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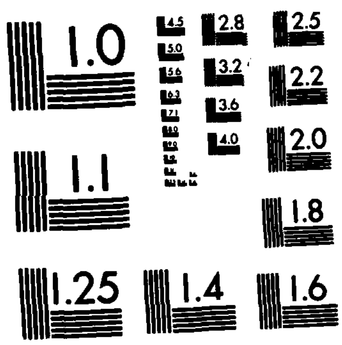

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A PRELIMINARY ASSESSMENT OF HELICOPTER/VSTOL HANDLING QUALITIES SPECIFICATIONS

K. Goldstein
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The flying quality characteristics of four state-of-the-art rotary wing aircraft have been compared to the present day helicopter and VSTOL flying qualities criteria. Hover control power and dynamic stability characteristics were analyzed for the longitudinal, lateral and directional axes. For forward flight, static and dynamic stability characteristics were analyzed for the longitudinal and lateral-directional axes. Results in terms of the applicability/utility of the

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MIL-H-8501A criteria are presented for each of the above flying qualities areas.

SUMMARY

The flying qualities characteristics of four state-of-the-art rotary wing aircraft have been compared to the present day helicopter and VSTOL flying qualities criteria. Longitudinal, lateral, and directional control power and dynamic stability charcteristics are analyzed for hovering conditions. Forward flight static and dynamic stability are analyzed for the longitudinal and lateral-directional axes. Results of the analyses in terms of the applicability/utility of the MIL-H-8501A criteria are presented for each of the above areas.

The review of the MIL-H-8501A criteria against those in MIL-F-83300, AGARD 577, and various helicopter type specifications indicated many areas for which MIL-H-8501A does not give adequate guidance.

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SECTION I

INTRODUCTION

With the development of a new generation of rotary wing aircraft for military operations, it has become apparent that the present helicopter handling qualities specification, MIL-H-8501A (reference (a)), cannot accurately assess the characteristics of these aircraft. The fact that MIL-H-8501A was last updated 20 years ago only tends to amplify this point. The Navy Light Airborne Multipurpose System (LAMPS) SH-60B, the Army Utility Tactical Transport Aircraft System (UTTAS) UH-60A, and the Advanced Attack Helicopter (AAH) all use advanced flight control systems for stability and control augmentation. The need to test the flying qualities of these state of the art vehicle/control systems has necessitated the use of "type specifications" or "prime item development specifications" uniquely devised for each new aircraft/control system. Many papers have been written describing the numerous shortcomings of MIL-H-8501A in realistically regulating handling qualities of present and future helicopters (references (b) through (f)). There is a need for an upated version of MIL-H-8501A. To facilitate the development of revised criteria it is necessary first to compile a data base of past and present helicopter stability and control characteristics. This report presents the beginning of such a compilation.

The SH-60B and the CH-53D single rotor helicopters were comparatively analyzed against the fundamental stability and control aspects addressed by MIL-H-8501A. Vertical control response, instrument flight and autorotation criteria were not included at this time. Where data were readily available for the XH-59A Advancing Blade Concept (ABC), the XV-15 tilt rotor, and the CH-46A tandem rotor, they were also included and discussed.

Comparing advanced vehicle control and stability characteristics to MIL-H-8501A provides useful information regarding applicability of criteria format. But it is the pilot's opinions of the aircraft handling qualities that form the final basis of evaluation. It was found throughout the analysis that qualitative pilot rating data were very limited for any helicopter. This points to the fact that reliable, fully documented pilot ratings should hold a high priority in future helicopter handling qualities data generation.

In the development of the present day VSTOL handling qualities specifications, MIL-F-83300 (reference (g)) and AGARD 577 (reference (h)), extensive rotary wing pilot rating data were analyzed to substantiate the finalized hover/low speed criteria. Documentation of these data was part of the specification development. Although AGARD 577 is not intended to be a helicopter specification and MIL-F-83300 has not been used by the Navy or Army for a helicopter development program, these specifications do supply alternative methods of addressing VTOL handling qualities characteristics. The alternative criteria from MIL-F-83300, AGARD 577, and the various helicopter type specifications were directly compared with the criteria from MIL-H-8501A to highlight specification deficiencies and vehicle anomalies.

It should be kept in mind that within AGARD 577, it is stated that the criteria are "intended to apply to all types of VTOL aircraft regardless of the lift method used except for certain phases of helicopter operation, since the helicopter is covered by MIL-H-8501A." This explains why certain criteria were developed solely from STOL aircraft test data, for example, low speed yaw control response. In contrast, MIL-F-83300 was intended to apply to helicopter handling qualities. Key (reference (d)) states that some of the reasons the U.S. Navy and U.S. Army chose not to adopt MIL-F-83300 may be related to the type of criticisms provided by Green (reference (c)). One of the problems in using MIL-F-83300 criteria for helicopter handling qualities is in the definition of V_{con}. According to Green and Richards "V_{con}, as defined, can not easily be applied to helicopters, and if the guidance of the MIL-F-83300 BTUG is followed, then the helicopter would be required to meet the airplane flying qualities requirements of MIL-F-8785B." Many of the other specific deficiencies raised by Green and Richards are discussed within the results section of this report.

Section II contains a brief description of the approach used to analyze the SH-60B and the CH-53D math models. The data from the XH-59A and the XV-15 were from recently completed Navy and Army flight test programs.

Section III is divided into the hover/low speed analysis results and the forward flight analysis results. Attitude response, angular rate damping and dynamic stability for the pitch, roll, and yaw axes are discussed for hover/low speed flight. Static and dynamic stability are analyzed for forward flight.

Finally, Section IV summarizes the overall conclusions and recommendations from the comparative analyses.

SECTION II

APPROACH

For the SH-60B and CH-53D single rotor helicopters, a three degree of freedom (DOF) linear model was used to generate open and closed loop control transfer functions. The 3 DOF analysis was decided upon for two major reasons. One, MIL-H-8501A decouples its criteria into longitudinal and lateral-directional modes. Two, a comparison between 3 DOF and 6 DOF control response time histories and characteristic equation roots revealed minimal differences for the flight conditions and aircraft configurations examined. Figures 1 and 2 are typical time history and frequency response comparisons generated for the CH-53D. Figure 3, taken from reference (i), shows a similar frequency response comparison between 2, 3, and 6 DOF models.

The calculated open and closed loop transfer functions were analyzed for hover control response, hover dynamic stability, and forward flight dynamic stability characteristics. The velocities analyzed included 0, 80, 120, and 150 knots. Because direct comparison between the aircraft response and MIL-H-8501A was intended, the control input types were those specified in MIL-H-8501A.

As previously mentioned, the XH-59A Advancing Blade Concept (ABC) and the XV-15 tilt rotor recently completed flight test programs. Control and stability data from those tests that were applicable to MIL-H-8501A criteria were included and discussed. Also, unlike the math modeled aircraft, quantitative and qualitative pilot rating data were available from the flight test reports (references (j), (k) and (l)). These data were extremely useful in identifying handling qualities differences due to the varied rotor configurations.

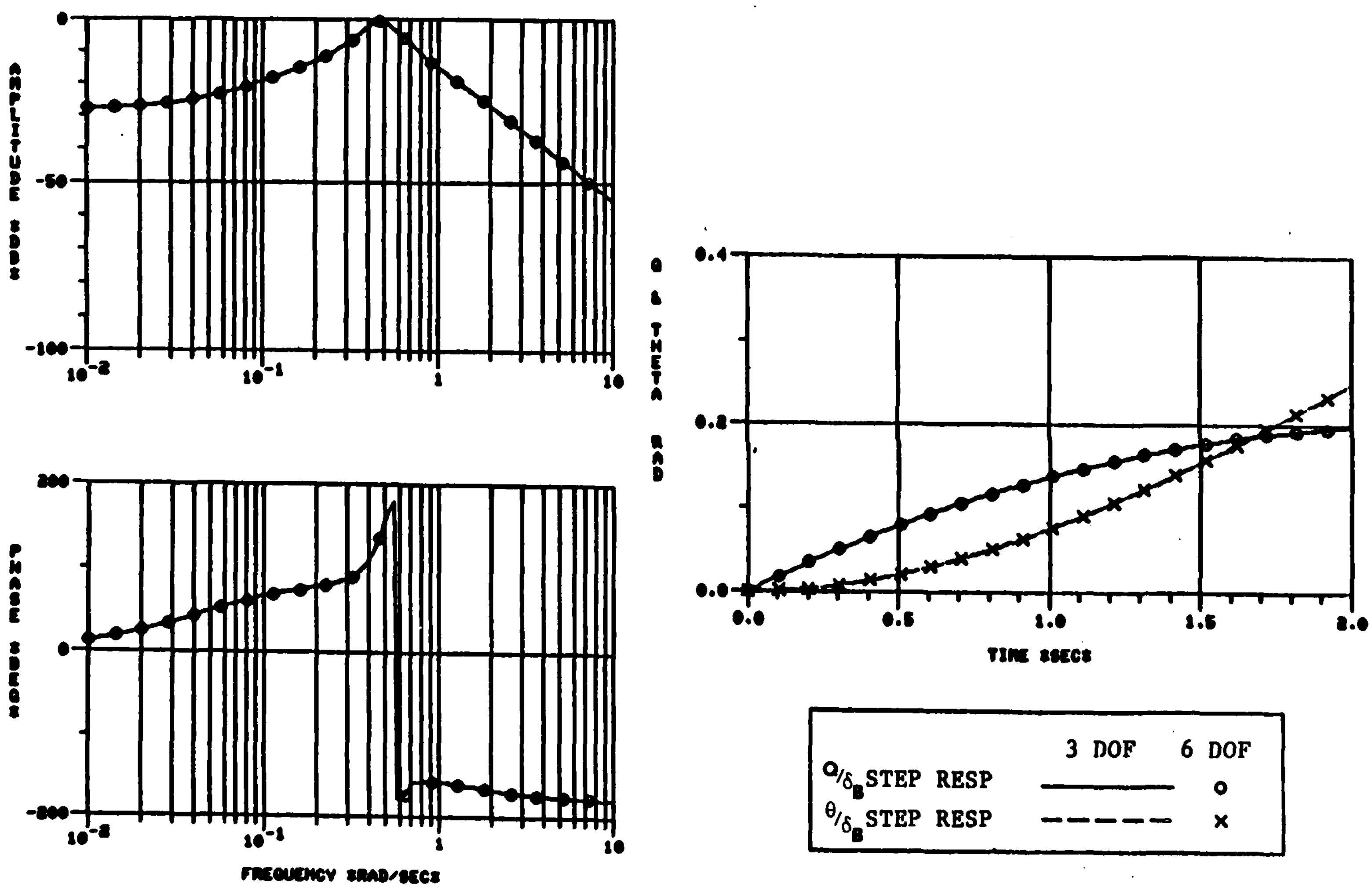

Figure 1. 3 DOF vs. 6 DOF Longitudinal Response Comparison for the CH-53D, Hover, AFCS OFF

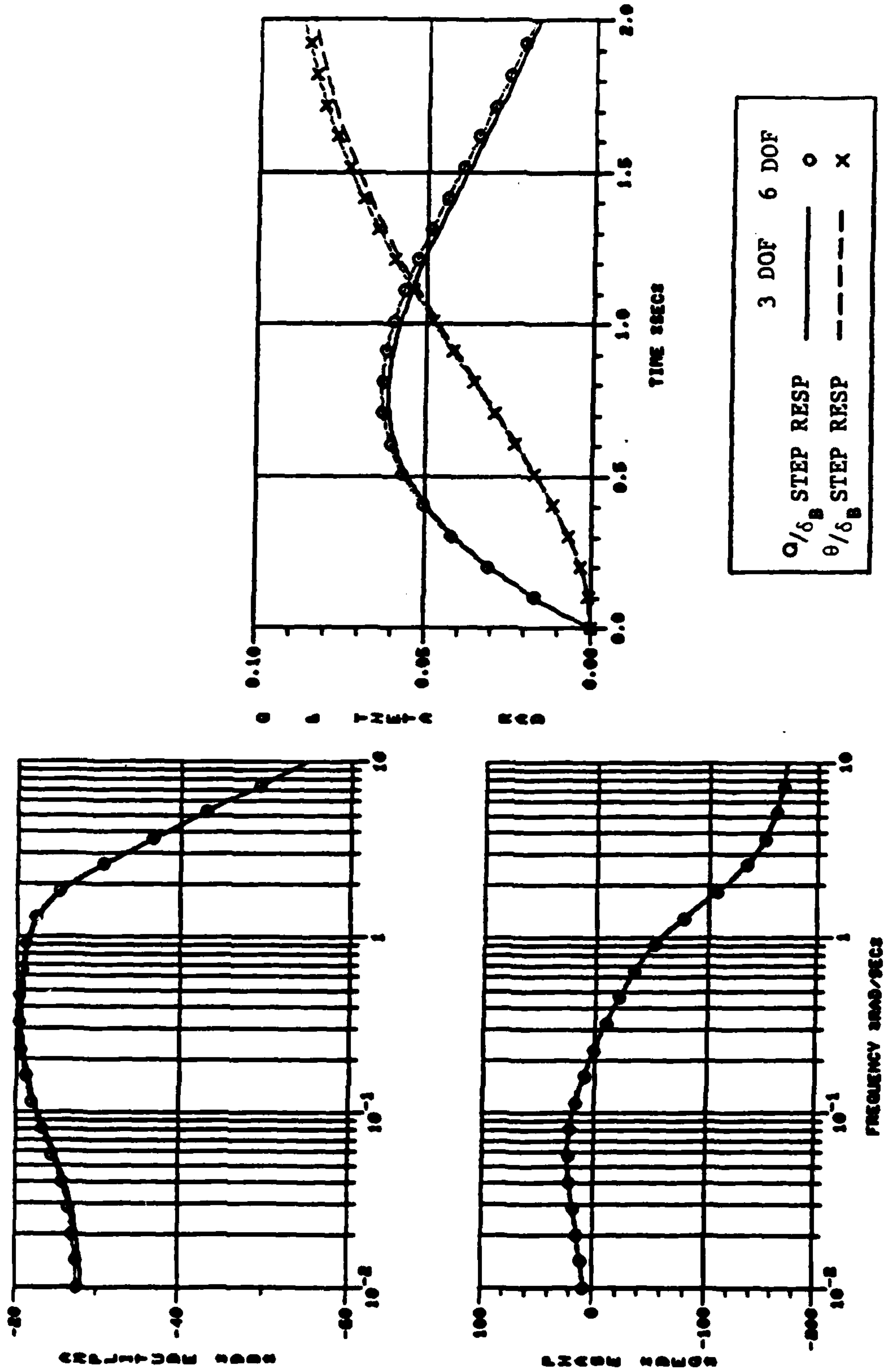

Figure 2. 3 DOF vs. 6 DOF Longitudinal Response Comparison for the CH-53D, Hover, AFCS ON

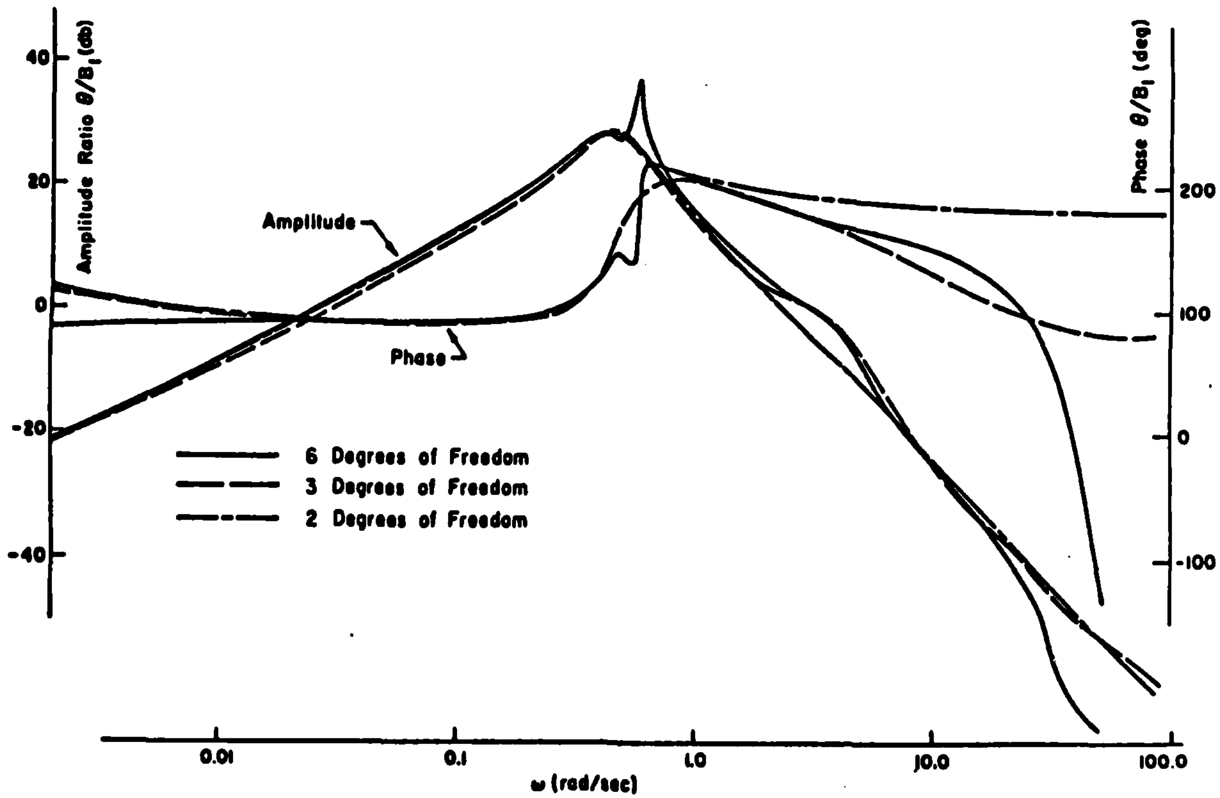

Figure 3. 2 DOF, 3 DOF, and 6 DOF Pitch Attitude Response Comparison, from reference 1

SECTION III

RESULTS

To present the results in as clear and concise a form as possible, a series of tables and graphs are used. A brief description and graphical interpretation of each criterion for each specification is first presented along with the specification paragraph. Contrasting points between the specification criteria are then discussed. Plots of the aircraft model and flight test data in relation to these criteria are next shown and discussed. Finally, a position on the acceptability/utility of the MIL-H-8501A criteria is presented.

The results are divided into hover/low speed and forward flight sections. MIL-H-8501A, on the other hand, has a general format of longitudinal and lateral-directional criteria. The significant differences in the stability and control characteristics of helicopters between hover and forward flight are more thoroughly addressed by a hover/low speed, forward flight breakdown. MIL-F-83300 uses this type of division for the specification requirements.

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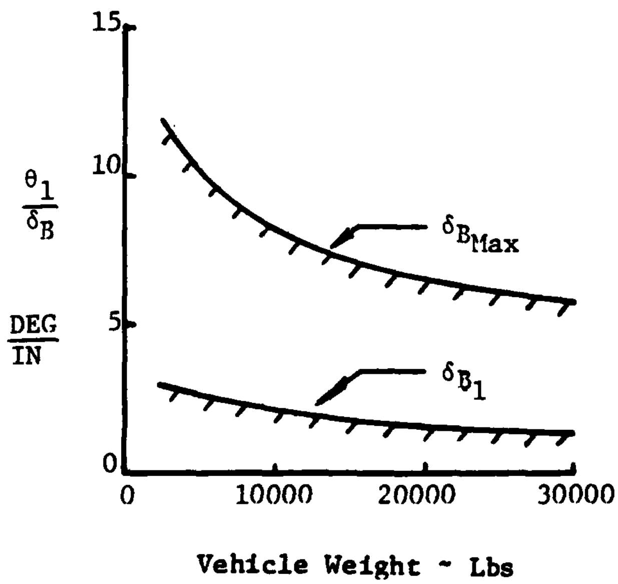
HOVER/LOW SPEED

- Hover Attitude Response; Longitudinal

MIL-H-8501A

3.2.13 Longitudinal control power shall be such that when the helicopter is hovering in still air at the maximum overload gross weight or at the rated power, a rapid 1.0-inch step displacement from trim of the longitudinal control shall produce an angular displacement at the end of 1.0 second which is at least $\frac{45}{\sqrt[3]{W+1000}}$ degrees. When maximum available displacement from trim of the longitudinal control is rapidly applied, the angular displacement at the end of 1.0 second shall be at least $\frac{180}{\sqrt[3]{W+1000}}$ degrees. In both expressions W represents the maximum overload gross weight of the helicopter in pounds.



Comments

The control power (control response) requirements for a helicopter are most demanding in a hovering flight mode. During a precision hover over a moving ship deck, for example, a pilot will be using rapid, small control inputs. Thus, the short term response characteristics are of primary importance. Present day helicopters achieve translational accelerations via attitude response in the pitch and roll axes, or thrust vector tilting. This is the reason attitude response within 1 second is specified for hover control power.

Walton and Ashkenas (reference (b)) describe the MIL-H-8501A response dependency on weight as inadequate. They suggest making the required response a function of the expected operational mission.

The full control displacement attitude response is 4 times the unit control input response. Through linear considerations, this suggests that at least 4 inches of longitudinal control displacement be available from the trimmed hover control position or for most helicopters roughly 40% longitudinal control motion.

Note that the specified test condition is still wind (less than 3 knots).

The SH-2F, CH-53D, and CH-53E type specifications use the above paragraph for longitudinal attitude response requirements.

MIL-F-83300

3.2.3.2 Longitudinal Response to Control Input. The ratio of the maximum change, occurring within the first second following an abrupt step displacement of the appropriate cockpit control, to the magnitude of the cockpit control command shall lie within the bounds of the following table. There shall be no objectionable nonlinearities in aircraft response to control deflections and forces.

Response to Control Input
in One Second or Less
(degrees per inch)

Level	Min	Max
1	3.0	20.0
2	2.0	30.0
3	1.0	40.0

Comments -

The level 1 boundaries are for a normal flight mode. Also note the maximum response limitation which quantifies an oversensitive aircraft.

AGARD 577

2.2 Pitch Control Power. From trimmed conditions in hover, and for the environmental conditions and the mission specified for each type of aircraft, the pitch control should be sufficient to achieve 4 degrees of pitch attitude per inch of stick deflection after 1 second.

Comments - AGARD 577 presented a range of attitude values and specified that the largest value (4 degrees would be for aircraft whose missions require extensive hover and low speed maneuvering. Thus the above 4 degrees is required for helicopters. The environment conditions are those specified by the procuring activity.

- Hover Attitude Response; Longitudinal

SPECIFICATION COMPARISONS

Of the three specifications presented only MIL-H-8501A includes a control power dependency on vehicle weight. Both MIL-F-83300 and AGARD 577 specify a maximum response for level 1 flying qualities, as defined by Table I, regardless of the aircraft size or mission. This is cited as a deficiency in MIL-F-83300 according to reference (c). Walton and Ashkenas (reference (b)) suggest that response requirements should be categorized according to vehicle mission to eliminate the use of a common design value for attack, utility and cargo helicopters. MIL-F-83300 has 4 classes of vehicles (see Table II) for control force and forward flight roll response criteria. Implementing a similar format into a helicopter/rotary wing specification would allow for the addition of a shipboard operations category as well as a nap of the earth (NOE) operations category. Both of these missions require the vehicle/pilot system to operate in extreme environments demanding performance in excess of the no-wind, out-of-ground effect control response design criteria requirements.

MIL-F-83300 specifies a maximum attitude response for a unit stick input thereby limiting sensitivity of the controls. Both AGARD 577 and MIL-H-8501A address control sensitivity by requiring a minimum value for control damping. Degraded responses due to failure states are specified in MIL-F-83300 only. The absence of specific degraded flying qualities levels in MIL-H-8501A is one of the major deficiencies cited about MIL-H-8501A by Key (reference (d)).

TABLE I. FLYING QUALITIES LEVELS

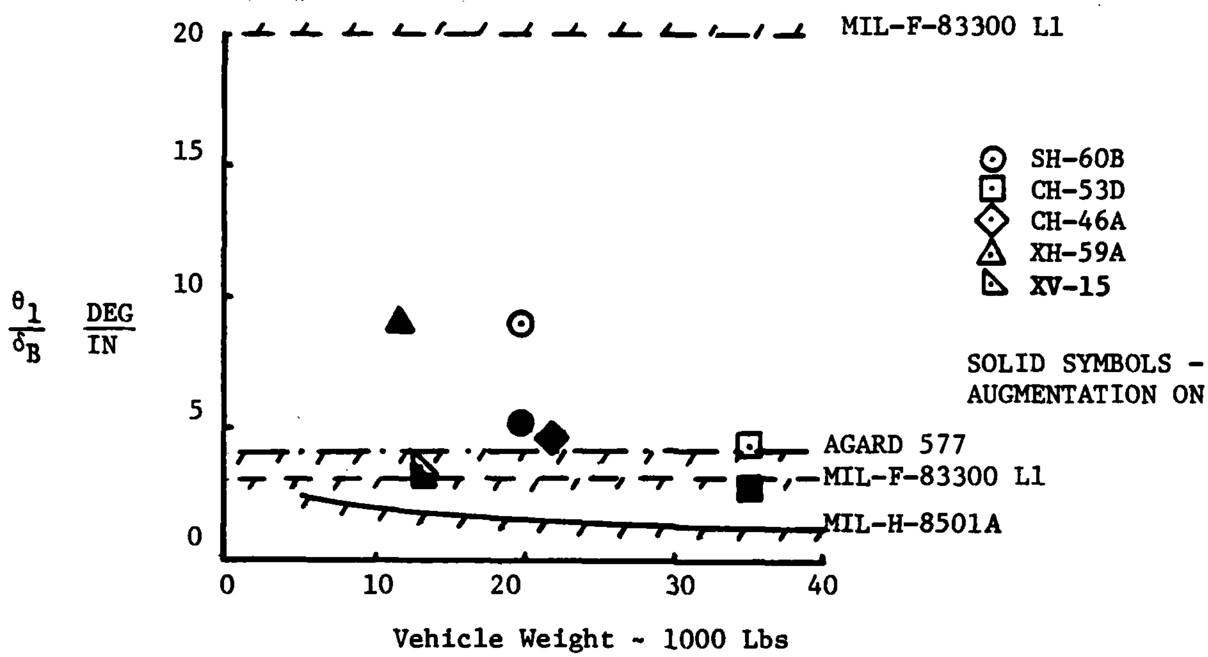
Pilot Rating	FQ Level	FQ Description
1.0 - 3.5	Level 1	Flying qualities clearly adequate for the mission Flight Phase.
3.5 - 6.5	Level 2	Flying qualities adequate to accomplish the mission Flight Phase, but some increase in pilot workload or degradation in mission effectiveness, or both, exists.
6.5 - 9.0	Level 3	Flying qualities such that the airplane can be controlled safely, but pilot workload is excessive or mission effectiveness is inadequate, or both.

TABLE II. MIL-F-83300 CLASSIFICATION OF AIRCRAFT

Class	Description
I	Small, light aircraft such as - light utility - light observation
II	Medium weight, low-to-medium maneuverability aircraft such as - utility - search and rescue - anti-submarine - assault transport
III	Large, heavy, low-to-medium maneuverability aircraft such as - heavy transport - heavy bomber
IV	High maneuverability aircraft such as - fighter - attack

- Hover Attitude Response, Longitudinal

DATA COMPARISONS



The above plot shows that all the aircraft satisfy MIL-H-8501A but the CH-53D does not meet the MIL-F-83300 limit. The CH-53D is a current fleet aircraft with hover control power that is qualitatively described as adequate. This lends credence to the MIL-H-8501A weight factor, i.e., heavier vehicles can have lower longitudinal attitude response. The pilots reported the XV-15 response to be a little sluggish and indicated more control sensitivity would be desirable, yet the aircraft easily meets the MIL-H-8501A boundary. Note that the XH-59A, rigid rotor, with similar gross weight to the XV-15, shows twice the control response. Pilots described the XH-59A response as adequate. Lateral and directional response characteristics highlight the differences between rotor configurations more so.

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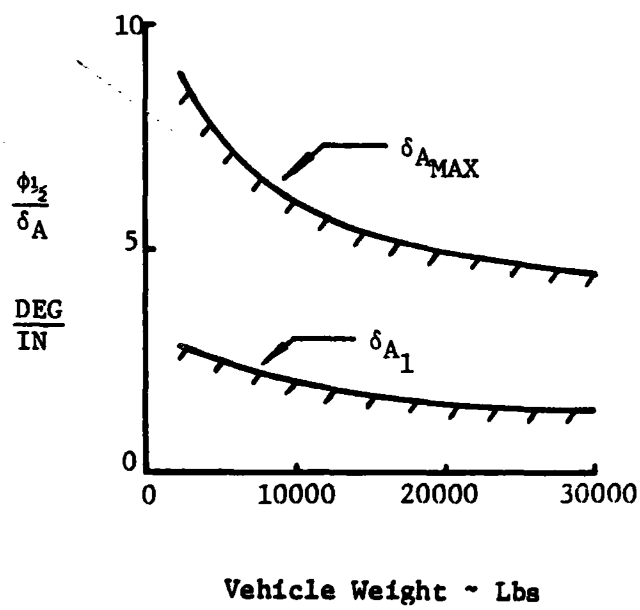
- Hover Attitude Response; Lateral

MIL-H-8501A

3.3.18 Lateral control power shall be such that when the helicopter is hovering in still air at the maximum overload gross weight or at the rated power, a rapid 1-inch step displacement from trim of the lateral control shall produce an angular displacement at the end of one-half second of at least $\frac{27}{\sqrt[3]{W+1000}}$ degrees. When maximum available displacement from trim of the lateral control is rapidly applied at the conditions specified above, the resulting angular displacement at the end of one-half second shall be at least $\frac{81}{\sqrt[3]{W+1000}}$ degrees. In both expressions W represents the maximum overload gross weight of the helicopter in pounds.



Comments

Precision hover over a spot requires using longitudinal and lateral controls to develop translational accelerations along either axis. Just as described in 3.2.13 Longitudinal Attitude Response, the acceleration is developed through a tilting of the main rotor thrust vector or by an initial attitude response. This lateral control power criteria is exactly the same as 3.2.13 except that the response has to be within one-half second. There is no reason specified in MIL-H-8501A as to why the lateral response should be within one-half second instead of one second. Walton (reference (b)) states that the use of one-half second places a premium on aileron deflection rate, and represents a difficult flight test procedure. To allow for a direct comparison of this criteria with the other specifications the multiplying factor presented in reference (b) will be used. The factor ($\doteq 4$) was determined with the assumption that the vehicle would have moderate to low roll rate damping (i.e., $\doteq -1$ sec^{-1}). With higher damping the factor decreases. For instance, $L_p = -8\ sec^{-1}$ the factor should be 2.6.

Weight parameter, full control input and still wind comments are the same as described in 3.2.13, Longitudinal Attitude Response.

The SH-2F, CH-53D, and CH-53E type specifications use the above paragraph for lateral attitude response requirements.

MIL-F-83300

3.2.3.2 Lateral Response to Control Input. The ratio of the maximum change, occurring within the first second following an abrupt step displacement of the appropriate cockpit control to the magnitude of the cockpit control command shall lie within the bounds of the following table. There shall be no objectionable nonlinearities in aircraft response to control deflections and forces.

Response to Control Input
in One Second or Less
(degrees per inch)

Level	Min	Max
1	4.0	20.0
2	2.5	30.0
3	1.0	40.0

Comments -

Same as 3.2.3.2 Longitudinal Response to Control Input.

AGARD 577

3.2 Roll Control Power. From trimmed conditions in hover, and for the environmental conditions and the mission specified for each type of aircraft, the roll control should be sufficient to achieve 4 degrees of roll attitude per inch of stick deflection after one second.

Comments -

Same as 2.2 Pitch Control Power.

-Hover Attitude Response; Lateral

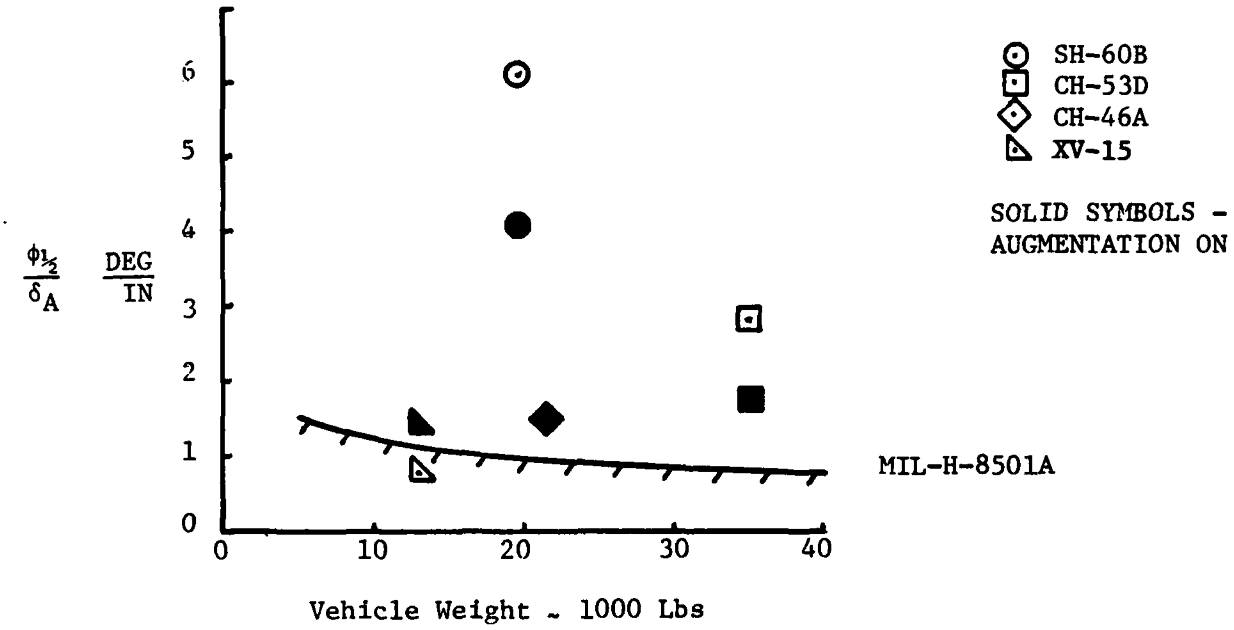
SPECIFICATION COMPARISONS

As noted MIL-H-8501A requires the roll response to be within one-half second unlike MIL-F-83300 or AGARD 577. Both of the VSTOL specifications require a minimum bank angle response of 4 deg/in within one second of control application regardless of the vehicle weight or mission.

Other comments on weight vs. mission control power dependencies are discussed in the longitudinal hover attitude response specification comparisons.

- Hover Attitude Response; Lateral

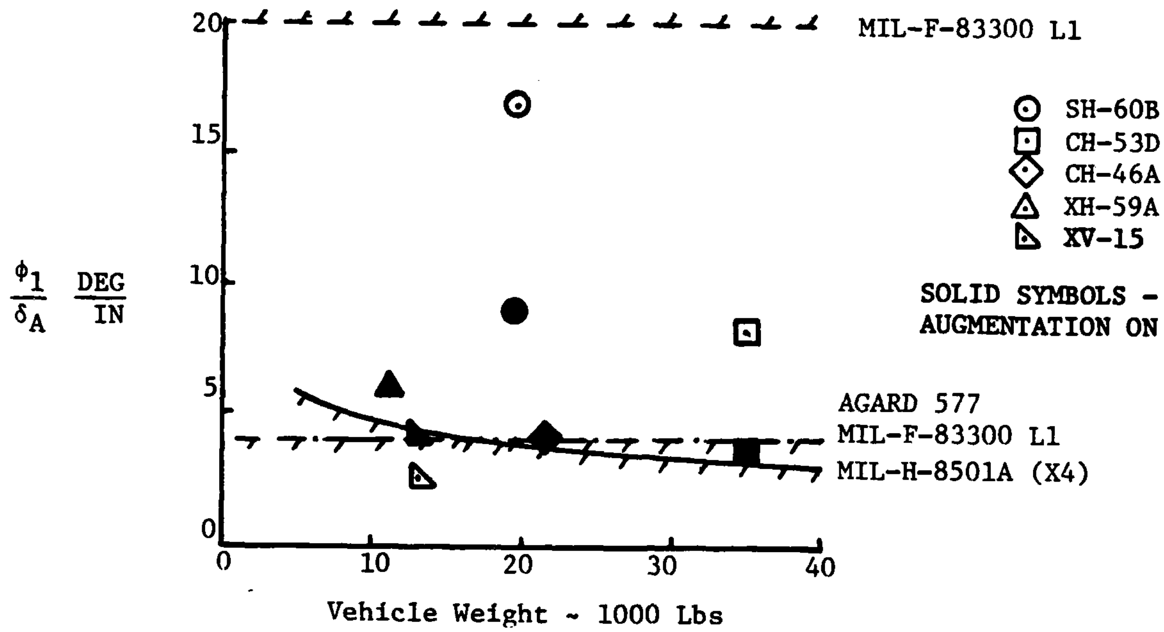
DATA COMPARISONS



For the MIL-H-8501A roll response within one-half second boundary all the aircraft compared favorably. The variation in response due to rotor configurations is very apparent between the SH-60B (single rotor) and the CH-46A (tandem rotor). The SH-60B with the tail rotor augmenting the roll control moment has over twice the response of the similar weight tandem rotor. A single rotor helicopter with a tail rotor sitting moderately above the vehicle center of gravity can, through control system cross coupling, develop large roll moments due to the tail rotor.

- Hover Attitude Response; Lateral

DATA COMPARISONS



The MIL-H-8501A (X4) curve is the one-half second response multiplied by the factor presented in reference (b). This allows for a direct comparison between the different specifications. As in the longitudinal response the CH-53D is just below the MIL-F-83300 limit. Again the weight dependency may be suggested. Note that in contrast to pitch control the CH-46A barely satisfies the specifications. According to reference (c), MIL-F-83300 is currently unsatisfactory for helicopter applications because tandem rotor aircraft are not adequately addressed. It should be noted the MIL-H-8501A also does not account for varied rotor configurations, tandem or otherwise.

Note that the CH-53D and CH-46A barely meet the MIL-H-8501A (X4) limit while the XV-15 does not satisfy it. This is in contrast to the MIL-H-8501A (one-half second response) plot that shows all three of these aircraft easily meet the specification. The CH-53D, CH-46A and XV-15 are all highly damped vehicles in roll, while the reference (c) factor was developed for moderately damped aircraft.

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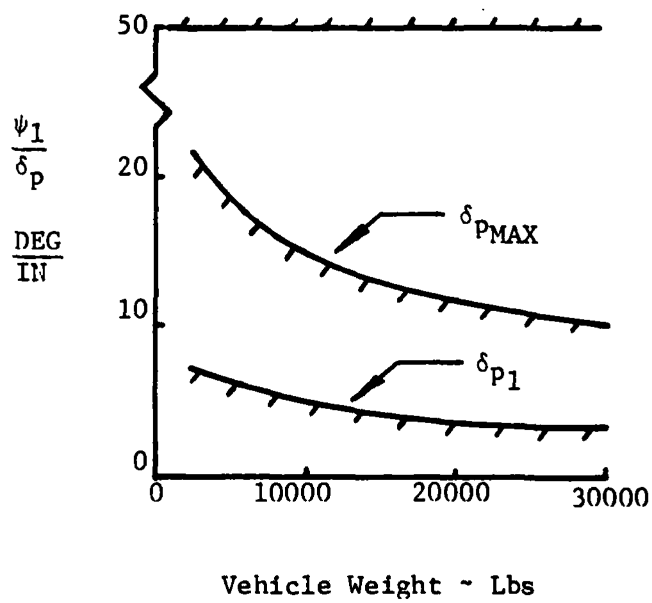
- Hover Attitude Response; Directional

MIL-H-8501A	Comments
3.3.5 Directional control power shall be such that when the helicopter is hovering in still air at the maximum overload gross weight or at rated take-off power, a rapid 1.0-inch step displacement from trim of the directional control shall produce a yaw displacement at the end of 1.0 second which is at least $\frac{110}{\sqrt[3]{W+1000}}$ degrees. When maximum available displacement from trim of the directional control is rapidly applied at the conditions specified above, the yaw angular displacement at the end of 1.0 second shall be at least $\frac{330}{\sqrt[3]{W+1000}}$ degrees. In both equations W represents the maximum overload gross weight of the helicopter in pounds.	Yaw control in hover is used primarily for azimuth positioning. To keep the aircraft response from being overly sensitive an additional paragraph states that a 50 degree attitude variation in the first second after the control input is excessive. Weight parameter, full control input and wind condition comments are as discussed under 3.2.13 longitudinal attitude response. The SH-60B type, which used MIL-H-8501A extensively as a base specification, changed the 50 degrees in 1 second requirement to 30 degrees in 1 second.
3.3.7 The response of the helicopter to directional-control deflection, as indicated by the maximum rate of yaw per inch of sudden pedal displacement from trim while hovering shall not be so high as to cause a tendency for the pilot to overcontrol unintentionally. In any case the sensitivity shall be considered excessive if the yaw displacement is greater than 50 degrees in the first second following a sudden pedal displacement of 1 inch from trim while hovering at the lightest normal service loading.	The SH-2F, CH-53D, and the CH-53E type specifications used the above paragraph for directional attitude response requirements.



MIL-F-83300

3.2.3.2 Directional Response to Control Input. The ratio of the maximum change occurring within the first second following an abrupt step displacement of the appropriate cockpit control to the magnitude of the cockpit control command shall lie within the bounds of the following table. There shall be no objectionable nonlinearities in aircraft response to control deflections and forces.

Response to Control Input in One Second or Less (degrees per inch)

Level	Min	Max
1	6.0	23.0
2	3.0	45.0
3	1.0	50.0

Comments -

Same as 3.2.3.2 Longitudinal Response to Control Input.

AGARD 577

3.12 Yaw Control Power. From trimmed conditions in hover, and for the wind conditions specified the yaw control should be sufficient to achieve 15 degrees of heading change in 1 to 2.5 seconds after an abrupt control input.

Comments -

For directional control a specific heading change has to be met within a range of time for a full pedal (directional control) input. It is not clear within AGARD 577 where helicopters or similar vehicles lie in the 2.5 to 1.0 second band. The substantiation data used in the development of this criteria is taken largely from STOL flight tests. It was assumed in this report that the lower time (1 second) should be used for vehicles requiring high hover directional control power, i.e., helicopters. The average full pedal range for the vehicles analyzed is approximately 5 inches. Assuming in trim the pedal is at 50%, this leaves 2.5 inches of travel available for an abrupt input. The response per inch of input is found to be exactly that specified by MIL-F-83300: 6 degrees within one second. This value will be used in subsequent comparisons.

- Hover Attitude Response; Directional

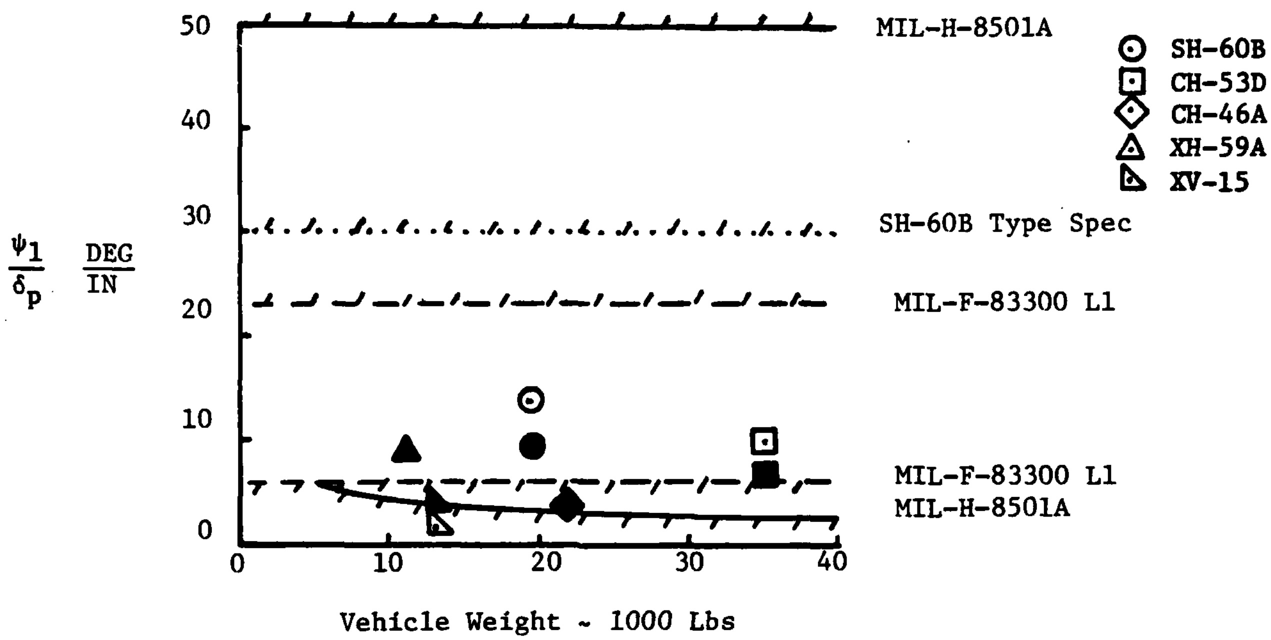
SPECIFICATION COMPARISONS

Each of the specifications require a particular heading change in 1 second or less to demonstrate yaw control power. Both MIL-H-8501A and MIL-F-83300 also have a sensitivity limit, though the MIL-H-8501A value is extremely large. The SH-60B type specification upper limit value is more consistent with that of MIL-F-83300.

Weight vs. mission control power dependencies are the same as discussed in the longitudinal hover attitude response specification comparisons.

- Hover Attitude Response; Directional

DATA COMPARISONS



As seen in the pitch and roll response comparisons, here again each of the aircraft satisfy the MIL-H-8501A criteria. The CH-46A and the XV-15 have the least directional control power, which is characteristic of the rotor configurations without a tail rotor. The SH-60B has more than twice the yaw response of the CH-46A just as the in roll case. This again suggests the possible need for criteria accounting for varied rotor concepts. With the new systems presently being proposed for future Navy and Army missions (e.g., ABC, X-Wing/CCR, tilt-rotor) it can be expected that flying qualities differences between rotor configurations will be uncovered. Whether a pilot will allow for a lower response because of rotor configuration or specific mission, however, still needs to be answered.

- Hover Attitude Response

The MIL-H-8501A hover control response criteria are the means by which helicopter flying qualities control power requirements are established. Each of the aircraft tested faired well against the MIL-H-8501A criteria, overall. The CH-46A was low on yaw response, just passing the required attitude change, and likewise the XV-15 appeared low on yaw and roll control power by barely meeting the criteria. The interesting point is that the CH-46A is described by pilots as having low directional control power, but more than adequate for the assault/transport mission. The XV-15 in contrast was given level 2 ratings but still satisfied MIL-H-8501A. A control power dependency on aircraft mission could eliminate the problem of designing similar weight attack and transport helicopters with the same control power requirements. The effect of varied rotor configurations upon control power needs further data and analysis to be quantified into criteria. Although the MIL-H-8501A weight parameter is more applicable to helicopters than the MIL-F-83300 and AGARD 577 constant attitudes, it can not adequately address mission and rotor configuration differences.

Comparing the ratio of absolute values for hover control power between the three axes, as below,

	REFERENCE	$\Theta_1/\Phi_1/\Psi_1$
(a)	MIL-H-8501A	1/2.40/2.44
(g)	MIL-F-83300	1/1.33/2.00
(h)	AGARD 577	1/1.00/1.50
(b)	STI Report No. 143-1	1/2.00/2.00

shows that the VSTOL specifications (references (g) and (h)) require only slightly more roll control power than pitch. MIL-H-8501A and the

STI report show that helicopters should have at least twice as much roll control as pitch. Part of this difference could be explained by the high lateral-directional gust sensitivity of single rotor helicopters. Directional control power is on the order of twice the pitch control for all the above references. In comparison, the VSTOL Type A RFQ/I (reference (p)) had the required directional control power less than roll and pitch. Whether or not the fixed wing lift cruise fan model data used to substantiate the reference (p) criteria are applicable to helicopters requires further data and analysis.

Another significant difference between the specifications is that MIL-H-8501A specifies still wind conditions for the response test while MIL-F-83300 and AGARD 577 neglect to spell out the conditions, although the MIL-F-83300 criteria is applicable in steady wind conditions up to the limits of the service flight envelope. Paragraph 3.2.3.2 of MIL-F-83300 is also supplemented with a worst case control power criteria. It is stated that for the wind (strength not quantified) from the most critical directions to the aircraft, minimum level 1 pitch, roll and yaw attitudes of at least ± 3, ± 4 and ± 6 degrees respectively, must be demonstrated within 1 second for simultaneous abrupt, full pitch, roll and yaw control inputs. In contrast MIL-H-8501A requires a multiple of the unit control input response be demonstrated for full control input. As discussed this places a minimum on the control displacement range for linear systems. A helicopter meeting the MIL-H-8501A full throw requirements will not necessarily have adequate control power in turbulent conditions. MIL-H-8501A does have an additional directional control response minimum for a 35 knot wind from the most critical heading angle to the aircraft. The full pedal input response for this condition must be as large as the still wind unit input response. This type of criteria should be extended to include the longitudinal and lateral axes (as in MIL-F-83300) as well for aircraft required to maneuver and frequently operate on adverse wind conditions. The small landing platforms and wind and sea conditions Navy helicopters will be expected to launch and recover from is one example of a mission that may not be adequately designed for by the still wind, out-of-ground effect control power criteria in MIL-H-8501A.

The MIL-H-8501A hover attitude response criteria is applicable and quite comparable to the present Navy helicopters analyzed. The weight parameter used in MIL-H-8501A does account for response differences due to aircraft size that neither MIL-F-83300 or AGARD 577 could cover. The possibility of making the attitude response a function of the vehicle mission should be considered. Using these mission categories a shipboard operations group for the Navy and an NOE operations group for the Army could be included. The other area needing further analysis is the inclusion of a means to address response differences due to varied rotor configurations.

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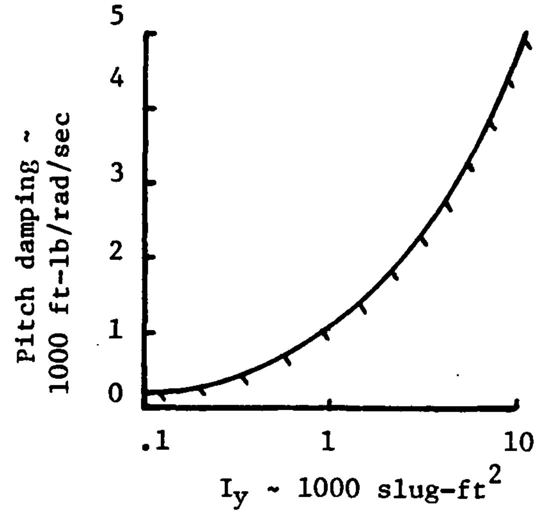
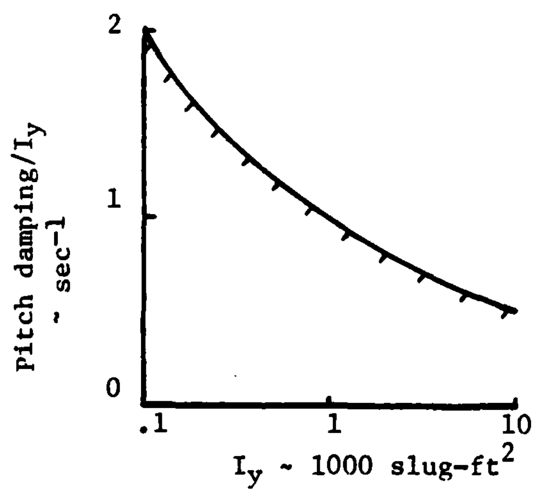
- Hover Control Damping; Longitudinal

MIL-H-8501A

3.2.14 To insure satisfactory initial response characteristics following a longitudinal control input and to minimize the effects of external disturbances, the helicopter in hovering shall exhibit pitch angular velocity damping (that is, a moment tending to oppose the angular motion and proportional in magnitude to the angular velocity) of at least $8\,(I_y)^{0.7}$ ft-lb/rad/sec, where I_y is the moment of inertia about the pitch axis expressed in slug-ft^2.





Comments

Along with the attitude response criteria MIL-H-8501A includes angular velocity damping limitations. By requiring a specific amount of rate damping, an upper bound is placed on control/gust sensitivity. The attitude response criteria is aligned to flight test procedures. It accounts for the control moment generated by the control input (M_{d_B}, L_{d_A}, N_{d_p}), the damping moment (M_q, M_p, N_r), velocity stability (M_u, L_v, N_v) and aircraft inertia.

By assuming a straight forward one-degree-of-freedom response as

$$\frac{M_{d_B} \quad d_B}{(S + M_q)} = \theta$$

the effects of damping and control input on attitude response can be analyzed. Thus by using both 3.2.13 longitudinal control power and 3.2.14 longitudinal control damping a range of satisfactory hover control response designs is determined. This is accomplished by plots of control damping vs. sensitivity.

Walton and Ashkenas (reference (b)) suggest that longitudinal control damping should be between -1 and -1.5 sec^{-1} regardless of aircraft inertia or mission. This will reduce the pilot's lead requirements. The higher damping (-1.5 sec^{-1}) is for multiloop control systems.

The SH-2F, CH-53D, and CH-53E type specifications use the above criteria for longitudinal rate damping requirements.

MIL-F-83300	AGARD 577
Pitch rate damping is not included in the specification.	2.4 Pitch Damping. For hover conditions the aircraft should possess pitch angular velocity damping of at least $-\frac{1}{2}$ to $-2\ sec^{-1}$.
Comment - MIL-F-83300 accounts for initial response and sensitivity constraints by specifying a minimum and maximum allowable pitch attitude response per inch of control input in one second.	Comment - The above range of values is for a rate stabilized system. An attitude stabilized system must have a damping value of at least $-2\ sec^{-1}$. The least amount of damping permissible ($-\frac{1}{2} sec^{-1}$) will be used in the data comparisons.

- Hover Control Damping; Longitudinal

SPECIFICATION COMPARISONS

Both MIL-H-8501A and AGARD 577 explicitly specify pitch control damping, although different definitions are used. The MIL-H-8501A value should be divided by I_y to bring it in line with the AGARD 577 definition of $M_q \sim sec^{-1}$. The lower plot under the MIL-H-8501A criteria 3.2.14 shows this as

$$M_q\ (sec^{-1}) = 8\ I_y^{-.3}$$

MIL-F-83300 does not specify pitch damping but the range of pitch attitude response presented in longitudinal hover attitude response was determined by analyzing pilot rating data for various control damping and sensitivity values. Figure 4 taken from reference (q) shows how one set of data for a light weight single rotor helicopter compares with the MIL-F-83300 level 1 attitude response boundaries.

There is very little explanation within reference (h) on how the range of values given by AGARD 577 should be used. The higher damping ($-2\ sec^{-1}$) is to be used as a minimum for attitude stabilized systems. The MIL-H-8501A values are a function of aircraft inertia. A very small single rotor helicopter can have $I_y = 1000$ slug-ft^2 which would require an $M_q = -1\ sec.^{-1}$ Larger helicopters in general would require progressively less damping. The value presented in reference (b) ($M_q = -1\ sec^{-1}$) is in general more demanding than the other specifications.

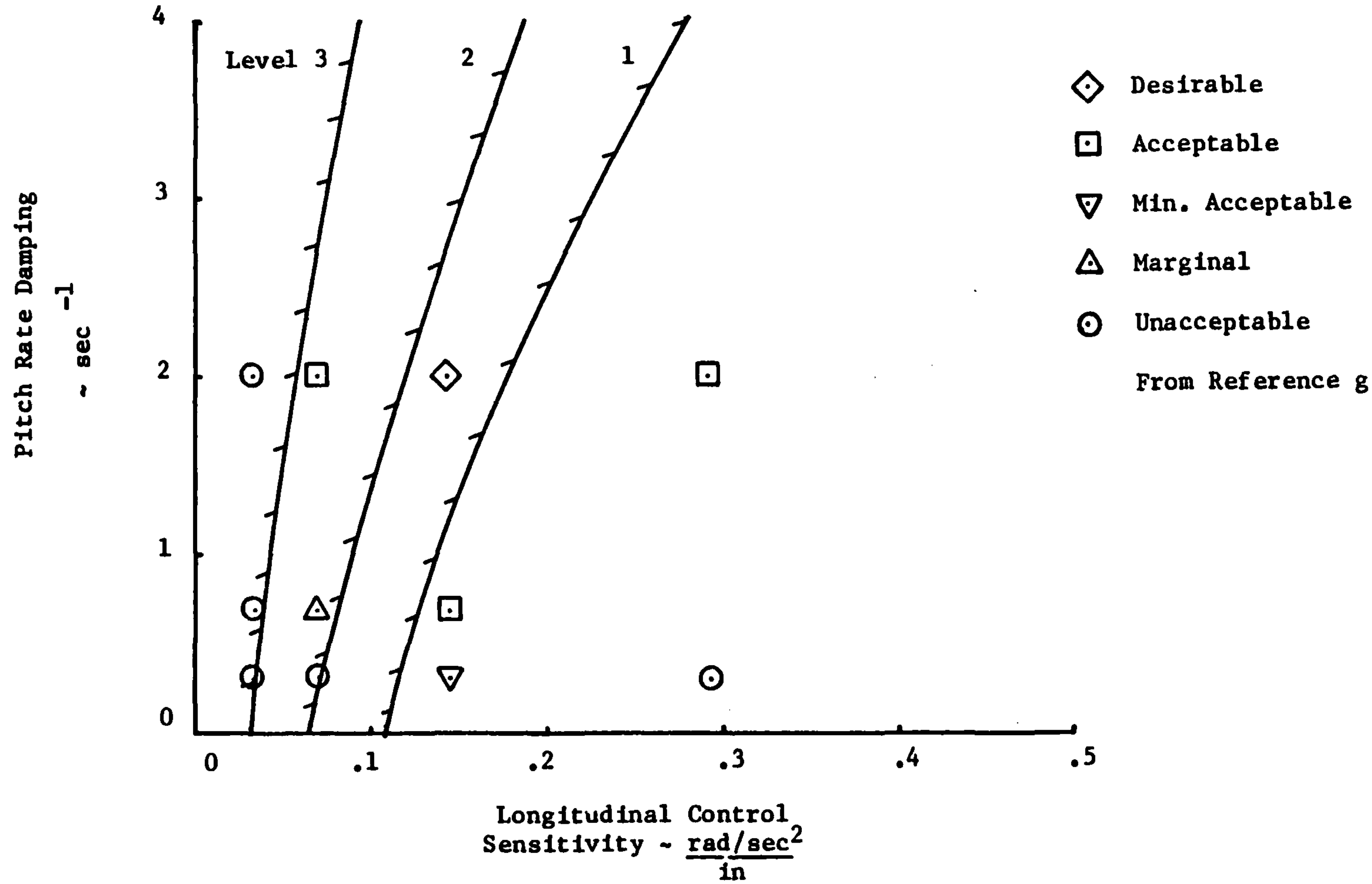
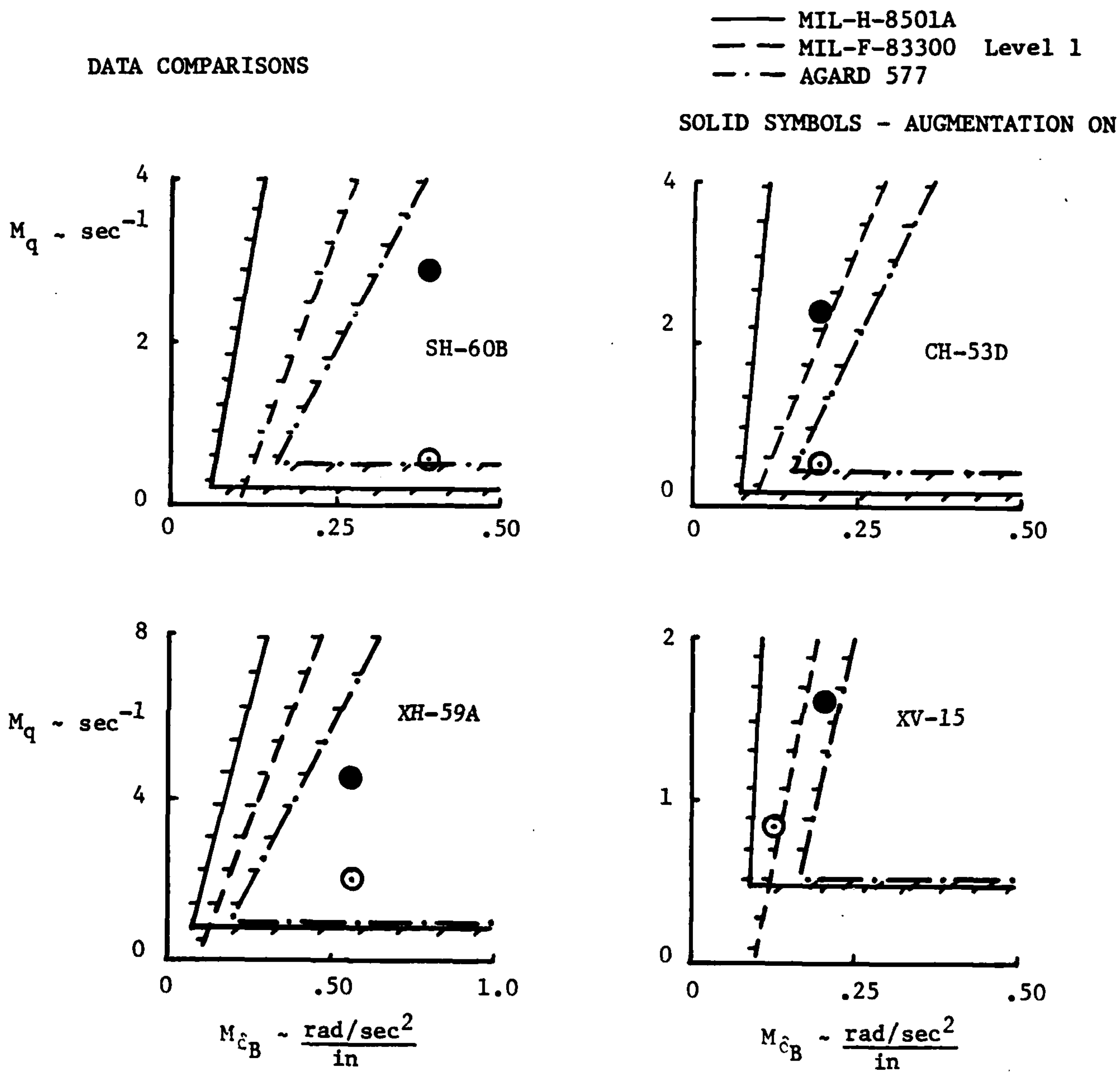


Figure 4. Qualitative Pilot Ratings for Various Combinations of Pitch Control Damping and Sensitivity

- Hover Control Damping; Longitudinal

DATA COMPARISONS



For normal flight conditions with augmentation systems on, each of the analyzed vehicles easily meet the MIL-H-8501A pitch damping criteria. As in the pitch attitude response plot shown earlier, the CH-53D is unsatisfactory in comparison to the MIL-F-83300 boundary. One interesting point lies in the XV-15 data from a 1977 flight test. The pilots gave an overall rating of level 2 for control response, yet MIL-H-8501A shows the response to be satisfactory. MIL-F-83300 and AGARD 577 correlate better with the qualitative ratings for the XV-15 response.

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- Hover Control Damping; Lateral

MIL-H-8501A

3.3.19 To insure satisfactory initial response characteristics following a lateral control input and to minimize the effect of external disturbances, the helicopter in hovering, shall exhibit roll angular velocity damping (that is, a moment tending to oppose the angular motion and proportional in magnitude to the rolling angular velocity) of at least 18 $(I_x)^{0.7}$ ft-lb/rad/sec, where I_x is the moment of inertia about the roll axis expressed in slug-ft^2.

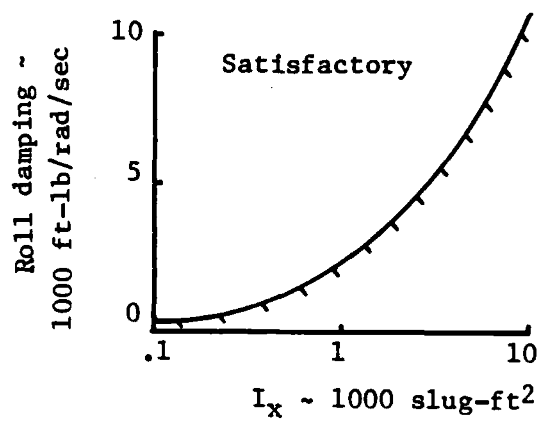
3.3.15 The response of the helicopter to lateral-control deflection, as indicated by the maximum rate of roll per inch of sudden control deflection from the trim setting, shall not be so high as to cause a tendency for the pilot to overcontrol unintentionally. In any case, at all level flight speeds, including hovering the control effectiveness shall be considered excessive if the maximum rate of roll per inch of stick displacement is greater than 20 degrees per second.

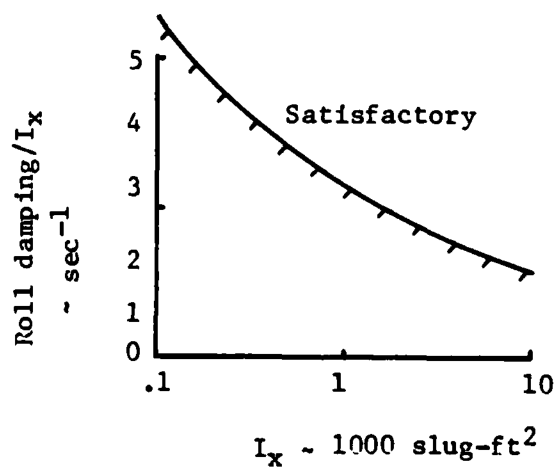
Comments

Roll damping in hover is regulated similar to pitch damping previously discussed. The moment of inertia about the roll axis I_x is used to determine satisfactory damping characteristics as shown. MIL-H-8501A also includes a criteria limiting maximum roll rate per inch of control input. The 20 deg/sec criteria tends to require higher control damping than that specified by 3.3.19 for high control sensitivity. This is pointed out on the Data Comparison plots.

For other comments see 3.2.14 longitudinal hover control damping.

The SH-2F, CH-53D, and the CH-53E type specifications use the above criteria for lateral rate damping requirements.





MIL-F-83300

Roll rate damping is not specified in MIL-F-83300.

Comments - Same as for hover control damping in pitch.

AGARD 577

3.6 Roll Damping. For hover conditions the aircraft should possess roll angular velocity damping of at least -2 to -4 sec^{-1}.

Comments - Similar to the pitch damping criteria AGARD 577 presents a range of values for roll damping. The attitude stabilized systems should have roll damping characteristics of at least -1.5 to -4 sec^{-1}. Very little guidance is presented in reference (q) on how to choose an appropriate value within the range given. In further data comparisons the lower value (-2 sec^{-1}) will be employed.

- Hover Control Damping; Lateral

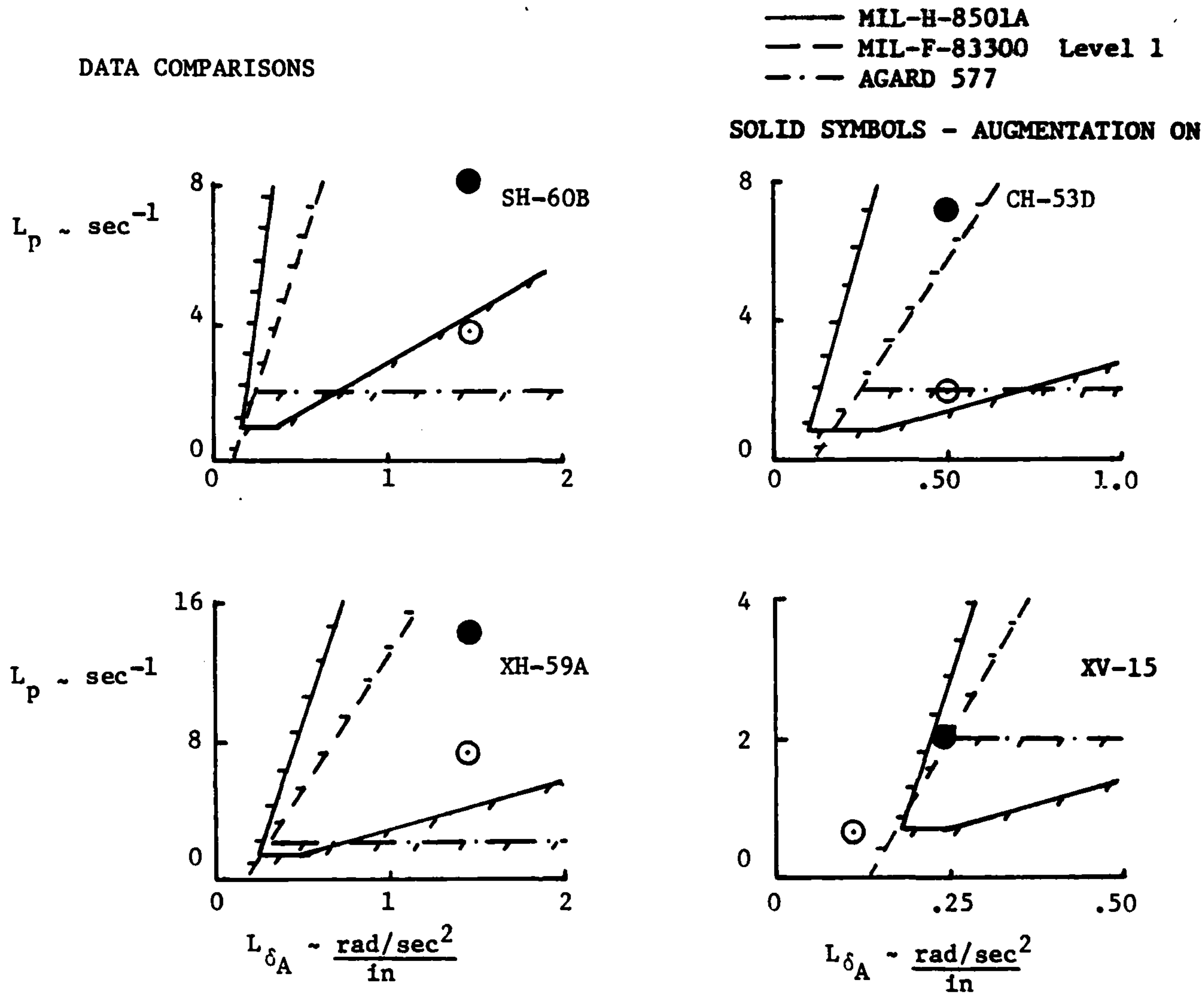
SPECIFICATION COMPARISONS

As in the longitudinal control damping case both MIL-H-8501A and AGARD 577 specify roll control damping limitations. MIL-F-83300 uses minimum and maximum roll control attitude responses to specify satisfactory roll control power. The additional MIL-H-8501A criteria limiting roll rate to 20 deg/sec/in highlights the concern of over controlling a helicopter laterally.

Other comments follow those discussed in the longitudinal hover control damping specification comparisons.

- Hover Control Damping; Lateral

DATA COMPARISONS

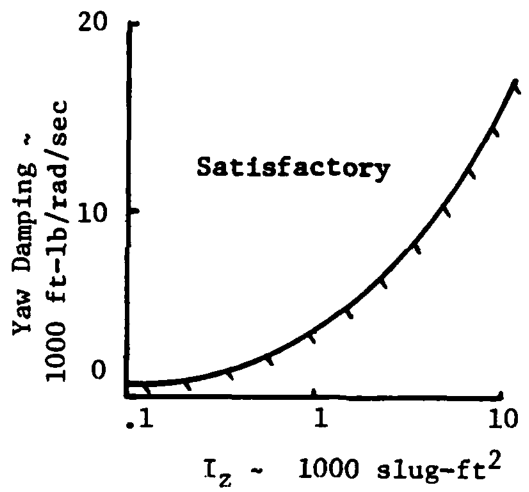


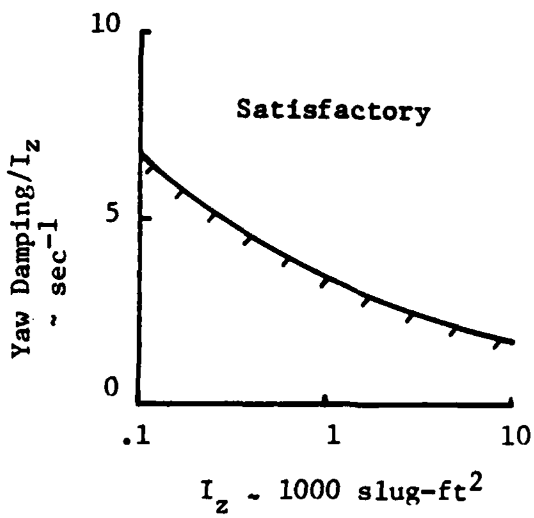
Each of the aircraft analyzed meet the MIL-H-8501A limitations including the 20 deg/sec boundary. The CH-53D and XV-15 again, as in pitch, show lower roll control sensitivity than that specified by MIL-F-83300 and AGARD 577.

Overall the MIL-8501A roll damping criteria is adequate and applicable to the vehicles tested.

- Hover Control Damping; Directional

MIL-H-8501A	Comments
3.3.19 To insure satisfactory, initial response characteristics following either a directional control input and to minimize the effect of external disturbances, the helicopter in hovering shall exhibit yaw angular velocity damping (that is, a moment tending to oppose the angular motion and proportional in magnitude to the yawing angular velocity) of at least $27\,(I_z)^{.7}$ ft-lb/rad/sec, where I_z is the moment of inertia about the yaw axis expressed in slug-ft^2.	Yaw damping is regulated in a similar manner to pitch and roll damping. Comments regarding its use are the same as in the longitudinal control damping discussion. The SH-2F, CH-53D, and the CH-53E use the above paragraph (3.3.19) for directional control damping requirements.





MIL-F-83300

3.2.2.2 Directional Damping. While hovering at zero airspeed, the yaw mode shall be stable and the time constant shall not exceed the following:

Level 1: 1 second
Level 2: 2 seconds

For level 3 operation there shall be no tendency toward aperiodic divergence in yaw.

Comment - In addition to the maximum yaw attitude response per inch of control input MIL-F-83300 also limits the yaw mode time constant. As defined in reference (q)

$$\tau = -\frac{1}{N_r}$$

where N_r the yaw damping corresponds to M_q and L_p already discussed. One of the reasons MIL-F-83300 has a yaw damping criteria and not a pitch or roll criteria is described in reference (q) as a means to ensure compatability of gust and control response. Single rotor helicopters, in particular, are susceptible to yaw gust response problems. If the tail rotor is located far above the center of gravity the gust response could also cross-couple into roll response.

AGARD 577

Yaw rate damping is not specified in AGARD 577.

Comment - The directional damping characteristics of a fixed wing VSTOL aircraft tend to be very different than those of a helicopter. Cross-coupling between yaw and roll tends to be more prevalent in fixed wing vehicles in hover. A majority of the test data analyzed in the development of AGARD 577 was from fixed wing vehicles. AGARD 577 addresses directional damping by specifying ζ, ω_n for lateral-directional modes.

- Hover Control Damping; Directional

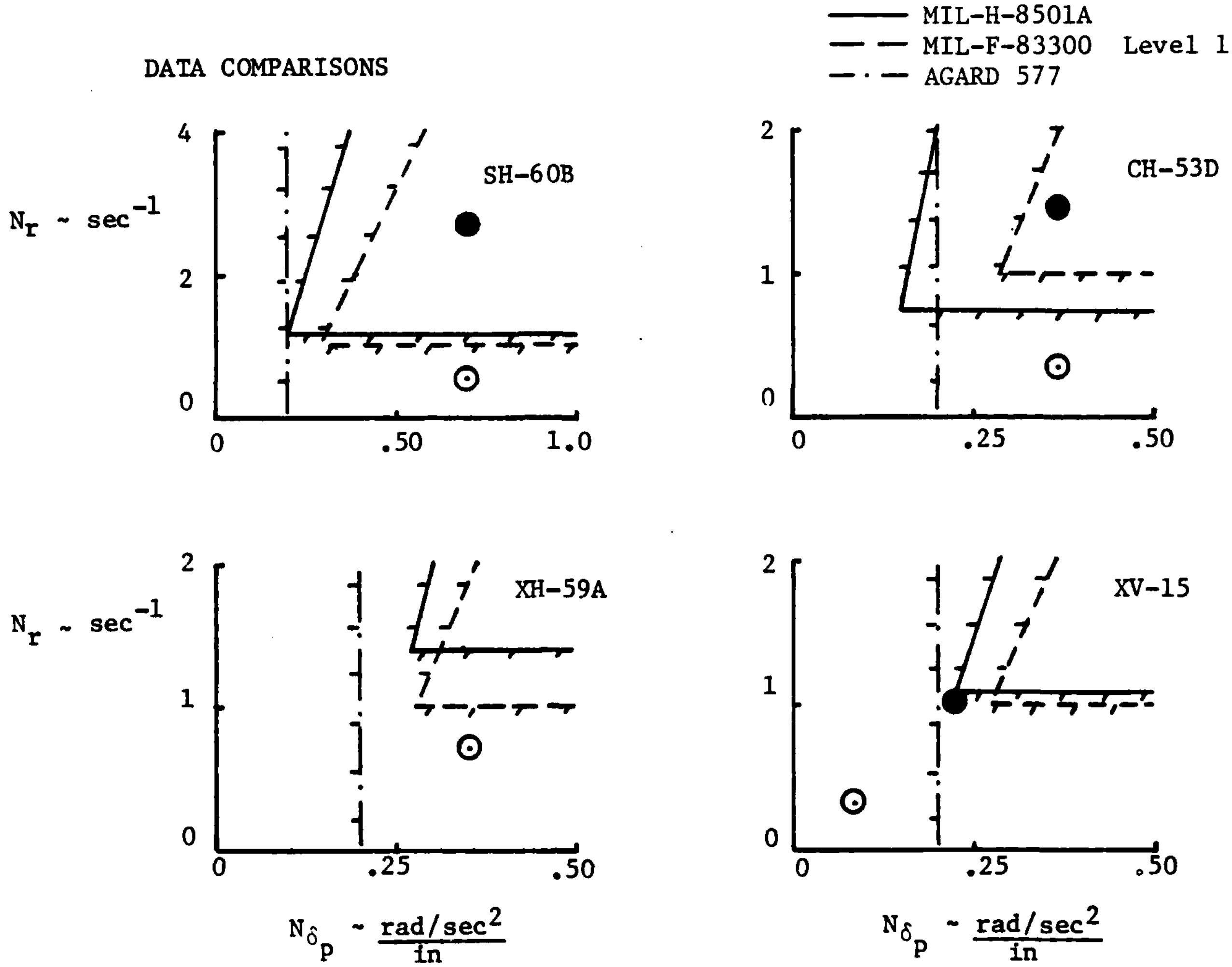
SPECIFICATION COMPARISONS

The only significant difference between yaw rate damping and the previously discussed pitch and roll rate damping is that MIL-F-83300 has a criteria limiting N_r while AGARD 577 does not. This is primarily due to the type of data analyzed for the criteria development. MIL-F-83300, originally intended to be applicable to helicopter flying qualities, included numerous helicopters in the yaw rate damping analysis. AGARD 577 in contrast, not to be used for helicopters, primarily analyzed fixed wing VTOL and VSTOL aircraft.

Other comments follow the longitudinal hover control damping section.

- Hover Control Damping; Directional

DATA COMPARISONS



The previous discussions about flying qualities differences due to varied rotor configurations show up vividly in the above plots. Both the SH-60B and CH-53D meet the specifications criteria and have been qualitatively described by fleet pilots as quite adequate. Neither the XH-59A nor the XV-15, however, satisfy the MIL-H-8501A or MIL-F-83300 limitations. The XV-15 for SCAS on flight is right on the MIL-H-8501A limit. This correlates quite well with the overall pilot rating of level 2 flying qualities in hover. The XH-59A in contrast is well below the MIL-H-8501A damping limitation yet pilot comments described yaw responses as "crisp, predictable" and the "high yaw rates (in excess of 45 deg/sec) that resulted from 1 inch pedal step inputs were well-damped and easily arrested, allowing large, rapid heading changes." A level 1 rating was given for the aircraft characteristics in yaw. There is a need for more pilot rating of the ABC yaw control flying qualities to completely analyze the apparent anomaly between MIL-H-8501A and the ABC.

- Hover Control Damping

For each of the vehicles analyzed the MIL-H-8501A longitudinal and lateral hover control damping requirements were easily satisfied. The XH-59A and XV-15 did not compare favorably with the MIL-H-8501A directional damping criteria though. An interesting point was found with the XH-59A. Although the vehicle did not satisfy the minimum MIL-H-8501A directional damping requirement, pilots gave the aircraft favorable ratings, describing the response as well-damped. Further testing is necessary to analyze this apparent anomaly between MIL-H-8501A and the ABC.

Rate damping, as previously discussed, is one of four parameters effecting the hover response characteristics. Velocity stability (M_u, L_v, N_v) is one of the other parameters which is not directly addressed by any of the specifications reviewed. The effect of the velocity stability term shows up as gust sensitivity of the vehicle. An example of flight test data from the Princeton HUP-1 helicopter shows the effect M_u can have on pilot ratings in figure 5a. Walton and Ashkenas (reference (b)) also analyzed the effects velocity stability have on an optimum control sensitivity. The following expression

$$(1)\ .\ .\ .\ M_{d_{opt}}\left(\frac{\text{rad/sec}^2}{\text{in}}\right) = .23 - .03\ M_q + 6\ M_u$$

$$1 \le -M_q \le 6$$
$$0 \le M_u \le .031$$

from reference (b) (see figure 5b) presents the direct effect increased longitudinal velocity stability has on control sensitivity. An increase in gust sensitivity (M_u) necessitates an increase in control sensitivity (M_{d_B}) to keep control response at an optimum. A minimum of tracking/translational errors was described in reference (b) as the optimum response conditions. It was also found in the analysis presented in reference (b) that for severe wind conditions pilot opinion is a direct function of rms stick deflection (σ_δ), i.e., degraded ratings for large σ_δ.

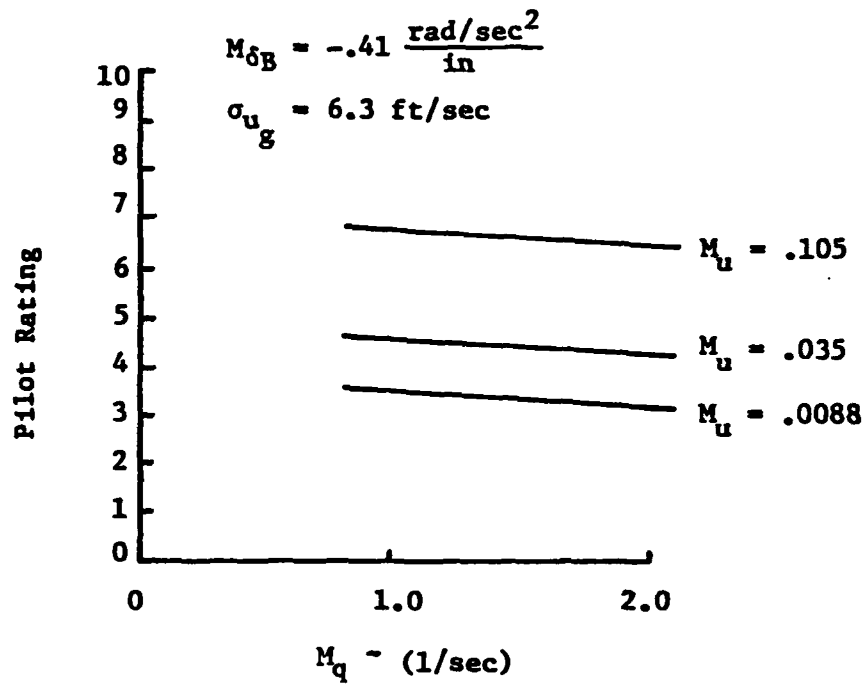


Figure 5a. Longitudinal Velocity Stability Effect on Qualitative Pilot Ratings (from reference r)

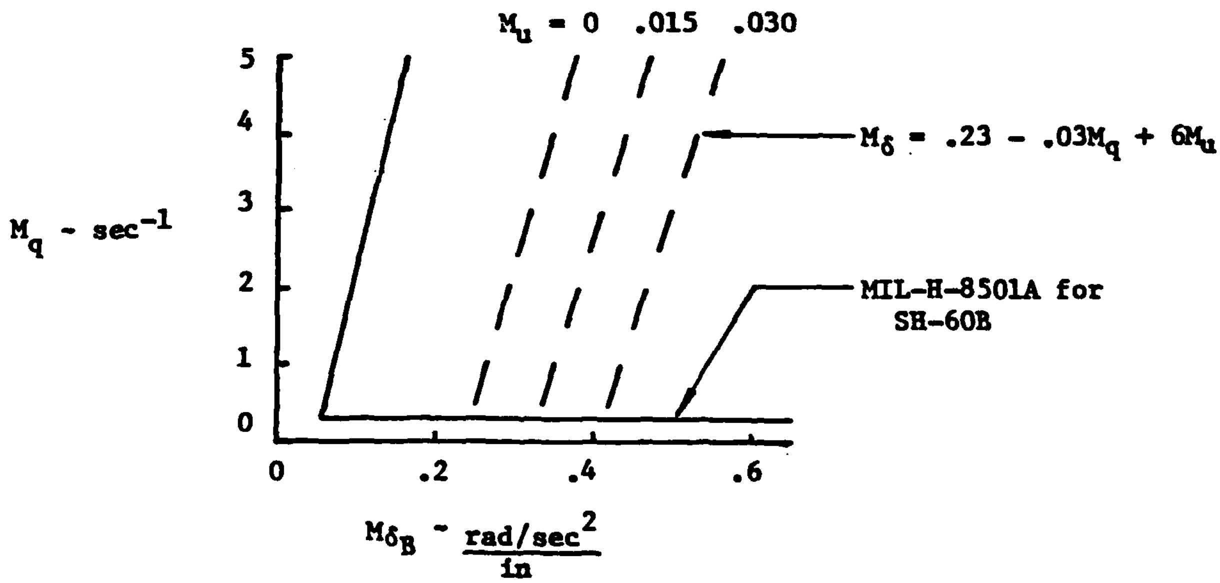


Figure 5b. Longitudinal Velocity Stability Effect on Longitudinal Control Sensitivity.

Figure 5b also has the MIL-H-8501A longitudinal damping and sensitivity boundaries for the SH-60B, for comparison. The MIL-H-8501A criteria for control damping and attitude response in still wind require significantly lower control sensitivity values than the reference (b) expression, even for zero M_u. Considering the shipboard wind conditions Navy helicopters routinely operate in, the possible need for increased control sensitivity for certain missions should be further analyzed.

Roll and yaw control sensitivities showed similar dependencies with damping and velocity stability with the following substitutions.

$$M_q \rightarrow L_p \rightarrow N_r$$

$$M_{d_B} \rightarrow L_{d_a} \rightarrow N_{d_p}$$

$$M_u \rightarrow -L_v \rightarrow N_u$$

In an overall sense the MIL-H-8501A control damping criteria are applicable and readily comparable to present day Navy aircraft. Similar to hover attitude response the adequacy of the criteria is questioned in two areas: Further analysis and data is needed to determine the effect of varied missions and varied rotor configurations.

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- Hover Dynamic Stability; Longitudinal

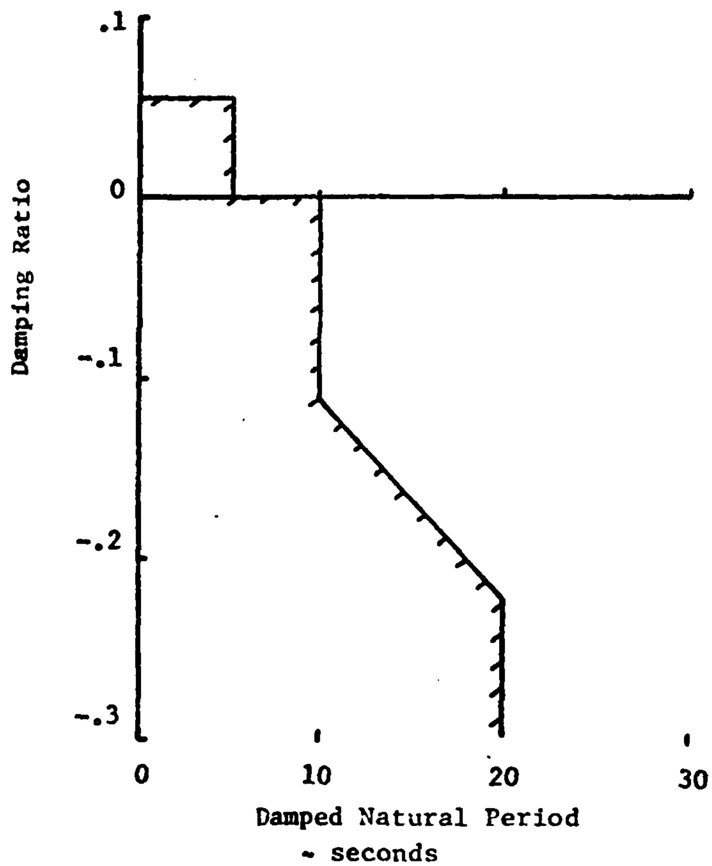
MIL-H-8501A

3.2.11 The helicopter shall exhibit satisfactory dynamic stability characteristics following longitudinal disturbances in forward flight. Specifically, the stability characteristics shall be unacceptable if the following are not met for a single disturbance in smooth air:

a) Any oscillation having a period of less than 5 seconds shall damp to one-half amplitude in not more than 2 cycles, and there shall be no tendency for undamped small amplitude oscillations to persist.
b) Any oscillation having a period greater than 5 seconds but less than 10 seconds shall be at least lightly damped.
c) Any oscillation having a period greater than 10 seconds but less than 20 seconds shall not achieve double amplitude in less than 10 seconds.

3.2.11.1 The following is intended to insure acceptable maneuver stability characteristics. The angular velocity stipulations shall apply at all forward speeds, including hovering.

- After the longitudinal control stick is suddenly displaced rearward from trim a sufficient distance to generate a 0.2 radian/sec pitching rate within 2 seconds, or a sufficient distance to develop a normal acceleration of 1.5 g within 3 seconds, or 1 inch, whichever is less, and then held fixed, the time-history of angular velocity shall become concave downward within 2.0 seconds following the start of the maneuver, and remain concave downward until the attainment of maximum angular velocity; with the exception that for this purpose, a faired curve may be drawn through any oscillations in angular velocity not in themselves objectionable to the pilot. Preferably, the time-history of angular velocity should be distinctly concave downward throughout the period between 0.2 second after the start of the maneuver and the attainment of maximum angular velocity. The figure below is illustrative of the angular velocity response considered acceptable.



- Hover Dynamic Stability; Longitudinal

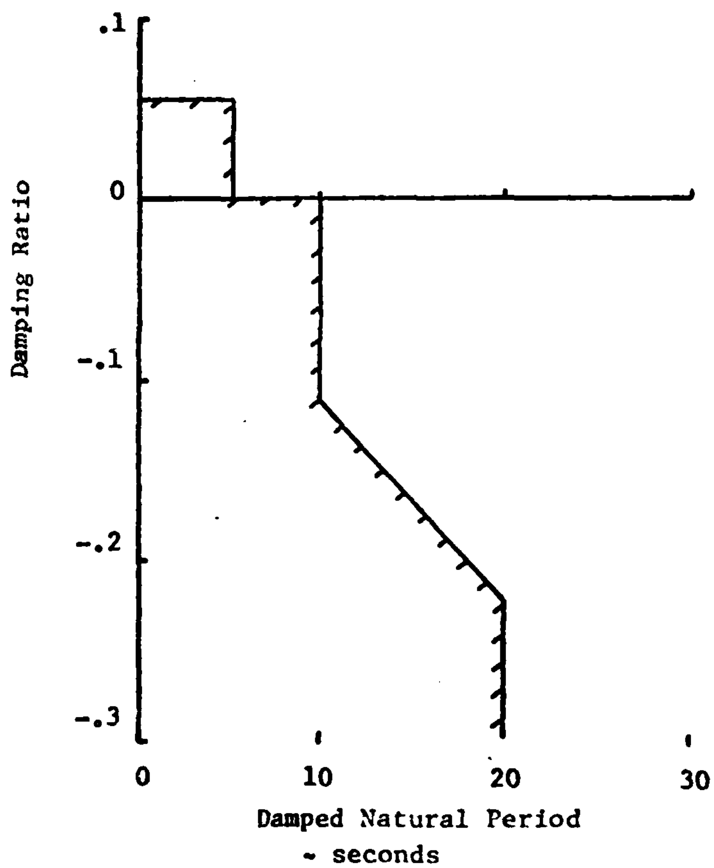
MIL-H-8501A

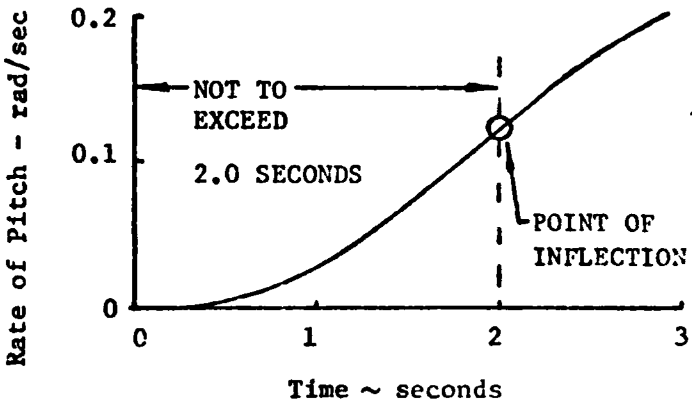
3.2.11 The helicopter shall exhibit satisfactory dynamic stability characteristics following longitudinal disturbances in forward flight. Specifically, the stability characteristics shall be unacceptable if the following are not met for a single disturbance in smooth air:

a) Any oscillation having a period of less than 5 seconds shall damp to one-half amplitude in not more than 2 cycles, and there shall be no tendency for undamped small amplitude oscillations to persist.
b) Any oscillation having a period greater than 5 seconds but less than 10 seconds shall be at least lightly damped.
c) Any oscillation having a period greater than 10 seconds but less than 20 seconds shall not achieve double amplitude in less than 10 seconds.

3.2.11.1 The following is intended to insure acceptable maneuver stability characteristics. The angular velocity stipulations shall apply at all forward speeds, including hovering.

- After the longitudinal control stick is suddenly displaced rearward from trim a sufficient distance to generate a 0.2 radian/sec pitching rate within 2 seconds, or a sufficient distance to develop a normal acceleration of 1.5 g within 3 seconds, or 1 inch, whichever is less, and then held fixed, the time-history of angular velocity shall become concave downward within 2.0 seconds following the start of the maneuver, and remain concave downward until the attainment of maximum angular velocity; with the exception that for this purpose a faired curve may be drawn through any oscillations in angular velocity not in themselves objectionable to the pilot. Preferably, the time-history of angular velocity should be distinctly concave downward throughout the period between 0.2 second after the start of the maneuver and the attainment of maximum angular velocity. The figure below is illustrative of the angular velocity response considered acceptable.





Comments

Following a disturbance (control or wind) to a helicopter in hover the previously discussed rate damping criteria will ensure an initial satisfactory response. After this initial response the aircraft may have an unacceptable oscillatory mode. For any type of hovering operation it is mandatory that the pilot be able to easily correct for unwanted dynamic responses. In the same way that attitude response is the means of developing translational control in hover, uncommanded pitch responses can cause tracking errors and station keeping problems. Uncommanded residual pitch oscillations, would make the helicopter an unacceptable gun platform for example. Short period dynamic responses must be well damped so as not to impede precise control of the aircraft.

Reference (b) presents the point that longitudinal control damping of at least -1 sec^{-1} will automatically damp conventional short-period oscillations. Two problems with this approach are that 1) objectionable phugoid oscillations may still develop, and 2) with the advanced flight control systems being used on helicopters today unconventional oscillatory modes may be generated.

The above MIL-H-8501A criteria specify requirements for oscillatory responses to ensure a dynamically stable/controllable helicopter. Short period modes must be damped while longer period oscillations may be divergent. Note that responses with a damped natural period greater than 20 seconds need not satisfy the criteria.

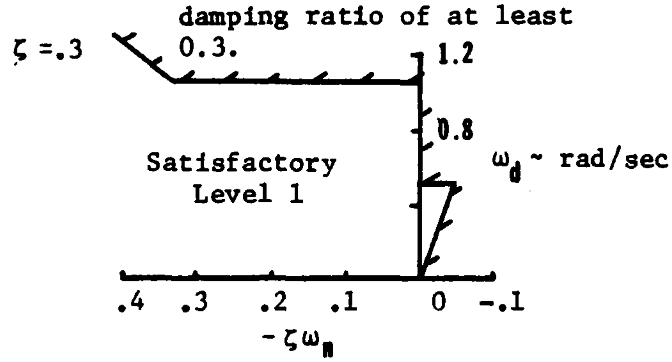
The SH-2F and CH-53E type specifications use the above criterion for longitudinal dynamic stability requirements.

2

MIL-F-83300

3.2.2.1 Pitch Dynamic Response Requirements. The following requirements shall apply to the dynamic responses of the aircraft with the cockpit controls free and with them fixed following an external disturbance or an abrupt pitch or roll control input in either direction. The requirements apply for responses of any magnitude that might be experienced in operational use. If oscillations are nonlinear with amplitude, the oscillatory requirements shall apply to each cycle of the oscillation.

Level 1: All aperiodic responses (real roots of the longitudinal characteristic equation) shall be stable. Oscillatory modes of frequency greater than 0.5 radians per second shall be stable. Oscillatory modes with frequency less than or equal to 0.5 radians per second may be unstable provided the damping ratio is less unstable than -.10. Oscillatory modes of frequency greater than 1.1 radians per second shall have a damping ratio of at least 0.3.



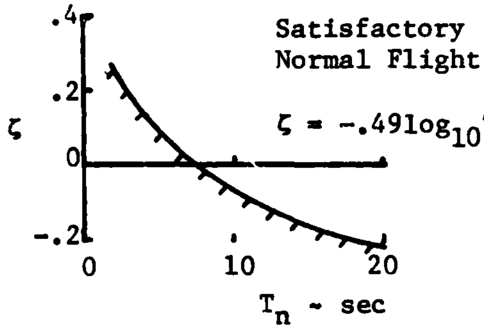
Comment - MIL-F-83300 presents the dynamic response criteria in terms of simple second-order response parameters. For high frequency (short period) oscillations the response must be damped. The longer period responses can be unstable as long as they meet the $\zeta \geq -.10$ restriction.

AGARD 577

2.8 Longitudinal Dynamic Stability. The responses of the aircraft should not be divergent (i.e., all roots of the longitudinal characteristic equations should be stable). In addition the damping ratio of the second-order pair of roots that primarily determine the short-term response of angle of attack and pitch attitude following an abrupt pitch control input should be at least 0.3 for the most critical undamped natural frequency.

The frequency and damping characteristics of any oscillation superimposed on the normal control modes for VTOL aircraft in hover should meet at least the value shown in the figure below. Any sustained residual oscillations should not degrade the pilot's ability to perform the required tasks.

These criteria apply with the pitch cockpit control free and fixed.



Comment - The above AGARD 577 boundary was generated by using qualitative pilot rating data from numerous flight tests on helicopters and fixed wing VSTOL aircraft. Similar to MIL-F-83300 the criteria is defined in terms of second order response parameters. For oscillations with an undamped natural period greater than 20 seconds the following equation applies.

$$\zeta = -1.15 \log_{10} T_n + 1.29$$

$$\text{for } T_n > 20 \text{ sec}$$

The range of periods to be considered for the above short period requirement is 3 to 6 seconds.

SH-60B TYPE SPEC

10.3.3.2 <u>Longitudinal</u> <u>Dynamic</u> <u>Stability</u>. The following conditions shall be met for a single disturbance in smooth air with controls fixed. These conditions shall also apply to all permissible airspeeds, rotor rpm and loadings, both in straight, climbing, descending, and turning flight, and at high, medium, and low altitude.

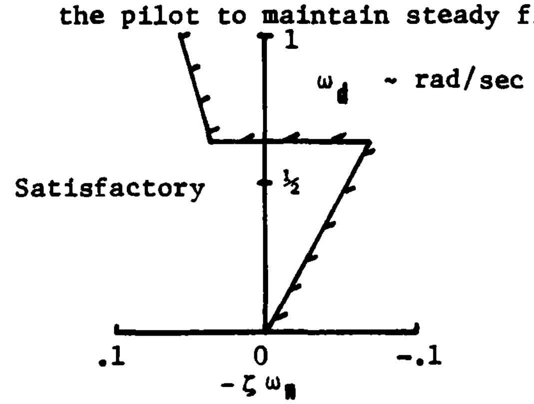
a) Any oscillation having a period of less than 10 seconds, shall damp to one-half amplitude in not more than two cycles. There shall be no tendency for undamped small oscillations to persist.

b) Any oscillation having a period greater than 10 seconds shall not achieve double amplitude in less than one cycle.

c) There shall be no tendencies for small amplitude, short period residual oscillations to exist.

d) There shall be no objectionable flight characteristics attributable to apparent poor phugoid damping.

e) There shall be no tendency for a sustained or uncontrollable oscillation resulting from efforts of the pilot to maintain steady flight.



Comment - Because the MIL-H-8501A longitudinal dynamic stability criteria were found to be inadequate for current ASW mission requirements, the above criteria was included in the SH-60B handling qualities type specification to give stricter design guidance for hovering and forward flight dynamic stability.

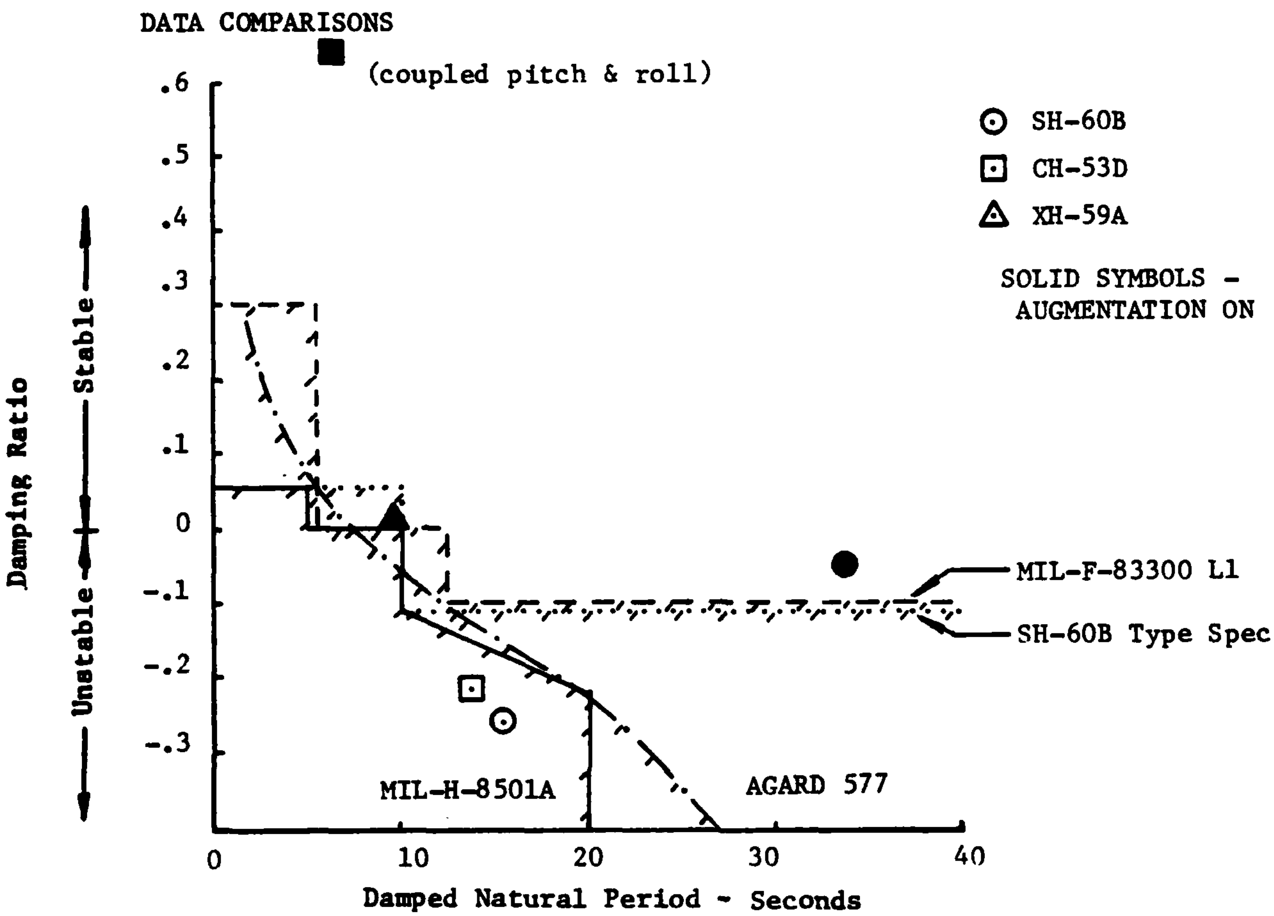
- Hover Dynamic Stability; Longitudinal

SPECIFICATION COMPARISONS

All of the specifications reviewed use second-order response parameters to define satisfactory boundaries for dynamic stability characteristics. This is in contrast to the reference (b) conclusion that ζ, ω parameters are not by themselves good correlators of handling qualities. The general trend is similar for all criteria such that short period oscillations require a damped response while for longer periods divergent conditions are acceptable. The MIL-H-8501A requirements are by far the most lenient, particularly for longer period responses. The SH-60B type specification criteria is more in line with the VSTOL specifications.

It should be noted that MIL-F-83300 combines pitch and roll hover dynamic stability. In hover lateral axis stability and control characteristics tend to be very similar to the longitudinal axis, as discussed in the control response section. MIL-H-8501A, AGARD 577 and the SH-60B type specification have general formats of longitudinal criteria and lateral-directional criteria. This type of a breakdown does not easily allow for the combination of longitudinal and lateral criteria for hovering flight.

- Hover Dynamic Stability; Longitudinal



For the limited data available very few conclusions can be drawn about the adequacy of the specification boundaries. Of the three aircraft analyzed only the SH-60B model shows a conventional phugoid mode. The XH-59A has a neutrally stable longitudinal oscillation of moderate frequency. Labeling this mode a phugoid is questionable due to the 10 second period. The response satisfies all the specifications anyway. The CH-53D model shows a heavily damped coupled pitch and roll oscillation. Many helicopters show this type of a coupled longitudinal-lateral response in hover.

Reference (c) presents the point that for modern helicopters the above MIL-F-83300 boundary is generally undemanding. This is debatable in light of the fact that the SH-60B type specification criteria is more lenient than the MIL-F-83300 criteria. The plot format used above was chosen as a suitable compromise between the various specification formats.

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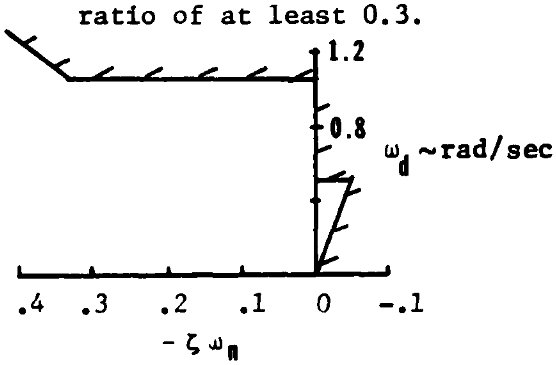
- Hover Dynamic Stability; Lateral

MIL-H-8501A	Comments
Lateral hover dynamic stability for VFR conditions is not included within MIL-H-8501A.	The lateral dynamic stability characteristics of a hovering helicopter, like longitudinal dynamic stability, directly effect a pilot's ability to precisely control and maneuver the aircraft. Oscillations must be stable enough to keep the vehicle from developing significant lateral translations. The SH-2F and CH-53E type specifications like MIL-H-8501A do not have VFR lateral dynamic stability requirements for hover.

MIL-F-83300

3.2.2.1 Roll Dynamic Response Requirements. The following requirements shall apply to the dynamic responses of the aircraft with the cockpit controls free and with them fixed following an external disturbance or an abrupt pitch or roll control input in either direction. The requirements apply for responses of any magnitude that might be experienced in operational use. If oscillations are nonlinear with amplitude, the oscillatory requirements shall apply to each cycle of the oscillation.

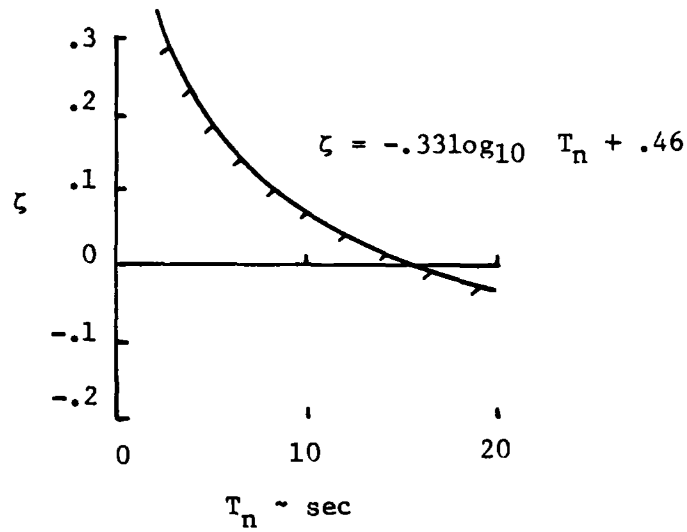
Level 1: All aperiodic responses (real roots of the lateral-directional characteristic equation) shall be stable. Oscillatory modes of frequency greater than 0.5 radians per second shall be stable. Oscillatory modes with frequency less than or equal to 0.5 radians per second may be unstable provided the damping ratio is less unstable -.10. Oscillatory modes of frequency greater than 1.1 radians per second shall have a damping ratio of at least 0.3.



Comment - The above criteria for roll dynamic stability is the same as that specified for longitudinal dynamic stability. MIL-F-83300 combines pitch and roll dynamic stability in hover because the pilot tends to use pitch and roll controls similarly in hovering flight. There are also many helicopters, in particular single rotor, that have a coupled pitch-roll oscillation.

AGARD 577

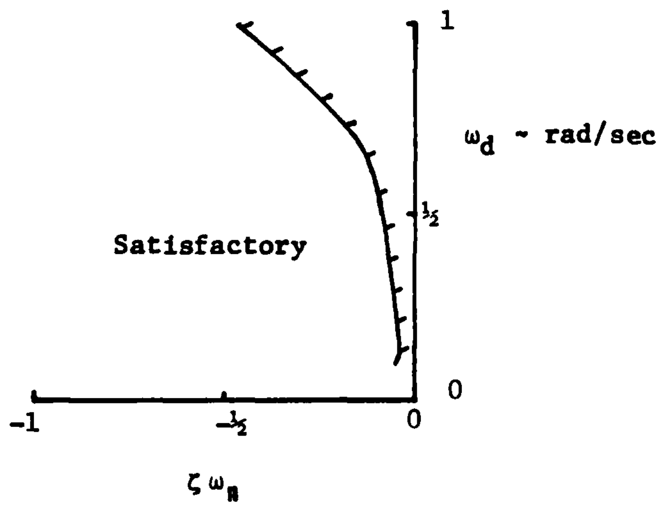
3.19 Lateral-Directional Dynamic Stability. Any roll yaw oscillations superimposed on the normal control mode due to a disturbance input should exhibit at least the frequency-damping characteristics shown in the figure below for hovering flight. Also, there should be no tendency for perceptible small-amplitude oscillations to persist or for pilot-induced oscillations to result from the pilot's attempts to perform the required flight tasks.



Comment - Similar to MIL-H-8501A the AGARD VSTOL specification is divided into longitudinal and lateral-directional criteria. Thus, the lateral and directional dynamic stability characteristics are combined. The above boundary was generated by fitting constant level 1 pilot ratings. Some of the flight test data used in the criteria analysis was from a light weight single rotor helicopter. Second order responses were superimposed on first order roll and yaw responses to see the effect on pilot workload.

SH-60B TYPE SPEC

10.3.4.3 Lateral-Directional Stability. Lateral-directional oscillations with controls fixed or free following a single disturbance in smooth air shall exhibit minimum damping characteristics as a function of the damped natural frequency corresponding to the figure below. In addition, any oscillation having a period greater than 10 seconds shall not achieve double amplitude in less than one cycle. There shall be no tendency for undamped small oscillations to persist.



Comment - The above criteria was added to the SH-60B type specification to cover VFR hover lateral dynamic stability; a characteristic not addressed by MIL-H-8501A.

- Hover Dynamic Stability; Lateral

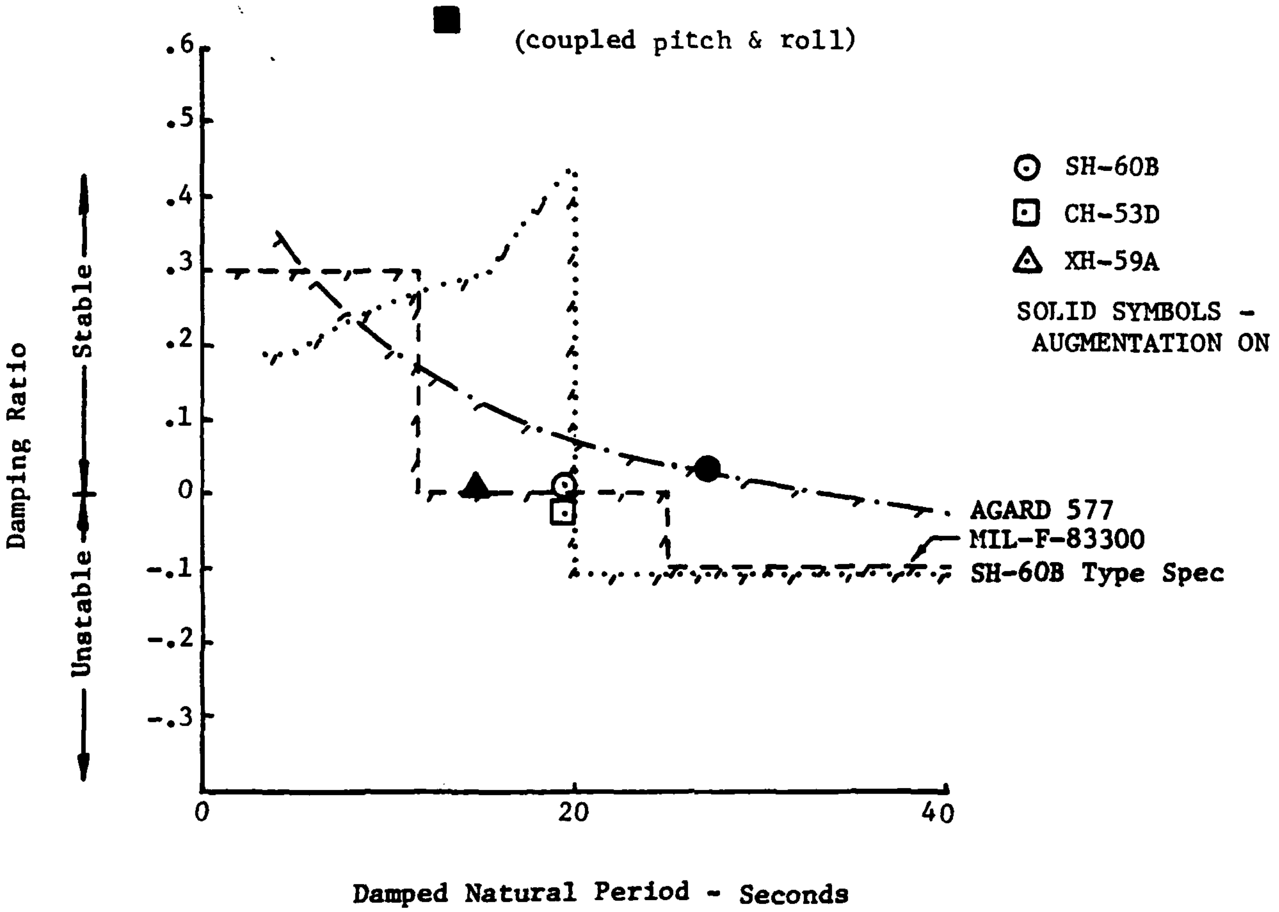
SPECIFICATION COMPARISONS

MIL-H-8501A is the only specification reviewed that does not address VFR lateral dynamic stability. Each of the other specifications present second order response boundaries for any lateral oscillations the vehicle develops.

Other comments are discussed in longitudinal hover dynamic stability specification comparisons.

- Hover Dynamic Stability; Lateral

DATA SPECIFICATIONS



For the limited data available no conclusions can be drawn on the adequacy of any of the specifications. The SH-60B type specification boundary was generated for the UH-60A Army UTTAS. The reason for the sharp increase in damping for oscillations of moderate period is not readily apparent. The SH-60B has a lateral phugoid mode that easily meets the requirement. The XH-59A roll oscillation was qualitatively described as being slightly coupled to pitch, though not objectionable. This response satisfies only the MIL-F-83300 criteria. The CH-53D has the heavily damped coupled pitch roll response shown on the longitudinal dynamic stability plot.

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- Hover Dynamic Stability; Directional

MIL-H-8501A	Comments
Directional hover dynamic stability criteria for VFR conditions is not included within MIL-H-8501A.	Heading oscillatory stability for a hovering helicopter is just as necessary as pitch and roll stability. For shipboard helicopter operations uncommanded yaw oscillations are a safety hazard (especially for single rotor helicopters) as well as making pilot sighting more difficult. Large residual yaw oscillations would be unacceptable for a gun platform. Single rotor helicopters tend to be very susceptible to lateral gusts causing yaw responses. Most helicopters today, however, do have heading hold functions to reduce gust effects. MIL-H-8501A addresses VFR directional stability with the previously discussed yaw rate damping criteria. Second order type responses are not accounted for. Like MIL-H-8501A, the SH-2F and CH-53E type specifications do not include directional dynamic stability criterion for VFR hovering conditions.

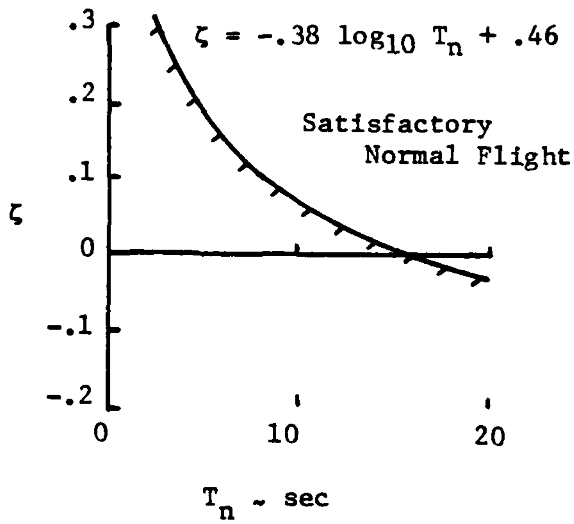
MIL-F-83300

Hover directional dynamic stability addressing yaw oscillatory responses is not included as a criteria in MIL-F-83300.

Comment - Like MIL-H-8501A directional dynamic stability is addressed by MIL-F-83300 only with yaw rate damping.

AGARD 577

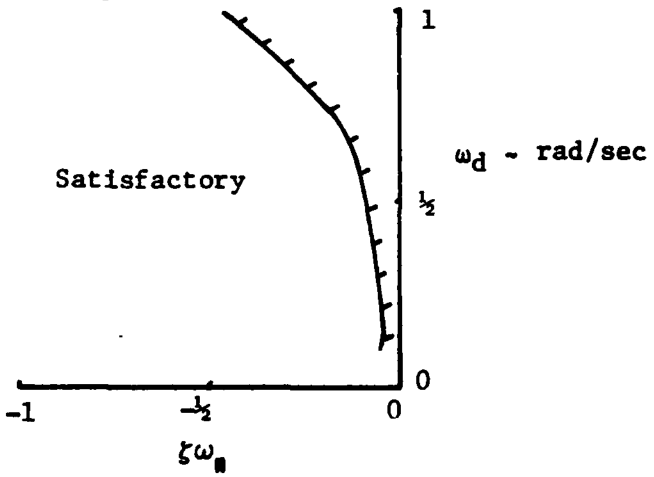
3.19 Lateral-Directional Dynamic Stability. Any roll-yaw oscillations superimposed on the normal control mode due to a disturbance input should exhibit at least the frequency-damping characteristics shown in the figure below for hovering flight. Also, there should be no tendency for perceptible small-amplitude oscillations to persist or for pilot-induced oscillations to result from the pilot's attempts to perform the required flight tasks.



Comment - Same as lateral hover dynamic stability.

SH-60B TYPE SPEC

10.3.4.3 Lateral-Directional Stability. Lateral-directional oscillations with controls fixed or free following a single disturbance in smooth air shall exhibit minimum damping characteristics as a function of the damped natural frequency corresponding to the figure below. In addition, any oscillation having a period greater than 10 seconds shall not achieve double amplitude in less than one cycle. There shall be no tendency for undamped small oscillations to persist.



Comment - The above criteria was added to the SH-60B type specification to address VFR directional dynamic stability, which is not addressed by MIL-H-8501A.

- Hover Dynamic Stability; Directional

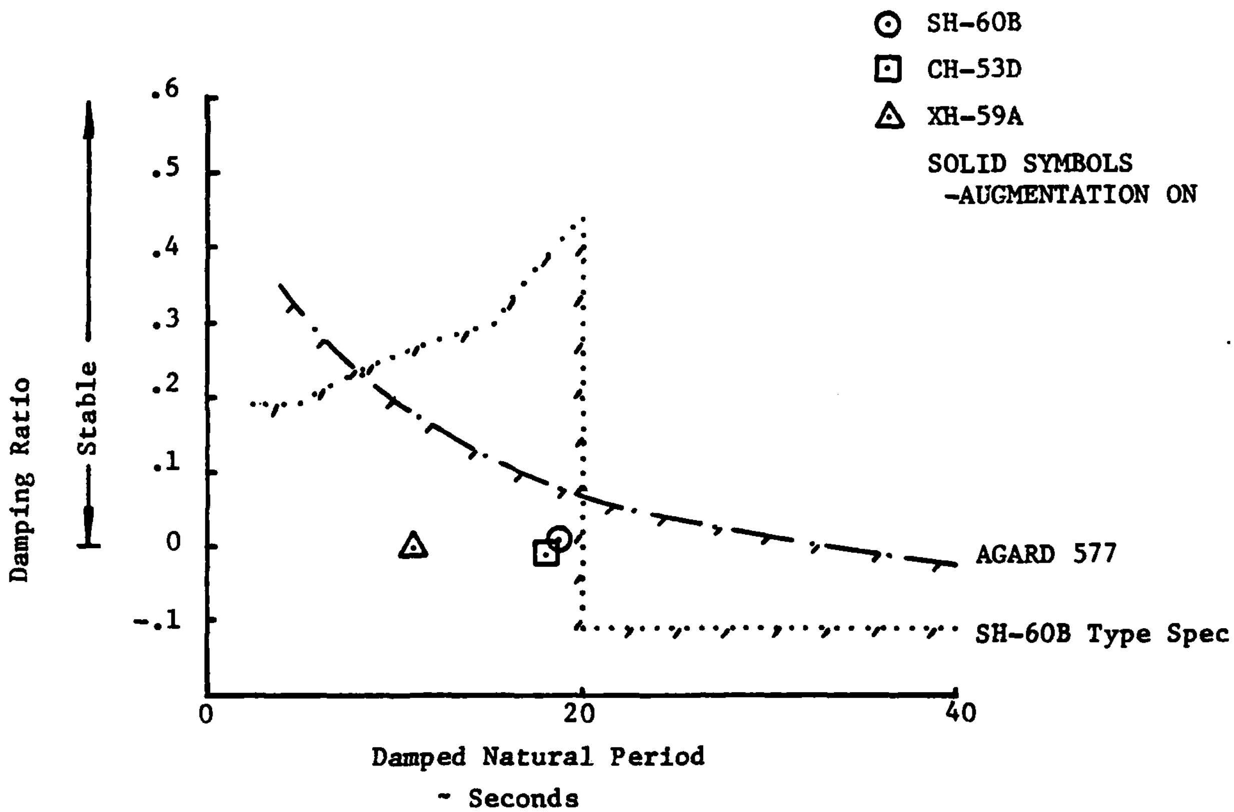
SPECIFICATION COMPARISONS

Both AGARD 577 and the SH-60B type specification have criterion for VFR hover directional dynamic stability. MIL-F-83300 and MIL-H-8501A have yaw rate damping limitations only.

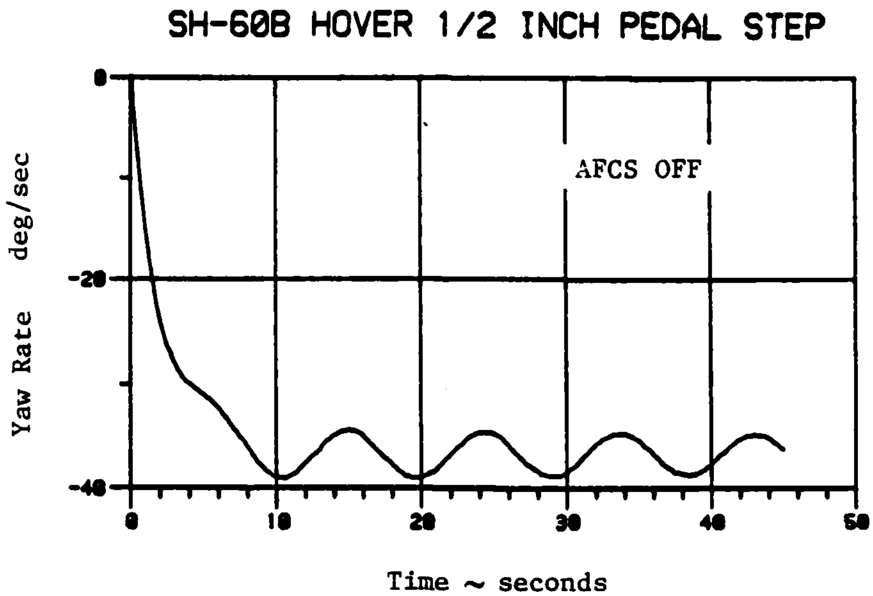
Other comments on specification format as presented in longitudinal and lateral hover dynamic stability specification comparisons.

- Hover Dynamic Stability; Directional

DATA COMPARISONS



With their Automatic Flight Control Systems (AFCS) off the SH-60B and CH-53D show directional oscillations that are neutrally stable. Time histories of the modelled responses are shown in figure 6. The resulting yaw motion from a one-half inch pedal pulse for both vehicles is a moderate frequency oscillation superimposed on a first order response. For AFCS on flight both the SH-60B and CH-53D have pure aperiodic directional responses, thus easily satisfying the AGARD 577 and the SH-60B type specification criterion. The XH-59A has a yaw oscillatory of moderate frequency that is slightly coupled to pitch and roll. Pilot comment in reference (j) describes this pitch-roll-yaw coupling as a characteristic unique to the ABC rotor system downwash/ground effects on the cylindrical XH-59A fuselage. Because the XH-59A has no augmentation in the directional axis it would not satisfy the AGARD or SH-60B criteria.



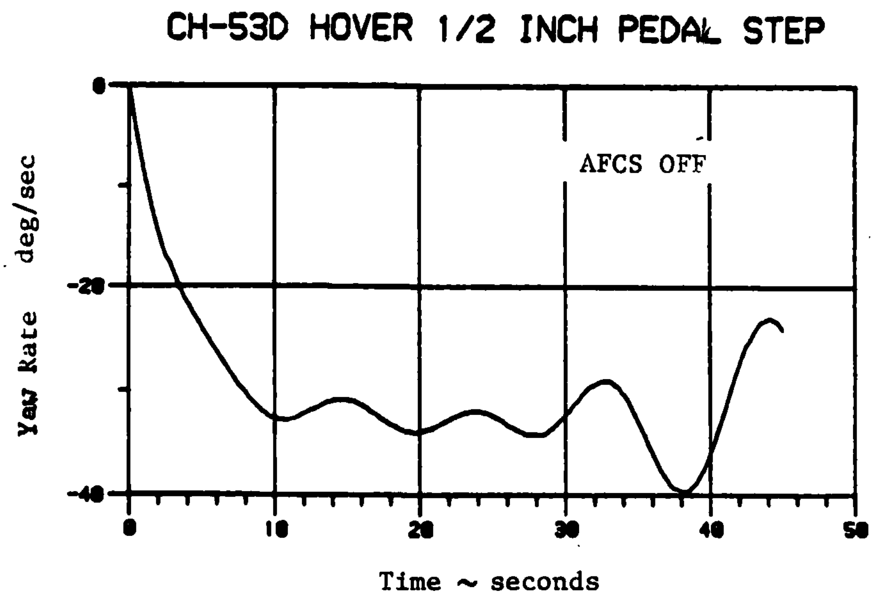


Figure 6. SH-60B and CH-53D Hover Heading Time Histories

- Hover Dynamic Stability

The unique hover dynamic stability characteristics of helicopters are addressed explicitly by MIL-F-83300 only. The hover, low speed and forward flight divisions allow MIL-F-83300 to combine pitch and roll dynamic stability for hovering flight. MIL-H-8501A, AGARD 577 and the SH-60B type specification have only longitudinal and lateral-directional criteria divisions. The only VFR dynamic stability criteria in MIL-H-8501A is for longitudinal characteristics. MIL-H-8501A does not give adequate guidance for VFR lateral, or directional dynamic stability design criteria.

For normal flight conditions the CH-53D model shows essentially dead beat responses for longitudinal, lateral, or directional disturbances. The CH-53D does have a coupled pitch-roll oscillation, characteristic of single rotor helicopters in hover. Each of the CH-53D dynamic modes easily satisfies all the specifications criteria. The SH-60B model with augmentation engaged has a longitudinal phugoid and a lateral phugoid. Both responses are neutrally stable, but of long enough period to pass the comparison criteria. The SH-60B like the CH-53D has a nonoscillatory directional mode in hover for augmentation on conditions. The other aircraft used in the data comparisons, the XH-59A, has a pitch-roll-yaw coupled response unique to the ABC rotor system. The response is primarily a pitch and roll oscillation, although yaw deviations were noticed for in-ground-effect hover conditions. The roll and yaw dynamic response would not satisfy the AGARD 577 or the SH-60B type specification lateral-directional criteria. Qualitative rating of the XH-59A hover dynamic response were satisfactory until an in-ground-effect (< 10 feet) hover was attempted. Uncommanded lateral and directional responses developed in this low hover condition required frequent pilot inputs for correction.

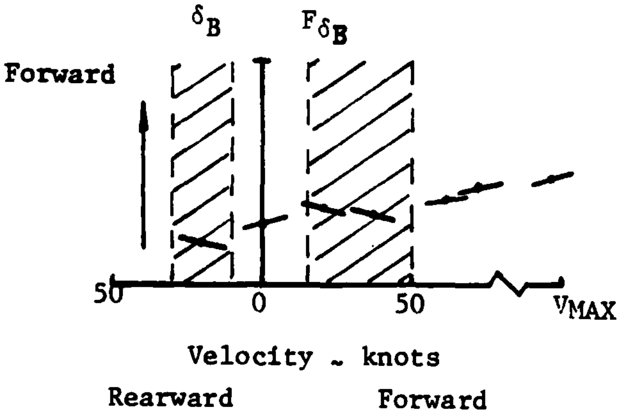
MIL-H-8501A should include VFR hover dynamic stability criteria for lateral and directional responses. Although the CH-53D and SH-60B have aperiodic yaw modes for augmentation on flight, the XH-59A in hover does have an inherent directional oscillation. Flying qualities design criteria for hover roll and yaw dynamic stability should be available for future rotary wing vehicles like the ABC.

FORWARD FLIGHT

- Forward Flight Static Stability; Longitudinal

MIL-H-8501A

3.2.10 The helicopter shall, at all forward speeds and at all trim and power conditions specified in the table below, possess positive, static longitudinal control force, and control position stability with respect to speed. This stability shall be apparent in that at constant throttle and collective pitch-control settings a rearward displacement of and pull force on the longitudinal-control stick shall be required to hold a decreased value of steady, forward speed, and a forward displacement and push force be required to hold an increased value of speed. In the speed range between 15 and 50 knots forward, and 10 to 30 knots rearward, the same characteristics are desired, but a moderate degree of instability may be permitted. However, the magnitude of the change in the unstable direction shall not exceed 0.5 inch for stick position or 1.0 pound for stick force.



- allowable amounts of instability:
  ± ½ inch long stick position
  ± 1 lb long stick force

Comments

One of the primary flying qualities characteristics a helicopter pilot senses in forward flight is the aircraft static stability margin. Through stable longitudinal control position and force variations with respect to speed and attitude the pilot can keep airspeed and attitude deviations from trim to a minimum. Stable gradients are as described in 3.2.10.

MIL-H-8501A requires a helicopter to demonstrate positive longitudinal static stability for control force and control position variations with airspeed. Note that for transition airspeeds the gradients may be slightly unstable. Many single rotor helicopters show this characteristic (control stick position reversals) during transition as the main rotor downwash sweeps over the stabilizer surface at the tail.

The SH-60B, SH-2F and CH-53E type specifications use this criteria for longitudinal static stability requirements.

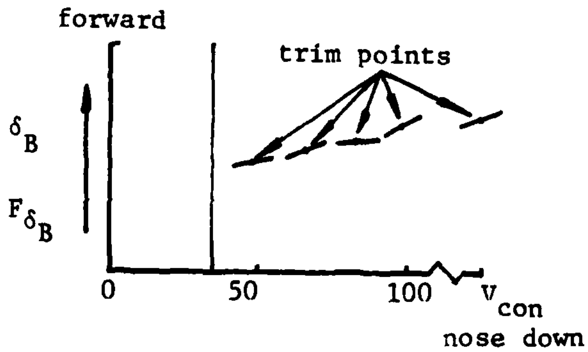
Initial trim & power condition	Speed range of interest
Hovering	0 to 30 kts
Level flight at 35 kts . . .	15 to 60 kts
Level flight at 80% Vmax . .	60% Vmax to Vmax
Level flight at Vmax	80% Vmax to Vlim
Climb at best rate of climb.	Vmax R/C ± 15 kts
Partial power descent. . . . at 300 to 500 fpm	15 to 60 kts
Autorotation with trim as. . in "Level flight at 80% Vmax" above	60% Vmax to Vmax for autorotation
Autorotation at speed for. . minimum rate of descent	15 kts to Vtrim +20 kts

MIL-F-83300

3.3.1 Longitudinal Equilibrium. With the aircraft trimmed at speeds from 35 knots forward to V_{con}, the following requirements shall be satisfied for perturbations of $\pm$ 10 knots from the trim speed except where limited by the boundaries of the Service Flight Envelope. The configuration and trim may be different at each trim condition, but shall remain fixed while determining the control gradients.

Level 1: The variations of pitch control force and control position with pitch attitude and airspeed shall be smooth and the local gradients stable or zero.

Stable pitch control gradients mean that incremental pull force and aft displacement of the cockpit control are required to maintain nose-up attitudes or slower airspeeds and the opposite to maintain nose-down attitudes or higher airspeeds. The term gradient does not include that portion of the control force or control position versus pitch attitude or airspeed curve within the preloaded breakout force or friction band.



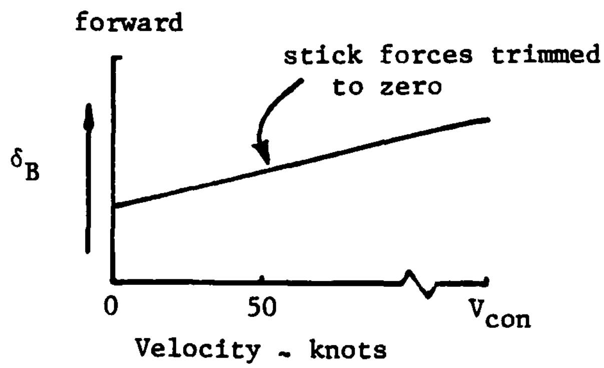
Velocity ~ knots,
Attitude ~ degrees

Comments

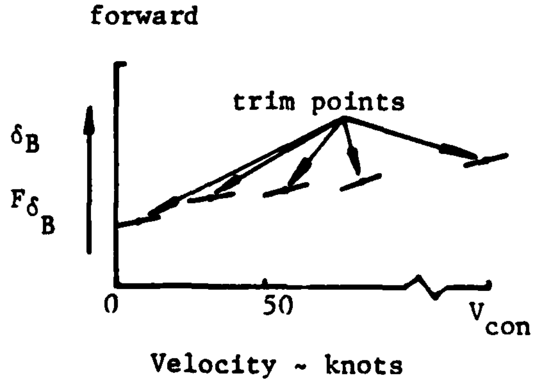
MIL-F-83300 requires for level 1 flying qualities that the aircraft have neutral or positive static stability for longitudinal control force and position. This stability of control force and position is with respect to airspeed and attitude. Also the aircraft need only demonstrate positive stability above 35 knots. The above criteria also explictly states the range about trim that positive stability must be demonstrated for, namely $\pm$ 10 knots about the trim airspeed. This range was decided upon under the assumption that a VSTOL aircraft will reconfigure or retrim for a larger speed variation.

AGARD 577

2.6.1 Trim Speed Stability. With the pitch cockpit control forces continuously trimmed to zero at airspeeds covering the range from V_{con} to hover, the curve of pitch control position versus airspeed should not be negative, that is, forward control deflection associated with decreasing trim airspeed and vice versa. These requirements should be satisfied in level, descending, and climbing flight.



2.6.2 Stability With Respect to Speed. With the pitch trim, thrust vector, throttle, or collective controls at the trim setting, the variation of pitch control position and force with airspeed should be in a stable direction over a range of approximately ± 10 knots about the trim speed. If speed stability is obtained by means of a SAS, SAS failure should result in only mild instability (more than 5 seconds for divergence to double in amplitude). In addition, the pilot should be made aware of any unstable variation in pitch control as a warning of the possibility of insufficient control for recovery.



Comments

Similar to MIL-F-83300 paragraph 3.3.1 the above AGARD criteria (2.6.2) requires positive longitudinal control position and force stability over a ± 10 knot range about the trim airspeed. Positive stability with respect to pitch attitude is not required. Also, the vehicle must be statically stable for all airspeeds, zero to V_{con}.

AGARD 577 includes another criteria requiring positive speed stability for the trimmed control position curve, as shown above.

- Forward Flight Static Stability; Longitudinal

SPECIFICATION COMPARISONS

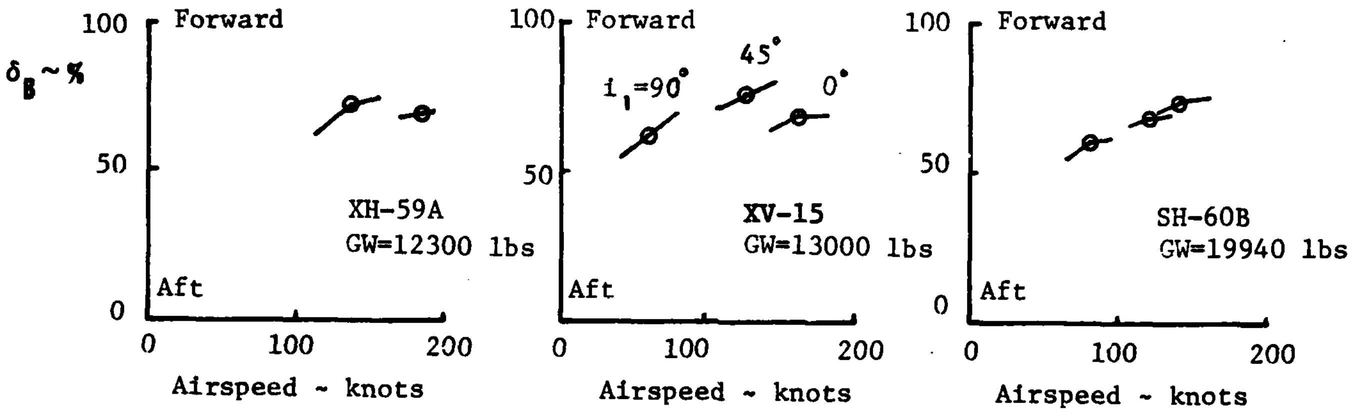
Each of the specifications reviewed has a requirement for longitudinal static stability. The basic stipulation is that positive control position and control force gradients be demonstrated with respect to speed. There are noteworthy differences though. MIL-H-8501A is the only specification reviewed that allows for static position and force instability in a limited and defined range. It has been proposed that limited stick position instability be permitted as long as the control force gradient is stable with speed. Recent simulator tests have shown that for IFR conditions pilots desire both control force and position stability with respect to speed. The SH-60B was designed for positive stick position and force stability by making the stabilizer movable, and scheduled to the vehicle airspeed.

Another difference between the specifications is that both MIL-F-83300 and AGARD 577 quantify that positive stability must exist for $\pm$ 10 knots about the trim airspeed, while MIL-H-8501A does not define a speed pertubation range. It is not clear whether static longitudinal stability be required for $\pm$ 10, $\pm$ 2 or $\pm$ 50 knots about the trimmed airspeed. In their review of MIL-F-83300 Green and Richards (reference (c)) state that the $\pm$ 10 knot pertubation is too lenient for helicopters, suggesting instead that the range be $\pm$ 50 knots or $\pm$ (10 knots + .1 V_{trim}) whichever is less. This will be further discussed in the data comparisons.

Another difference is that MIL-F-83300 requires positive stability with pitch attitude as well as airspeed. Neither AGARD 577 or MIL-H-8501A require this. Also only AGARD 577 requires that the trimmed stick position curve always be stable. The data comparisons will address these considerations.

- Forward Flight Static Stability; Longitudinal

DATA COMPARISONS

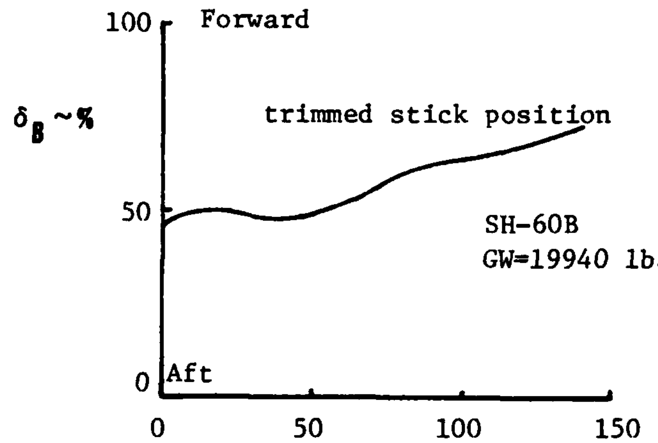


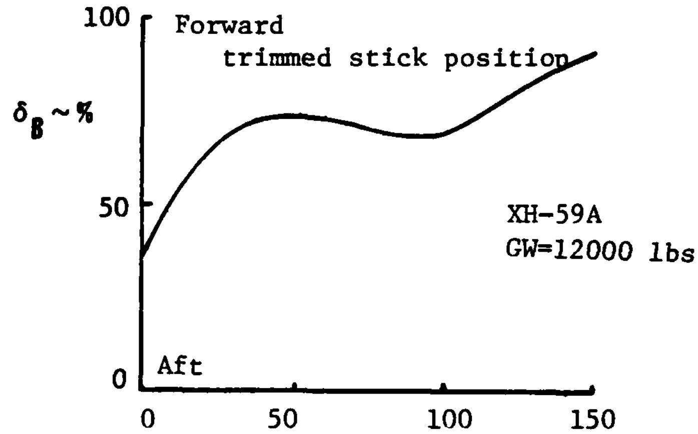
For the airspeeds tested for the XH-59A and XV-15, and those modelled for the SH-60B, the vehicles satisfied all the specifications requirements. That is each aircraft demonstrated positive longitudinal stick position static stability with respect to speed. The XH-59A and XV-15 were described as having adequate cues to allow the pilot to make small airspeed changes. The attitude stability of the XH-59A was qualitatively tested and described as adequate. The 11 degree nose down trim attitude at 156 knots did not draw adverse pilot comments. Attitude stability was not tested for or explicitly addressed in the XV-15 test program. The pilots were satisfied with both of the vehicles speed stability characteristics.

The pertubation range used to test for static stability varied for each aircraft. The XV-15 was perturbed ± 20 knots from the trim airspeed while the XH-59A was perturbed 10 to 35 knots from the trim speed. Although the SH-60B model was reviewed against the type specification, an arbitrary range of ± 15 knots was used for the test. What the velocity pertubation should qualitatively be is debatable, but for consistency a range should be explicitly presented in the helicopter flying qualities specification. The two aircraft tested were qualitatively found to have satisfactory control force gradients. The SH-60B control system is configured such that control force is directly proportional to control displacement according to reference (n), thus satisfying the specifications.

- Forward Flight Static Stability; Longitudinal

DATA COMPARISONS



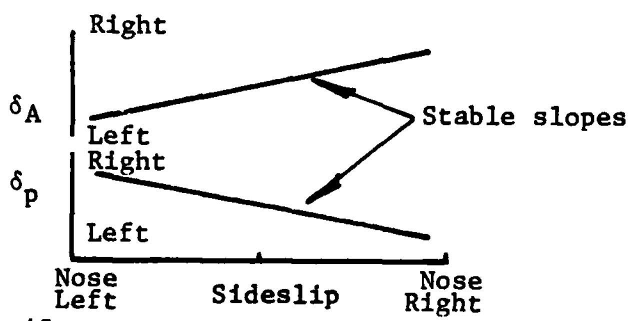


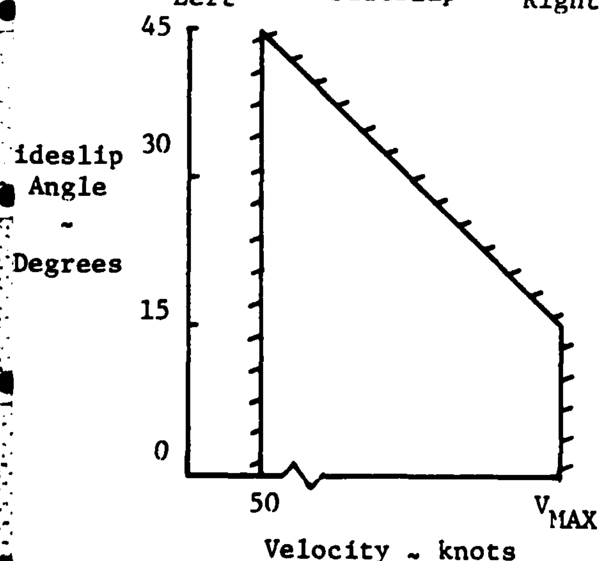
The above figures present the longitudinal stick trimmed position curves for the SH-60B and the XH-59A. The only specification directly addressing this characteristic is AGARD 577. Neither of the above vehicles satisfy the AGARD requirement which specifies that negative slopes are unacceptable. The SH-60B has a slight reversal in trimmed stick position in the low speed range that has been qualitatively described as acceptable. There have been modifications to the airspeed sensing system, and thus to the horizontal stabilizer to minimize the above negative slope. The XH-59A has a fairly large reversal in stick position which has been associated with the large tail surfaces. The trim requirements of the XH-59A were described as satisfactory by Navy pilots although moderate pilot compensation was required. The XH-59A tail surfaces are being redesigned to alleviate some of these problems.

- Forward Flight Static Stability; Lateral-Directional

MIL-H-8501A

3.3.9 The helicopter shall possess positive, control fixed, directional stability, and effective dihedral in both powered and autorotative flight at all forward speeds above 50 knots, 0.5 V_{max}, or the speed for maximum rate of climb, whichever is the lowest. At these flight conditions with zero yawing and rolling velocity, the variations of pedal displacement and lateral control displacement with steady sideslip angle shall be stable (left pedal and right stick displacement for right sideslip) up to full pedal displacement in both directions, but not necessarily beyond a sideslip angle of 15 degrees at V_{max}, 45 degrees at the low speed determined above, or beyond a sideslip angle determined by a linear variation with speed between these two angles. Between sideslip angles of $\pm$15 degrees, the curve of pedal displacement and lateral control displacement plotted against sideslip angle shall be approximately linear.





Comments

Lateral-directional static stability characteristics, like the longitudinal axis, are used by a helicopter pilot to setup and maintain a specific flight path. Steady sideslip (i.e., cross wind landings) flight is very common in helicopter missions.

The requirement addressing lateral-directional stability for helicopters calls for positive directional stability and positive effective dihedral. Thus the lateral and directional controls should be displaced in a stable sense as the vehicle sideslip varies. There is a separate paragraph requiring positive slopes for lateral stick force versus displacement curves. Directional control force stability is not addressed. For the helicopters analyzed the lower velocity used for determining the sideslip range was 50 knots.

The CH-53E and SH-2F type specifications both use the above criteria for lateral-directional static stability guidelines.

3.3.11 Lateral-Directional Characteristics in Steady Sideslips. The requirements of 3.3.11.1 through 3.3.11.3 are expressed in terms of characteristics in yaw-control-induced steady zero-yaw-rate sideslips with the aircraft trimmed for zero-bank-angle straight flight. Sideslip angles to be demonstrated shall be the lesser of 25 degrees or $\sin^{-1}$ (30/airspeed in knots). In any event, the minimum sideslip to be demonstrated shall be the lesser of 15 degrees or $\sin^{-1}$ (30/airspeed in knots).

3.3.11.1 Yawing Moments in Steady Sideslip. For the sideslips specified in 3.3.11, right yaw control deflection and force shall be required in left sideslips and left yaw control force and deflection shall be required in right sideslips.

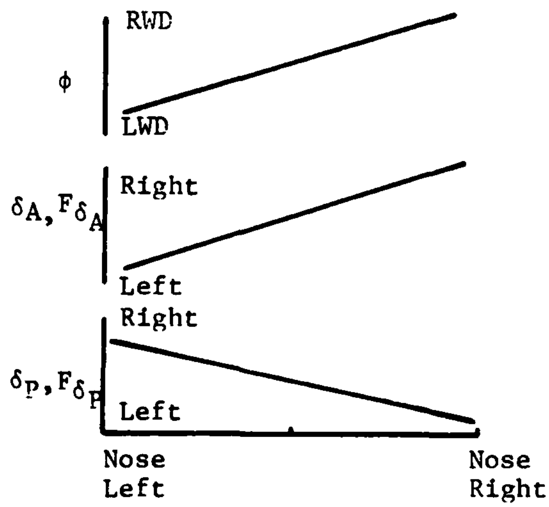
For levels 1 and 2, the following requirements apply. The variation of sideslip angle with yaw control deflection and force shall be essentially linear for sideslip angles between + 15 and - 15 degrees. For larger sideslip angles, an increase in yaw control deflection shall always be required for an increase in sideslip and, although a reduction of yaw control force gradient is acceptable outside this range, the following requirements shall apply.

Level 1: The gradient of sideslip angle with yaw control force shall not reverse slope.

The term gradient does not include that portion of the yaw control force versus sideslip-angle curve within the preloaded breakout force or friction band.

3.3.11.2 Bank Angle in Steady Sideslips. For the sideslips specified in 3.3.11, an increase in right bank angle shall accompany an increase in right sideslip, and an increase in left angle shall accompany an increase in left sideslip.

3.3.11.3 Rolling Moments in Steady Sideslips. For the sideslips specified in 3.3.11, left roll control deflection and force shall be required in left sideslips, and right roll control deflection and force shall be required in right sideslips. For levels 1 and 2, the variation of roll control deflection and force with sideslips angle shall be essentially linear.



Sideslip ~ Degrees

Comments - The above group of criteria address the lateral and directional control displacement and force characteristics in forward flight. Positive stability must be demonstrated for both displacement and force gradients with respect to sideslip deviations. Bank angle variations with respect to sideslip angles are also defined.

AGARD 577

3.10 Dihedral Effect. For operation *at and above the reference approach* speed and for the sideslip conditions specified, the rolling moment variation with sideslip should be such that for conventional control systems left roll control deflection and force are required in left sideslips and vice versa.

The variation of roll cockpit control deflection and force with sideslip angle should be essentially linear.

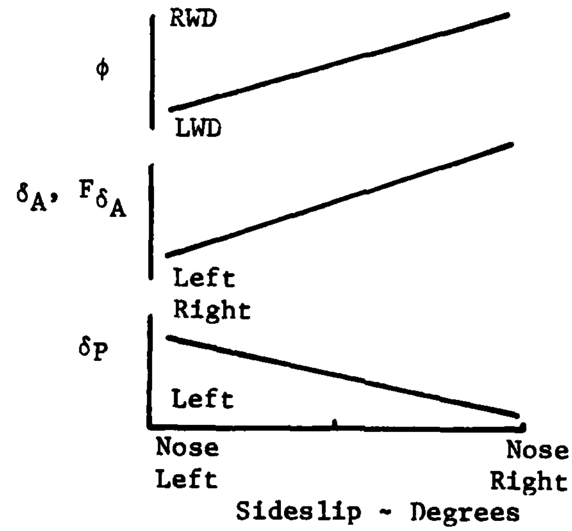
The positive effective dihedral should be limited so that sufficient roll control remains to correct for gusts or other self-induced upsets and to maneuver as required with a force not to exceed 10 lb for maximum sideslip angles that may be experienced in operational flying.

3.17 Directional Characteristics in Steady Sideslip. For the sideslip angles obtainable in the speed range from 30 knots to V_{con}, right yaw cockpit control deflection should be required for left sideslips and vice versa.

For angles of sideslip around $\pm$ 15°, the variation of yaw cockpit control deflection with sideslip angle should be essentially linear. For larger sideslip angles, an increase in deflection should always be required to increase sideslip.

The variation of yaw cockpit pedal force with sideslip angle should be essentially linear for sideslip angles of $\pm$ 15°. At greater angles of sideslip, a gradual lessening of force is acceptable, however, the pedal force should never reduce to one-half the maximum value.

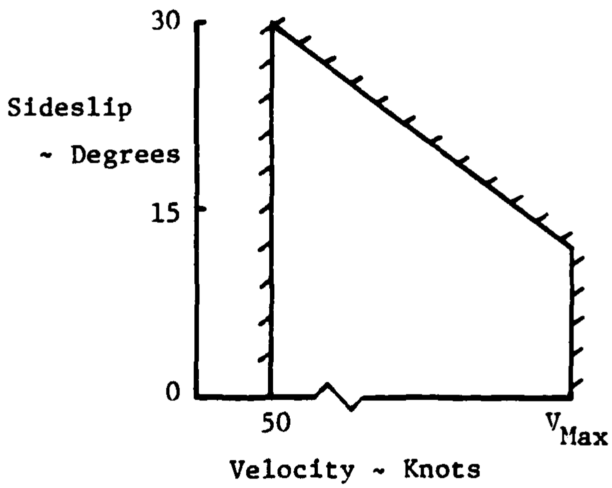
3.18 Side Force Characteristics in Steady Sideslips. For the sideslip conditions and speeds specified in STOL operation an increase in right bank angle should accompany an increase in right sideslip and vice versa.

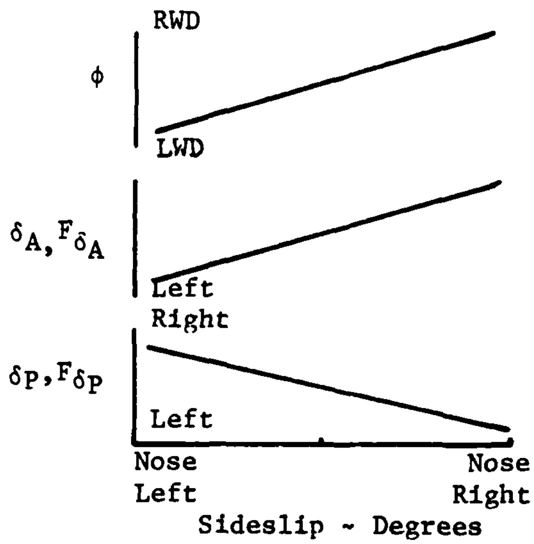


Comments - AGARD 577 presents criteria defining satisfactory lateral-directional static stability characteristics. Lateral control displacement and control force positive stability must be demonstrated. Only directional control displacement gradients with respect to sideslip angles need be satisfied.

SH-60B TYPE SPEC

10.3.4.1.7 The aircraft shall possess positive control-fixed, directional stability, positive sideforce characteristics autorotative flight at all forward speeds above 50 knots. At these flight conditions with zero yawing and rolling velocity, the variations of pedal displacement and force and lateral control displacement and force with steady sideslip angle shall be stable (left pedal and right stick displacement for right sideslip) up to full pedal displacement in both directions, but not necessarily beyond a sideslip angle of 12 degrees at V_{max}, 30 degrees at 50 knots or beyond a sideslip angle determined by a linear variation with speed between these two angles. Between sideslip angles of $\pm$ 15 degrees, the curve of pedal displacement and lateral control displacement plotted against sideslip angle shall be approximately linear. Throughout the remainder of the required sideslip range an increase in directional control motion and force shall be required to produce an increase in sideslip. The side force characteristics shall be such that in all specified sideslips, an increase in left bank angle accompanies an increase in left sideslip. All the above requirements shall be extended to include control force stability. The variations in pedal force and lateral control force with sideslip shall conform to the above requirements for the corresponding control displacements.





Comment - The SH-60B type specification included additional guidance for lateral-directional static stability over that provided by MIL-H-8501A. Positive stability for both displacement and force gradients must be demonstrated by the helicopter. Bank angle stability with respect to sideslip angle must also be satisfied.

Note that the sideslip range of interest for the type specification is significantly less than MIL-H-8501A, particularly at the lower airspeeds.

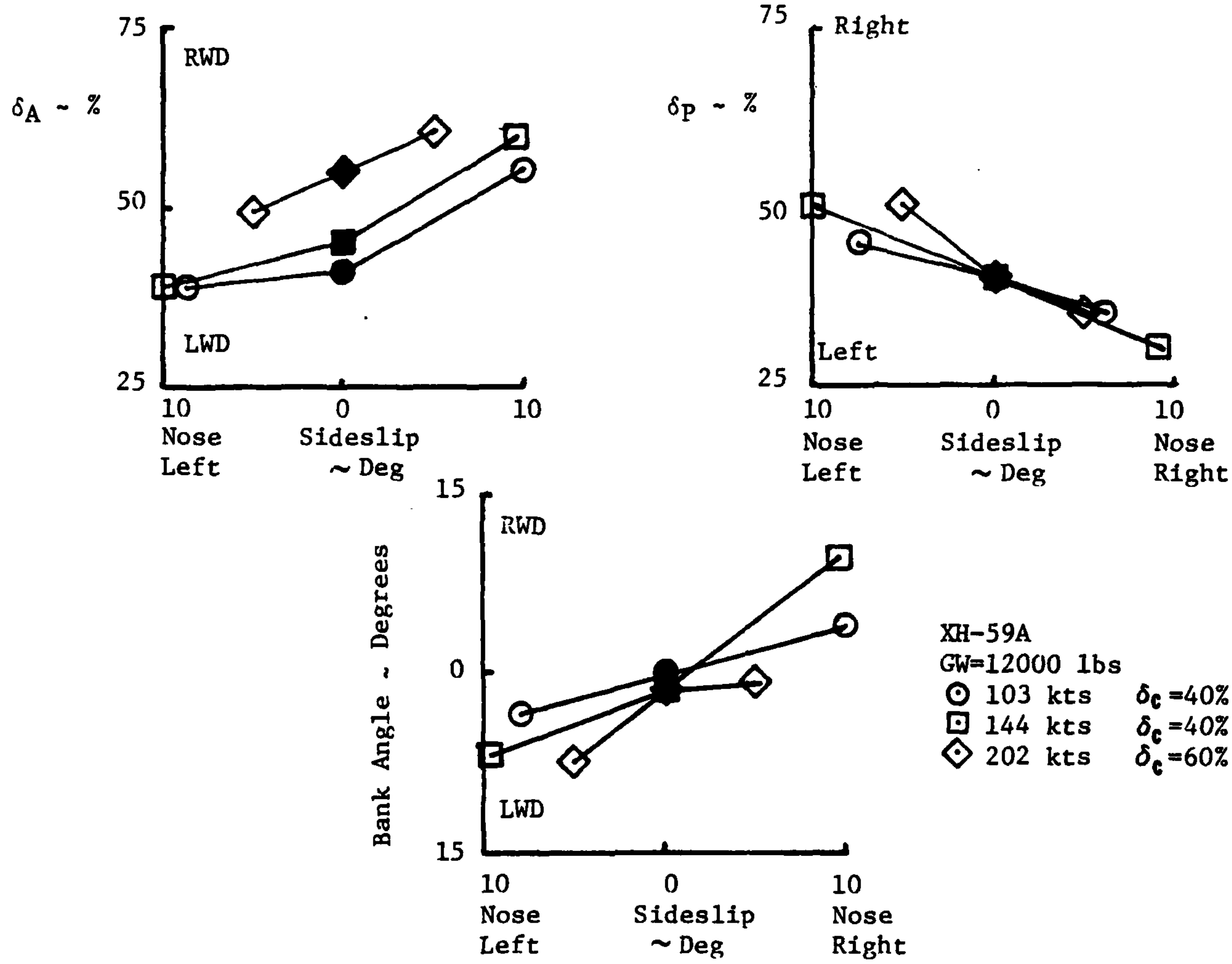
- Forward Flight Static Stability; Lateral-Directional

SPECIFICATION COMPARISON

Design guidance is presented by all of the specifications reviewed for lateral-directional forward flight stability. The variation between the specifications is extensive. MIL-H-8501A requires only control displacement stability with respect to sideslip while the other three specifications additionally require force stability in at least one axis. One of the major differences between the specifications is the required static stability speed range. MIL-H-8501A and the SH-60B type specification state that the airspeed range of interest is 50 knots to V_{max}. AGARD 577 requires the directional characteristics in steady sideslips be satisfied for the 30 knot to V_{con} range. The MIL-F-83300 criteria presented are for forward flight conditions, or the 35 knot to V_{con} airspeed range. MIL-F-83300 also presents guidelines for hover pitch and roll static stability. MIL-H-8501A has no guidance for hover lateral or directional static stability. It is of interest to note that Green and Richards (reference (c)) describe MIL-F-83300 as being deficient in hover static stability for helicopters because no guidelines for the directional axis are given. Accordingly it should be noted that MIL-H-8501A is also deficient in lateral-directional hover static stability.

- Forward Flight Static Stability; Lateral-Directional

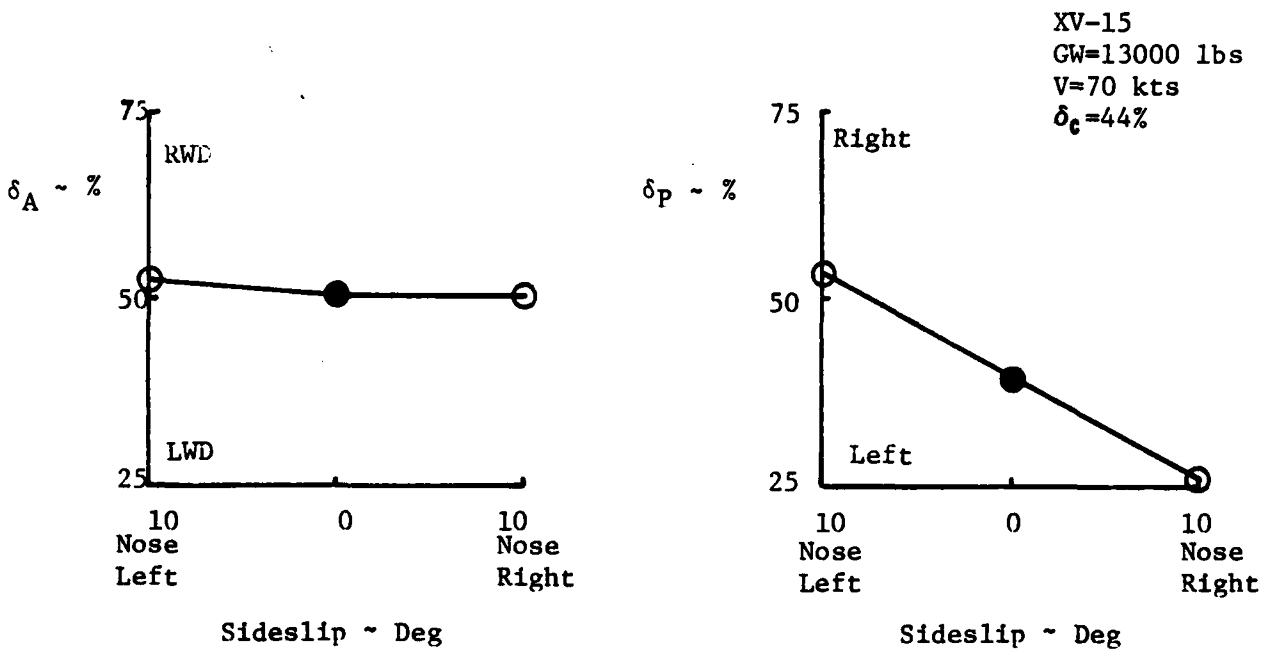
DATA COMPARISONS



During the flight tests of the XH-59A lateral-directional static stability was tested. The above plots show the control displacement variation and bank angle variation with sideslip angle. Control force was qualitatively measured by the pilots. The vehicle was described as having adequate lateral-directional static stability characteristics. Note that the sideslip range tested was at the most ± 10 degrees, which is less than that stated in MIL-H-8501A.

- Forward Flight Static Stability; Lateral-Directional

DATA COMPARISONS

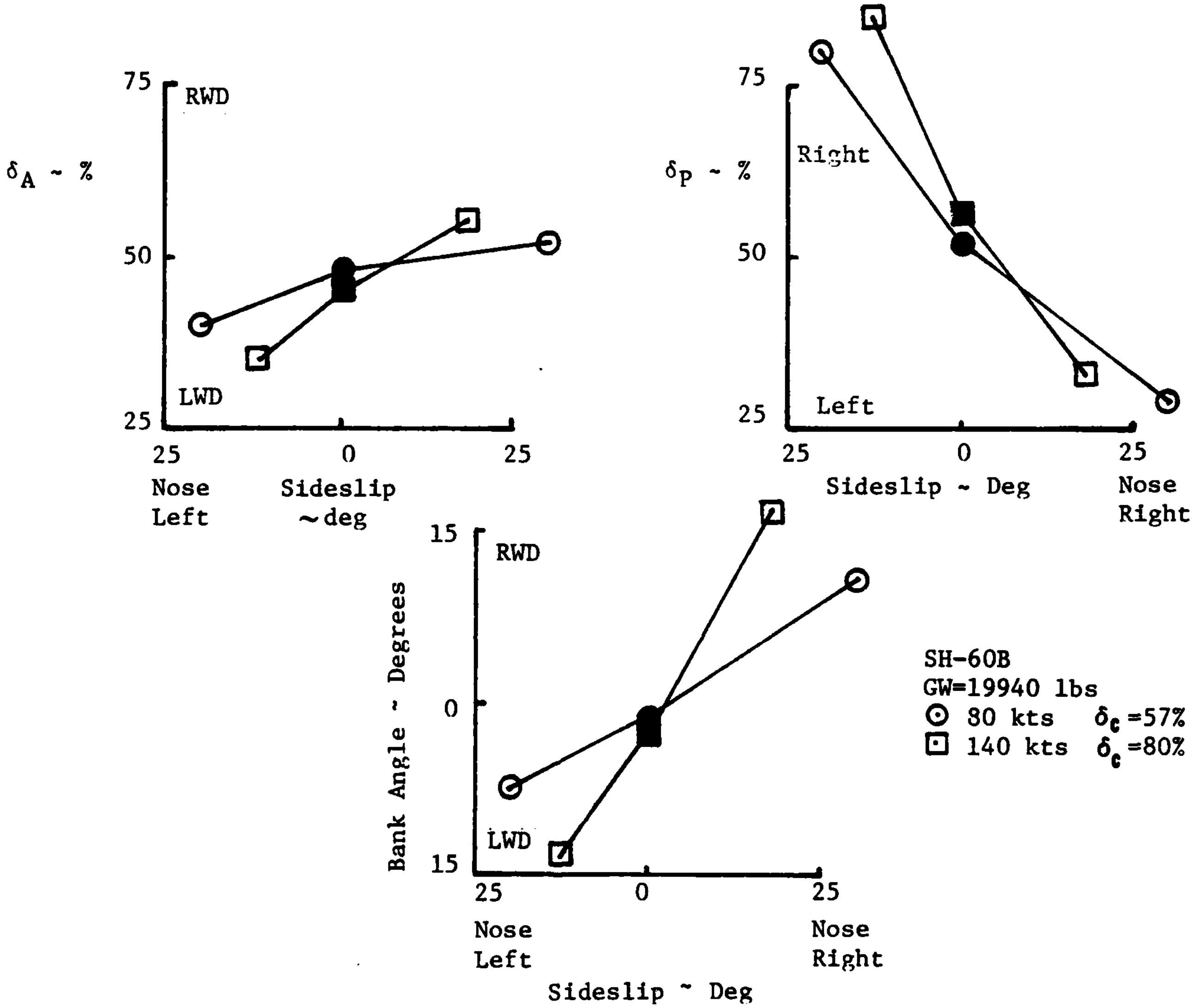


The above plots are the quantitative results of the XV-15 static lateral-directional stability flight tests. The pedal displacement gradient is stable with sideslip but the lateral stick displacement is at best neutral. Pilots (reference (1)) described the aircraft as having little or no effective dihedral but also did not find any adverse handling qualities because of this. An overall level 1 rating was given for the static stability characteristics.

Note that, like the XH-59A, the XV-15 was perturbed only ± 10 degrees of sideslip, less than that required by MIL-H-8501A.

- Forward Flight Static Stability; Lateral-Directional

DATA COMPARISONS



The SH-60B model lateral-directional static stability data shown above are taken from reference (m). Control displacement and bank angle gradients with respect to sideslip angle showed the necessary positive stability characteristics. The range of sideslip that the aircraft was tested for are within the SH-60B type specification limits previously presented.

- Forward Flight Static Stability

Design guidance for static stability characteristics was presented in each of the specifications reviewed. Positive stable characteristics were required by each specification for control and attitude gradients as specified. There is extensive variation between the specifications concerning the gradients addressed and the required range of stability.

For the longitudinal axis MIL-H-8501A, MIL-F-83300 and AGARD 577 require positive control force and position stability with respect to airspeed. MIL-H-8501A allows for limited negative (unstable) gradients in the transition speed ranges. Also MIL-H-8501A gives no guidance on the airspeed range from trim for which the stable gradient must be demonstrated. The static longitudinal stability criteria in MIL-H-8501A are applicable and adequate for the helicopter missions, and vehicles analyzed though a range of airspeed perturbation should be defined. A ± 15 knot range would be appropriate considering the test data shown and the VSTOL specification ranges defined.

There are many differences between the lateral-directional static stability criteria as addressed by each of the specifications. MIL-H-8501A has VFR guidelines for control displacement gradients only. In addition to the MIL-H-8501A criteria the SH-60B type specification also required positive control force stability for lateral and directional controls, as well as stable bank angle variations with sideslip. The MIL-F-83300 criteria are as extensive as those in the SH-60B type specification. The range of sideslip that stability need be demonstrated for in MIL-H-8501A varied between ± 45 degrees for the low speeds and ± 10 degrees for the higher speeds. The XH-59A and the XV-15 flight test programs used a range of ± 10 degrees throughout the tests. MIL-H-8501A does not give guidance for control force stability or bank angle gradients, as well as omitting VFR hover/low speed lateral and directional static stability criteria. The MIL-H-8501A criteria for VFR lateral-directional static stability does not give adequate design guidance.

There is a need for more consistent design guidance for static stability characteristics. MIL-F-83300 has the most complete set of criteria to cover hover, low speed and forward flight longitudinal and lateral-directional static stability. Determining what the perturbation ranges for airspeed and sideslip angles should be will need further testing.

- Forward Flight Dynamic Stability; Longitudinal

MIL-H-8501A

3.2.11 The helicopter shall exhibit satisfactory dynamic stability characteristics following longitudinal disturbances in forward flight. Specifically, the stability characteristics shall be unacceptable if the following are not met for a single disturbance in smooth air:

a) Any oscillation having a period of less than 5 seconds shall damp to one-half amplitude in not more than 2 cycles, and there shall be no tendency for undamped small amplitude oscillations to persist.

b) Any oscillation having a period greater than 5 seconds but less than 10 seconds shall be at least lightly damped.

c) Any oscillation having a period greater than 10 seconds but less than 20 seconds shall not achieve double amplitude in less than 10 seconds.

3.2.11.1 The following is intended to insure acceptable maneuver stability characteristics. The normal acceleration stipulations are intended to cover all speeds above that for minimum power required; the angular velocity stipulations shall apply at all forward speeds, including hovering.

a) After the longitudinal control stick is suddenly displaced rearward from trim sufficient distance to generate a 0.2 radian/sec. pitching rate within 2 seconds, or a sufficient distance to develop a normal acceleration of 1.5 g within 3 seconds, or 1 inch, whichever is less, and then held fixed, the time-history of normal acceleration shall become concave downward within 2 seconds following the start of the maneuver, and remain concave downward until the attainment of maximum acceleration. Preferably, the time-history of normal acceleration shall be concave downward throughout the period between the start of the maneuver and the attainment of maximum acceleration. The figure below is illustrative of the normal acceleration response considered acceptable.

b) During this maneuver, the time-history of angular velocity shall become concave downward within 2.0 seconds following the start of the maneuver, and remain concave downward until the attainment of maximum angular velocity; with the exception that for this purpose, a faired curve may be drawn through any oscillations in angular velocity not in themselves objectionable to the pilot. Preferably, the time-history of angular velocity should be distinctly concave downward throughout the period between 0.2 second after the start of the maneuver and the attainment of maximum angular velocity. The figure below is illustrative of the angular velocity response considered acceptable.

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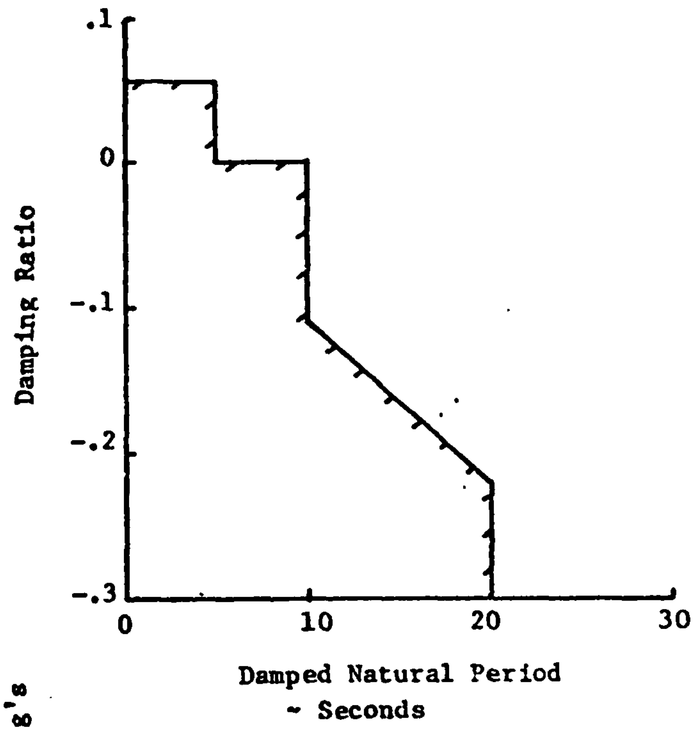

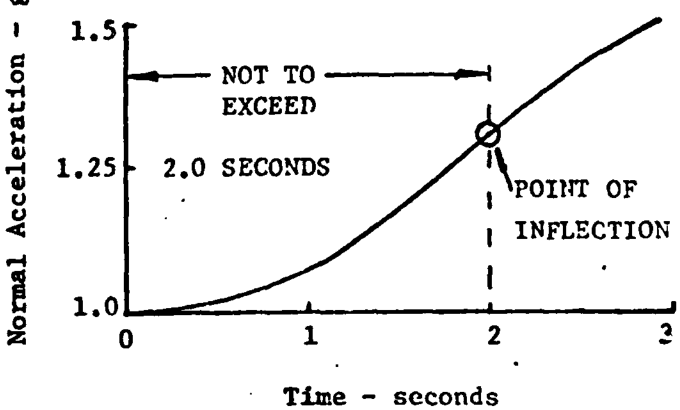

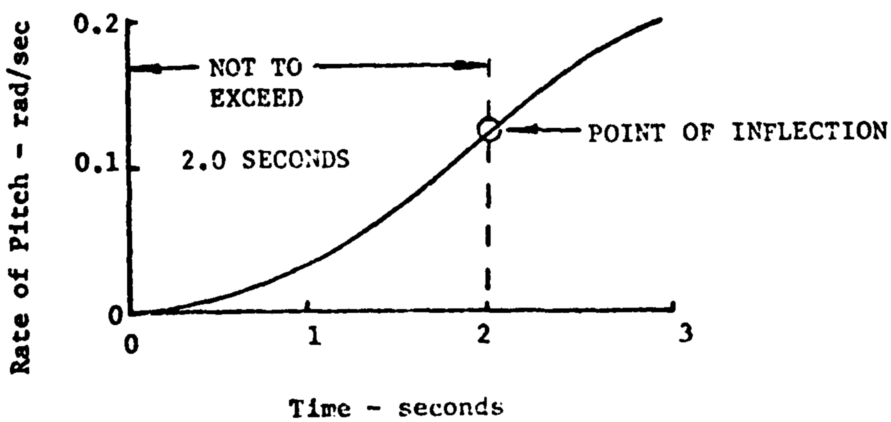

Comments

A helicopter in forward flight tends to have dynamic stability characteristics similar to fixed wing aircraft. The typical longitudinal dynamic modes a helicopter has in forward flight are a "phugoid" type response and a response resembling a short period mode. The short period mode should be well damped to keep flight path deviations to a minimum. The long period response should be stable and have frequency low enough for the pilot to easily correct the response. A slowly divergent phugoid with altitude loss can hinder low altitude night flying, especially at sea with little or no surface visual cues. Attitude hold functions are presently being used to ensure against extreme altitude loss.

The above MIL-H-8501A criteria is very lenient, even for VFR flight. For any oscillation having a period longer than 20 seconds there is no requirement.

The type specifications for the SH-2F and CH-53E use the above MIL-H-8501A criterion for VFR forward flight dynamic stability requirements.

2

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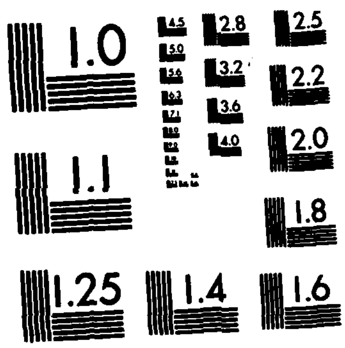
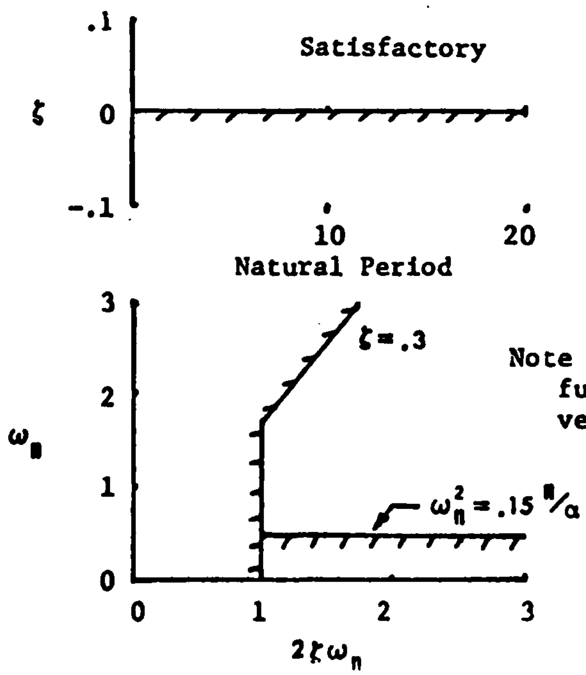


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

MIL-F-83300

3.3.2 Longitudinal Dynamic Response. The following requirements shall apply to the dynamic response of the aircraft with the pitch control free and with it fixed. These requirements apply following a disturbance in smooth air, and following abrupt pitch control inputs in each direction for responses of any magnitude that might be experienced in operational use. If the oscillations are nonlinear in amplitude, the requirements shall apply to each cycle of the oscillation.

Level 1: The response of the aircraft shall not be divergent (i.e., all roots of the longitudinal characteristic equation of the aircraft shall be stable). In addition, the undamped natural frequency, ω_n, and damping ratio, ζ, of the second-order pair of roots (real or complex) that primarily determine the short-term response of angle of attack following an abrupt pitch control input shall meet the level 1 requirements of the bottom figure shown below.



Note the minimum ω_n is a function of the vehicle n/α

Comment - The above criteria addresse[d] longitudinal dynamic stability only. Unlike the pitch-roll coupling charac[-]teristic in hovering flight, a helicopter in forward flight has primaril[y] decoupled longitudinal modes and coupled lateral-directional modes, simil[ar] to fixed wing aircraft. The requirement is divided to account for the usual short period and long period responses.

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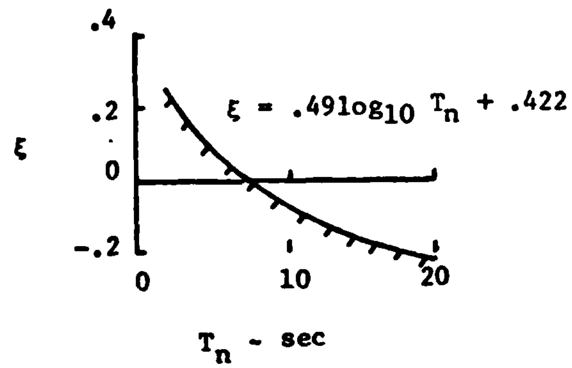
long period

2.8 Longitudinal Dynamic Stability. The responses of the aircraft should not be divergent (i.e., all roots of the longitudinal characteristic equations should be stable). In addition the damping ratio of the second-order pair of roots that primarily determine the short-term response of angle of attack and pitch attitude following an abrupt pitch control input should be at least 0.3 for the most critical undamped natural frequency.

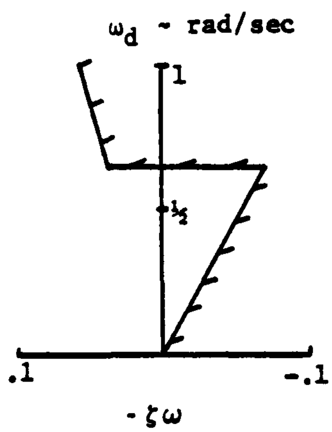
The frequency and damping characteristics of any oscillation superimposed on the normal control modes for VTOL aircraft in hover and VSTOL aircraft at the approach reference speed should meet at least the value shown in the figure below. Any sustained residual oscillations should not degrade the pilot's ability to perform the required tasks.

These criteria apply with the pitch cockpit control free and fixed.



Comment - See longitudinal hover dynamic stability.

SH-60B TYPE SPEC	Comments
10.3.3.2 Longitudinal Dynamic Stability. The following conditions shall be met for a single disturbance in smooth air with controls fixed. These conditions shall also apply at all permissible airspeeds, rotor rpm and loadings, both in straight, climbing, descending, and turning flight, and at high, medium, and low altitude.	Although MIL-H-8501A does have a forward flight longitudinal dynamic stability criteria the allowable instabilities are too permissive for many present day ASW missions. The SH-60B type specification includes the above criteria (the same for longitudinal hover dynamic stability) to restrict any extreme divergent phugoid responses.
a) Any oscillation having a period of less than 10 seconds shall damp to one-half amplitude in not more than two cycles. There shall be no tendency for undamped small oscillations to persist.	The MIL-H-8501A maneuvering stability criteria (paragraph 3.2.11.1) is also used in SH-60B type specification without variation.
b) Any oscillation having a period greater than 10 seconds shall not achieve double amplitude in less than one cycle.	
c) There shall be no tendencies for small amplitude, short period residual oscillations to exist.	
d) There shall be no objectionable flight characteristics attributable to apparent poor phugoid damping.	
e) There shall be no tendency for a sustained or uncontrollable oscillation resulting from efforts of the pilot to maintain steady flight.	



- Forward Flight Dynamic Stability; Longitudinal

SPECIFICATION COMPARISONS

Of the specifications reviewed only MIL-F-83300 has a separate criteria for forward flight longitudinal dynamic stability over the hover criteria. For forward flight MIL-F-83300 specifies short and long period longitudinal oscillations separately from lateral modes.

As in the hover case, MIL-H-8501A has the most lenient criteria of the specifications reviewed. Second-order response parameters are used by all the specifications to specify desired stability characteristics. Both of the VSTOL specifications require that all roots of the longitudinal characteristic equation be stable. Short period responses are required to have a damping ratio of at least .3. The documentation of AGARD 577 states that the lowest frequency allowed for the short period is between 1 and 2 rad/sec, or a period of between 3 and 6 seconds.

Within reference (c) the above MIL-F-83300 dynamic stability criteria were described as much too lenient for helicopter applications. A lightly damped phugoid causing a gradual but drastic altitude loss in low altitude high speed flight (i.e., contour flying) was presented as an example. If using the MIL-F-83300 criteria is too lenient for helicopters then the MIL-H-8501A criteria is completely inadequate for design considerations.

It is of interest to note that the MIL-H-8501A maneuvering stability criteria, the so called "concave downward" criteria, can be compared to the MIL-F-83300 short period plot. Seckel (reference (s)) shows that the normal acceleration concave downward requirement ($n_z = 0$ within 2 seconds) can be expressed by second-order response parameters. Figure 7 shows the ζ, ω_n boundary, representing the MIL-H-8501A concave downward criteria, compared to the MIL-F-83300 short period requirement boundary.

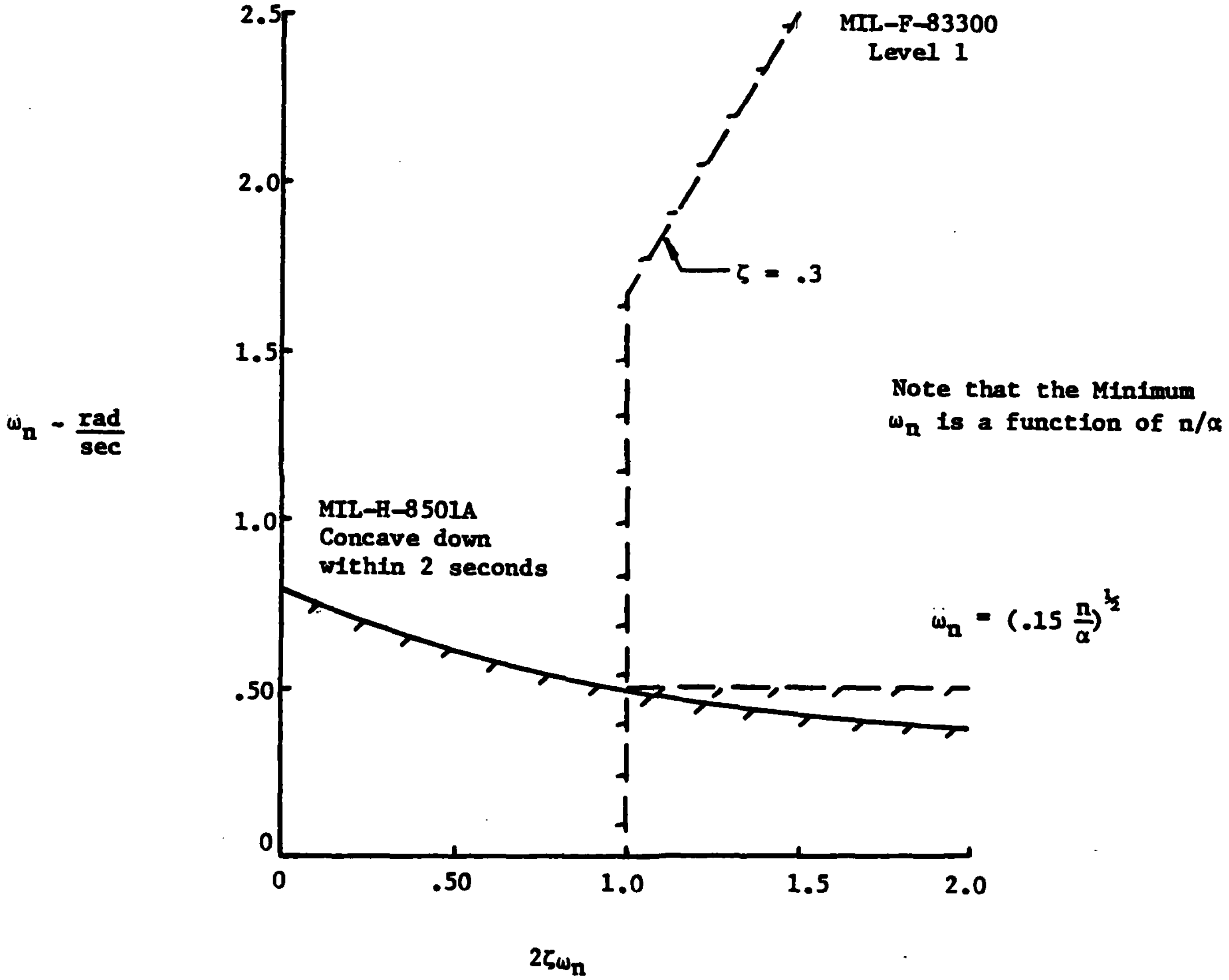
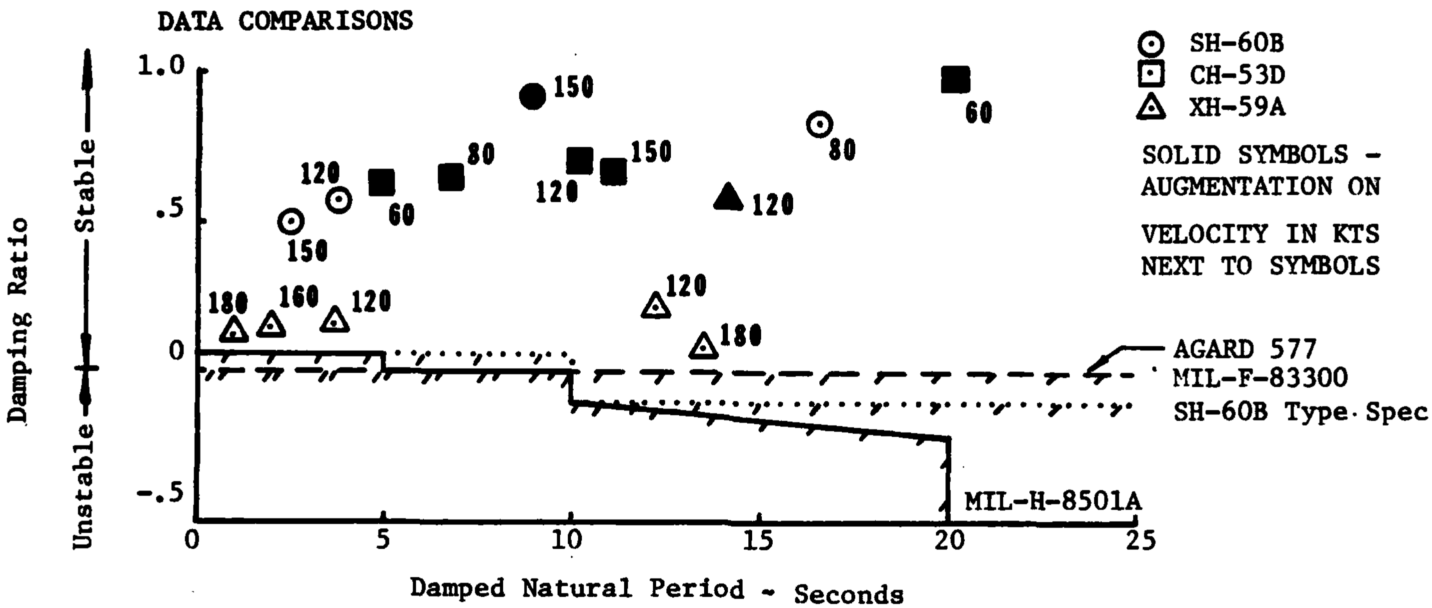


Figure 7. MIL-F-83300 Short-Term Dynamic Stability Comparison with MIL-H-8501A Maneuvering Stability.

The minimum frequency boundary, specified by MIL-F-83300, limits satisfactory short period frequency in a similar manner to the MIL-H-8501A concave downward criteria. The MIL-F-83300 short period could be used as a guide in preliminary design for maneuvering stability where as the actual MIL-H-8501A criteria directly addresses flight test procedures.

- Forward Flight Dynamic Stability; Longitudinal

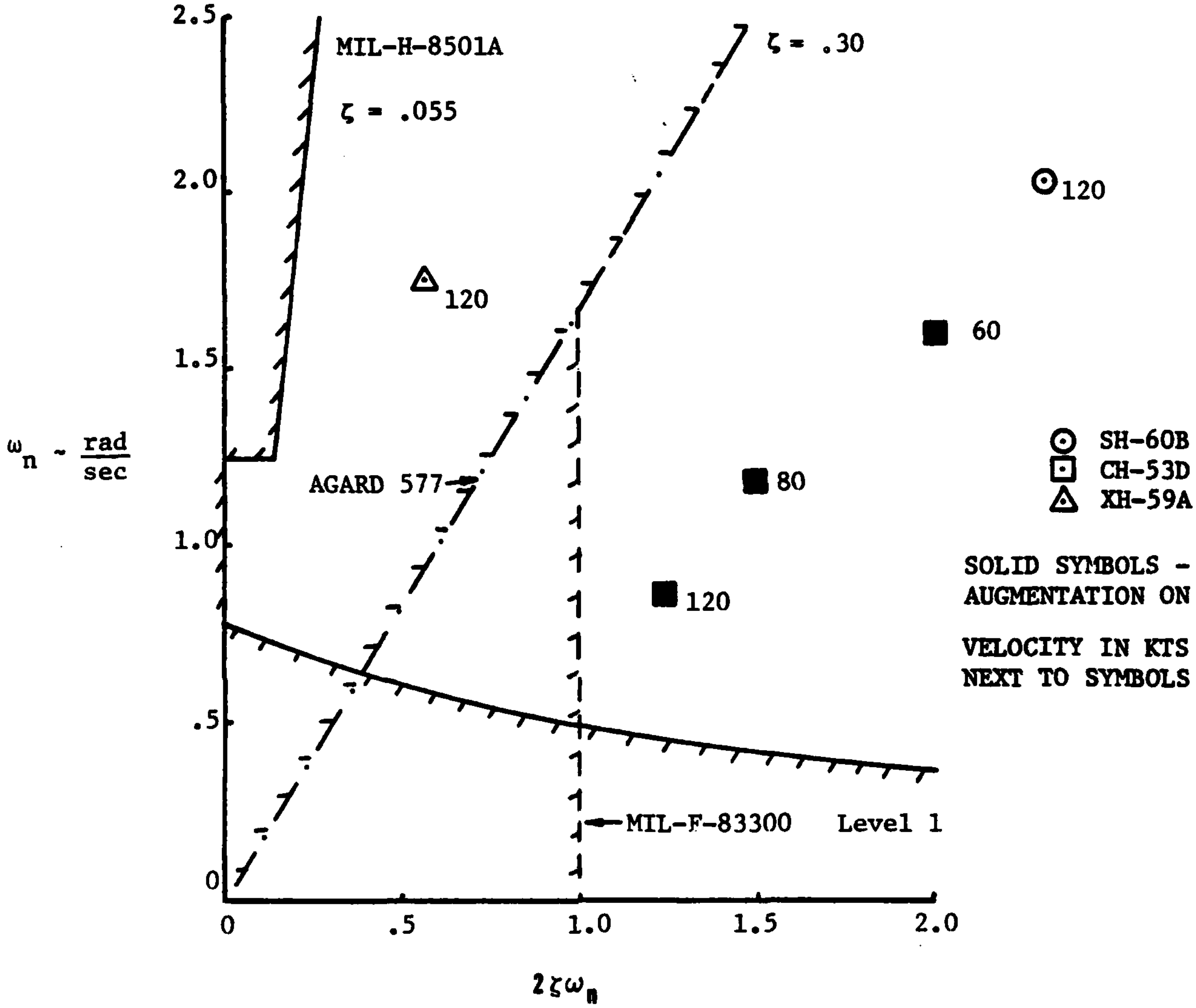


Each of the vehicles analyzed easily satisfied all the specification boundaries for normal flight conditions (the solid symbols). This compares well with qualitative pilot ratings for the three aircraft. All the vehicles were described as having good longitudinal dynamic stability characteristics, in particular the SH-60B having excellent phugoid damping. For lower speeds (80 and 120 kts) the SH-60B model showed convergent phugoids with periods of 100 seconds and 60 seconds respectively.

One problem encountered in the analysis was in determining the appropriate short period and long period modes. Although rotary wing forward flight dynamic stability responses are similar to conventional fixed wing modes there are distinct differences. The typical rotary wing short and long period responses can have the same frequency. The CH-53D and SH-60B, with augmentation on, exemplify some of the problems in labelling a certain response. There is no short period response from the SH-60B model until the 150 knot case. The CH-53D model, in contrast, shows only a short period response. At 60 knots the CH-53D also has a heavily damped pitch-roll response. This is the same pitch-roll coupling observed in the hover model. With augmentation off (open loop responses) the modes look more like conventional responses.

- Forward Flight Dynamic Stability; Longitudinal

DATA COMPARISONS



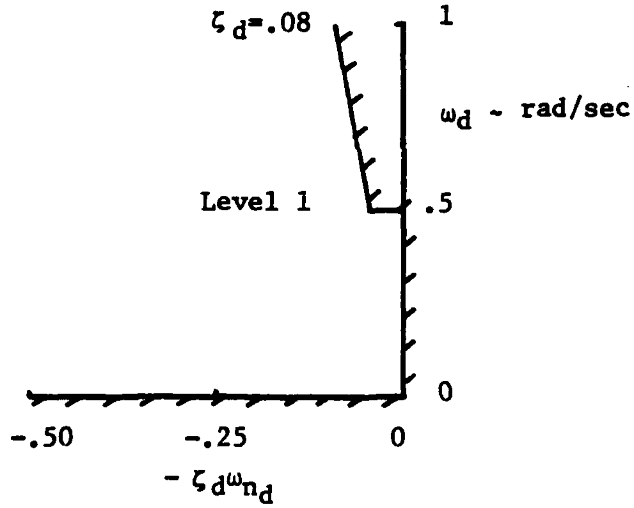
For normal flight conditions (AFCS on) the three vehicles analyzed easily satisfied all the specifications' requirements for short period responses. The CH-53D model shows a short period of decreasing frequency. By 150 knots the 11 second period is not characteristic of a conventional short term response. For AFCS on flight the SH-60B model shows no response representative of a short period. This is also true for the XH-59A. Yet for AFCS off conditions both vehicles revealed modes similar to a conventional short period.

- Forward Flight Dynamic Stability; Lateral-Directional

MIL-H-8501A	Comments
VFR lateral-directional dynamic stability criterion for forward flight are not included in MIL-H-8501A.	Forward flight lateral and directional dynamic stability characteristics of helicopters are similar to conventional fixed wing lateral-directional modes. That is, in forward flight the lateral and directional responses tend to couple. A dutch roll type response is typical for helicopters in forward flight. This coupling of roll and yaw responses separates forward flight from hover dynamic stability where a pitch-roll coupling is prevalent. With objectionable dutch roll damping or lateral phugoid characteristics a pilot may experience difficulty in flight path control and turn coordination. With roll attitude deviations altitude loss can occur. The only VFR lateral or directional response requirements in MIL-H-8501A are the previously discussed roll and yaw rate damping derivatives. These do not give adequate design guidance for dutch roll or lateral phugoid responses. Like MIL-H-8501A, the SH-2F and CH-53E type specifications do not include criteria for VFR lateral-directional forward flight requirements.

MIL-F-83300

3.3.7.1 Lateral-Directional Oscillations (Dutch Roll). The frequency, ω_{nd} and damping ratio, ζ_d, of the lateral-directional oscillations following a disturbance input, for example a yaw control doublet, shall exceed the minimums specified in the figure below. The requirements shall be met with controls fixed and with them free for oscillations of any magnitude that might be experienced in operational use. If the oscillation is nonlinear with amplitude, the requirements shall apply to each cycle of the oscillation. Residual oscillations may be tolerated only if the amplitude is sufficiently small that the motions are not objectionable and do not impair mission performance. With control surfaces fixed, ω_{nd}^2 shall always be greater than zero.

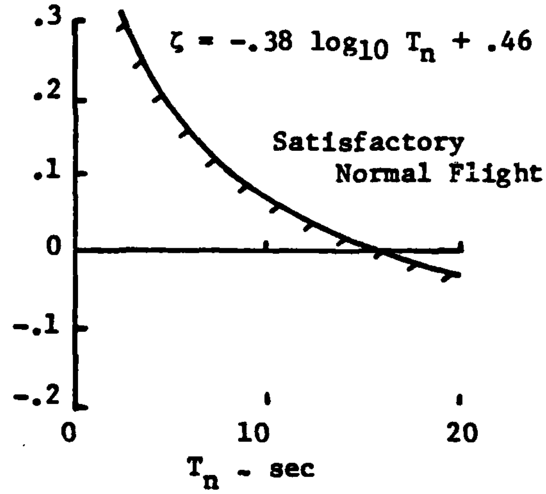


Comment - The expected differences between hover and forward flight dynamic stability characteristics for VTOL/VSTOL vehicles are accounted for by MIL-F-83300.

The above criteria for forward flight lateral-directional responses is separate from the hover lateral or directional stability criteria.

AGARD 577

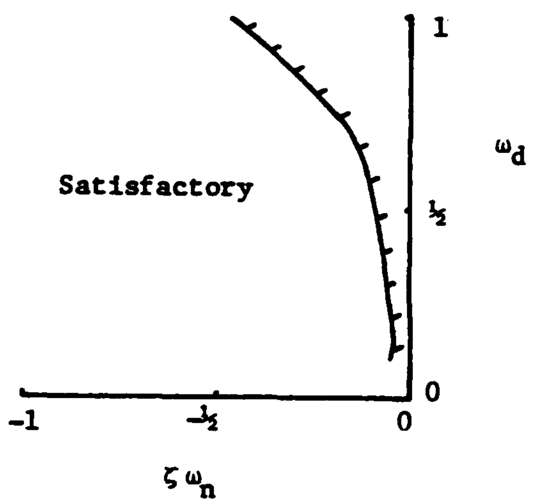
3.9 Lateral-Directional Dynamic Stability. Any roll-yaw oscillations superimposed on the normal control mode due to a disturbance input should exhibit at least the frequency - damping characteristics shown in the figure below for the forward flight speed range specified. Also, there should be no tendency for perceptible small-amplitude oscillations to persist or for pilot-induced oscillations to result from the pilot's attempts to perform the required flight tasks.



Comment - See lateral dynamic stability for hover conditions. AGARD 577 uses the above criteria for hover responses also.

SH-60B TYPE SPEC

10.3.4.3 Lateral-Directional Stability. Lateral-directional oscillations with controls fixed or free following a single disturbance in smooth air shall exhibit minimum damping characteristics as a function of the damped natural frequency corresponding to the figure below. In addition, any oscillation having a period greater than 10 seconds shall not achieve double amplitude in less than one cycle. There shall be no tendency for undamped small oscillations to persist.



Comment - See lateral dynamic stability for hover conditions. The type specification uses the above criteria for hover responses also.

- Forward Flight Dynamic Stability; Lateral-Directional

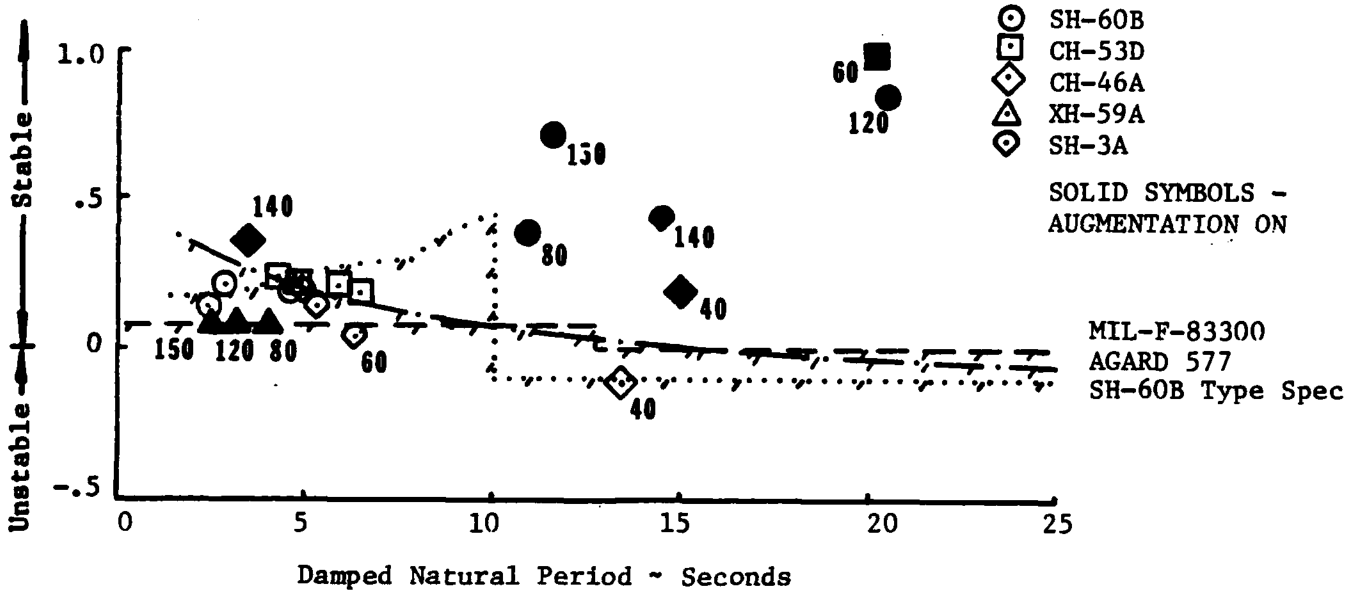
SPECIFICATION COMPARISONS

MIL-H-8501A is the only specification reviewed that does not include a VFR lateral-directional dynamic stability criteria. The SH-60B type specification includes a lateral-directional dynamic stability criteria to cover both hover and forward flight. Each specification with a requirement uses ζ, ω_n parameters to define satisfactory responses.

Green and Richards (reference (c)) state that the MIL-F-83300 dutch roll criteria is too lenient for helicopter missions, in particular IFR missions. Their conclusion was reached by comparing available helicopter data with the MIL-F-83300 level 1 and level 2 requirements. Their comparisons showed the production helicopters easily satisfied the criteria. These helicopters were designed under the guidance of MIL-H-8501A, which has no VFR lateral-directional dynamic stability criteria, thus the point that the MIL-F-83300 criteria is too lenient may not be valid.

- Forward Flight Dynamic Stability; Lateral-Directional

DATA COMPARISONS



The cluster of open symbols show a common damped dutch roll response for the single rotor helicopters analyzed. The CH-46A has a directional divergent response characteristic of tandem rotors. For augmentation on (the solid symbols) the responses are all well-damped over a wide range of frequency. The CH-53D for example has non-oscillatory modes at the higher speeds. The production helicopters easily satisfy all the boundaries. The XH-59A in contrast has a short period dutch roll that falls right on the MIL-F-83300 level 1 boundary. The XH-59A data is from reference (o) for a nonauxiliary power configuration. A similar dutch roll response was also found with the auxiliary power engines installed. Pilots described the XH-59A as having forward flight flying qualities characteristics similar to a fixed wing aircraft, particularly in the lateral-directional axes. Within reference (o) the above response was compared to MIL-F-8785, the fixed wing flying qualities specification. The dutch roll response specifically was described as being a well-damped yaw oscillation with weak pitch and roll coupling. Navy pilots found difficulty in exciting this response and thus described it as an enhancing characteristic of the XH-59A airframe.

- Forward Flight Dynamic Stability

Only MIL-F-83300 has criteria explictly for forward flight dynamic stability. MIL-H-8501A, AGARD 577, and the SH-60B type specification all use the same longitudinal dynamic stability criteria for forward flight and hovering conditions. Both AGARD 577 and the SH-60B type specification use the hover lateral-directional dynamic stability criteria for forward flight as well. MIL-H-8501A has no VFR forward flight lateral-directional dynamic stability criteria.

Each of the aircraft analyzed compared favorably to all the longitudinal dynamic stability boundaries. MIL-H-8501A has by far the most lenient criteria for longitudinal short period or phugoid responses. The two VSTOL specifications require that longitudinal dynamic short period angle-of-attack responses have a damping ratio greater than or equal to 0.3. The two helicopter specifications have the maneuvering stability concave downward criteria. The MIL-F-83300 short period boundaries and the concave downward criteria plotted together are very similar. The one problem with addressing short period and phugoid responses is that helicopters may not show these conventional modes. This is especially true of the new aircraft with highly augmented control systems. There were many problems encountered in determining which responses to compare against the MIL-F-83300 short period criteria. The SH-60B model does not even show a short period type response until 150 knots. Using an approach similar to that in MIL-F-8785C, that is, reduced order equivalent systems methods could possibly eliminate some of these problems. Further analysis to see if the reduced order equivalents can accurately represent the higher order rotary wing models is necessary. Only the XH-59A did not satisfy all the lateral-directional requirements. The helicopters analyzed against the specifications easily met the criteria for normal flight conditions. Each of these helicopters has been qualitatively described as having adequate forward flight lateral-directional dynamic stability characteristics. The XH-59A was also described as having satisfactory characteristics. For augmentation off flight the CH-46A showed the typical tandem rotor divergent directional response, while the single rotor helicopters showed a damped short period dutch roll mode. Rotor configurations like the CH-46A and the XH-59A that do not have tail rotors may have unusual lateral-directional modes. Varied rotor configurations, like the XH-59A, may show up as anomalies in comparison to the present specifications.

Overall, MIL-H-8501A has a longitudinal forward flight dynamic stability criteria which gives very lenient design guidelines and has no design guidance for VFR lateral-directional forward flight dynamic stability. A criteria addressing a dutch roll or lateral phugoid response should be included within the helicopter specification to give guidelines for future aircraft like the ABC.

CONCLUSIONS AND RECOMMENDATIONS

A preliminary comparative analysis between four state of the art rotary wing aircraft and the current helicopter and VSTOL handling qualities specifications has been completed. The conclusion that MIL-H-8501A cannot give adequate design guidance for current or future helicopter/rotary wing aircraft has been previously presented in many papers (references (b) thru (f)). The present analysis including the SH-60B, XH-59A, and XV-15 aircraft, substantiates this conclusion. A summary of the major deficiencies found within MIL-H-8501A are:

1. The hover control power criteria (attitude response and rate damping criteria) inadequately address mission or rotor configuration differences. Although the MIL-H-8501A weight parameter tended to be more applicable to the analyzed vehicles than the VSTOL specifications the differences in control response due to mission/rotor configuration were not adequately represented. The CH-46A and the XH-59A exemplify these anomalies, in particular for the lateral and directional axes. The possibility of defining control power criteria according to vehicle mission (see Table I) should be analyzed. This could allow for the addition of categories for ship-based operations and nap-of-the earth flight conditions, where still wind, out-of-ground effect criteria may not require sufficient control power levels.

2. No guidance is given for VFR hover lateral or directional dynamic stability characteristics. The CH-53D and SH-60B easily satisfied all the specifications for longitudinal, lateral and directional responses, and have been qualitatively described as having level 1 characteristics. The XH-59A, in contrast, has an ABC unique pitch-roll-yaw coupled response that in low hover has been described as a level 2 response. In the lateral and directional axes the XH-59A response barely satisfies MIL-F-83300 and fails to meet the AGARD 577 boundary. The inclusion of criteria for VFR lateral or directional dynamic stability for hovering flight should be considered so design guidance will be available for new vehicles like the XH-59A.

3. No guidance is given for VFR forward flight lateral-directional dynamic stability characteristics. Each of the vehicles analyzed has been qualitatively described as having adequate lateral-directional dynamic stability characteristics. The XH-59A was described as having characteristics similar to a fixed wing aircraft in forward flight. The data for the XH-59A does not satisfy the AGARD 577 boundary or the SH-60B type specification boundary, yet falls right on a MIL-F-8785 level 1 boundary. A criteria for VFR lateral-directional stability (i.e., dutch roll and lateral phugoids) should be including in the helicopter specification for design guidance for newly developed vehicles.

4. The airspeed range about the trimmed airspeed for which longitudinal static stability must be demonstrated is not quantified in MIL-H-8501A. The two flight test programs reviewed used 15 to 40 knot variations. For consistency and clarity a quantified range should be considered for addition to the helicopter specification criteria.

The reviewing and comparative analysis between the VSTOL specifications, the helicopter type specifications and MIL-H-8501A resulted in supplementary conclusions about MIL-H-8501A and the type specifications. These points include:

1. MIL-H-8501A does not give adequate guidance to address the differences in handling quality characteristics between hovering and forward flight conditions. The format used in MIL-H-8501A does not easily allow for a thorough description of necessary requirements. The hover/low speed and forward flight divisions used by MIL-F-83300 did address the longitudinal/lateral response similarities in hover while also addressing the lateral-directional response coupling for forward flight conditions. Throughout the review of the specifications it was apparent that MIL-F-83300 has the most thorough format for VSTOL/rotary wing vehicles.

   MIL-H-8501A has very limited guidance for degraded flying qualities. Again the format of MIL-F-83300, defining the three levels of flying qualities for each criterion, is the most thorough approach. Considering the increasing complexity of helicopter automatic flight control systems to fulfill increased mission requirements, the helicopter handling qualities specification should define minimum characteristics with AFCS failures. MIL-H-8501A, last revised in 1962, gives incomplete design guidance for such failures. As suggested by Key (reference (d)) the reformatting of the helicopter specification in line with MIL-F-83300 and MIL-F-8785 would allow for a more thorough description of normal flight level 1 flying qualities (hover and forward flight) and of degraded level 2 and 3 flying qualities. This reformatting of MIL-H-8501A would be a large positive step in updating the helicopter specification.

2. The three helicopter type specifications reviewed for the SH-2F, SH-60B, and the CH-53E all used MIL-H-8501A as a base. Thus, they also separated criteria into longitudinal, lateral, and directional characteristics. For the SH-2F and CH-53E, the helicopters had to meet the requirements of MIL-H-8501A except for modified control force criteria. The SH-60B type specification has additional criteria not addressed within MIL-H-8501A, but for the majority MIL-H-8501A was the basis for the specification. Considering the deficiencies in MIL-H-8501A, the completeness of the type specifications should be in doubt. In particular there is little or no systematic guidance in any of the type specifications for degraded flying qualities.

3. There is an overall lack of rotary wing handling qualities data. Pilot ratings for the SH-60B, CH-53D, XH-59A, and XV-15, for example, are few and far between. To substantiate any revised criteria, data for varied missions and rotor configurations would be extremely useful. A future Army-Navy program designed to fill many of these data gaps is presently being considered. A Background Information and User Guide (BIUG) similar to those developed for MIL-F-83300 and MIL-F-8785 should be generated for the helicopter specification to describe the criteria substantiation data (new and old) and clarify how to apply the criteria to the vehicle in question. MIL-H-8501A presently has no user guide or substantiation data report.

4. Although MIL-F-83300 is more up to date and complete than MIL-H-8501A in many areas, there are handling qualities characteristics particular to helicopters/rotary wing aircraft that the VSTOL specification does not adequately cover. The review of MIL-F-83300 by Green and Richards (reference (c)) presents many of these characteristics. One in particular is that the definition of V_{con} is not easily applied to helicopters. As well as the question of whether or not helicopters would be required to meet

MIL-F-8785 criteria for speeds above V_{con}. It is interesting to note that many of the criticisms and deficiencies of MIL-F-83300 according to reference (c) also apply to MIL-H-8501A.

NAVAIRDEVCEN is currently continuing with helicopter stability and control analyses including additional aircraft and criteria. Supplementing the analysis presented in this report the following areas are being investigated:

1. Vertical control response characteristics and criteria,
2. IFR requirements and criteria,
3. Aerodynamic and gyroscopic cross-coupling characteristics and criteria, and
4. Equivalent systems.

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r) Seckel, E., et al, "Longitudinal Handling Qualities for Hovering," Princeton University Department of Aeron Eng., Report 594, Dec 1961.

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LIST OF SYMBOLS

Symbol		Units
B_1	Longitudinal cyclic pitch	rad
CG	Center of gravity of the vehicle	% or inch
F	Control force	lb
GW	Gross weight of the vehicle	lb
h	Altitude of the vehicle	ft
i_n	Nacelle incidence angle; 90° in helicopter mode	deg
I_x	Rolling moment of inertia	slug-ft^2
I_y	Pitching moment of inertia	slug-ft^2
I_z	Yawing moment of inertia	slug-ft^2
L_p	Roll rate damping	sec^{-1}
L_v	Lateral velocity stability	rad/ft sec
L_{d_a}	Lateral control sensitivity	rad/sec^2/in
M_q	Pitch rate damping	sec^{-1}
M_u	Longitudinal velocity stability	rad/ft sec
M_{d_B}	Longitudinal control sensitivity	rad/sec^2/in
N_r	Yaw rate damping	sec^{-1}
N_v	Directional velocity stability	rad/ft sec
N_{d_p}	Directional control sensitivity	rad/sec^2/in
n_z	Normal acceleration	ft/sec^2
p	Roll rate	deg/sec
q	Pitch rate	deg/sec

LIST OF SYMBOLS (cont'd)

Symbol		Units
T_d	Damped natural period	sec
T_n	Undamped natural period	sec
V	Velocity of the vehicle	knot
α	Angle of attack	deg
d_A	Lateral control displacement	in
d_B	Longitudinal control displacement	in
d_c	Height control displacement	in
d_f	Flap deflection	deg
d_p	Directional control displacement	in
θ	Pitch attitude	deg
ϕ	Roll attitude	deg
ψ	Yaw attitude	deg
τ	Time constant	sec
ω	Frequency	rad/sec
ω_n	Undamped natural frequency	rad/sec
ω_d	Damped natural frequency	rad/sec
ζ	Damping ratio	----

Subscripts

opt	Optimum	
MAX	Maximum	
1	Unit displacement or unit time elapsed	inch or sec
1/2	One-half second time elapsed	sec
con	conversion	

APPENDIX A

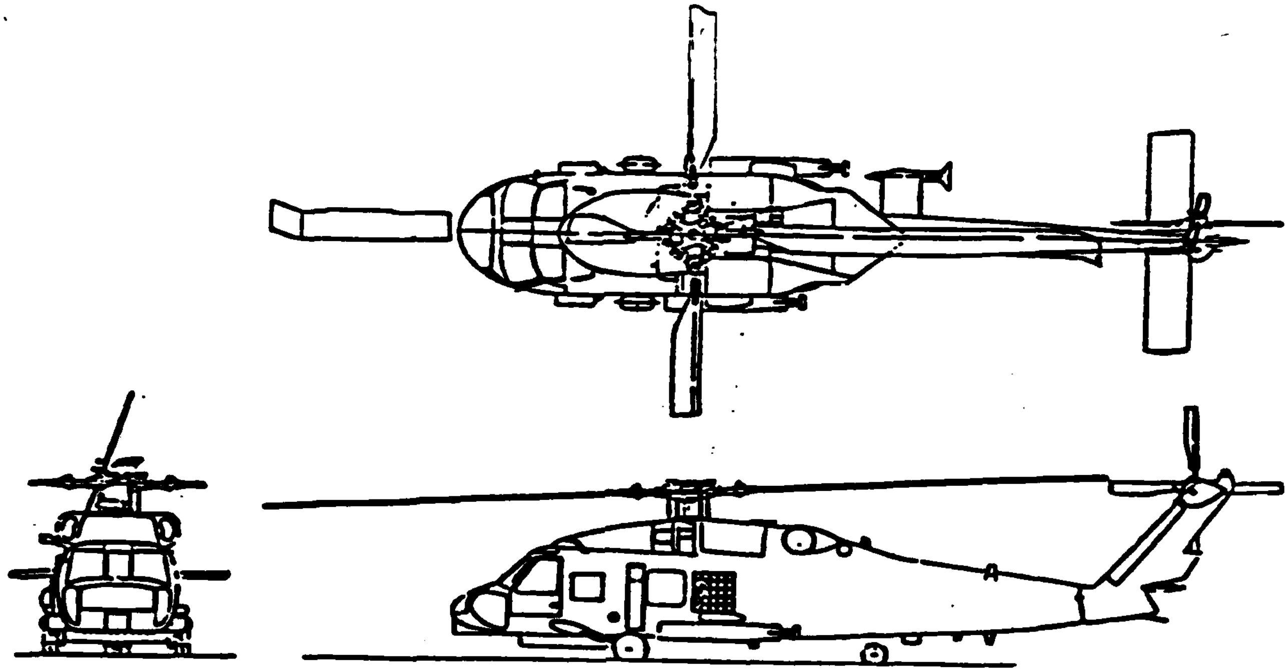
AIRCRAFT DETAILS

SH-60B

The SH-60B (figure A-1) is a single rotor, twin turbine Anti-Submarine Warfare (ASW) and Anti-Ship Surveillance and Targeting (ASST) helicopter with a nominal mission gross weight of 19,950 lbs. The rotor system is characterized by a four bladed fully articulated main rotor with a four bladed bearingless tail rotor canted 20 degrees for additional lift capability. Two T700-GE-401 engines rated at 1558 shp power the rotor system.

An Automatic Flight Control System (AFCS) comprised of a Stability Augmentation System (SAS), an Electronic Flight Control System (EFCS), and the stabilator control system is part of the SH-60B. The SAS and EFCS augment dynamic stability while the stabilator is controlled via an airspeed schedule to reduce large longitudinal cyclic stick variations in transitioning from hover to forward flight. Aircraft attitude, heading, altitude and airspeed retention functions are controlled by the outer loop functions of the AFCS.

The basic airframe stability and control derivatives used in the development of the analyzed model were taken from reference (m). These derivatives were then modified to account for the horizontal stabilator and pitch bias actuator effects.



Physical Characteristics

Main rotor

Vehicle overall length 64.83 ft

Blades	4
Radius	26.88 ft
Hub type	fully-articulated

Tail rotor (canted 20°)

Blades	4
Radius	5.5 ft
Hub type	bearingless

Horizontal stabilizer (moveable)

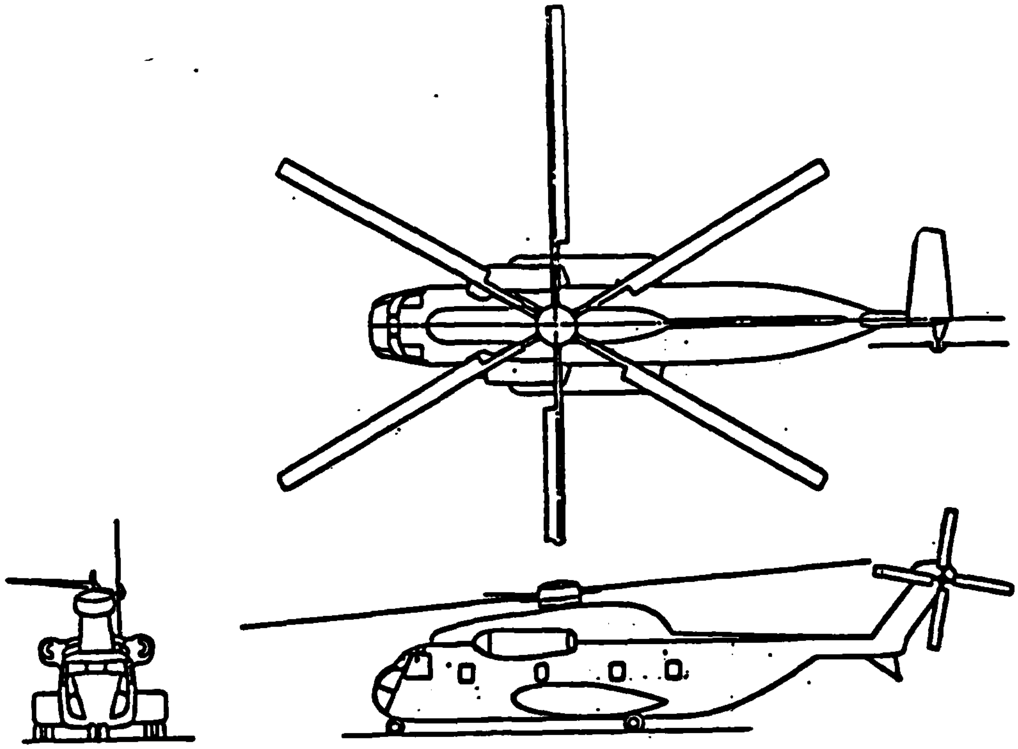
Area	41.21 ft^2
Span	14.33 ft
Dihedral	0.0

Figure A-1. SH-60B 3-View

CH-53D

The CH-53D (figure A-2) is a single rotor, twin turbine, heavy assault, transport helicopter with a nominal mission gross weight of 35,000 lb. The rotor system is comprised of a six-bladed, fully articulated main rotor with a four-bladed conventional semi-articulated tail rotor. Two T64-GE-413 engines rated at 3695 shp drive the rotor system.

An AFCS is part of the CH-53D flight controls to augment stability similar to the SH-60B though the horizontal stabilator has a fixed incidence contrasting the movable SH-60B stabilator. Attitude, heading and altitude hold functions are included in the AFCS. The stability and control derivatives as well as the hover transfer functions used in the analysis are from reference (n).



Physical Characteristics

Main rotor

Blades	6
Radius	36.12 ft
Hub type	fully-articulated

Vehicle overall length 88.10 ft

Tail rotor

Blades	5
Radius	8 ft
Hub type	semi-articulated

Horizontal stabilizer (fixed)

Area	40.00 ft^2
Span	10.18 ft
Dihedral	5.0°
Incidence	3.0°

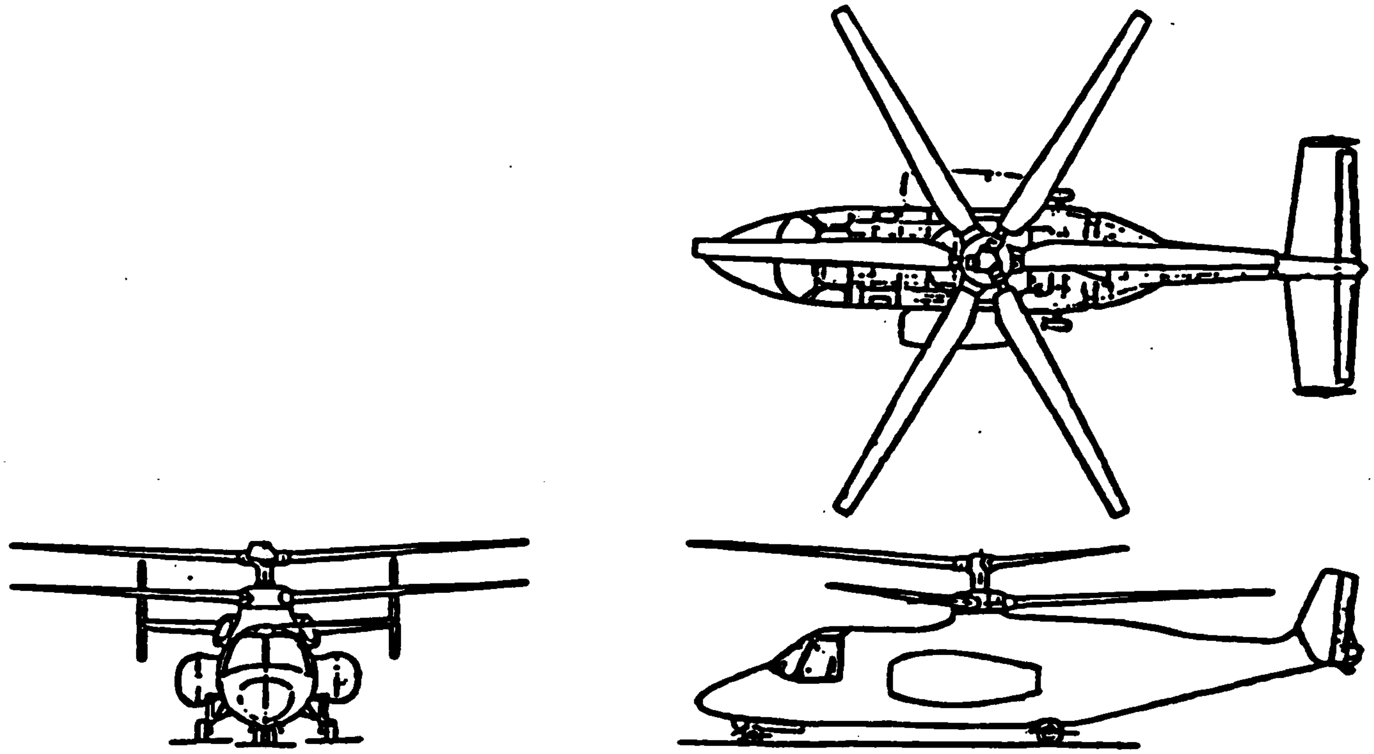
Figure A-2. CH-53D 3-View

XH-59A

The XH-59A (figure A-3) is an experimental aircraft developed by Sikorsky Aircraft using two coaxial counterrotating three-bladed rigid rotors. This Advancing Blade Concept (ABC) eliminates the need for an anti-torque tail rotor as well as the asymmetry of lift in forward flight, characteristic of single rotor helicopters. The rotor system is driven by a Pratt and Whitney PT6T-3 twin-pack turboshaft power plant rated at 1452 shp. The XH-59A was also outfitted with two auxiliary propulsion Pratt and Whitney J60-P-3A turbojets for high speed flight testing (above 150 kts). The engines were side mounted as shown in figure A-3 with each generating 3300 lb of static thrust. Nominal aircraft gross weight is 12,500 lbs with the auxiliary power engines and 9000 lbs without.

A simple rate damping SAS is provided for the longitudinal and lateral control axes. No retention functions are included in the XH-59A.

Navy and Army interest in varied concepts for VTOL/VSTOL missions led to an extensive flight test program on the XH-59A. All of the data included in this report are taken from these test flights documented in references (j), (k), and (o).



Physical Characteristics

Rotors 2 coaxial

Vehicle overall length 41.67 ft

Blades per rotor	3
Rotor separation	30 in
Radius	18 ft
Hub type	hingeless

Horizontal stabilizer (fixed)

Area	60 ft^2
Span	15.5 ft
Elevator	25% of horizontal tail area

Vertical stabilizer (2 fins)

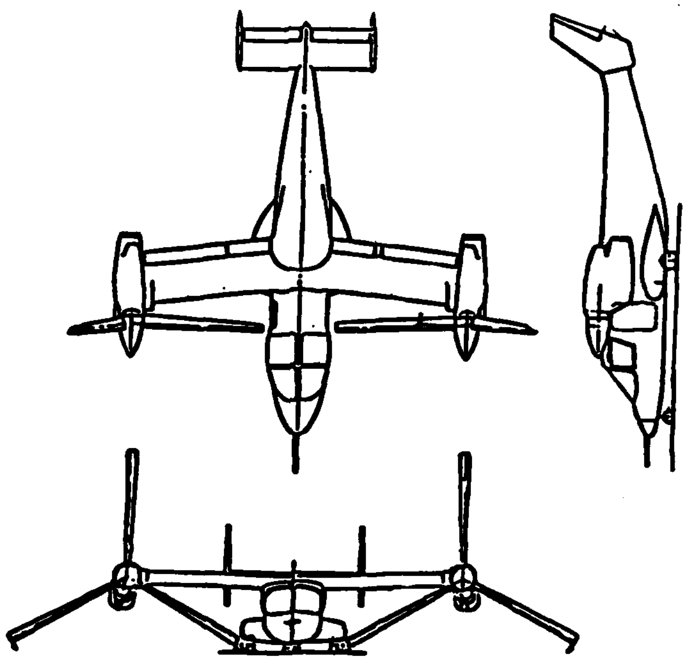
Area (total)	30 ft^2
Rudder	30% of vertical tail area

Figure A-3. XH-59A 3-View

XV-15

The XV-15 (figure A-4) is an experimental aircraft developed by Bell Helicopter using a tilt-rotor configuration. Each wing tip of the aircraft holds an engine, transmission, and rotor assembly. Tilting range of the nacelles are 96.5 degrees (helicopter mode) to 0 degrees (airplane mode). The engines for each rotor are Lycoming LTC1K-4K rated at 1250 shp. The aircraft design gross weight is 13,000 lb.

A Stability and Control Augmentation System (SCAS) is included in the XV-15 to aid dynamic stability and to enhance controllability. Rate damping is provided for the longitudinal, lateral, and directional axes, while only pitch and roll attitude hold functions are included. Reference (1) contains portions of the data presented.



Physical Characteristics

Rotors 2 side-by-side

Vehicle overall length 46.25 ft
Vehicle overall width 57.17 ft

Blades per rotor	3
Radius	12.5 ft
Span between hubs	32.17 ft
Hub type	gimbal mounted, stiff in-plane

Horizontal stabilizer (fixed)

Area	51.50 ft^2
Span	12.83 ft
Elevator	25% of horizontal tail area

Vertical stabilizer (2 fins)

Area (total)	50.50 ft^2
Rudder	15% of vertical tail area

Figure A-4. XV-15 3-View

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