilot workload and pilot dynamics
Robert P. Crombie, Captain, USAF, NASA-Dryden Flight Research Facility

Flight testing of equivalent systems
Professor Robert F. Stengel, Princeton University

Comparison of handling qualities criteria
John Gibson, British Aerospace

Failures in advanced flight control systems
M.F.C. van Gool, NLR, Netherlands

Modern approaches to handling qualities research
Professor David K. Schmidt, Purdue University

The helicopter flying qualities specification - status & plans
David L. Key, US Army Aeromechanics Laboratory

A few remarks on the contents of each paper will be given next:

C. Chalk emphasized that ratings are only valid for the specific task definition and performance standard used by the pilot. Therefore it is mandatory to define all aspects specifically.
He suggested that it would be better to define levels of flying qualities based on the most severe environmental condition to be specified by the contractor, rather than letting the level 1 definition slide as a function of turbulence intensity, as proposed in the revision. In practise, however, application of this concept seems questionable, certainly for approach and landing flight tests.

K. Citurs reported on a literature investigation carried out under sub-contract for STI into requirements for controllers for uncoupled 6 degrees of freedom aircraft motion.
An ambitious experiment is desigred toinvestigate aspects like break-out forces, force-deflection gradients, hysteresis, position accuracy, time lags, control harmony and crosstalk between different modes.

C. Chalk elaborated on the "roll ratchet" phenomenon observed in the in-flight experiments carried out by Calspan. In his opinion this is caused by the bad effects of a pure k/s control system combined with a time delay at high frequencies.
In the discussion it appeared that another explanation for the roll ratcheting may be the lateral accelerations in abrupt roll manoeuvres when a pilot sits above the c.g.

W. Rickard expressed the views of a commercial airplane company (Douglas) towards the MIL-8785 revision. He agreed with the organization in axes and he liked the equivalent systems approach, however some points were unclear
- Digital systems were not mentioned specifically
- Static stability is not mentioned specifically
- Which stall speed is meant in the spec, military stall speed is defined differently than the FAA stall speed.
- The time to bank boundary is still in the current revision although the C5A experience showed a need for change



As a general comment he indicated that Class III airplanes (large and heavy) are not covered adequately.

D. Mitchell, who is an important co-author of the MIL-F-8785C revision, indicated that the high angle of attack requirements were modified again slightly from the proposed revision in that high angle of attack stalls were covered as combined axes requirements and some specifications were made more precise.

E. Moore urged the flying qualities and flight control community to be more concerned about the aircraft mission than with the aircraft handling as such. Weapon system effectiveness was the key word in his views.

R. Bailey presented the paper by R. Smith on today's fighter aircraft. In most of the recent aircraft designs, F16, F17, F18, Space Shuttle, problems occurred in test flights that were not predicted before in the analysis and ground tests. A movie on the inadvertant take-off of F16, and the pilot-induced oscillations in an F18 and in the Space Shuttle illustrated this point.
A strong plea for valid in-flight simulation was made.

B. Powers presented another paper on the use of equivalent systems in which free or fixed numerator time constant was an issue.
Simultaneously matching pitch rate and normal acceleration did not lead to satisfactory results in this case.

J. McDaniel presented information on biomechanics for crewstation design. Issues as reach, strength and endurance of males and females were investigated for different positions of the control handles in an aircraft. He showed that a large percentage of female pilots were unable to exert the MIL 8785B-specified maximum forces for more than 4 seconds.
Especially stick forces to the right (35 lbs, 1 hand) were too high for 50 % of the men and for 100 % of the women. In the specification for the Next Generation Trainer the requirements have been changed and he advised to change the numbers in the MIL STANDARD accordingly.

C. Abrams made a very controversial presentation indicating that he did not use MIL-F-8785 at all and that he developed his own time response parameter criterion consisting of a weighted sum of rise time, overshoot, settling time of pitch rate and normal acceleration.

C. Crothers indicated that the B1 ride qualities showed that the criteria in MIL-F-9490D were too strict in the low frequency area.

R. Crombie gave a summary of the results of the AIAA workshop on pilot dynamics and workload at Edwards AFB 19-21 Jan. 1982. That workshop was attended by Mr. R.C. van de Graaff of NLR who wrote a tripreport: NLR Memorandum VS-82-004 L.

R. Stengel presented the results of flight tests of equivalent systems on the Navion variable response research aircraft of Princeton University. Rise time of the pitch rate response to a step input in combination with time delay were considered to be the most important handling qualities parameters. For configurations with large rise time, additional time delay had a large effect on pilot opinion and for configurations with low rise time the effect of additional time delay was low.

J. Gibson produced a comprehensive study of several handling qualities criteria using Nichols diagrams to present a common presentation format. Using a number of Calspan studies he showed that it is possible to present boundaries that explain a large deal of the experimental results.
He is in the process of publishing this study and he has promised to send NLR a copy as soon as he is finished.

M. van Gool presented the intended design of experiments on the flight simulator of NLR directed at the influence of failures in an advanced flight control system on transport aircraft handling qualities.
A summary of his presentation and a copy of the viewgraphs is presented in Appendix 2.

D. Schmidt tried to bridge the gap between frequency domain and time domain by applying the Neal Smith analysis with the optimal control pilot model. Using a cost function including pitch attitude, pitch rate and control rate he obtained good correspondence between this time domain approach and the original frequency domain results.

D. Key presented the history of the helicopters flying qualities specification 8501 which became MIL-F-83300 in 1970 but which was mainly an Air Force V/STOL specification. In 1973 a revision of 8501 was published mainly directed at helicopters which contained many unsubstantiated criteria and at present it is proposed to have a new update to 8501B which should be completed by 1985.

4.2 General discussions

Many of the papers and certainly those in the workshop gave rise to extensive commentary.

A selection of important subjects is given next:

1. Organization of the MIL standard for handling qualities in axes instead of control modes is generally accepted,but problems are foreseen in some combined axes cases.

2. Equivalent systems
   Generally accepted. The problem of fixing or freeing numerator time constant is not solved.

3. Using pilot opinion ratings for flying qualities level definition and sliding the scale with turbulence.
   It was stressed many times that defining the task and required performance very explicitly was of the utmost importance in obtaining pilot opinion ratings. A surprising aspect was that there are legal problems to define handling qualities by subjective pilot ratings which then slide with turbulence intensity.

4. Failures
   This item did not receive as much attention as the author would have wished. The idea of generic failures analysis (identify all failures and treat them as if they have a probability of 1 to happen) did not give rise to extensive discussions in the flying qualities workshops.

5. Relation between different pitch response criteria.
   It was recognized that different criteria that are proposed or that are deleted from the MIL standard have a tight relation in many cases. In each criterion a certain aspect is displayed most clearly so rather than competitive the different criteria should be regared as complementary.

6. Force-deflection relationships for sidestick controllers
   This is not considered to be critical when a pilot gets time to adapt.

7. In determining maximum forces to be applied at centerstick controllers it is considered to be important to take into account female pilots.

8. Combining the specifications for flying qualities and flight control
   No consensus was reached on this topic.
   It was stated several times that it is extremely important to have a good understanding between flying qualities and flight control departments but actually tying the specifications was considered to be not worth the effort.

9. Finally it was mentioned that it is essential to use the documents to its basic intentions rather than to argue about the exact numbers to be used in criteria, to avoid the situation in which contractors or government would disregard the specifications because the people that ought to use them do not agree among themselves.

5 CONCLUDING REMARKS

From the discussions it is concluded that the symposium has been extremely valuable to most participants. The papers given were of a very high level, the discussions were lively bringing up many more issues of interest. The organization was very smooth and provided everyone ample time to express his opinions.
In view of future developments it is important that more information exchange between flying qualities and flight control organizations take place and probably this symposium will have a follow-up in the not too distant future.
As for the NLR participation it is felt that the exchange of ideas has been very

worthwile. The STI representatives responsible for the Flying Qualities Spec. revision were very interested in the results of the NLR investigations and decided to study the NLR reports more thorougly.

The communications with many participants concerning the proposed NLR investigations on failures provided new ideas that will possibly influence the design of the experiment.

As always the personal contact with engineers from other research institutes was very stimulating for new ideas.

Summarizing a very sucessful symposium!

SECTION VI.
OTHER RESULTS

CONFERENCE QUESTIONNAIRES SUMMARIES

One of the best ways feedback from participants of the conference was obtained was through the use of both the flying qualities and the flight control systems questionnaires distributed to all attendees. All attendees had access to both sets of questions. Numerous forms were returned with many valid and pertinent comments. These will be useful in the preparation of the new MIL-Prime documents. In addition, the information gives insight and ideas into the use and interpretation of the present requirements in the field and highlights areas of possible future research and analysis.

The format of this section is as follows: Example questionnaires are included, with number of responses in the blocks marked and comments listed where they were given. General conclusions and comments then follow, first for the flying qualities questionnaire and then for the flight control system questionnaire.

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FLYING QUALITIES QUESTIONNAIRE

Please help the Flying Qualities Group of the Flight Dynamics Laboratory by filling out the following questionnaire. Your candid responses will help us in finalizing the Military Flying Qualities STANDARD and HANDBOOK. Please add any comments that you deem appropriate while filling out the questionnaire. Use the back of the sheets if you need to. We realize that filling out this questionnaire will take several minutes of your time, but feel that it will be very valuable to us in obtaining input to make a better and more useful flying qualities specification.

Thank you. Your cooperation is greatly appreciated.

NAME & COMPANY (Optional)

_____

_____

BACKGROUND

Flying Qualities	31	Flight Control Systems	18
Line Engineering	20	Management	10

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1. How familiar are you with MIL-F-8785?

	B Revision (1969)	C Revision (1980)
Intimately	15	10
Moderately	17	12
Vaguely	1	6
Not at all	0	2

2. a) Did you receive a copy of the proposed MIL-STANDARD & HANDBOOK?

25 Yes 7 No

b) How much of a review and critique were you personally able to complete?

4 In-depth 8 Read-thru 13 Overview/Skim 7 Little

c) If you concentrated on any particular sections, please specify

Pitch Axis	5	Turbulence	1
General Requirements	2	Lateral-Directional Requirements	2
Departures/Spins	2		

3. How extensively do you see the military flying qualities specification being used? How extensively should it be used? Rank High (H), Medium (M), Low (L) or Nil (N):

	Is used	Should be used
a. As a firm specification to best assure satisfactory flying qualities for military aircraft	14	18
b. As guidance during design and development	19	23
c. In providing guidance for the control laws of the flight control system	8	18
d. During development flight test		
(1) As a guide for flight test planning	18	21
(2) As an aid in problem definition	10	17
(3) As an aid in defining solution alternatives	6	13
(4) As a basis for communicating deficiencies	15	20
e. As a communication aid between government and contractor flying qualities engineers	15	21
f. As a flying qualities status check list for program management	11	19
g. As a focus for coordination and cooperation between flying qualities and flight controls engineers	7	21

4. From your experience, what are the most important factors inhibiting satisfactory flying qualities in aircraft? Rank High (H), Medium (M), Low (L), and Nil (N):

15 MIL-F-8785 inadequacies
9 Poor recognition of MIL-F-8785 by contractor management
5 Poor recognition of MIL-F-8785 by government management
13 Inadequacies in criteria separate from MIL-F-8785
5 Use of design criteria which are inconsistent with the intent of 8785
14 Poor working relationship between flying qualities and flight controls engineers
7 Poor implementation of specification by procuring agency
13 Inaccurate data (aerodynamic, structural, etc.)
16 Inadequate ground-based flight simulation during design
18 Inherent drawbacks of ground-based simulation
14 Inadequate ground-based flight simulation facilities
18 Inadequate use of in-flight simulation
5 Inherent drawbacks of in-flight simulation
5 Excessive commitment of funds to simulation, as opposed to analysis

Additional Comments:

- Not enough mission variety
- Inadequate synthesis techniques
- Poor communication (Industry - Government - Pilots)
- Lack of research
- Lack of Competitive environment
- Choice of requirements over flight test
- Poor understanding of requirements intent by Flight Controls people
- Reluctance to use MIL-F-8785 as design guidance

5. What are the negative results of utilizing MIL-F-8785C in a military procurement? Check appropriate responses and add to the list:

2 Does not set aircraft configuration
2 Meeting requirements at moderate (15-30) degrees angle of attack drives configurations to impractical extremes
5 High alpha and beta not adequately covered
16 May not satisfy pilot
3 Tendency of flight control system designers to keep flying qualities characteristics invariant in center of acceptance region
14 Not task oriented
6 Automatic flight control system relief modes not included
4 Not enough detailed design criteria
7 Results in overdesign or too restrictive an approach
10 Design to meet specification at the expense of cost effectiveness—tradeoffs discouraged
7 Cookbook—leading to acceptable but not excellent flying qualities
16 Blind confidence that meeting MIL-F-8785 will give good flying qualities
9 Insistence on strict compliance
4 Excessive requirements
9 Requirements not ranked in order to focus on those most important
2 Inappropriate test requirements
4 Cost and time involved in showing compliance with secondary details early in development
7 Proliferation of criteria, configurations, aircraft states, etc. puts more emphasis on generating data than understanding results
10 Specification does not allow enough alternate criteria or methods of assuring good flying qualities
10 Uncertainties of qualitative requirements
2 Based on esoteric flying qualities experiments with which flight control designers cannot be expected to become familiar
10 If minimum values of all specification parameters were met, aircraft would probably be unacceptable
4 Criteria addressing the airframe/control combination can obscure deficiencies in the separate systems
14 Inability to meaningfully interpret the specification for high technology aircraft
11 Direct force controllers are not adequately addressed
11 MIL-F-8785C lags flying qualities and control technology and tends to inhibit advances
10 Specification draws too heavily on fighter aircraft experience
14 Suffers from a lack of research into large aircraft requirements

Additional Comments:

- Lack of understanding of human controller
- Some boundaries not backed by data
- Too much emphasis on frequency domain

6. What are the positive results of utilizing MIL-F-8785C in a military procurement? Check appropriate responses and add to the list:

22 Useful for preliminary design
15 Mostly provides early guidance prior to simulation
25 Common method for describing flying qualities
15 Starting point for detail specification
12 A standard by which to judge competing contractors
7 Standard for all aircraft to be used in design
11 Contractor knows what is expected
15 Guidance for flight test planning
Assures satisfactory flying qualities
12 Generally 7 Often 6 Sometimes 0 Rarely
14 Relates pilot perceived flying qualities to quantitative data
6 Imposes performance and safety requirements
3 Useful as a guide for high technology aircraft design
9 Guideline for system synthesis
13 Requires specific analysis of important flying qualities areas
11 Assures adequate flying qualities at least for general flying

Additional Comments:

None

7. How would you improve MIL-F-8785C? Check appropriate comments. Further comments are welcomed.

17 Provide more task-oriented requirements
2 Reduce the amount of detail in the overall specification
6 Provide more options
14 Specify pilot-in-the-loop performance as an alternative
7 Specify pilot rating as an alternative
8 Give criteria for excellent flying qualities
5 Remove hard limits - let simulation prove acceptability
3 Restrict requirement parameters to those which can be measured in flight
2 Make requirements quantitative in mid-AOA ($15 < AOA < 30$) range
0 Delete or quantify all qualitative requirements
14 Update for large aircraft
13 Add requirements for integrated flight/fire control, display interface
14 Add requirements for attitude-stabilized, flight-path-stabilized and speed-stabilized modes
15 Coordinate thoroughly with flight control system, structural specifications
7 Replace probabilistic requirements for Airplane Failure States with a list of generic failures
4 Clarify requirements

Additional Comments:

•Separate performance and workload •Define Key tasks

•Relate frequency domain to time domain

•Coordinate with human factors and propulsion

•Address highly augmented systems without using equivalent systems

8. Rate the priority of the following areas of flying qualities research. Rank High (H), Medium (M), Low (L):

23 Limit of performance regimes, such as high angle of attack, STOL
20 Nonlinear flight regimes, such as large-amplitude maneuvering
14 Effects of nonlinear flight control system elements
16 Effects of control deflections, rate limits
20 Effects of higher-order flight control systems
Equivalent systems: Low 4 Medium/High 27
11 Determination 16 Application, including limits of validity
19 Desired effective vehicle dynamic characteristics, such as bandwidth, 5 or 6 degrees of freedom in roll or high angle of attack, hands-on vs. hands-off stability requirements (Underline or comment on the most important)
23 Task or mission-phase dependent dynamic characteristics
20 Flying qualities requirements/criteria stated in closed-loop (pilot in the loop) terms
13 Manipulator characteristics
21 Criteria for interfacing the pilot with display and other elements of the control system
16 Improved appreciation of harmony of multi-axis requirements and near-Level boundaries
18 Impact of digital software
18 Effects of atmospheric disturbances (List specifics in comment section)
19 Multi-task control, both continuous and discrete, with emphasis on pilot workload
13 Crew role in total mission concept
20 Integration with weapons delivery, automatic terrain-following/terrain-avoidance, etc.
Direct force control:
12 Normal force 10 Side force

Additional Comments:
•Time domain - frequency domain relationship

9. The basic flying quality Level definitions in MIL-F-8785C are unchanged from MIL-F-8785B. However, for disturbances of moderate intensity, at any given Level a degradation in subjective flying qualities (i.e., Cooper- Harper rating) is allowed. In Severe disturbances, the given Level allows a further subjective deterioration, and flying qualities requirements are only qualitative. Did you notice these changes in MIL-F-8785C? 14 Yes 7 No. Do you understand them? 14 Yes 1 No. Are these changes acceptable? 13 Yes 3 No. How should the specification treat atmospheric disturbance effects?

Additional Comments:
•It's perfect now

10. Is it acceptable to state qualitative flying qualities requirements in terms of pilot ratings (i.e., Cooper-Harper scale)? _25_ Yes _5_ No. Would that be an improvement over subjective terms, such as "not objection- able", "adequate", etc.? _14_ Yes _7_ No

Comments:

No difference in the two means noted. A C-H rating is a number attached to a subjective term.

Number of pilots and quality of pilots needs consideration.

Pilot ratings are a good metric as long as there is no pressure on the pilot to produce good or bad ratings. If requirements are stated as C-H ratings - company pilot will be unable to count numbers above 3, government pilot will think the number system starts with 4.

Pilots background and experience should be taken into account when weighing or averaging pilot ratings.

If you have the procuring activity define the environment and desired task performance and workload margin so that the test pilot can calibrate himself.

Cooper-Harper ratings may very well be the ONLY valid criteria. It certainly is the basis for all of the so-called quantitative criteria.

It's good to have a quantitative way of rating, but there are plenty of times when "unobjectionable" is descriptive enough.

We should implement standard tasks on simulators and in-flight simulators and test the test pilots for consistency and accuracy prior to their use on new tasks/aircraft.

To obtain statistically significant C-H ratings takes pilot training, familiarity, several pilots and repeat runs. Program managers will want to fund a minimum necessary verification test program and will be reluctant to pay for a program three or four times as large.

C-H scale has been essentially used to define flying qualities limits; hence, it should be used in the specification.

Use the Cooper-Harper scale plus pilot comments.

Provided adequate sample size of ratings are available and with assurance the rating scale was understood.

Acceptance of the C-H rating system is fairly general now.

Judgement is difficult to define and often relative in nature!

Leave pilot ratings qualitative. Tasks are too hard to define without losing track of missions requirements.

This is a way of stating that a characteristic is or is not adequate.

11. The specification has few requirements aimed at specific tasks. For example, the Category C ω_{sp} vs. n/α boundaries apply for landing a given class of airplane in all conditions (long runway—day, VFR to carrier deck—night, IFR). One possible change would be to allow compliance via demonstration of closed-loop performance and workload (pilot rating) for certain well-defined mission phases and tasks. Would you support such a requirement as an alternative? 27 Yes 4 No. As a replacement for some requirements? 14 Yes 10 No.

Comments:

Change the requirement boundaries.

It should be recognized that ω_{sp} vs n/α is, at best, a simplification that becomes less good as aircraft become more complex. However, quantitative criteria should be the result of intensive research and not potentially uncertain compliance tests. In any case, requirements should be task-specific.

Same problem as Question #10. Do need further breakdown on tasks. For example, the last part of landing (short final, flare, touchdown) are much more demanding than approach - also true for LAPES.

This is true tailoring. This is the way development decisions are made in the flight test phase. Define each phase of the mission and how well you want it done and how much disturbance or emergency workload you want to tolerate.

Support if that task was the primary mission of the aircraft.

Closed-loop pilot performance information should be used only as a guide. Reason is that the task will most likely be performed on a simulator of questionable validity.

Allow compliance via demonstration of closed-loop performance tasks.

Be careful! It is possible to get bit on accepting an aircraft based on one task-oriented test. The task must be very clear and identical to what is needed.

Where short period is not classic, talk initial response and oscillations in a mission task -- that's the heart of the matter, anyway. But forget about handling quality ratings in the requirements.

Such could always be written in as an amended requirement when necessary.

12. With regard to question # 11, would you support compliance via demonstration in simulators which meet certain specified standards derived for each specific requirement: Generally? 14 Yes 16 No. For certain requirements? 16 Yes 5 No. What level of simulation validation would be required?

Comments:

The level of simulation should be a very good representation of the aircraft dynamics and representative tasks of the required missions.

OK for Level 3.

Fixed-base ground simulator with visual scene for some requirements. In-flight simulation for a very limited number of requirements (e.g., short final, flare, touchdown).

Simulators and simulations are very useful in design but should never be used to determine specification compliance or mission suitability. An extrapolation of flight data into the "difficult" areas would be preferred.

With simulators you've got to know what you're doing. On AFTI/F-16, the simulator will be used for mission effectiveness demonstration compliance. On AFTI/F-111, the contractor's simulation had to be validated filter by filter and piece by piece. This is extreme unless you don't have a warm feeling for the contractor's ability. This should be negotiated with each competing contractor. Therefore simulator standards should be up front in the specification.

Simulation may be used as experimental guidance and verification of an analytic concept. Demonstration in a simulator does NOT show that the AIRCRAFT will have acceptable flying qualities. Simulation may be OK as a step in test and evaluation. It does not replace flight test.

Parameter ID type to verify derivatives and system adequacy as far as time representation. Also possibly frequency analysis of systems.

Simulation responses will have to match flight test very closely for a range of flight conditions, e.g., loading, and configuration. Could be used to fill in "holes" in the flight test results.

In-flight simulation could be used in areas not handled by ground-based simulators.

Compliance by simulator is OK for some requirements - not for some others.

Correlation between different real aircraft handling qualities with simulation results to establish validity will be required.

Pilot opinion should be correlated between flight test and simulator for selected conditions for critical piloting tasks during less extreme environments. More extreme environmental conditions can then be demonstrated with the use of simulation.

Moving base, with visual cues, also large amplitude motion.

Quantitive comparison (e.g., time response) as well as pilot evaluations.

Need work to define this. Important research area for new mission-oriented requirements.

Vehicle and control dynamics specification; validation of motion system where applicable; display characteristics validated where important to task.

Those generally validated by flight test.

Question 12
Comments, continued

Be careful that simulation is totally adequate. Very task-dependent.

Validation should be for task objectives only.

You need to test the article to meet requirements. Satifactory simulators won't satisfy the customer.

Should require agreement with known flight ratings of existing aircraft.

13. The current MIL-F-8785C specification requires the calculation of failure mode probabilities. Are such calculations meaningful? 10 Yes 7 No 7 Maybe. Do they add much expense? 7 Yes 2 No 13 Maybe. Are they worth the cost? 6 Yes 2 No 12 Maybe. Do you propose alter- natives? 7 Yes 7 No.

Comments and Alternatives:

Use generic failure approach.

Generic failures provide a more direct way. I've never seen any data that shows predicted failures probability and actual failure results compared.

Probabilities are OK, but what they refer to should be more specific.

Need to make more meaningful. Should combine failure and atmospheric environmental probabilities.

Handling Qualities experts lack the expertise to perform reliable failure mode probabilities. Therefore they will tend to reject this technique, regardless of its merits.

You need some way of recognizing failures, and a way to distinguish between more likely ones and the criticality of them. However, probabilities as such are overworked and misleading.

Use generic failure approach by assuming 100% probability of failure and requiring certain resulting characteristics. Should be done in conjunction with the flight control/electrical system failure modes and effects analysis (FMEA) and circuit analysis.

Assume probability of failure = 1.0.

Don't know another solution besides probability!

I think generic failure analysis is a better way to go.

Generic failure analysis except in extremely remote cases.

Generic failure analysis.

We certainly need to continue to upgrade the capability to do this well. Maybe in the past, it may not have been too useful to some. More important as control systems become more complex and integrated.

Failure mode calculations make the pilot feel better. They're still no comfort when the failure occurs. Maybe we should concentrate on the reliability requirements, and not try to design airplanes for failure states. After all, we want to buy the full system. Why spend money to ensure a certain level of performance for degraded systems? Penalize the contractor for full-system reliability problems (regardless of the component involved).

Generic failure analysis preferable.

14. Do you feel that using lower-order equivalent systems is a useful way to specify requirements for highly augmented airplanes? 15 Yes 9 No 3 Maybe. If not, why not? What alternatives, if any, would you suggest?

Comments:

We don't understand what mismatch really means.

Use equivalent systems to try and understand the higher order system. Suggest mission-oriented performance parameters be specified.

Equivalent systems are an unnecessary and uncertain intermediate step. They should be eliminated entirely.

As long as a good match of LOES and HOS is obtained, then it's OK. Should not be used if match is poor. Example: if $\dot{\theta}$ and n_z are matched with $L_{\alpha_{FREE}}$, and $L_{\alpha_{FREE}} = L_{\alpha_{TRUE}}$, then OK. Otherwise, no good. Need velocity too. Equivalent systems won't work for highly augmented aircraft (e.g. rate-command/attitude-hold).

It is one way -- not the only way (as in MIL-F-8785C).

Lack of successful demonstration. Lack of accuracy. Loopholes.

Allows use of present data base. Time delay plus pole/zero location is a mixed time and frequency domain definition. Perhaps an equivalent first-order lag for touchdown and higher-order effects would be more consistent.

Effort spent trying to understand equivalent systems approach could be better spent understanding how to handle the higher-order modes themselves.

Use of equivalent systems is a necessary exercise for the designer of today's aircraft, but for specification purposes, it may be awkward.

Equivalent systems do not give unique representations. Process is not reversible, i.e., what causes time delay? Digital control, lags, etc. This can't be obtained from equivalent systems match. Also, it gives no information on what control system parameters to change to meet specification requirements.

You are restricted to a pre-defined format. HOS may not fall into this format. Flight control systems with bobweights which feedback to stick forces may cause problems with this approach. Further, different flight modes may demand different types of responses. The lower-order equivalent systems is probably good for nominal up and away flight.

Wrong answers are obtained.

Extreme caution is warrented since LOES does not always work and sometimes leads to ambiguous results. LOES is not the whole solution.

Can miss coupling and non-linear effects of higher-order systems. Dynamic stability might be different.

As long as we keep track of the implications of what we are doing.

Time response is much better.

If you prove that the equivalent 2nd-order system is OK, you really haven't said anything about the real airplane.

Question 14
Comments, continued

This is a hopeful development if adequate correlation is demonstrated. More to the point; if HOS cannot be reduced to a LOES, it probably should be suspect.

Recommended Alternatives:

Simulation - ground and in flight.

Time-domain parameters seem more appropriate.

Response-centered criteria using the best models, simulations and flight test results that are available. Frequency response and time response are both appropriate and complementary. Each is better for certain problems ..... frequency response for basically oscillatory problems, e.g., PIO and Stability, time response for non-linear, large amplitude and transient problems.

Neal-Smith closed-loop frequency-domain approach needs to be expanded to include n_z, h, α; subsequently, V. Need criteria for each control, separately, if possible, in combination if necessary. Get moving on Neal-Smith multi-variable approach.

Low order CLAW synthesis using full state feedback.

The Handbook should give the contractor options to meet the intent of the specification.

Time - domain analysis.

Quantitative response.

Need to define if an airplane-like dynamics are really acceptable or not.

Use frequency response criteria to specify acceptable characteristics in the pilot's frequency range of interest, say, .1 to 20 rad/sec and don't be concerned with "mode" labels like short period, etc.

Use all applicable techniques such as time/frequency domain characteristics for HOS.

Neal-Smith type criteria. It is more fundamental and easier to apply and presented in control system terms.

If possible, a bound defined in the time domain, in conjunction with stability margin requirements, may be more meaningful.

Any alternative which is acceptable to the pilot.

Simulation with higher-order systems.

I am strongly in favor of closed-loop pilot/vehicle analysis and task-oriented requirements.

Can use equivalent systems during preliminary design and analysis. Still need to demonstrate full-order system.

Time response.

Standard open- and closed-loop maneuvers. Match traces of certain variables to acceptable envelopes.

15. Should the MIL-HANDBOOK include additional criteria as design guidance, beyond those recommended as possible requirements? 18 Yes 9 No.

Comments:

Just hope that the procuring activity doesn't just pile them on as additional requirements.

Especially in areas where criteria are tentative or not completely substantiated.

Keep it simple.

Standard and Handbook is bad for flying qualities. Need Standard as is. Need Handbook as concise and brief as possible. Need guide (Handbook appendix, BIUG). Include rationale, supporting data, additional criteria, guidance for application. Handbook is unwieldy -- it will get worse. Move as much as possible to BIUG.

It's too volumous now. No one document can be all encompassing.

Publish a TR that relates FQ requirements to terms a flight control designer can use such as Abrams' Time Response criterion.

The Neal-Smith criterion should be included, even as a requirement. It is much more intuitive than the bandwidth criterion.

There has to be a cut-off somewhere.

Supplemental information which is not directly relevant to the specification should be placed in Volume III.

I would give references as to where to find alternate criteria.

Specification should include requirements for very large aircraft.

I disagree with those who complain about the Handbook size. I think it should be a compendium of all the guidance we can provide.

Whenever such criteria are known.

Should have as much "lessons learned" as possible.

16. Do you have any general comments on areas we should consider in improving the Proposed Draft of the MIL-STANDARD and HANDBOOK?

Comments:

The "lessons learned" sections should be very brief or in a summary table since in time, the Handbook could get quite large.

Change format to By Controller! Industry designs by controller. The airplane responds by controller. The pilot flies by controller.

MIL-Standard OK. Handbook - too volumous. Just too much detail and in many areas, format leads to many repetitive phrases.

Needs to be PIO requirement. There should be no tendency to PIO. Make it qualitative and make the contractor comply by analysis or flight test.

Needs departure/spin section improved. Determining direction of motion (pilot) should be a procuring activity call. Influences motions and displays. I agree with others that departure resistance is good for low-level.

Combine yaw and roll axis response. In aircraft such as we build, they are inseparable.

Stalls and spins must be addressed as controllable flight regimes. Pilots should be able to enter and leave these regimes at will as normal occurances.

Handbook appears to be growing too large and unmanageable.

In one of the two specifications, we need to establish guidance for total aircraft dynamics including unpiloted modes.

Make sure that all quantitative requirements can reasonably easily be verified by flight test. That is, does a flight test task or maneuver and data reduction technique exist that provides good results?

Have someone review tha "whole" thing, since many areas are contradicted by later sections; that is, data to support one requirement refutes a previous requirement.

Define some "critical tasks" that represent important mission elements, and are "handling qualities -critical or -sensitive."

Improve the effects of turbulence section.

I think that it is a mistake to go to a "fill-in-the-blanks" Standard. Better to modify the current specification to meet particular cases and requirements.

17. Much discussion concerning the general organizational format of the Flying Qualities Specification has taken place. Several formats have been suggested. Which do you prefer?

__11__ Response by control axis(as is proposed draft)
__9__ Response by controller/input
__1__ Grouped by aircraft systems
__6__ MIL-F-8785C format

Other:

I don't think it really matters. If forced to pick, I would choose "by axis," since I think it's a more general approach.

As it is now, by response axis, it's a mess. In fact, it isn't even by response axis because it's impossible to do. LOES for pitch has N_Z/δ transfer function in it, for example.

Change to "By controller/input."

Response by axis, but have only two of them: pitch and lateral-directional.

Lateral-directional together and longitudianl (pitch, vertical, and speed) together. Both of these have sub-paragraphs by controller. Have a test and evaluation index or checklist to help guide the compliance demonstration process.

Either MIL-F-8785C or "by controller/input."

Controller/input especially for de-coupled systems. Handling is a pilot's opinion. Pilots see performance as response to inputs. It might be acceptable to use control axis format during initial design stages.

This is not such a critical issue. Suggest picking an approach and then provide a cross-reference matrix of paragraph numbers to convert to other structures as desired by the users of the Standard.

The format is relatively irrelevant. Any format, if well written, will eventually be accepted by all.

Consider "by controller/input" if substantial simplification would result. Otherwise stick with control axis.

In terms of pilot needs, overall aircraft response is more meaningful.

Both the "by controller/input" and "by control axis" are acceptable, but I would prefer the formal.

Controller/input allows for coupled, decoupled and task-related requirements.

Any organization will have problems; any organization can work.

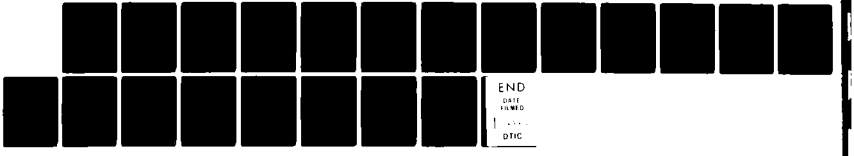
I am comfortable with MIL-F-8785C format. Unless there is difficulty worth the change, I would prefer not to change. Possible the new integrated systems call for a change.

Any of these formats can be used, and none will be ranked first by all. But flying qualities are the motions of the airplane from the perspective of the pilot, and he sees the coupled modes. Further, it is disruptive to keep changing from one format to another. It is difficult for me to accept the axis format is really better for heavily augmented aircraft. If augmentation changes response drastically from normal modes, we probably won't have satisfactory flying qualities, anyhow.

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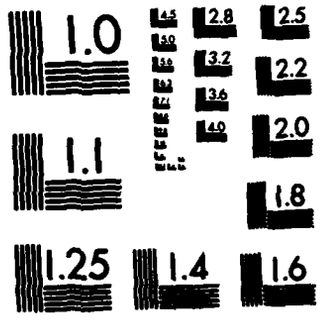
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FLYING QUALITIES QUESTIONNAIRE

SUMMARY OF RESPONSES

Flying qualities questionnaires were distributed to all participants of the symposium. Responses were received from approximately 30% of those who indicated affiliation with the flying qualities discipline. Principally, those who responded considered themselves line engineers and closely involved with the application and interpretation of the specification. It is to be noted that these comments reflect the views and comments expressed by those attending the conference and do not necessarily reflect current or projected Department of Defense priorities or viewpoints.

1. Almost all responses indicated at least a moderate familiarity with both MIL-F-8785B and MIL-F-8785C.

2. Most participants had received copies of the proposed MIL-Standard and Handbook and had spent some time reviewing the documents. Some emphasis was spent on several specific sections.

3. The flying qualities specification is used quite extensively in some areas and should be used more in several other areas. Specifically

A. The specification is used highly as a guide during design and development. Most indicated it should be used more.

B. More interface with flight control system engineers is needed. The intent of the individual requirements needs to be highlighted.

C. Overwhelming response was obtained concerning use of the specification during developmental flight test: for planning, problem definition and discussing deficiencies. Less felt the specification offered much in the way of solution alternatives.

D. Flight control system personnel, both mangement and line engineering levels, need to be more cognizant of the flying quality requirements and their intent.

4. Several factors were annotated which inhibit the achievement of satisfactory flying qualities in aircraft.

A. Inadequacies in the specification.

B. Inadequate use of both ground and in-flight simulations/simulators. Part of this is due to poor facilities.

C. A poor working relationship with little or no crosstalk between flight control systems personnel and flying qualities engineers is a major factor.

D. Other criteria to aid the flying qualities picture are also considered inadequate.

5. Military procurements are negatively affected by MIL-F-8785C.

A. Compliance with the requirements may not necessarily produce a vehicle which will satisfy the pilot.

B. Task-orientation is vague and not definitized.

C. Tradeoffs between efficiency and cost-effectiveness tend to be discouraged. There is a blind requirement to meet the specification, no matter what the outcome in performance.

D. Belief from the military that the specification will produce good flying qualities. Too much blind confidence in the requirements.

E. The specification suffers from too few alternate criteria.

F. Dated. Requirements based on past data base and do not deal effectively with today's airplanes (highly augmented, large size, etc).

6. Similarly, the flying qualities requirements are beneficial in a military acquisition.

A. The specification offers much guidance, especially during the preliminary design stage; acts as starting point for the detailed system specification, flight test planning, simulation, etc.

B. The specification is a good baseline. It's the common ground for engineering use across the board. All know of MIL-F-8785.

7. MIL-F-8785C has much room for improvement.

A. Requirements should be more task-oriented.

B. There need to be pilot-in-the-loop requirements, especially with display dynamics, integrated flight control, integrated propulsion, etc. Upgrade with high technology issues.

C. Large aircraft flying qualities requirements are not substantiated by data and are, in general, lacking.

D. The requirements would be much more valid if more coordination was achieved with other disciplines -- structures, flight control, weapons, propulsion, etc.

8. Flying qualities research needs to be undertaken in the following areas:

A. Specialized operations limits - high AOA, STOL, etc.

B. Effect of higher-order systems

C. Task and mission-dependent dynamics

D. Non-linear flight control elements

E. Automatic modes of flight, including pilot-in-the-loop considerations, displays, etc.

F. Time domain criteria

9. Most responses indicated a liking to the way MIL-F-8785C handles atmospheric disturbances, using subjective degradation of ratings due to increasing intensity.

10. The Cooper-Harper rating was assessed generally to be a good metric for rating an aircraft. However, a more strict utilization of the scale will force the buyer to give a specific definition of task and mission and may extend simulation and flight test matrices during acquisition, thus increasing time and cost.

11. Most responses indicated attendees favored going to closed-loop compliance by demonstration of certain specific tasks. To do so means tasks and environment would have to be carefully defined. A matrix of related tasks should also be evaluated to keep from accepting an aircraft based on one parameter/one task. It's the overall performance which needs to be assessed. Such a procedure is the definition of tailoring -- the goal of the new MIL-Standard and Handbook.

12. Some requirements, with regard to question #11 could be validated using simulators. However, the majority deemed compliance via demonstration using simulators a risky means. There are too many variables. In-flight simulations need to be emphasized. Simulator fidelity, in general, is a constraint which must be taken into account.

13. Most considered the use of failure mode probabilities as a useful, but costly tool. As an alternative, almost all indicated they would rather use the generic failure approach. Probability analysis could be used in conjunction with generic analysis to further assess the aircraft and give confidence to engineers. The goal of a more reliable aircraft ought to be emphasized.

14. The use of lower-order equivalent systems to analyze higher-order aircraft continues to be a highly controversial issue. The magnitude and variety of comments and suggested alternatives attest to that fact. No single idea or conclusion is attainable. More effort is needed to understand the effects of higher-order systems and the techniques for evaluating such systems. Equivalent parameters are one way. Many suggested greater use of simulators. But again, simulator fidelity is a factor. So are non-linear terms. Another alternative suggested frequently was the use of time-domain analysis. Criteria have been suggested in the past and have not had the needed support. Nor have they correlated well with data. At best, this area needs to be looked at further in light of an aircraft's task and mission objectives.

15. Inclusion of alternate criteria in the MIL-Handbook was generally supported. Caution was expressed, however, that 1) the Handbook not get too large, and 2) that the alternate criteria are not viewed as additional requirements by the buyer.

16. Several general comments were given. They are too varied to summarize.

17. Format of the specification requirements was split about 50/50 between the control axis organization and a proposed controller/input organization. Serveral desired the current MIL-F-8785C organization. Overall, this issue was not considered crucial and most felt any format could be used.

FLIGHT CONTROLS QUESTIONNAIRE

BACKGROUND

Flying qualities, Flight controls, both FC 7, FC/FQ 6

Line engineer, management, etc. System Management, Supervisors, Professor, Staff Engineers

****

1. How familiar are you with MIL-F-9490?

	D Revision	(1975)
Intimately	4	2
Moderately	6	
Vaguely	1	1
Not at all	2	1

2. a) Did you receive a copy of the proposed MIL-Specification & HANDBOOK?

10 Yes 3 No

b) How much of a review and critique were you personally able to complete?

1 In-depth 8 Read-thru 1 Overview/Skim 1 Little

c) If you concentrated on any particular sections, please specify.

(1) Section 3.2 related to Flight Control Actuation components.
(2) Sections 3.8 and 3.9
(3) Loss of critical design type and mission standardization requirements. Section 3s requirements.

3. How extensively do you see the military flight control system specification being used? How extensively should it be used? Rank High (H), Medium (M), Low (L); give specific comments:

	Is used			Should be used		
	H	M	L	H	M	L
a) As a firm specification to best assure satisfactory flight controls for military aircraft	5	4	2	6	3	2
b) As guidance during design and development	5	1	5	7	4	1
c) In providing guidance for the detail specifications of the flight control system	4	3	4	6	5	

	Is used			Should be used		
	H	M	L	H	M	L
d) During the development testing						
(1) As a guide for test planning	3	5	1	6	3	2
(2) As an aid in problem definition		5	3	1	6	2
(3) As an aid in defining solution alternatives		2	5	2	3	5
(4) As a basis for communicating deficiencies	1	5	3	4	4	3
e) As a communication aid between Government and contractor flight control engineers	2	5	4	4	5	
f) As a flight controls status check list for program management	1	4	5	2	6	3
g) As a focus for coordination and cooperation between flying qualities and flight controls engineers (Don't split the community.)	1	3	4	7	3	1

4. From your experience, what are the most important factors affecting flight control systems in aircraft? Rank High (H), Medium (M), Low (L), and give specific comments:

	H	M	L
a) MIL-F-9490 inadequacies	2	2	6
b) Inadequacies in criteria separate from MIL-F-9490	3	3	5
c) Use of design criteria which are inconsistent with the intent of 9490	3	2	3
d) Poor working relationship between flying qualities and flight controls engineers	3	6	3
e) Poor implementation of specification by procuring agency	2	9	1
f) Inaccurate data (aerodynamic, structural, etc.)	7	3	2
g) Inadequate ground-based flight simulation during design	2	4	5

	H	M	L
h) Inadequate techniques for designing flight control systems	2	4	5
i) Inadequate technology to interface the numerous elements of the flight control system	3	3	4

Comments:

(1) Blindly following guidance of specification after test indicates inadequacies.

(2) 9490 too restrictive of new technology.

(3) There are no software quality standards in the same sense as is specified for hardware (1 in 10^7).

(4) Too design oriented - should be performance, function oriented.

(5) Cannot adequately address non-linear systems.

(6) Inadequacies of personnel experience.

5. What are the negative results of utilizing MIL-F-9490 in a military procurement? Check appropriate responses, give specific comments, and add to the list:

__1__ Requirements inconsistent

__2__ Rationale mistated/not clear
(Many of the procurement rules are inconsistent, making the use of a mil-prime-std by the numbers hard to adapt.)

__4__ Guidance inadequate/not specific

__4__ Not task oriented
(Generic requirements cannot be satisfied for all unique flight conditions, operations, etc.)

__4__ Not enough detailed design criteria
(Cannot get it because there are no means for feedback or exchange with industry.)

__4__ Design to meet specification at the expense of cost effectiveness-tradeoffs descouraged
(1. Drives up equipment cost.)
(2. Once locked in to contract, difficult to provide incentive to do it better. It costs contractor in up-front money.)

__1__ Cookbook inhibits innovation or design freedom
(1. Too restrictive in design of FCS components, interfacing subsystems.)
(2. Just write a Note of Exception (NOE).)

4 Blind confidence that meeting MIL-F-9490 will give results
(It is impossible for any specification to anticipate all problems relating to detail design.)

3 Insistence on strict compliance
(Hard data for strict compliance is seldom offered.

2 Excessive requirements
(Detail design of a system or component is too often "legislated."

3 Inappropriate test requirements

4 Cost and time involved in showing compliance with secondary details early in development
(It would be good to give AF visibility without contractual data submittal which are priced and require approval. Major contractor has to be the secondary level work right to get this job done anyway.

2 Proliferation of criteria, configurations, aircraft states, etc. puts more emphasis on generating data than understanding results

4 Uncertainties of qualitative requirements

5 If maximum tolerance of all specification parameters were met aircraft would probably be unacceptable

4 Criteria addressing the airframe/control combination can obscure deficiencies in the separate systems
(System integration is upon use, but the interface methods are not.)

4 Inability to meaningfully interpret the specification for high technology aircraft
(Integrated FCS functions cannot be designed or demonstrated piece meal. Especially true for high performance fighters.)

2 MIL-F-9490 lags control technology flying qualities and tends to inhibit advances

4 Specification draws too heavily on fighter aircraft experience
(1. Too big plane oriented.)
(2. In flying qualities area for heavy transport.)

4 Suffers from a lack of research into large aircraft requirements
(In flying qualities area.)

Other comments:

(1) New mil-prime does not reflect weapon system/mission requirement breakdown into flight control functional requirements.

(2) The Air Force should specify functions and performance: let the contractor and subcontractors determine the mechanization and design.

(3) Looks like business as usual; i.e., still requires a "spec negotiation phase" and a definitive strawman may not exist at start!! Therefore, negotiation phase could be more costly - especially in time.

6. What are the positive results of utilizing MIL-F-9490 in a military procurement? Check appropriate responses, give specific comment, and add to the list:

__8__ Useful for preliminary design - give corporate knowledge of good design practices requirements.

__4__ Mostly provides early guidance prior to simulation - unless spec is continuously updated.

__11__ Common method for describing flight control system - usual problem of trying to get a requirement to cover everything, becomes too general to mean anything.

__8__ Starting point for detail specification - the AF and industry need this. To maintain technical competence the AF has to generate initial requirements.

__7__ A standard by which to judge competing contractors.
(1) Definitely
(2) How if contractors filled in own requirements?
(3) Needed by both the AF and industry.

__3__ Performance specification to be used in design of all aircraft FCS - Should be

__5__ Contractor knows what is expected - agreement on job is basic to designing a flight control system which will meet AF needs.

__5__ Guidance for test planning and agreement. The requirement for detail verification of each requirement will improve with mil-prime.

Assures satisfactory and sufficient testing:

__1__ Generally __3__ Often __6__ Sometimes ____ Rarely

__6__ Imposes performance and safety requirements - should be 9490's function.

__4__ Useful as a guide for high technology aircraft design - Spec and handbook usually lag technology. Most R&D is now being accomplished on production work schedule development.

__2__ Guideline for system synthesis - not yet, needs work.

__4__ Requires specific analysis of important safety of flight areas - no, a better means is needed to do this.

7. How would you improve MIL-F-9490? Check appropriate comments. Further comments are welcomed.

__5__ Provide more task-oriented requirements - either in 9490 or in 8785.

__2__ Reduce the amount of detail in the overall specification.

__4__ Provide more options - allow freer application of new technology. Do not limit power requirement to hydraulic as indicated in 3.2.13.5 (User's guide).

__7__ Give criteria for achieving performance specified

__4__ Remove hard limits - let simulation prove acceptability
If hard limits don't exist, little effort will be expended to establish the correct acceptable limits.

__3__ Quantify all qualitative requirements - good concept and continuous effort should be expended.

__6__ Add requirements for integrated functions such as flight/fire control - Define interface hardness.

__7__ Coordinate thoroughly with flying qualities structural specifications and reliability, safety, hydraulic, electrical power, crew stations, etc.

__2__ Clarify requirements - where required.

____ Other (Please specify) - Relate requirements to specific tasks/flight control functions. This requires making some requirements less generic/ more applicable to vehicle/mission phase.

____ Other (Please specify) - Make sure vehicle RFP use of 9490 in the procurement includes explicitly the AF FCS functional requirements. Then subcontractors don't guess at proposing what they think the AF wants.
Don't make minimum requirements - that is what AF will receive.

8. Rate the priority of the following areas of flight control system research. Rank High (H), Medium (M), Low (L), give specific comments:

	H	M	L
a) Effects of nonlinear flight control systems elements	6	5	
b) Effects of control deflections, rate limits	6	2	3
c) Effects of higher-order flight control systems	8	4	
d) Desired effective vehicle dynamic characteristics, such as bandwidth, 5 or 6 degrees of freedom in roll or high angle of attack, hands-on vs hands-off stability requirements (Underline or comment on the most important) - All - pilot protection and warning - pasive active	7	1	
e) Task or mission-phase dependent dynamic characteristics - coordinate with flying qualities	9		

	H	M	L
f) Flying qualities requirements/criteria stated in closed loop (pilot in the loop) terms - should prove or disprove applicability	5	4	1
g) Criteria for interfacing the pilot with display and other elements of the control system	6	3	1
h) Impact of digital software - not an effective way to spend one's research money.	7	4	
i) Effects of atmospheric disturbances (List specifics in comment section) (1) Disturbance inputs to actuation system through control surfaces. (2) Is this really a problem?	4	7	2
j) Multivariable control, both continuous and discrete More important to understand the problems of the technique than the technique.	5	6	
k) Integration with weapons delivery, automatic terrain-following/terrain-avoidance, etc.	5	5	

Direct force control:

5 Normal force 4 Side force

Other (Please specify)

(1) We need research to define the advantages of direct force controls before they can be used effectively.
(2) Control surface duty cycle requirement specification.
(3) Acceptability of non-redundant load paths in critical FCS applications (actuators).
(4) Electromechanical actuation for primary flight controls.
(5) The AF should identify preferred fault tolerant architecture, frame sync, and voting planes. Suggest you start with the F-18s, it works.

	H	M	L
l) Highly relaxed static stability aircraft Applicability of full state/reduced state feedback design techniques and computer aided design tool used in realizing the multivariable control laws.	6	2	1
m) Multivariable control law design techniques, using computer aided design tools for direct digital control design. These techniques exist; they just aren't used or used properly, some of the claims being made for new multivariable techniques are nonsense.	7	3	1

	H	M	L
n) Validation and verification methods and tools for digital FCSs - much overworked. You just test it until you're sure it does what it is supposed to do. The same papers have been delivered again and again for the past 15 years on this topic.	6	3	1
o) Reliability of microprocessors, fiber optics, analytic redundancy vs equipment redundancy.	8	2	1
p) Fault tolerant software - A jungle	5	2	2
q) Distributed system/data base architecture	1		

Comments: Any assistance in the new technology must result in evaluation procedures - even though these will be changed as experience improves.

9. Are functional requirement complete, i.e. stated properly?
   (1) Lots of confusion.
   (2) No, they are usually too closely linked to FCS detail design requirements.
   (3) No. Classes of faults and specific faults to be tolerated need to be included. Priorities of functions for each flight phase should be defined. Crews' role in each function should be considered.
   (4) No - a list of functions does not specify A/C use or operation. This, of course, allows major contractor to develop the vehicle flight operational capability.

10. Are the definitions sufficient, descriptive, or outdated? Are new ones needed? List changes as needed.
   (1) The contractor should define all terminology used in the FCS specification. This would mitigate the problem of dated nomenclature.
   (2) Outdated - they should be changed to agree with rest of the world.
   (3) All need to be more closely related to task/flight phase.

11. Does the numbering sequence of the major ilities topics meet mission requirement priorities?
   (1) No
   (2) First, revise the ilities. Get the non ilities out.
   (3) Second, put the most important first—Safety. The mission reliability requirements, then maintenance, etc.

12. Should the MIL-HANDBOOK include additional criteria as design guidance, beyond those recommended as possible requirements?

COMMENTS:
(1) A mixiumum/minimum set of numbers should be required unless the particular vehicle needs a more stringent requirement.

(2) Problems is that, we can't keep updated what we already have.

(3) The AF should develop a formal means of documenting and exchanging this type of information.

(4) The MIL-HANDBOOK should include everything the AF wants in it as a system, and all items needed for a competitive evaluation. Airframe manufacturer designs the FCS to much more stringent/exacting requirements than the 9490 type spec. Reference McAir/GE spec.

(5) Major advances are being made in advanced samarium colbalt brushless motor and solid state motor control. This specification should not preclude their use as noted on page 238 of user's guide.

13. Do you have any general comments on areas we should consider in improving the Proposed Draft of the MIL-Specification and HANDBOOK?

COMMENTS:

(1) Address integrated FCS functions and engine control functions.
(2) Reorganize along lines to assist in use of various stages of design and development. Use current material; i.e., TF section is 20 years old.
(3) Passive/active pilot protection/warning techniques.
(4) Requirements and parametrics of crash and maintenance recorders.
(5) Displays that tell pilot what is wrong, law to determine what to do and his options.
(6) Mil-prime specification once it has been completed and is made a part of the contract must stand alone; i.e., HANDBOOK must not be needed to define requirements.
(7) Dynamic requirements for unpiloted models need to be in a specification.

SUMMARY

In general the questionnaires indicate that the MIL-PRIME format used for the specification is the proper direction to go. Performance and functional requirements are the criteria to be satisfied for a successful component on FCS design; not detail design restrictions.

However, the MIL-PRIME doesn't reflect weapon system/mission requirement breakdown into flight control functional requirements. The Air Force should specify functions and performance. Let the contractor and subcontractors determine the mechanization and design.

On the negative side, it looks like business as usual; i.e., still requires a "spec negotiation phase" and a definitive strawman may not exist at the start! Therefore, negotiation phase could be more costly--especially in time. To utilize the MIL-PRIME FCS specification in a procurement, the Air Force should provide a detail specification as a starting point in order to maintain technical competence. By making sure that the vehicle RFP use of 9490 in the procurement includes explicitly the FCS functional requirements then subcontractors don't guess at proposing what they think the Air Force wants. Most important, specify maximum requirements. If less is required, that is what the Air Force will receive in the FCS.

The survey shows that high priority should be given to Research and Development in many areas; i.e., effects of nonlinear flight control systems, control deflection, rate limits, and higher-order flight control systems. Others are mission-phase dependent dynamic characteristics, impact of digital software, highly relaxed static stability aircraft, multivariable control law design techniques and reliability of microprocessors, fiber optics.

Due to the present wording of 9490D (and the new draft) only hydraulic actuation is permitted in primary flight control applications. This restriction should be removed, and the contractor allowed to specify the type of control surface actuation used. Existing hydraulic actuation systems pose serious drawbacks in terms of maintainability, particular failure modes, and life cycle cost. They form a significant percentage of the nonrecurring and recurring cost of the total FCS. MIL-F-9490 (or its successor) should be modified to allow the investigation and use of alternate actuation concepts. Also, applicable component specifications for alternate actuation concepts should be drafted.

APPENDIX

DESIGN CRITERIA FOR THE FUTURE OF FLIGHT CONTROLS

STOUFFER'S DAYTON PLAZA HOTEL
MARCH2-5, 1982

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