ADA079911

NADC-77052-30

(12)

LEVEL

DEVELOPMENT OF VTOL FLYING QUALITIES CRITERIA

FOR LOW SPEED AND HOVER

by

ROGER H. HOH and IRVING L. ASHKENAS

SYSTEMS TECHNOLOGY, INC.

HAWTHORNE, CALIFORNIA 90250

DECEMBER 1979

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

PREPARED FOR

NAVAL AIR DEVELOPMENT CENTER

WARMINSTER, PENNSYLVANIA 18974

80 1 28 01

NOTICES

REPORT NUMBERING SYSTEM - The numbering of technical project reports issued by the Naval Air Development Center is arranged for specific identification purposes. Each number consists of the Center acronym, the calendar year in which the number was assigned, the sequence number of the report within the specific calendar year, and the official 2-digit correspondence code of the Command Office or the Functional Directorate responsible for the report. For example: Report No. NADC-78015-20 indicates the fifteeth Center report for the year 1978, and prepared by the Systems Directorate. The numerical codes are as follows:

CODE	OFFICE OR DEPARTMENT
00	Commander, Naval Air Development Center
01	Technical Director, Naval Air Development Center
02	Program and Financial Management Department
09	Technology Management Office
10	Naval Air Facility, Warminster
20	Aero Electronic Technology Department
30	Air Vehicle Technology Department
40	Crew Systems Department
50	Systems Department
60	Naval Navigation Laboratory
81	Technical Support Department
85	Computer Department

PRODUCT ENDORSEMENT - The discussion or instructions concerning commercial products herein do not constitute an endorsement by the Govenment nor do they convey or imply the license or right to use such products.

APPROVED BY: E. J. Sturm
E. J. STURM, USN

DATE: 11-16-77

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

19

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: 18 NADC-77052-30
2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle): 6 Development of VTOL Flying Qualities Criteria for Low Speed and Hover.

5. TYPE OF REPORT & PERIOD COVERED: 9 Final Report

6. PERFORMING ORG. REPORT NUMBER: 14 STI-TR-1116-1

7. AUTHOR(s): Hoh, Roger H. and Ashkenas, Irving L.

10 Roger H./Hoh Irving L./Ashkenas

8. CONTRACT OR GRANT NUMBER(s): 15 N62269-77-C-0278

9. PERFORMING ORGANIZATION NAME AND ADDRESS: Systems Technology, Inc.
13766 South Hawthorne Boulevard
Hawthorne, California 90250

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: PE 62241N
WF 41-421

11. CONTROLLING OFFICE NAME AND ADDRESS: Naval Air Development Center
Aircraft and Crew Systems Tech. Dir. (6053)
Warminster, PA 18974

12. REPORT DATE: 11 December 1979

13. NUMBER OF PAGES

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

12 146

15. SECURITY CLASS. (of this report): Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release: distribution unlimited

16 F41421

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Handling qualities
Displays
Powered lift
VTOL

340425

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

A classification scheme has been developed to account for outside visual cues and cockpit displays in determining the required equivalent system forms for low speed and hover. Tentative criteria are presented in terms of a visibility scale which quantifies environmental conditions for the intended mission in a more fine-grained manner than simply specifying IMC or VMC. There are indications that rate and attitude systems may be used

(continued)

DD FORM 1473, 1 JAN 73 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-LF-014-6601

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. ABSTRACT (concluded)

for partial IMC conditions but that a translational rate command system is required for low speed and hover in zero visibility. In general, most experiments indicate that advanced displays are not a substitute for augmentation. Tentative limiting conditions are defined for rate and attitude systems, but more data are required to define handling qualities for translational rate command systems. Since the existing data base is primarily oriented toward command/response characteristics, definition of the limiting conditions for turbulence and large discrete wind shears also requires more data.

FOREWORD

This study was conducted under Contract No. N6229-77-C-0278 to the Naval Air Development Center, and was monitored by Mr. John W. Clark, Jr., Flight Dynamics Branch (Code 60531). A significant portion of the study involved obtaining unpublished data, as well as advice and consultation from a number of researchers involved in VTOL experiments over the past 15 years. While space does not allow us to acknowledge all of the people who have given their time to assist us, we would like to offer special thanks to Mr. Richard Grief of NASA/Ames, Mr. James Kelly of NASA/Langley, and Dr. Victor Lebacqz of NASA/Ames.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SECTION I

INTRODUCTION

This report contains data correlations and background material required to develop updated handling quality criteria for VTOLs in the low speed and hover flight regime.

The data correlations have been accomplished in terms of lower order equivalent system (LOES) forms. These forms are presented in Section II.

It is felt that a primary deficiency of the current MIL-F-83300 specification is that it does not account for the combined effects of pilot outside visual cues, levels of augmentation, and cockpit displays. A first cut attempt to account for these variables is presented in Section III.

A primary objective of this study has been to collect, evaluate and, where appropriate, to correlate all available data obtained for low speed and hover. These results are presented in Section IV, VI, and VII.

In the process of collecting, evaluating and correlating the above data, deficiencies in the current data base have become apparent. These deficiencies are discussed in Section V and at the end of Sections VI and VII. A discussion of the experiments required to resolve these deficiencies is also included in each case.

The work is summarized in Section VIII through presentation of proposed modifications to each of the affected paragraphs in MIL-F-83300.

SECTION II

USE OF EQUIVALENT SYSTEM FORMS AS A SPECIFICATION FORMAT

There are a number of ways to specify handling qualities criteria, each having certain advantages and disadvantages. For flight vehicles which are characteristically nonclassical in terms of their dynamic modes, and which tend to be heavily augmented, the use of lower order equivalent systems (LOES) has certain advantages and disadvantages, both summarized below.

1. Advantages of LOES Specifications.

   - Higher order modes due to augmentation are accounted for implicitly.
   - The physical connection between the requirements and the response to control inputs is direct.
   - Unifies and reduces the number of (response) parameters needed to define the system properties.
   - It is intuitively satisfying in that it reflects the desire of the pilot to have lower order responses to control inputs (see Ref. 1).

2. Disadvantages of LOES Specification

   - A method for relating the degradation in pilot opinion with the degree of mismatch between the HOS and LOES is not yet well defined. Ongoing work to formulate such a method is currently being accomplished by Hodgkinson, et al.(see Ref. 2).
   - It is a relatively new concept and has not received acceptance in some segments of the handling qualities community.

In our opinion, the advantages of using LOES to specify handling quality criteria outweighs the disadvantages. Hence, the data analysis and handling requirements discussed in this report are presented in terms of LOES. It should be noted that many of the requirements which specify modes in the current MIL-F-83300 could easily be reinterpreted as the specification of an equivalent system.

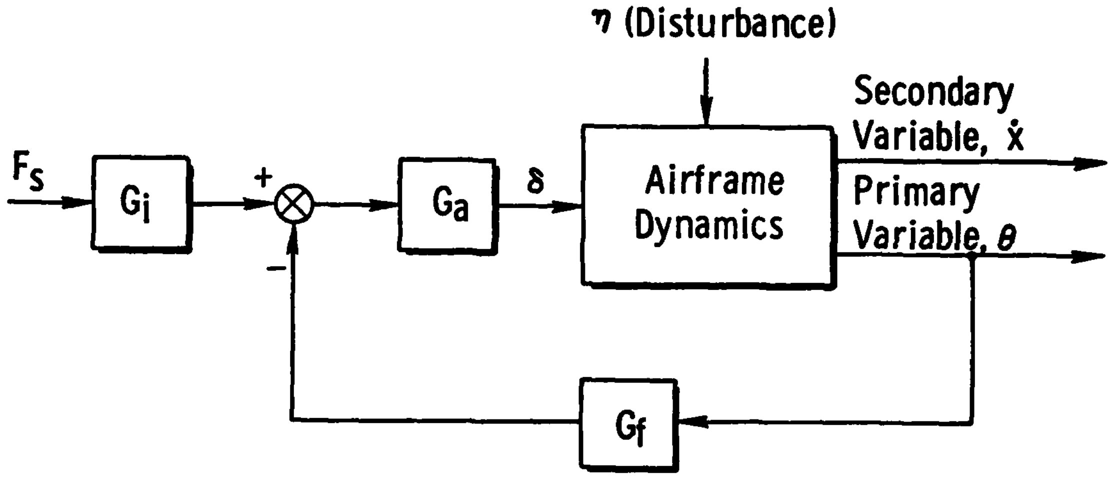
A. GENERIC CONSIDERATIONS

Some basic considerations which govern the use of LOES forms in the specification of handling quality criteria are summarized in Fig. 1. A generalized stability augmentation scheme is shown at the top of the figure. It illustrates that the equalization to achieve a desired set of control and disturbance response characteristics can be allocated to the forward loop, G_a, the feedback path, G_f, or at the input G_i. Several key concepts are illustrated. First the command response (Fig. 1a) can be made essentially independent of the basic vehicle dynamics (shown heavily outlined). The disturbance response (Fig. 1b) can be made arbitrarily small by increasing the overall loop gain G_aG_f. Even after consideration of the practical limits imposed by actuator dynamics, control system lags, gain limits, etc, the disturbance response can be highly attenuated and the command response tailored nearly independently of the basic vehicle dynamics. The effect of allocating the equalization to the feedback path (response feedback) or to the forward loop (command augmentation) can be an important consideration in the specification of handling qualities criteria. This is discussed in detail in the Vertical Axis section of the report (Section VII). Along this line, the separation of command from disturbance response is an important consideration for attitude control systems. Systems which utilize a large G_aG_f for disturbance suppression and a stick filter G_i to avoid overly abrupt command response characteristics are referred to as "model following attitude systems" in this report.

Secondary responses (Figs. 1c and 1d) are defined by variables which are not fed back to a control. In the example shown in Fig. 1c, the secondary response, $\dot{x}$, to a command input F_s can be tailored somewhat by the attitude augmentation

$$\frac{\theta}{F_s} \doteq \frac{G_i}{G_f}$$

The heavily outlined ratio of transfer functions is indicative of the aircraft response to commands with attitude constrained, i.e., $\dot{x}/\theta \doteq g/s$.



a) • Primary response/command

$$\frac{\theta}{F_s} = \frac{G_i}{G_f}\left\{\frac{G_aG_f\left[G_\delta^\theta\right]}{1 + G_aG_f\left[G_\delta^\theta\right]}\right\} \longrightarrow \frac{G_i}{G_f}$$

b) • Primary response/disturbance

$$\frac{\theta}{\eta} = \frac{G_\eta^\theta}{1 + G_aG_f\left[G_\delta^\theta\right]} \longrightarrow \frac{\left[G_\eta^\theta\right]}{G_aG_f\left[G_\delta^\theta\right]}$$

c) • Secondary response/command

$$\frac{\dot{x}}{F_s} = \frac{\theta}{F_s}\left[\frac{G_\delta^{\dot{x}}}{G_\delta^\theta}\right]$$

d) • Secondary response/disturbance

$$\frac{\dot{x}}{\eta} = \frac{G_\eta^{\dot{x}} + G_aG_f\left[G_{\delta\,\eta}^{\theta\,\dot{x}}\right]}{1 + G_aG_f\left[G_\delta^\theta\right]} \longrightarrow \left[\frac{G_{\delta\,\eta}^{\theta\,\dot{x}}}{G_\delta^\theta}\right]$$

Figure 1. Effective Aircraft Dynamics
Pilot-Command/Disturbance Aircraft Response Relationships

B. CLASSIFICATION OF PRIMARY AND SECONDARY RESPONSES

An example of the importance of properly classifying the primary and secondary responses to command inputs when using LOES as a criterion specification is illustrated in Ref. 3. Here is was noted that an appropriate LOES form for attitude control is the short period approximation defined in Ref. 4, e.g.,

$$\frac{\dot{\theta}}{F_s} = \frac{K_q(s + L_\alpha)e^{-\tau s}}{s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2} \tag{1}$$

In matching some of the configurations with the Eq. 1 form, it was necessary to free L_α to get a good fit. In some cases "unreasonably large" values of L_α were obtained. That is when taken in the context of the classical definition as obtained from a rigorous derivation of the equations of motion, L_α appears not only as a zero in the primary (attitude) command response transfer function (Fig. 1a) but also as the dominant mode of the <u>secondary</u> (path command response (Fig. 1b) e.g.,

$$\frac{\dot{h}}{\theta} = \frac{U_o}{(1/L_\alpha)s + 1} \tag{2}$$

If Eqs. 1 and 2 are classified as primary and secondary responses to a command input, then limits on "L_α" in Eq. 1 should be set purely on the basis of <u>attitude</u> control. There is no need to make L_α in Eq. 1 consistent with L_α in Eq. 2. In fact, it would be best to relabel L_α in Eq. 1 as a general first order time constant to avoid confusion. Handling quality boundaries for <u>path</u> control, in this case, are properly set by defining limits on the LOES form which defines the <u>secondary</u> response to commands. Again, using L_α may lead to confusion and another general first order time constant should be used.

C. EQUIVALENT SYSTEM FORM FOR ATTITUDE CONTROL

Consideration of available handling quality data for low speed and hover reveals that the lowest order system which adequately represents all realizable forms of VTOL attitude control is given as:

$$\frac{\theta}{\delta} = \frac{K\left(s + \frac{1}{T_\theta}\right)e^{-\tau s}}{(s + \lambda)(s^2 + 2\zeta\omega s + \omega^2)} \tag{3}$$

Practical combinations of ζ, ω and λ which represent both augmented and unaugmented systems are categorized in Fig. 2 according to their response characteristics at and below the region of crossover.

Attitude systems are inherently more satisfactory than rate systems for the low speed and hover tasks, especially in low visibility conditions. Analytical and experimental evidence supporting this contention is presented in Section III. We shall confine the present discussion, however, to dealing with the establishment of a classification scheme which can be used to quantitatively identify attitude systems. This is best accomplished by identifying the key features of attitude systems that make them desirable for low speed and hover. Based on the closed-loop pilot/vehicle analysis in Section III these are:

1. Attitude systems allow longer periods of unattended operation than rate systems because the pilot is not required to perform mid to high frequency attitude regulation.

2. There is one additional integration between stick deflection and aircraft velocity (or position) with a rate system when compared to an attitude system.

The first of these considerations arises from the natural tendency for an attitude system to return to trim when upset by a gust or an inadvertent pilot input. It follows that a straightforward way to identify an attitude system would be in terms of its tendency to return to trim when disturbed. This is somewhat analogous to the classical stick force per knot gradient used to define static stability in conventional airplanes. In fact, the use of stick force per attitude change from trim $\Delta F_s/\Delta\theta$ was considered as a criterion. $\Delta F_s/\Delta\theta$ was rejected as a viable approach because of problems

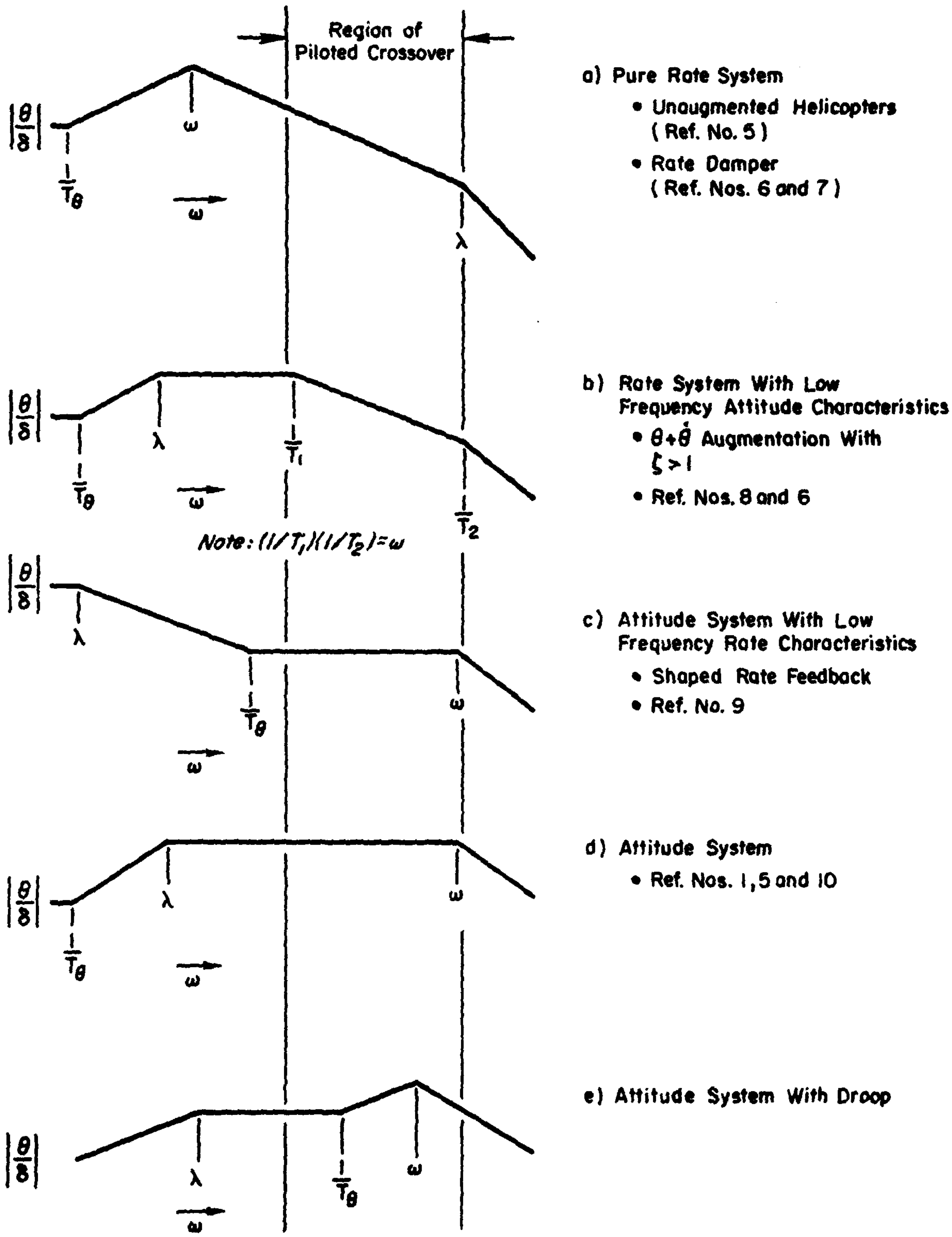


Figure 2. Practical Generic Forms of Attitude Response
for Low Speed and Hover

relative to the appropriate frequency at which it should be measured, and the complicating effects of stick force characteristics for sidearm controllers vs. center sticks. It was finally decided to use a time response criterion. The basis of the criterion is that the attitude should return to trim within some tolerance and within some time (T_A) after a stick pulse. It must also be specified that the attitude stay within some overshoot tolerance level for $T_B - T_A$ seconds to eliminate the possibility of compliance via a highly oscillatory system. A sketch of the proposed criterion form is given in Fig. 3. It should be emphasized that the Fig. 3 criterion simply classifies the response as to whether or not it can be considered an attitude system.

Tentative values of K_{θ_1}, K_{θ_2}, and T_A can be derived from considerations of the data correlations in Fig. 21 (Section IV-D). As noted in Section IV-D, a classical attitude system (Fig. 2d) becomes a rate system with low frequency attitude characteristics (Fig. 2b) as the damping ratio in Eq. 1 increases above unity (see Fig. 23, Section IV-D). Utilizing the boundary

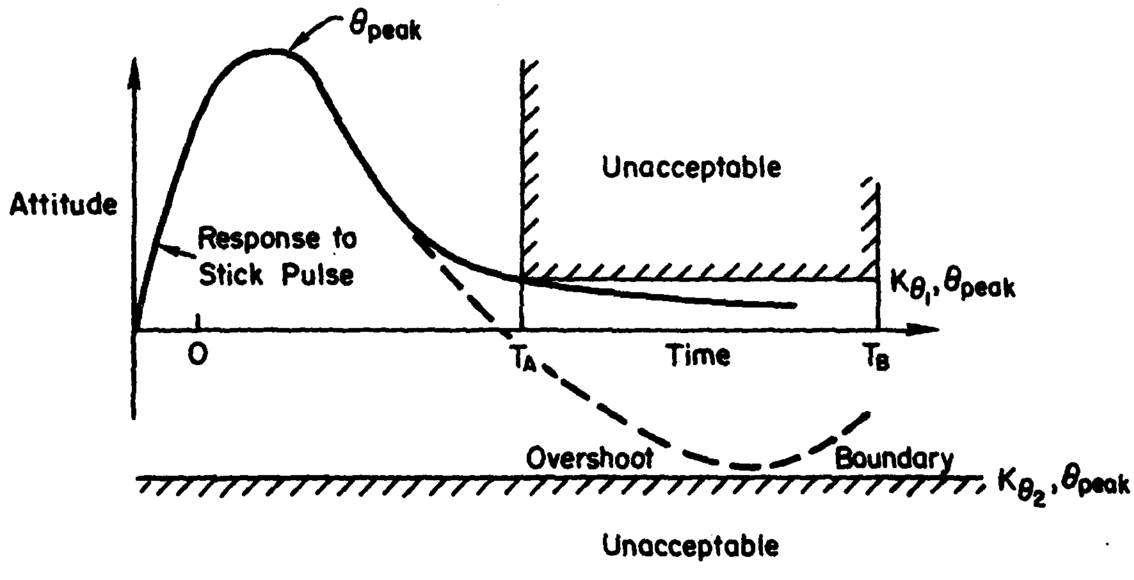


Figure 3. Form of Criterion for Specification of an Attitude System

between rate and attitude systems defined in Fig. 21 as $T_1 = 1$ sec we can estimate a value of T_A by noting where the $1/T_1 = 1.0$ line passes through the specification boundary. This point represents the most sluggish attitude system within the Level 1 boundaries and is approximated by:

$$\frac{\theta}{\delta} = \frac{K}{(s + .64)^2} \tag{4}$$

Based on past experience with evaluations of attitude systems, a reasonable classification of such systems can be based on their ability to return to within 20 percent of the peak value induced by a stick pulse; i.e., set the tentative value of K_{θ_1} at 0.20. The time required for the above system to return within 20 percent of peak following a unit pulse is approximately six seconds, and represents an initial estimate of T_A. The overshoot boundary would be properly set by an equivalent second order system damping ratio of 0.3 based on Fig. 21. In order to account for an effective decrease in damping due to a third order response an equivalent ζ_n of 0.2 has been tentatively selected resulting in a $K_{\theta_2} = 0.5$. While these numbers are supported by the data and seem reasonable intuitively (based on simulator and flight evaluation of rate and attitude systems) it would be desirable to conduct an experiment specifically oriented toward validating or refining these estimates. Such an experiment should be designed to insure that the final criterion serves its intended purpose, i.e., to identify attitude systems in terms of their ability to minimize pilot workload by allowing increased periods of unattended operation.

SECTION III

CLASSIFICATION OF HANDLING QUALITY CRITERIA IN TERMS OF OUTSIDE VISUAL CUES

Most of the available data for low speed and hover handling criteria has been obtained with good visual outside references and with no requirement for unattended operation. The real-life existence of secondary tasks, and intermittent to total loss of visual references, places increased demands on the pilot — an effect which is not discernible from such data. For example, pilot ratings for an unaugmented helicopter (Ref. 11) and a highly augmented translational rate command (TRC) system (Ref. 12) all fall within the satisfactory region (pilot rating better than 3.5). This result is a consequence of experimental scenarios which tend to be tailored toward the systems being investigated. That is, with pure rate systems the scenario is usually benign, thereby usually allowing intense, full-time pilot attention; whereas with a translational rate command (TRC) system the task tends to be more demanding. The most critical contributor to the total pilot workload appears to be the quality of out-the-window cues for detecting aircraft attitudes, and, to a lesser extent, position and velocity. Currently, these cues are categorized in a very gross way be designating the environment as either visual meteorological conditions (VMC) or instrument meteorological conditions (IMC). A more discriminating approach is to classify visibility in terms of the detailed attitude and position cues available during the experiment (or proposed mission); and to associate handling qualities requirements with these finer-grained classifications.

In the remainder of this section, existing data are utilized to make preliminary estimates of the equivalent low-order system hover dynamics required to cope with various classifications or levels of the operating environment. These estimates are based on a combination of closed-loop analysis and pilot commentary from flight and simulator experiments. The results are presented in terms of the specific levels of the maximum acceptable outside visual cues rating, OVC, (worst visibility) for each type of equivalent system response and display sophistication.

A. DEVELOPMENT OF OUTSIDE VISUAL CUE (OVC) SCALE

The longitudinal pilot/vehicle closure characteristics for different levels of augmentation for hover position control and for speed control are shown in Fig. 4. The comments below each root locus sketch indicate the required pilot workload function and OVCs to maintain adequate stability margins and path mode bandwidth (performance).

In the case of the rate augmented systems it can be seen that the pilot must close the attitude loop with a reasonably high gain to stabilize the phugoid mode, and to drive ω' into a favorable region as necessary for a good outer path loop closure. The requirement for a high-gain closure implies a need for high pilot scanning activity (Ref. 13). In addition to a high-gain attitude closure, the pilot must also develop lead on his position error to maintain path stability. Figure 4 indicates that a reduction in workload would be expected with attitude augmentation due to the elimination of the need for the pilot to perceive, stabilize, and constrain the pitch and roll attitudes. The degree of workload reduction will of course depend on the attitude SAS bandwidth and damping. Finally, with a translational rate command (TRC) system, the pilot simply has to perceive and feed back the aircraft position without equalization, i.e., the requirements for attitude stabilization and velocity feedback have been eliminated. The need for certain specific outside visual cues (OVC) has been inferred from such closed loop considerations; further, these OVC levels have been logically quantified in terms of a scale as shown in Fig. 5. Certain specific closed loop considerations which went into formulating the scale are summarized below and by the generic closed loop structure in Fig. 5.

- A requirement for closure of the attitude loop implies VMC conditions must prevail for adequate control. Two categories have been established for this condition: OVC = 1 and OVC = 2.

- If the equivalent system dynamics require closure of position and position rate, but not attitude, a minimum set of operating conditions quantified as OVC = 3 is defined.

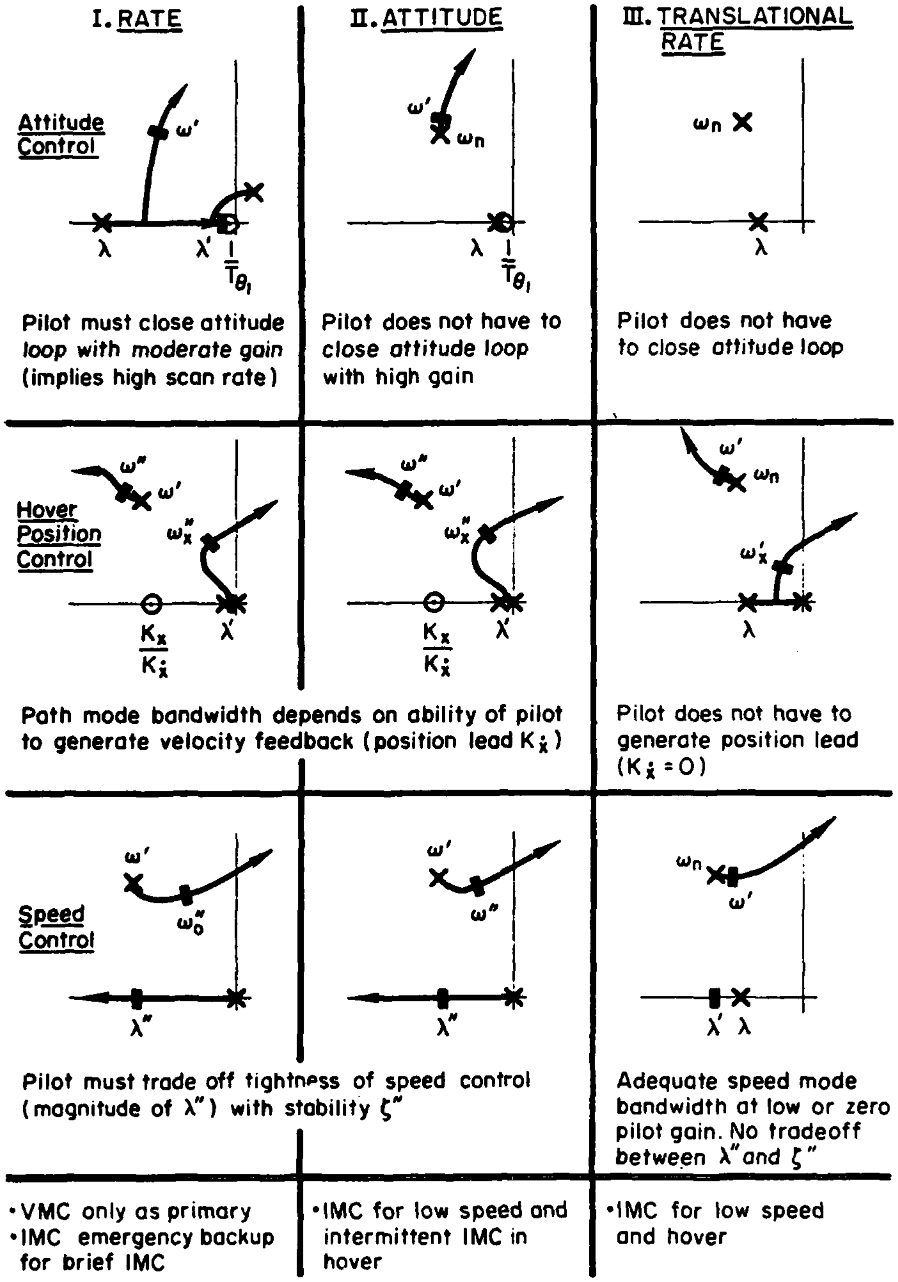
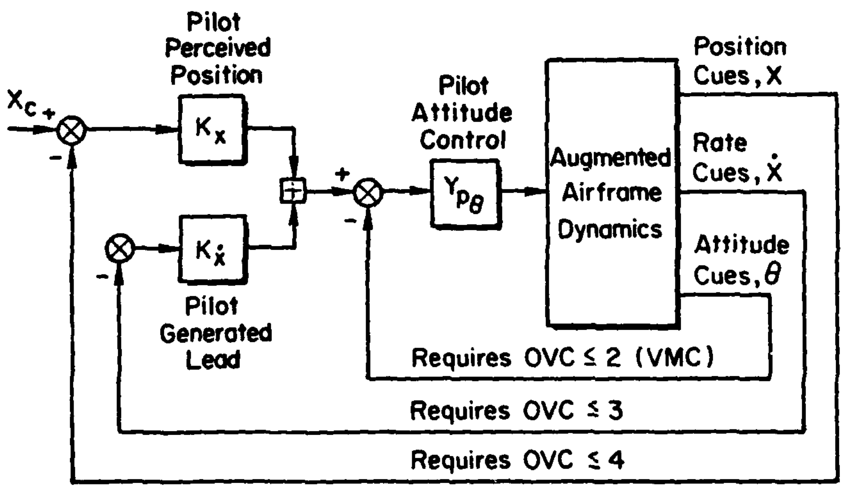


Figure 4. Pilot Loop Closure Characteristics

	Attitude Cues	Position and Velocity Cues	OVC Level
VMC	Easily obtained.	Easily obtained.	1
VMC	Somewhat obscured. Requires full concentration to obtain continuous attitude information	Easily obtained	2
Partial IMC	Inadequate in some sectors of the visual field.	Adequate position. Marginal rate cues.	3
Partial IMC	Inadequate over most of visual field.	Position and rate cues are marginal. Rate cues are intermittently unavailable.	4
IMC	Not available.	Not available.	5

a) Quantification of Outside Visual Cues (OVC)



b) Required Outside Visual Cues for Control

Figure 5. Development of Outside Visual Cue Scale

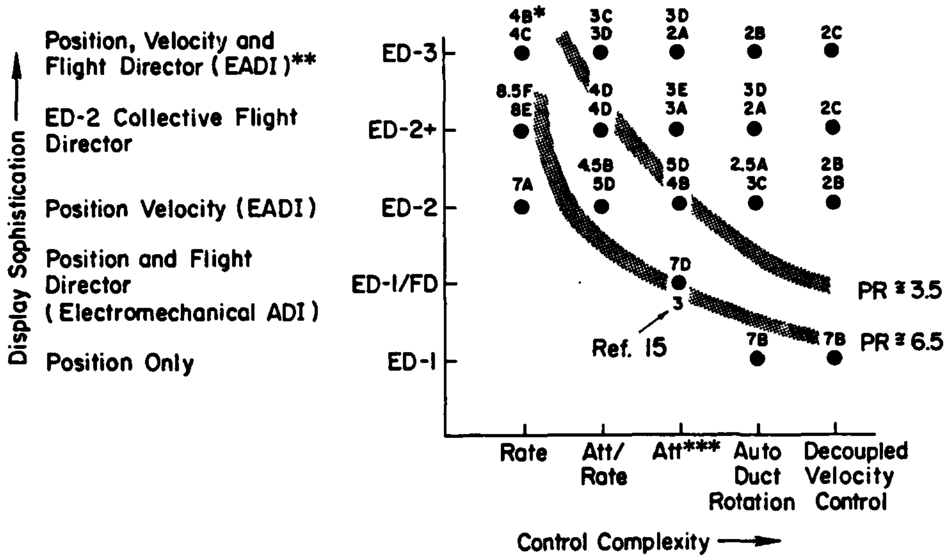
- OVC = 4 quantifies the operating condition where velocity and attitude cues are not available. That is, only the outer loop in Fig. 5b can be closed by the pilot.
- OVC = 5 indicates that no outside visual cues are available.

B. CONTROL/DISPLAY TRADEOFFS

Pilot workload can also be reduced via improved displays. Recent work in the control/display tradeoff area includes the Calspan X-22 flight tests (Ref. 14) and the CH-46/47 variable stability helicopter (Ref. 15).

Results of the X-22 experiment are summarized in Fig. 6 (Ref. 14). These data represent an ILS approach including deceleration to hover in IMC conditions (OVC = 5 in Fig. 5). The ratings reported were made by one pilot, although other pilots flew and rated some of the configurations. Perhaps the most significant result of these data is that increased augmentation is considerably more beneficial than improved displays. This conclusion is somewhat compromised by the pilot rating of 7 for the mechanical flight director (Configuration ED-1/FD). However, it should be noted that the very poor rating given to ED-1/FD in Fig. 6 is not consistent with the satisfactory rating (PR= 3) given to SCAS No. 3 in Fig. 7. Comments by the X-22 subject pilot indicated that he felt that reliance on the mechanical flight director was in itself a deficiency and that explicit velocity information is an absolute necessity for IMC hover. These comments along with the consideration that the experiment was primarily oriented toward integrated electronic displays could explain the surprisingly poor rating for ED-1/FD in Fig. 6. The improved rating from Ref. 15, when plotted on Fig. 6, tends to support the contention that displays have a significantly less dominant effect than augmentation on pilot workload reduction. It should be noted that the experiment described by Lebacqz and Aiken in Ref. 8 included the ED-1/FD data point specifically for comparison with the CH-47 helicopter experiments in Ref. 15.

Pilot rating data from Ref. 16 are also plotted on Fig. 7. The Ref. 16 experiment was specifically oriented toward the Navy mission and was conducted on the NASA Ames Flight Simulator for Advanced Aircraft (FSAA). It consisted of approaches and landings to a moving ship with various levels



**Numbers are Cooper-Harper pilot ratings, letters are turbulence effect ratings. Two ratings indicates two separate evaluations of a configuration.*

***EADI ⇒ electronic attitude director indicator on an integrated display on a CRT.*

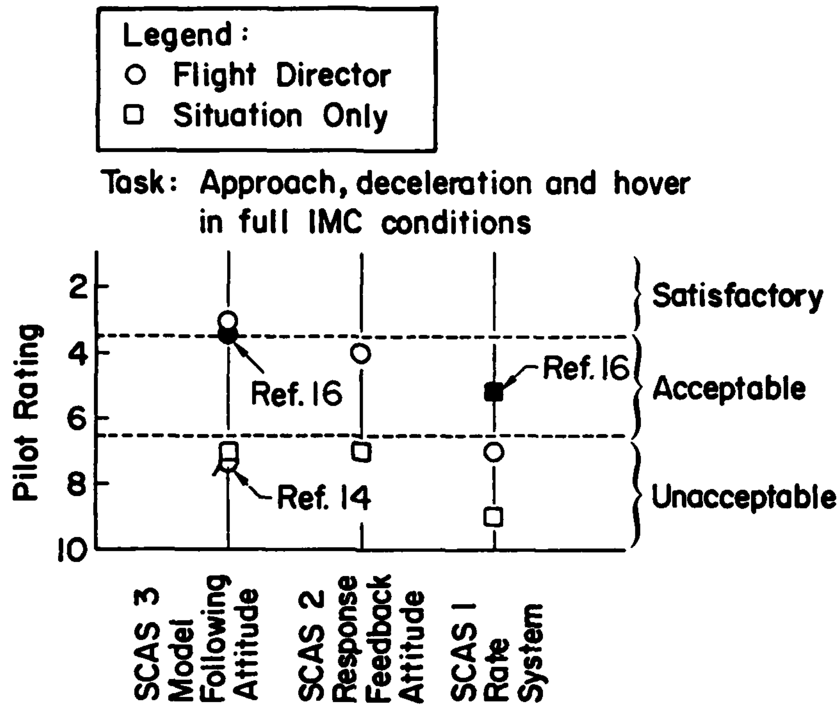
****Att refers to a model following attitude system with an inner loop bandwidth of 4 rad/sec.*

HOVER DYNAMICS

	θ/δ	ϕ/δ
Rate	$\dfrac{K(0)}{(2.94)[.10,.41]}$	$\dfrac{K(0)}{(2.71)[-.025,.45]}$
Att/Rate	$\dfrac{K}{[.7,2.0]}$	$\dfrac{K(2)}{(0)[.52,2.15]}$
Att	$\dfrac{K}{[.7,2.0]}$	$\dfrac{K}{[.7,2.0]}$

Note: $(1/T) \Rightarrow (s+1/T)$ $\quad [\zeta,\omega] \Rightarrow s^2+2\zeta\omega s+\omega^2$

Figure 6. Pilot Rating Data for Primary Matrix (X-22 Experiment, Taken from Ref. 14)



HOVER DYNAMICS - CH 47

	θ/δ	ϕ/δ
SCAS No. 1 (Rate)	$\frac{K(.094)}{(2.67)\,[0,.27]}$	$\frac{K(.29)}{(2.27)\,[.051,.37]}$
SCAS No. 2 (Response Feedback)	$\frac{.2}{[.79,1.62]}$	$\frac{.2}{[.88,1.10]}$
SCAS No. 3 (Model Following)	$\frac{.2}{[.75,1.41]}$	$\frac{.2}{[.75,1.41]}$

Figure 7. Results of CH-47 Variable Stability Helicopter Control/Display Experiment (Taken from Ref. 15)

of sea state and wind over the deck (WOD). The flight visibility was set to 700 ft. A head up display consisting of flight director and status information was available to each of the two subject pilots. The results shown in Fig. 7 indicate that reasonable agreement exists between Ref. 16 and Ref. 15 in that the pilots were able to hover the model following attitude system using primarily flight director information. However, it should be noted that some limited status information* was available to the Ref. 16 pilots since the visual range was set to 700 ft. The surprisingly good rating given to the rate system without a flight director in the Ref. 16 experiment was probably a consequence of the available outside visual cues.

A dramatic improvement in pilot opinion is shown in Fig. 6 (for IMC tasks) when upgrading from a rate system to an attitude system. This is supported by the results of the variable stability CH-47 helicopter (Ref. 15 (as shown in Fig. 7). The task on this latter experiment was an ILS approach to hover with an electromechanical flight director.

Unfortunately, the rate SAS had a divergent mode above 40 kt (Ref. 15 ($\lambda = -0.25$) and no pilot rating data were taken for low speed and hover per se. However, there was evidence from the pilot commentary that the rate SAS was unacceptable even below 40 kt (where the pitch divergence disappears). It was noted that "even though decelerations to hover could be consistently achieved with the rate SAS and flight director configuration, the pilot workload was considered to be unacceptably high." Thus, there is strong evidence that even with a good rate SAS and a flight director, the low speed and hover handling qualities are unacceptable for IMC flight.

Additional evidence that rate-like attitude response characteristics are unacceptable for low speed flight in IMC conditions may be found in the results of an instrument flight evaluation of the OH-6A helicopter. The following quote is taken from Ref. 17.

> "Associated with instrument flight are additional tasks of tuning radios, examining flight charts and approach plates, and various other required tasks. Accomplishment of these tasks requires the removal of the pilot's hands from at least one of the flight controls. Flight in instrument conditions requires total concentration with constant corrective control inputs just to maintain a trim condition. A copilot would therefore be required to aid the pilot in performing IFR operations if IFR flight were attempted."

*The status information was limited by the poor field of view of the FSAA visual display plus other deficiencies of the simulator visual system when used for low speed and hover (see Section IV).

The pilot/vehicle closure characteristics of the OH-6A are given in Fig. 8 (taken from Ref. 17) for speeds from hover to 40 kt. Utilizing the pilot model rules as stated in Ref. 13, the required compensation is seen to be a lead at 0.5 sec in order to equalize to a K/s. Such compensation is expected to produce only moderate penalties in pilot opinion, yet the pilot comments indicated 100 percent workload was required simply to maintain control in IMC conditions (pilot ratings of 6 to 7).

Based on the above evidence, it seems reasonable to conclude that rate-like attitude systems are acceptable for low speed and hover only in VMC conditions.

Figure 6 indicates that a rate SAS combined with an electromechanical flight director results in Level 3 flying qualities (PR = 7). However, the data indicate that rate augmentation may be suitable for backup systems (Level 2) in an electronic display which integrates position, velocity, and flight director commands (ED-3 in Fig. 6).

Rate command/attitude hold (RCAH) systems result in considerably improved pilot ratings over pure rate systems, a fact which stems from the disturbance regulation characteristics inherent to this type of system. There are very little data on RCAH systems for low speed and hover. One exception is a fixed-base simulation which was run to evaluate a system design to allow ILS (full IMC) approaches to hover and vertical letdown for the Army/NASA/Bell XV-15 Tilt Rotor (Ref. 18). The final manual system included a mechanical flight director plus moving map display and a fully automatic collective axis to keep pilot workload at a reasonable level. A constant attitude deceleration law was incorporated in the flight director — also to keep pilot workload at a reasonably level. A fully automatic system was also configured. The pilot ratings and commentary are summarized in Table 1. These data indicate that an RCAH system with a mechanical flight director is not satisfactory for low speed and hover in IMC conditions.

C. PILOT WORKLOAD

There is some evidence that the highest pilot workload occurs not during hover, but during the final phase of deceleration. Unfortunately, the pilot ratings for the control/display tradeoff experiments (Refs. 14 and 15) included

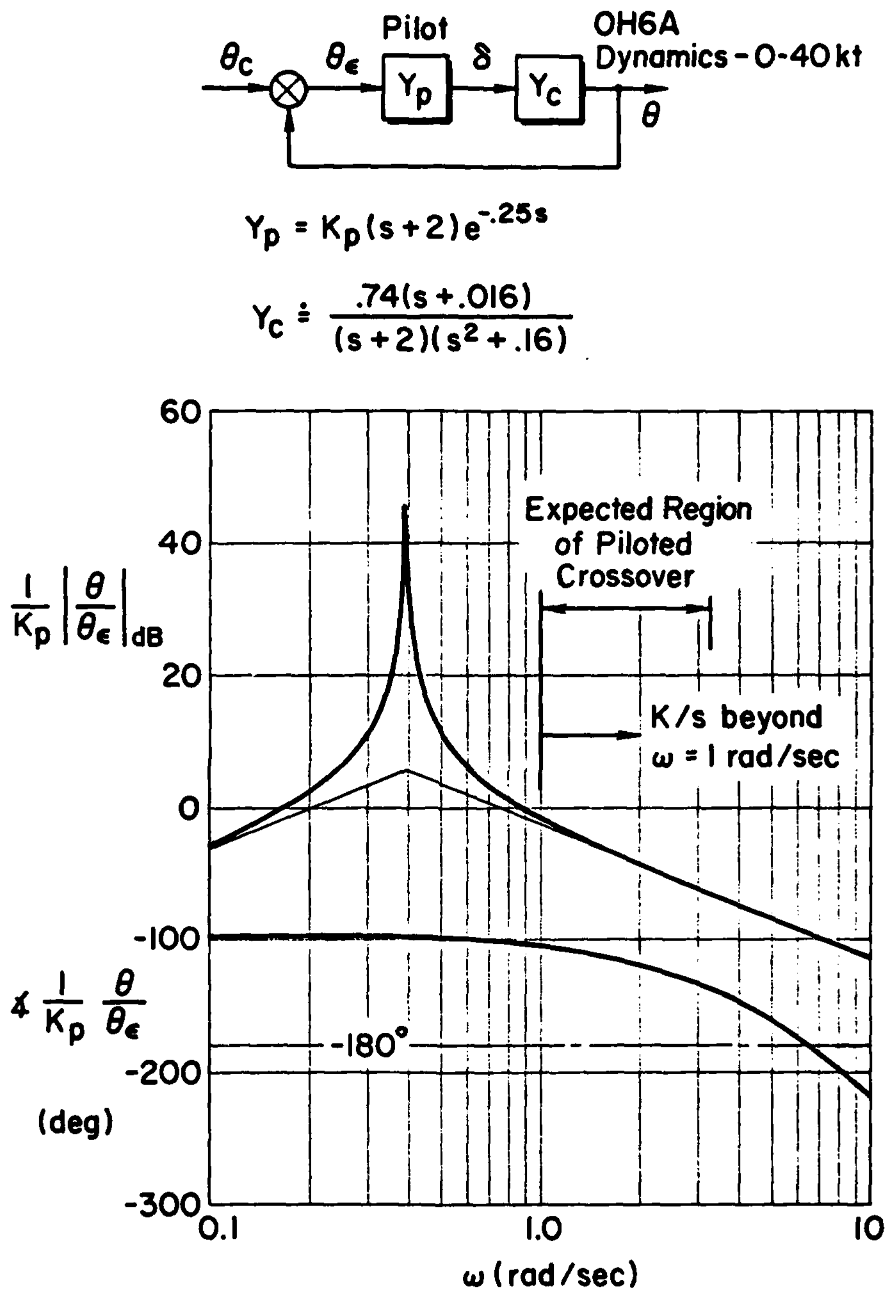


Figure 8. Piloted Attitude Control Characteristics of OH-6A for Hover to 40 kt

TABLE 1. PILOT RATINGS AND COMMENTARY FOR RATE COMMAND/ATTITUDE HOLD SYSTEM IN IMC (VISUAL LEVEL = 5) CONDITIONS

PILOT TASK	PILOT RATING	COMMENTS
Constant Speed Glide Slope Tracking	2 FD 2 AP	Longitudinal and lateral flight directors easy to track. Workload is low.
Deceleration to hover (IMC)	4-1/2 FD 2 AP	Constant attention required to keep flight director centered. Kind of wanders during deceleration cannot set and forget.
Hover (IMC) and vertical descent	4-1/2 to 5 FD 2 AP	1) Very little change in attitude results in pitch bar movement. Requires light touch on stick to keep from overcontrolling. Not unsafe. 2) Requires constant attention. Need time to scan other instruments (besides flight director) this close to ground.

FD ⇒ Pilot flying via longitudinal and lateral flight director bars. Collective is automatic

AP ⇒ Fully automatic to touchdown

the entire mission from constant speed glide slope tracking to a stabilized hover. A mission phase dependency of pilot workload is specifically indicated in NASA TN D-8480 (Ref. 19), where an approximate variation in pilot rating with approach phase was shown (see Fig. 9). This plot was formulated on the basis of data obtained from the collective experience gained in the CH-46/47 experiments conducted at NASA/Langley from 1962 through 1977 (Refs. 15 and 20). The comments on the plot reflect informal discussions with the authors.

Additional support to the hypothesis that the deceleration phase is critical stems from the apparent discrepancy in the two X-22 experiment reports described in Refs. 14 and 21. These data are compared directly in Fig. 10, where it is shown that a drastic improvement occurred in the later experiment as shown in Ref. 21. Comparison between the experiments

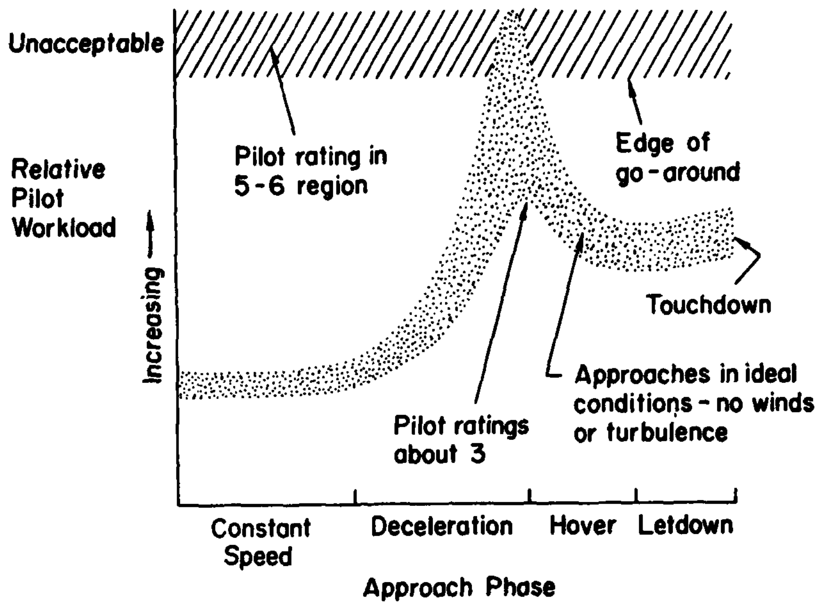


Figure 9. Relative Pilot Workload as Function of Approach Phase

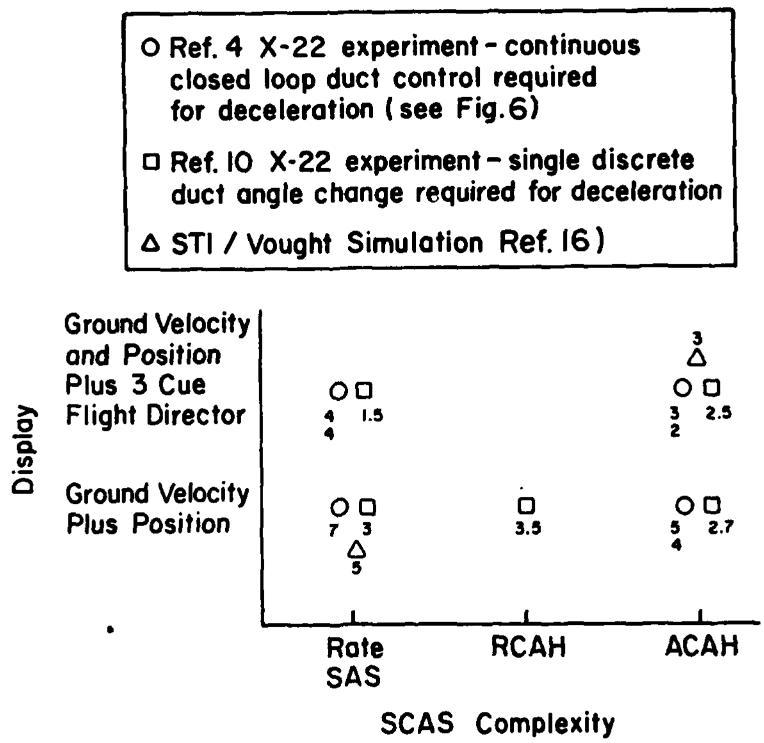


Figure 10. Comparison of Pilot Ratings for Similar Controls and Displays But Different Deceleration Profiles

reveals that two primary differences existed: 1) the display was projected on the windscreen (i.e., a HUD) in the second experiment; and 2) a much simpler deceleration profile was utilized. The evaluation pilot's view of the outside world was blocked so that any benefits that might accrue from the HUD were lost, i.e., the situation was essentially head down. This leaves the simpler deceleration profile (e.g., one discrete duct angle change vs. continuous closed-loop control of duct angle) as the most viable explanation of the difference in ratings. This is consistent with the pilot centered requirement for frequency separation of controls (see Ref. 1). That is, only one control should be primary in each axis with all others relegated to a secondary trim function.

Clearly, more experimental data are required to nail down such effects. However, there is considerable evidence which indicates that the minimum acceptable control/display combinations in Table 2 are strongly dependent on the final deceleration characteristics of each configuration.

D. RESULTS AND SUPPORTING RATIONALE

The following paragraphs summarize the rationale used to interpret the foregoing data and to finally arrive at the tentative allowable visual cue levels presented in Table 2 for each type of equivalent system form and display.

1. Rate Systems

All the evidence indicates that rate systems with raw data displays are acceptable for VMC flight only (OVC = 1). The addition of a mechanical flight director does not move the ratings out of the unacceptable range for full IMC (Fig. 7). However, there is sufficient anecdotal evidence to indicate that an increase to an OVC level of 2 is warranted. The high pilot workload associated with rate systems (Figs. 4 and 5) precludes the normal allowance of partial IMC even with a flight director, as confirmed by the pilot rating of 7 in Fig. 7. When used as an emergency backup, though, an increase to an OVC level of 4 seems indicated by pilot commentary, showing that deceleration to hover could be accomplished, even though the workload was extreme.

TABLE 2. MAXIMUM ALLOWABLE OUTSIDE VISUAL CUE LEVELS (OVC) FOR EACH CATEGORY OF EQUIVALENT SYSTEM RESPONSE

LOWER ORDER EQUIVALENT SYSTEM TYPE		PILOT DISPLAY		
	FLYING QUALITY LEVEL	X, Y and Z POSITION INFORMATION ONLY (RAW DATA)	RAW DATA PLUS FLIGHT DIRECTOR	INTEGRATED DISPLAY-FLIGHT DIRECTOR PLUS AIRCRAFT VELOCITY INFORMATION
Rate (Fig. 2a,b)	Level 1	1	2	3
	Level 2	2	4	5
Rate Command Attitude Hold (Fig. 2a)	Level 1	2	3	3
	Level 2	2	5	5
Attitude (response feedback) (Fig. 2c,d,e)	Level 1	2	3	3
	Level 2	2	5	5
Attitude (model following) (Fig. 2c,d,e)	Level 1	2	4	4
	Level 2	2	5	5
Translational Rate with	Level 1	3	5	5
	Level 2	3	5	5
Translational Rate with Direct Force Control	Level 1	3	5	5
	Level 2	3	5	5

Figure 6 indicates that a fully integrated display results in a pilot rating of 4 for an approach in OVC Level 5 conditions (full IMC). Again, because of the high scanning workload associated with rate systems, we have elected to tentatively restrict the allowable OVC to 3 even with the addition of a fully integrated display. This is increased to an OVC level

of 5 when utilized as a backup system (Level 2 flying qualities), primarily based on the pilot rating of 4 in Fig. 6 (ED-3/Rate).

2. Attitude Systems

Figure 7 indicates that response feedback and model-following attitude systems are unacceptable if only raw data displays are available. Therefore, an OVC level of 2 is specified in Table 2. There is considerable discrepancy between the X-22 results stated in Ref. 14 and the CH-46 results described in Ref. 15 regarding attitude systems with a mechanical flight director (PR = 7 vs. PR = 3, respectively). Until further data are available we have elected to compromise by allowing OVC Level 3 conditions for response feedback systems and OVC Level 4 conditions for model followers when the display consists of a mechanical flight director. The increase to OVC Level 4 for model following is based on the improvement indicated in Fig. 6 (pilot rating improves from 4 to 3) and on the obvious benefits which accrue from the gust regulation characteristics of a model-following system. Both the response feedback and model-following attitude systems should be adequate as a backup mode for full IMC conditions, and therefore an OVC level of 5 is indicated in Table 2 (for a mechanical flight director). The only reservation is the pilot rating of 7 (ED-1/FD) in Fig. 6. However, the pilot ratings of 3 and 4 in Fig. 7 are felt to carry enough weight to allow these systems for full IMC conditions, at least for Level 2 flying qualities.

The X-22 data in Fig. 6 indicate that a model-following attitude system with a fully integrated display results in pilot ratings in the satisfactory range (PR = 2-3). However, there are some unpublished data from visiting V/STOL pilots (from NASA/Langley and Ames) who gave ratings from 4 to 7 for even the best configurations in Fig. 6. These pilots were probably not up on the learning curve and did not have the benefit of the primary X-22 evaluation pilot in terms of comparing the best systems with the less desirable rate systems. However, because of the critical nature of hovering in IMC, a conservative approach seems warranted. Therefore, until more experience is gained (e.g., more pilots with adequate evaluation time), it was decided to restrict the response feedback system to OVC Level 3 and

the model follower to OVC Level 4. This may be unduly restrictive and should be subjected to flight testing for validation.

3. TRC Systems

The translational rate command (TRC) systems represent a significant decrease in pilot workload according to the analysis in Fig. 4. There are some experimental results (Refs. 22 and 23 which support the analysis, but neither reference specifically addresses the IMC hover task. Additionally, there are some fixed-base simulation results which indicate that a TRC system will be satisfactory for IMC hover as shown in Refs. 13 and 23 Based on these results, it seems reasonable to allow light IMC (OVC Level = 3) even with raw data. Considering the minimal pilot workload to hold speed or position (see Fig. 4) with a TRC system, an OVC level of 5 (full IMC) is allowed for the mechanical flight director or the integrated display.

E. EFFECT OF TURBULENCE

The data utilized to obtain the results shown in Table 2 were obtained with very little or no turbulence. The effect of atmospheric disturbances was studied in Ref. 16 in terms of increasing WOD with the results shown in Fig. 11. When ψ_{WOD} = −30 deg, an area of low pressure occurred on the lee side of the hanger tending to pull the aircraft into the structure. Figure 11 shows that this effect was quite pronounced for rate and attitude systems but had little effect on the TRC SAS with position hold. Pilot commentary indicated that the turbulence and wind shears generated by increasing WOD completely dominated the task and that ship motion (up to sea state 5) and low visibility were, by comparison, secondary effects. The effect of the data in Fig. 11 on the interpretation of Table 2 may be summarized as follows:

- If the OVC level is such that a <u>rate</u> system is indicated in Table 2 the maximum allowable WOD would be as follows:

ψ_{WOD} −deg	MAXIMUM WOD − kt	
	LEVEL 1	LEVEL 2
0	10	20
−30	15	25

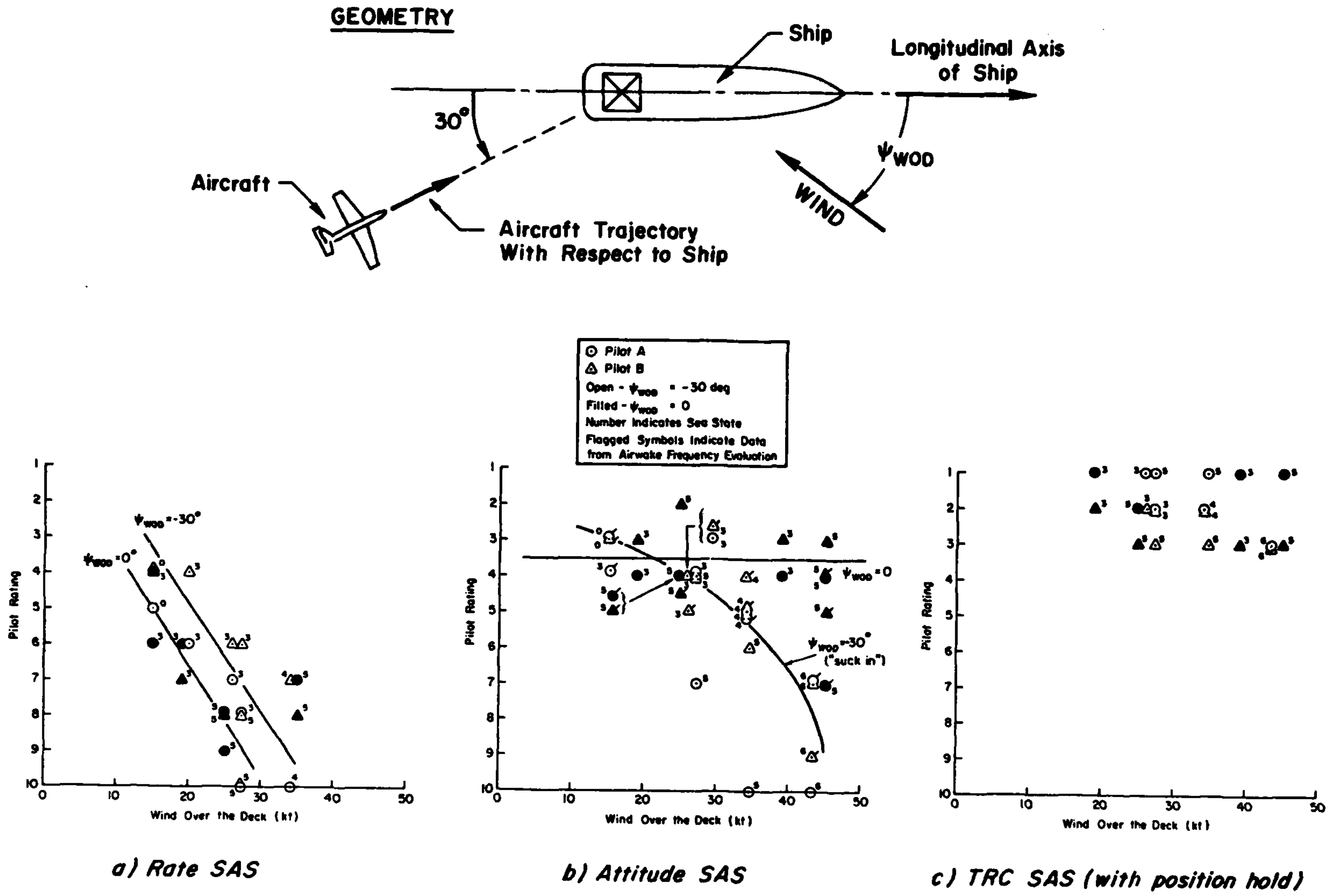


Figure 11. Effect of Atmospheric Disturbance on Cooper-Harper Pilot Ratings
(Taken from Ref. 16)

- If an attitude system is indicated, the maximum allowable WOD would be as follows:

ψ_{WOD} –deg	MAXIMUM WOD – kt	
	LEVEL 1	LEVEL 2
0	40	45
–30	20	40

A tight attitude system (5 rad/sec bandwidth) was used in Ref. 16. The effect of decreasing the attitude bandwidth is not currently known.

- If a TRC system with position hold is utilized, the Fig. 11 data indicates that Level 1 flying qualities can be achieved up to the maximum tested WOD of 45 kts. The system tested had a 1 rad/sec bandwidth in the x and y position loops. The effect of lower bandwidth position or velocity loops and of removing the position hold feature are currently being analyzed.

F. SUMMARY COMMENTS

Based on existing data, a firstcut attempt at establishing minimum acceptable systems for operations in specified levels of visibility has been accomplished (Table 2). It indicates that rate augmentation is acceptable for VMC only and that a TRC system will probably be required for hovering in full IMC conditions.

There is evidence that the final phase of deceleration constitutes the most critical flight condition for certain deceleration schemes. Further experiments should concentrate on this area.

There is a substantial amount of disagreement within and among the experiments regarding the minimum acceptable controls and displays. These disagreements result in specific requirements for further experiments.

Finally, most of the existing data indicate that advanced displays are not a substitute for augmentation.

SECTION IV

DATA CORRELATIONS FOR LATERAL AND LONGITUDINAL AXES

A. DATA SELECTION FOR LOW SPEED AND HOVER

Pilot ratings and performance in this flight regime are extremely sensitive to the available visual and motion cues. This fact eliminates from consideration all VMC or partial VMC data taken without an adequate visual display. For example, experienced VTOL and helicopter pilots were unable to hover with any precision with even the best attitude augmentation systems using the Redifon display on the FSAA simulator. The reasons for this are not entirely clear. However, there is evidence that the lack of peripheral cues was not the answer. This result is in the form of an unpublished experiment at NASA Ames where a research pilot hovered a UH-1H helicopter with increasingly reduced field of view with little or no reduction in performance or increase in workload. The same pilot indicated that the Redifon hover cues were inadequate to hover the FSAA simulator with UH-1H dynamics. Possible explanations are lack of resolution and/or deadbands in the camera drive. Because of these problems, all data taken using the Redifon display require special interpretation (see Section IV-E-1) are primarily useful for determining possible trends. A similar situation exists with the UARL (Ref. 24) data which utilized a contact analog display. Experienced VTOL pilots were unable to give valid ratings on that simulator because of problems with the display. It was, therefore, decided to use the Ref. 24 data to establish trends rather than specific boundaries. Two simulators appear to have adequate visual and motion cues, the NASA Ames S01 and the NORAIR three axis flight simulator. The S01 is a six degree of freedom moving base simulator which utilizes one to one motion (no washouts) and outside, real-world visual cues. Its drawback is a limited maneuvering area (a cube 18 ft on a side). The NORAIR simulator utilized a visual scene generated by a point light source on a 12 ft radius hemispherical screen. Pilot comments indicate that adequate hover cues were available. This included a NASA research pilot who compared actual X-14A hover with an X-14A simulation at NORAIR.

SECTION IV

DATA CORRELATIONS FOR LATERAL AND LONGITUDINAL AXES

A. DATA SELECTION FOR LOW SPEED AND HOVER

Pilot ratings and performance in this flight regime are extremely sensitive to the available visual and motion cues. This fact eliminates from consideration all VMC or partial VMC data taken without an adequate visual display. For example, experienced VTOL and helicopter pilots were unable to hover with any precision with even the best attitude augmentation systems using the Redifon display on the FSAA simulator. The reasons for this are not entirely clear. However, there is evidence that the lack of peripheral cues was not the answer. This result is in the form of an unpublished experiment at NASA Ames where a research pilot hovered a UH-1H helicopter with increasingly reduced field of view with little or no reduction in performance or increase in workload. The same pilot indicated that the Redifon hover cues were inadequate to hover the FSAA simulator with UH-1H dynamics. Possible explanations are lack of resolution and/or deadbands in the camera drive. Because of these problems, all data taken using the Redifon display require special interpretation (see Section IV-E-1) are primarily useful for determining possible trends. A similar situation exists with the UARL (Ref. 24) data which utilized a contact analog display. Experienced VTOL pilots were unable to give valid ratings on that simulator because of problems with the display. It was, therefore, decided to use the Ref. 24 data to establish trends rather than specific boundaries. Two simulators appear to have adequate visual and motion cues, the NASA Ames S01 and the NORAIR three axis flight simulator. The S01 is a six degree of freedom moving base simulator which utilizes one to one motion (no washouts) and outside, real-world visual cues. Its drawback is a limited maneuvering area (a cube 18 ft on a side). The NORAIR simulator utilized a visual scene generated by a point light source on a 12 ft radius hemispherical screen. Pilot comments indicate that adequate hover cues were available. This included a NASA research pilot who compared actual X-14A hover with an X-14A simulation at NORAIR.

Flight data is available in two categories. Category one consists of a series of experimental VTOL aircraft, which includes the XV-5, CL-84, XC-142, TAGS helicopter and VAK-191B etc. The second category consists of variable stability research vehicles such as the X-22A, the NASA Langley CH-46/47, the NRC Bell helicopter, and the NASA Ames X-14. Data correlations in this report have concentrated on Category 2 flight experiments and simulation results from the NASA Ames S01 and the NORAIR simulation reported in Ref. 6. This is a result of the fact that most of the problems in the category one experiments were vehicle-dependent, and, in most cases the pilots did not give ratings nor were they assigned specific tasks.

Two meetings were conducted at NASA Ames to review results obtained during the past 12 years using the S01 simulator and X-14A test aircraft. A synopsis of these results has been published in a recent AIAA Journal of Guidance and Control article (Ref. 25). The detailed pilot ratings and commentary from these experiments have been made available to STI by Mr. Richard Greif of NASA Ames. This data base includes 440 runs on the S01 simulator where two experienced VTOL pilots evaluated parametric variations in rate and attitude augmentation as well as control power. These data combined with the NORAIR data of Ref. 6, the X-14A data (Ref. 26), as well as the variable stability helicopter data from Refs. 11, 27 and 28 result in a reasonably good data base from which to establish flying qualities boundaries for rate and attitude equivalent system parameters.

B. PURE RATE SYSTEMS (See Fig. 2a)

The variable stability helicopter experiments conducted at Princeton University (see Ref. 11) as well as the simulator experiments of Refs. 6 and 24 include a reasonably wide range of rate system parameters [ω_n, ζ_n and λ (see Fig. 2a)]. The results of Ref. 11 are presented in terms of pilot rating boundaries on a grid of M_q vs. $M_u g$ in Fig. 12 (taken directly from Ref. 11). However, further light can be shed on these results as well as the results of Refs. 6 and 24 by plotting the pilot ratings vs. ω_n.

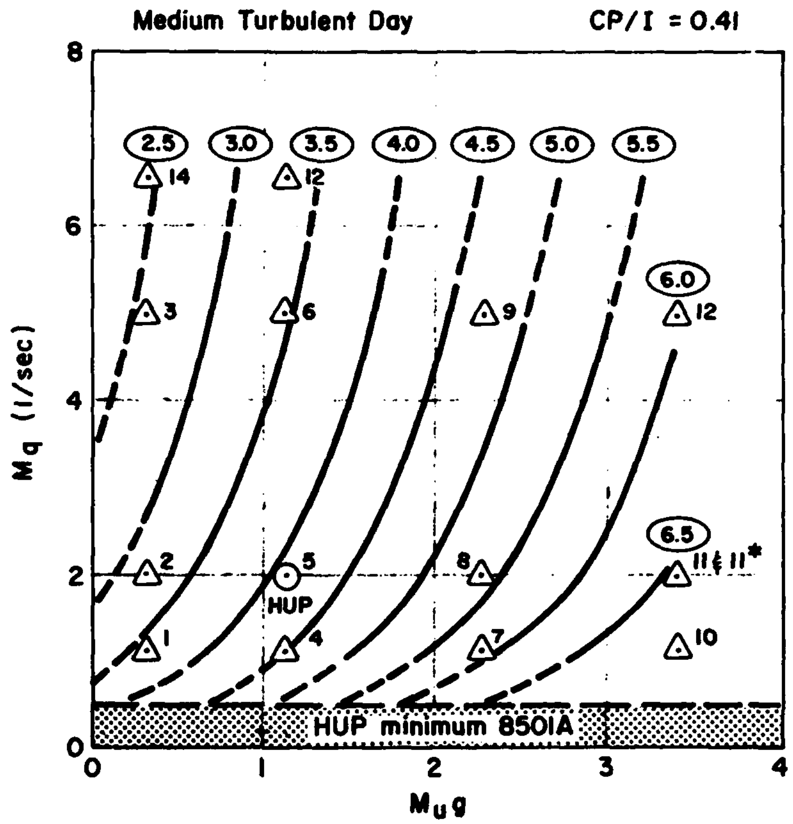


Figure 12. Longitudinal Handling Qualities Boundaries as Plotted in Ref. 11

1. Effect of ζ_n and ω_n

As shown in Fig. 13, the correlation with ω_n tends to be grouped into low and high values of ζ_n. Within each group the pilot ratings are seen to be relatively independent of damping ratio. While not shown on the plot, it also turns out that the ratings are independent of λ (λ varies from 1 to 6 1/sec). Based on these results we would surmise that satisfactory pilot ratings (less than 3-1/2) are reasonably assured if $\omega_n \leq 0.5$ rad/sec for $\zeta_n \leq 0$ and $\omega_n \leq 0.9$ rad/sec if $\zeta_n > 0$. The requirement for $\omega_n < 0.5$ (for $\zeta_n \leq 0$) is in agreement with Ref. 29. However, the lack of sensitivity of the pilot ratings to ζ_n and λ was somewhat surprising until considered in the light of the closed-loop pilot/vehicle system. System surveys for

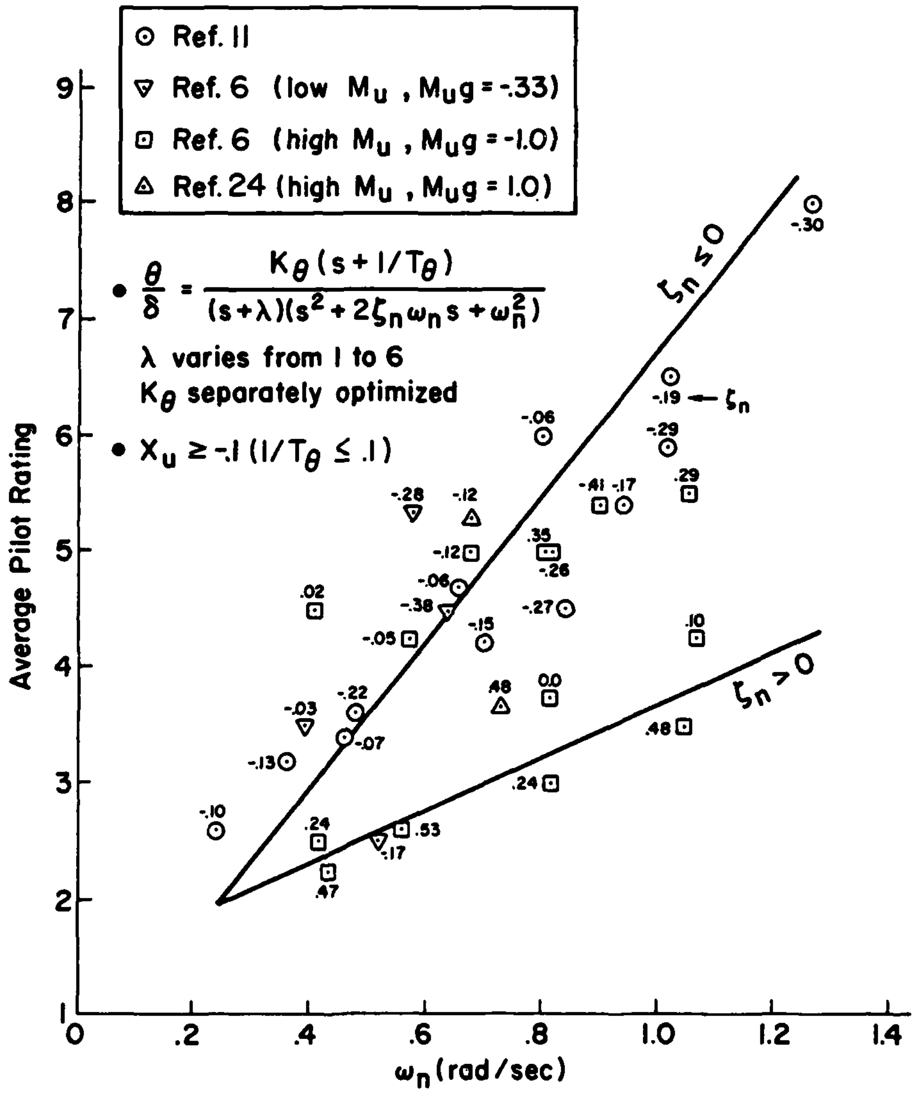


Figure 13. Pilot Rating vs. Frequency for a Variety of ζ_n's and λ's (longitudinal axis)

piloted loop closures of two of the Ref. 11 configurations are shown in Fig. 14. Configuration 1 has large negative damping ($\zeta_n = -.22$) and a marginally low value of λ whereas Configuration 12 has nearly zero damping ($\zeta_n = -.06$) and a large value of λ. Without pilot equalization (lead), both configurations are non K/s-like in the region of piloted crossover (approximately 1 to 3 rad/sec). Addition of pilot lead (to cancel λ) results in a considerable improvement in Configuration 1, i.e., the system is equalized to K/s at all frequencies above about 0.8 rad/sec. However, lead equalization has little effect on Configuration 12 in the region of piloted crossover. Thus we may surmise that the physical interpretation of poor pilot ratings for large ω_n ($\omega_n > 0.5$ rad/sec) is that the pilot is unable to equalize these dynamics to a suitable set of response characteristics (e.g., K/s in the region of crossover which is approximately 1 to 3 rad/sec). The data in Fig. 13 indicate that this effect is less critical when $\zeta_n > 0$, thereby allowing the minimum level of ω_n to be increased to 0.9 rad/sec.

The implications of the results shown in Fig. 13 and explained in Fig. 14 are that acceptable rate systems are defined as follows:

$$\omega_n \leq 0.5 \text{ rad/sec} \qquad -0.22 < \zeta_n < 0$$

$$\omega_n \leq 0.9 \text{ rad/sec} \qquad \zeta_n \geq 0$$

2. Effect of λ

The basis for specifying λ is found in Ref. 13 where it is shown that excessive degradation in pilot opinion occurs when lead time constants (T_L) greater than one second are required. This is supported by the results of several flight and simulator experiments which employed rate augmentation with $\omega_n < 0.5$. These results are plotted in Fig. 15.

3. Maximum Allowable Instabilities

Specification of a minimum value of ζ_n is somewhat confounded by the fact that there is little data for negative ζ_n where $\omega_n < 0.5$ and $\lambda > 1.0$. The data in Fig. 13 include cases which the pilots rated as satisfactory ($PR \leq 3\text{-}1/2$) where the damping ratio varied from -0.07 to -0.22. Until more data is obtained, a minimum ζ_n of -0.2 represents a conservative estimate

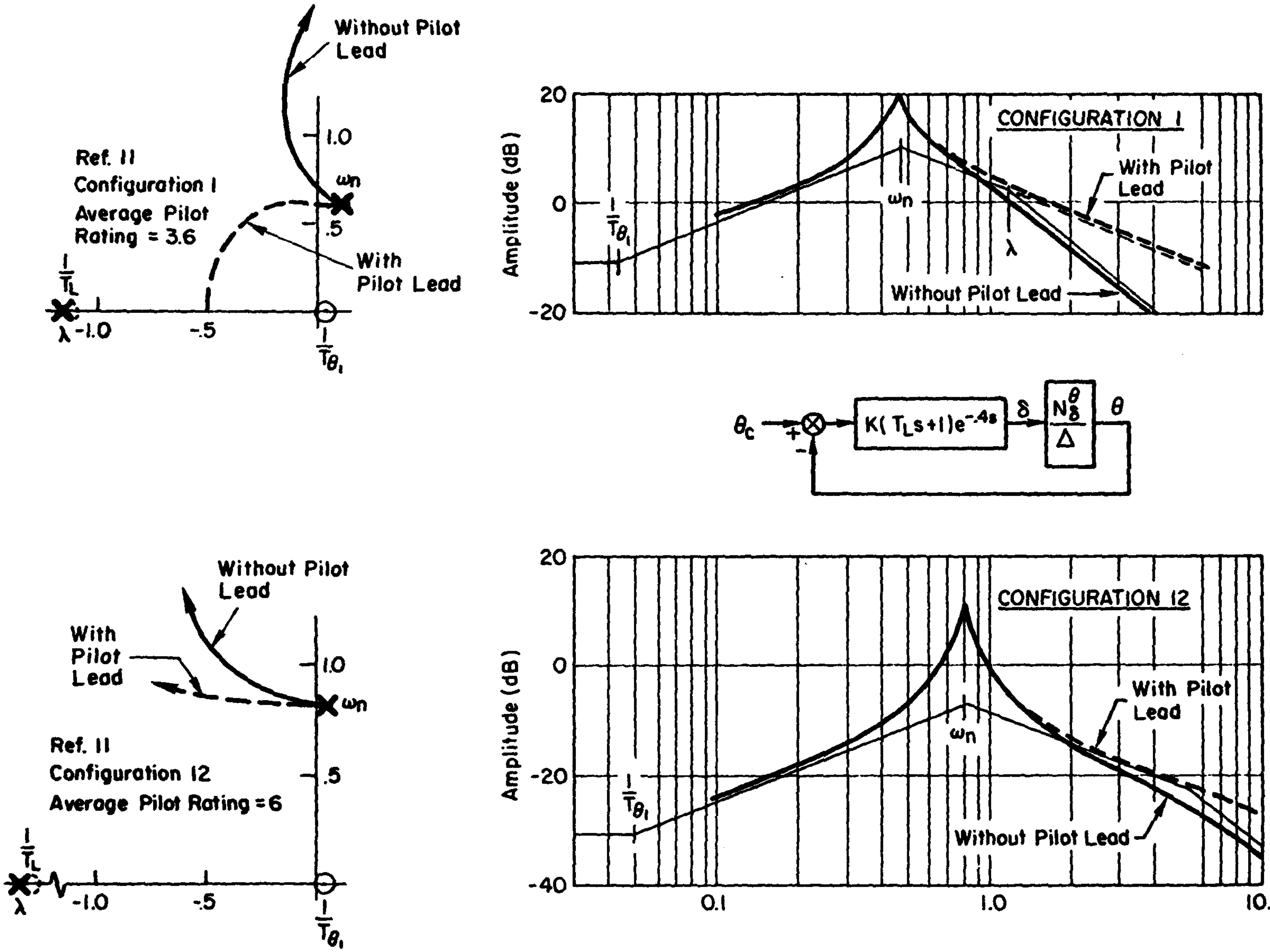


Figure 14. Piloted Loop Closures of Two Configurations from the Ref. 11 Experiments

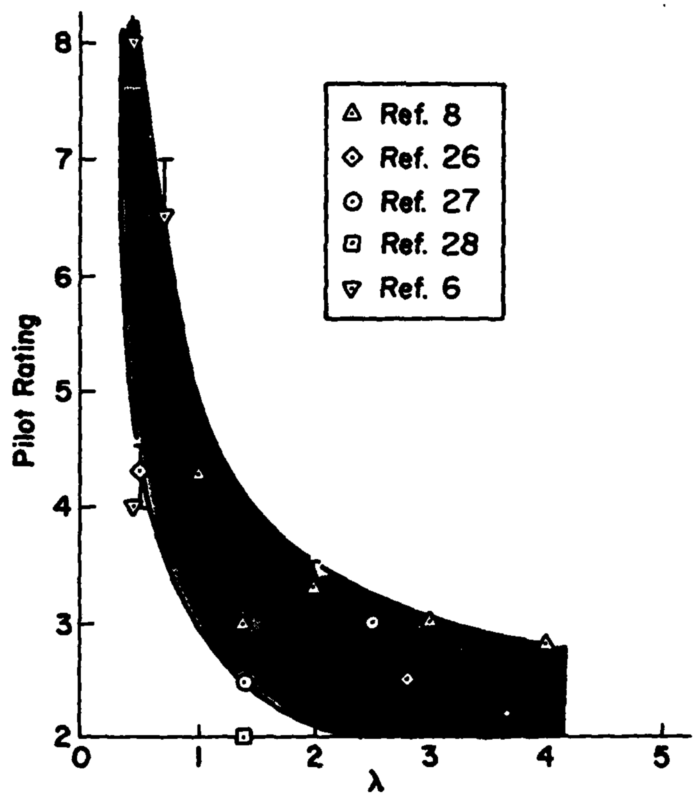


Figure 15. Pilot Ratings vs. λ for Rate Augmented Configurations Where $\omega_n \leq 0.5$

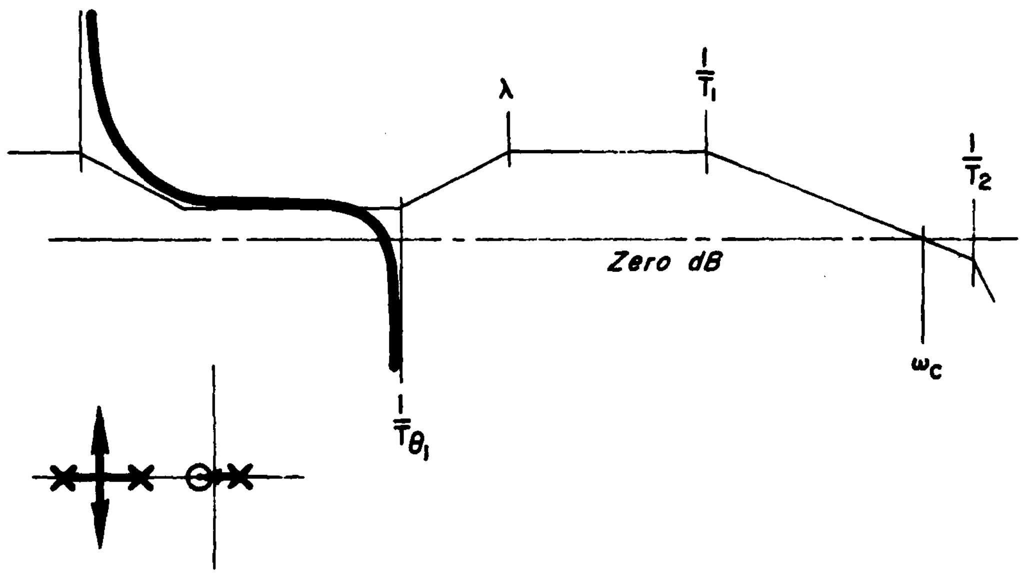
of the acceptable boundary. For a frequency of 0.5 rad/sec this represents a time to double amplitude of 7 sec which seems reasonable for fully attended operation (consistent with the basic characteristics of a rate system).

The current MIL-F-83300 does not allow unstable real roots. However, there is operational and flight test data which indicate that for some piloting tasks, such first order divergences are acceptable. For example, the AV-8A is acceptable for VMC operations in relatively low sea states even though it has a rather severe first order divergence below 85 kt (first order root at about −0.5). This pitch divergence was found to be unacceptable for IMC flight (see Ref. 30).

The CH-47 variable stability helicopter control display experiment (Ref. 15) included a rate SAS configuration with a first order divergence at and above

40 kt ($1/T_1 = -0.26$) the pilot rating for the approach task was 5 with a flight director and 7 without. Finally the MIL 8785B specification allows times to double amplitude in roll (spiral mode) of 12 sec ($1/T_1 = -0.06$). Based on the above noted results it seems unduly restrictive to disallow low magnitude real roots in the right half plane for rate systems, e.g., systems where the mission requirements assume a piloting task without unattended operation.

For the low permissible values of (negative) λ indicated above, the system will look like Fig. 2b. Accordingly tenable values of unstable λ will depend heavily on the corresponding $1/T_{\theta_1}$ and $1/T_1$. That is, to drive λ stable the loop must be closed at a dc gain greater than unity as sketched below. If that gain closure is outside the desired crossover bandwidth



(1-3 rad/sec) the system will probably be unacceptable. Taking 1 rad/sec as a desirable minimum ω_c means then that

$$\frac{-\lambda}{1/T_{\theta_1}} = \frac{1}{1/T_1} \quad ; \quad -\lambda = \frac{T_1}{T_{\theta_1}}$$

is the maximum permissible unstable λ. Experimental data to support this analytic conclusion are needed.

Up to this point all the data correlations have involved the longitudinal axis. It would be expected that for very low speeds and hover, the lateral and longitudinal requirements should be identical. The only lateral data available for correlating ζ_n, ω_n and λ are from Ref. 6. These data are plotted in Fig. 16 where it is shown that the straight line correlations which fit the longitudinal data tend to fit the lateral data as well.

4. Effect of Gain

Development of a criterion boundary for the magnitude of the response to control inputs requires some assumption on the frequency range which dominates pilot opinion. Specification of control sensitivity as a criterion parameter implies that the high frequency or initial response is most important. The current version of the MIL-F-83300 weights the initial response heavily by placing requirements on the attitude in the first second (Para. 3.2.3.2). From a closed loop pilot/vehicle analysis viewpoint we would suspect that the frequency range of piloted crossover would dominate the pilot opinion. For a rate system this would imply that we should specify a value for K in the region where the equivalent system is K/s. This hypothesis is consistent with earlier correlations (e.g., Ref. 31) and is further tested in Fig. 17 where $K_{\dot{\phi}}$ is plotted vs. pilot rating for a number of data points from moving base simulator and flight experiments. With the exception of a few points, good correlation is seen to result. The very dramatic knee in the data at $K_{\dot{\phi}} = 5$ deg/sec/in is strong evidence that a limiting value has been reached. Hence we may conclude that for the lateral axis, Level 1 flying qualities are represented by $K_{\dot{\phi}} \geq 5$ deg/sec/in. For classical rate systems this is equivalent to specifying a minimum level of the ratio of control sensitivity to damping. This is illustrated by the Bode asymptotes in Fig. 18. From Fig. 1 an approximate upper bound on $K_{\dot{\phi}}$ would be 18 deg/sec/in.

The configurations used to generate the majority of the available data on rate systems are well represented by the form shown in Fig. 2a (for example Refs. 8, 26, 27, and 32). The results of these experiments are frequently

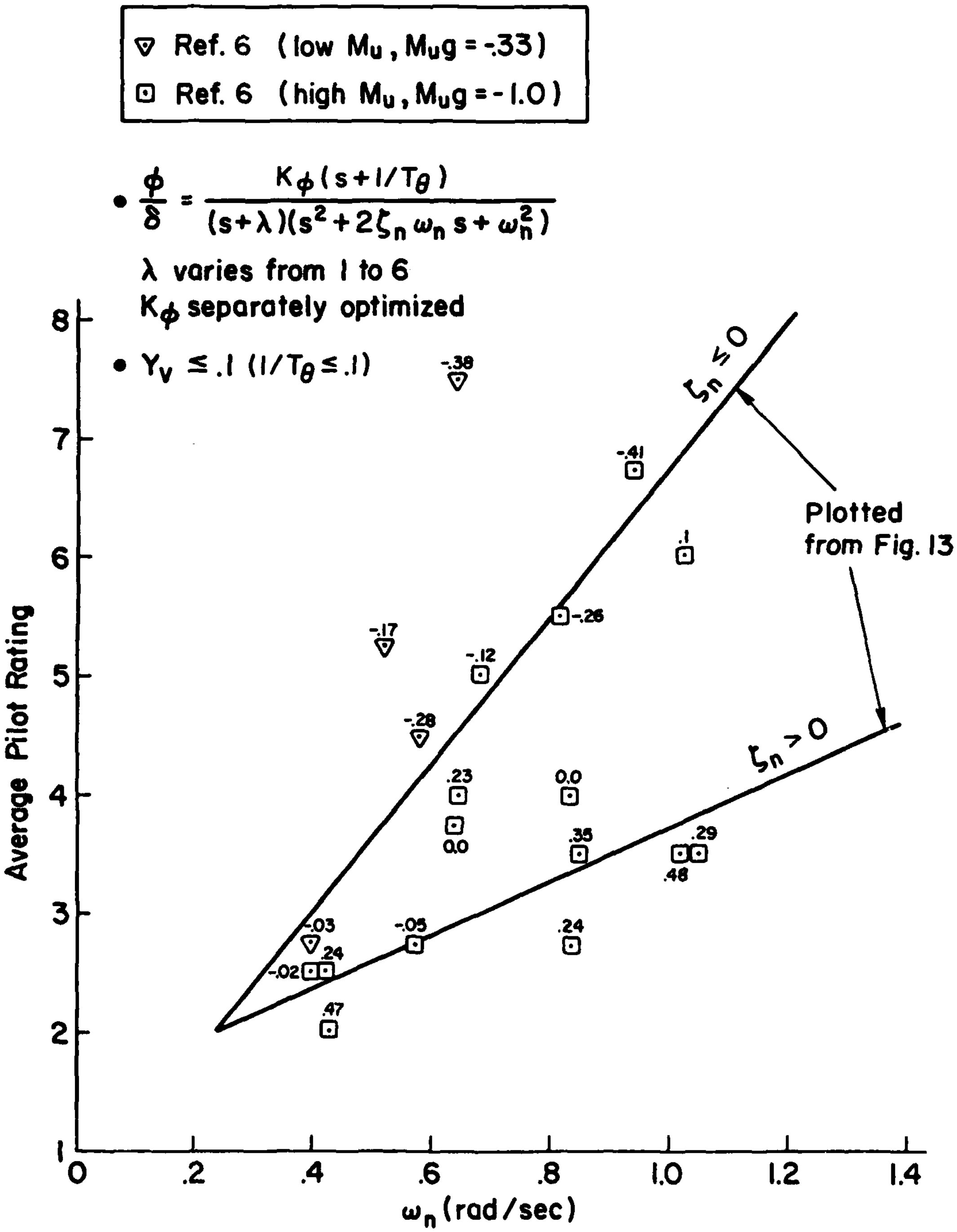


Figure 16. Pilot Rating vs. Frequency for a Variety of λ's and ζ's (Lateral Axis)

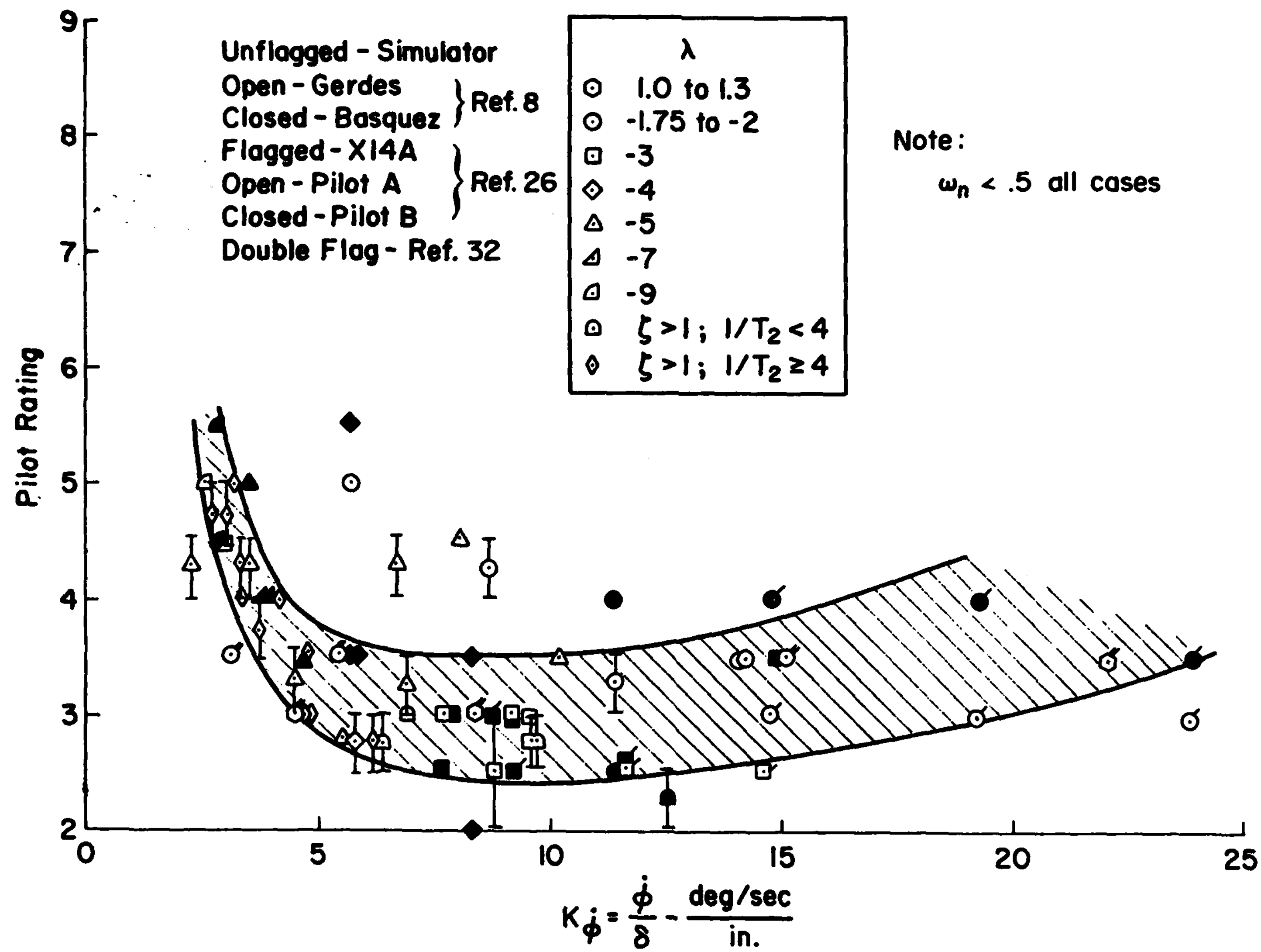


Figure 17. Pilot Rating vs. Gain ($K_{\dot{\varphi}}$) Where the Controlled Element is $K_{\dot{\varphi}}/s$ in the Region of Piloted Crossover

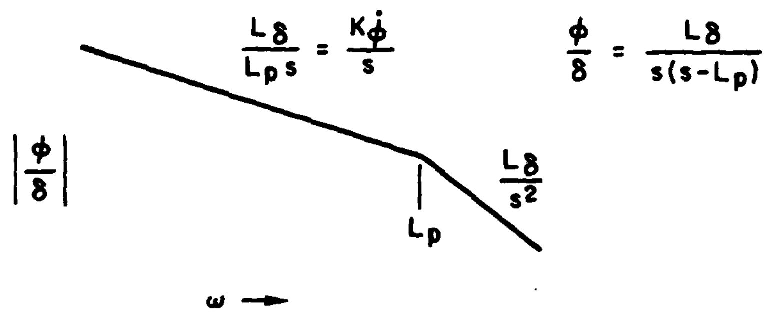


Figure 18. Literal Factors for Simplified Classical Rate System

plotted on a grid of control sensitivity vs. damping such as shown in Fig. 19. Also plotted in Fig. 19 are the lines which represent the boundary at $K_{\dot\phi} = 5$ (deg/sec)/in. and the MIL-F-83300 requirement for attaining 4 degrees in one second. The two boundaries are seen to be equivalent for all practical purposes. Inasmuch as the attitude in one second is easily measured it should be retained* as the flight testable part of the proposed specification.

C. GUST SENSITIVITY — RATE SYSTEMS

The simulator experiments of Ref.   contain a systematic variation of vehicle dynamics (λ, ζ_n, ω_n) and gust sensitivity (X_u and M_u). Reference to Fig. 13 reveals that the low and high M_u cases tend to plot along the same straight line indicating that the increased value of M_u was not a dominant factor in the pilot opinion (this conclusion was also reached in Ref. 6. The large X_u cases from Ref. 6 are plotted in Fig. 20 and are seen to result in a significant deterioration in pilot rating. A review of the associated pilot comments reveals that the primary complaint with the large X_u cases was the large pitch attitudes required to regulate against steady winds and gusts. Several cases were run without winds or gusts to investigate the effect of a large value of X_u on the basic dynamics. Two of these

*Also a conclusion of Ref. 31.

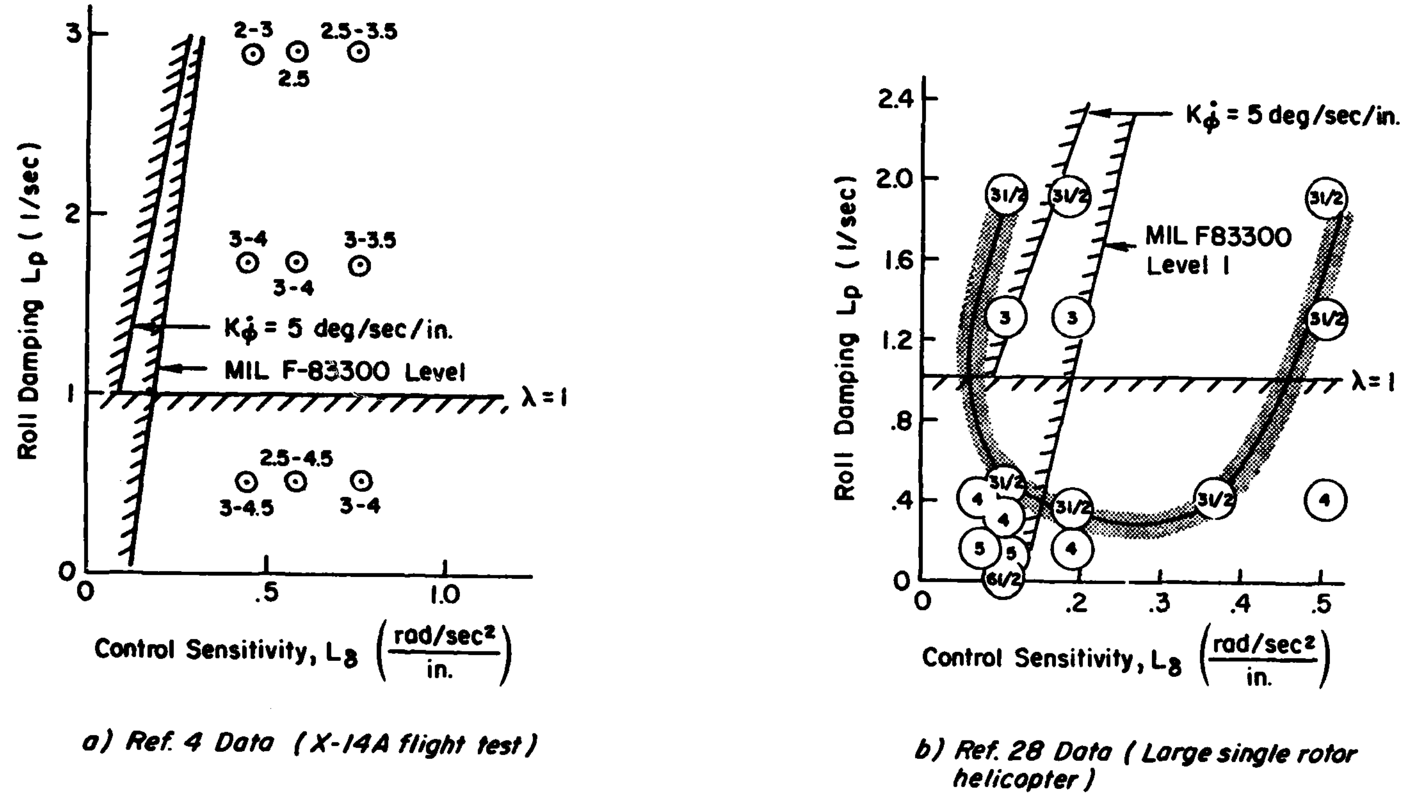


Figure 19. Comparison of Criterion Boundaries on a Grid of Roll Damping vs. Control Sensitivity

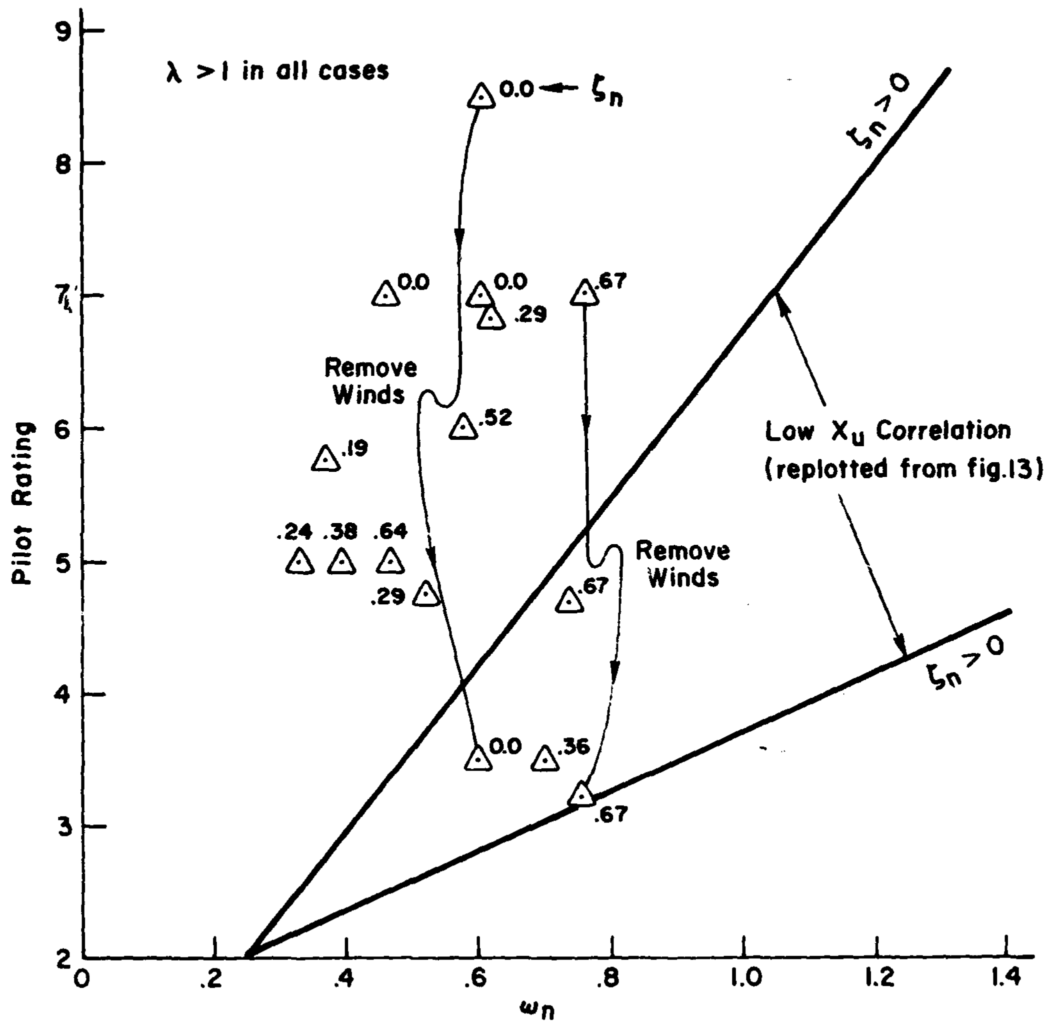


Figure 20. Pilot Rating vs. Frequency for Large X_u ($X_u = -0.2$)

cases are connected in Fig. 20 indicating that without steady winds or gusts the large X_u cases were entirely satisfactory.

Up to this point we have assumed that speed and position (in hover) are being controlled with attitude. It is very probable that future generation NAVY V/STOLs will utilize direct force control (DFC) which can have two possible effects on the above results. The DFC can be used as a secondary trim control, thereby eliminating the need for large trim attitudes when X_u

is large; or the DFC can be utilized as the primary speed/position controller. In the latter case, attitude is relegated to the role of a secondary controller.

The current MIL-F-83300 specifies X_u (and Y_v) in terms of the local slope of the equilibrium attitude-speed curve. The results of Ref. 6 tend to support this format. That is, the Ref. 6 pilot ratings and commentary indicate that the primary deficiencies associated with large X_u and Y_v are the large attitudes required to regulate against winds and to initiate or stop motion. Paragraph 3.2.1.1 of MIL-F-83300 specifies a maximum of 0.6 degrees per knot which is approximately equivalent to X_u (or Y_v) = −0.2. The data in Fig. 20 indicate this value is generally unsatisfactory (pilot ratings ≥ 5). The value of X_u for the points in Fig. 13 was 0.05 and Y_v was 0.1. It would therefore seem that the limiting value of X_u or Y_v lies somewhere between 0.1 and 0.2.

D. ATTITUDE SYSTEMS

A system is classified as an attitude system when it meets the criterion established in Section IIC.

The system in Fig. 2b is basically a rate system (because it is K/s in the region of crossover). However, it usually results from a SCAS with attitude feedback; i.e., the ratio of rate and attitude gains is such that an overdamped system results. Analytically such systems derive naturally from parametric variations of classical attitude systems (Fig. 2d). Data correlations with these types of systems are therefore handled in this section. It is important to note, however, that the generic characteristics of this type system are consistent with the analytically derived pilot workload requirements of a rate system.

The series of experiments reported in Ref. 25 (S01 simulator) and Ref. 6 (Norair simulation) provide a significant data base for attitude systems (Fig. 2d) and rate systems with low frequency attitude (Fig. 2b). For VTOLs where $1/T_{\theta_1}$ is near zero (all practical configurations without speed feedback), the feedback gains are usually high enough to drive λ to values

approaching $1/T_{\theta_1}$. Hence there is a large class of attitude augmented VTOLs for which Eq. 3 becomes:

$$\frac{\theta}{\delta} = \frac{K_{\theta_c} e^{-\tau s}}{s^2 + 2\zeta_n\omega_n s + \omega_n^2} \tag{5}$$

Data for these types of systems are plotted on a grid of ω_n vs. $2\zeta_n\omega_n$ in Fig. 21 for the lateral axis. These data represent cases which have been separately optimized in terms of control power and gain (K_{θ_c}). The boundaries in Fig. 21 represent approximate fairings through the data corresponding to a pilot rating of 3.5. Data for the longitudinal axis are plotted in Fig. 22. The boundaries which faired the 3.5 pilot ratings in Fig. 21 are seen to be equally applicable to the longitudinal axis. This is not surprising considering the basic symmetry of the low speed and hover situation.

The response characteristics in the region of piloted crossover change from attitude to rate as the damping ratio increases beyond 1.0. This point is illustrated in Fig. 23. From Fig. 23 it can be seen that $1/T_1$ and $1/T_2$ separate quite rapidly as ζ_n becomes only slightly greater than unity. As can be seen from Fig. 21 there is no discernable change in pilot rating between the attitude and rate response regions. This could be misinterpreted as evidence that there is no need to distinguish between a rate response with low frequency attitude (Fig. 2b) or a "pure" attitude response (Fig. 2d). It must be remembered, however, that all the data in Figs. 21 and 22 are for low speed and hover maneuvering in VMC conditions. Based on the analytical workload estimates in Fig. 4 and the unsatisfactory experimental results for IMC low speed flight with rate systems (discussed earlier) it would be somewhat unconservative to allow rate systems with low frequency attitude as a primary system when IMC operation is a requirement. We have selected to classify systems where $1/T_1 < 1.0$ as a rate system based on pilot commentary associated with points located on either side of this line. Some of these pilot comments are located next to their associated data points in Fig. 21. The practical implication of this is that all points falling below the $1/T_1 = 1.0$ line in Fig. 21 are subject to the visibility limitations association with rate systems in Table 2.

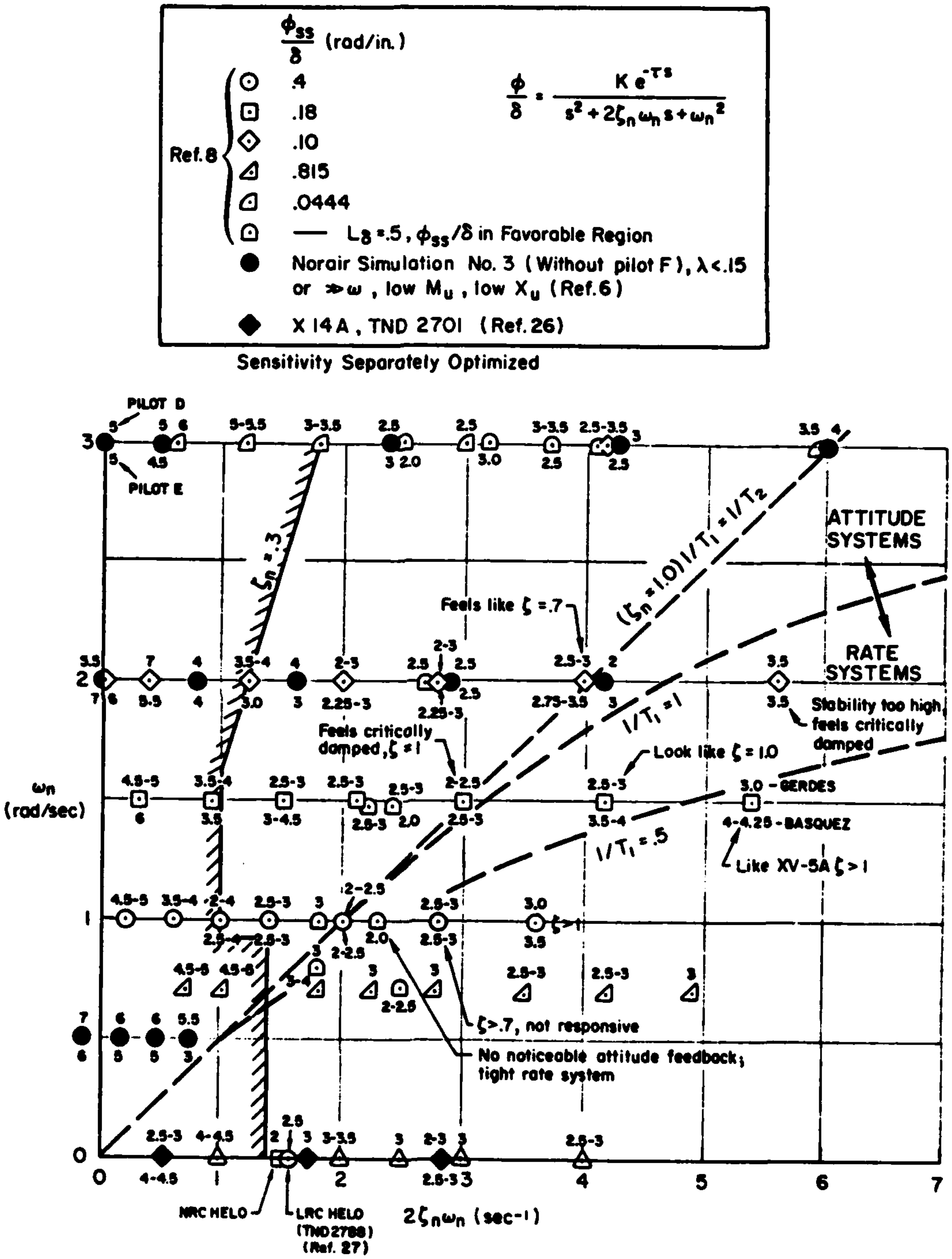


Figure 21. Pilot Rating Correlations with Ideal Second Order System Responses — Lateral Axis

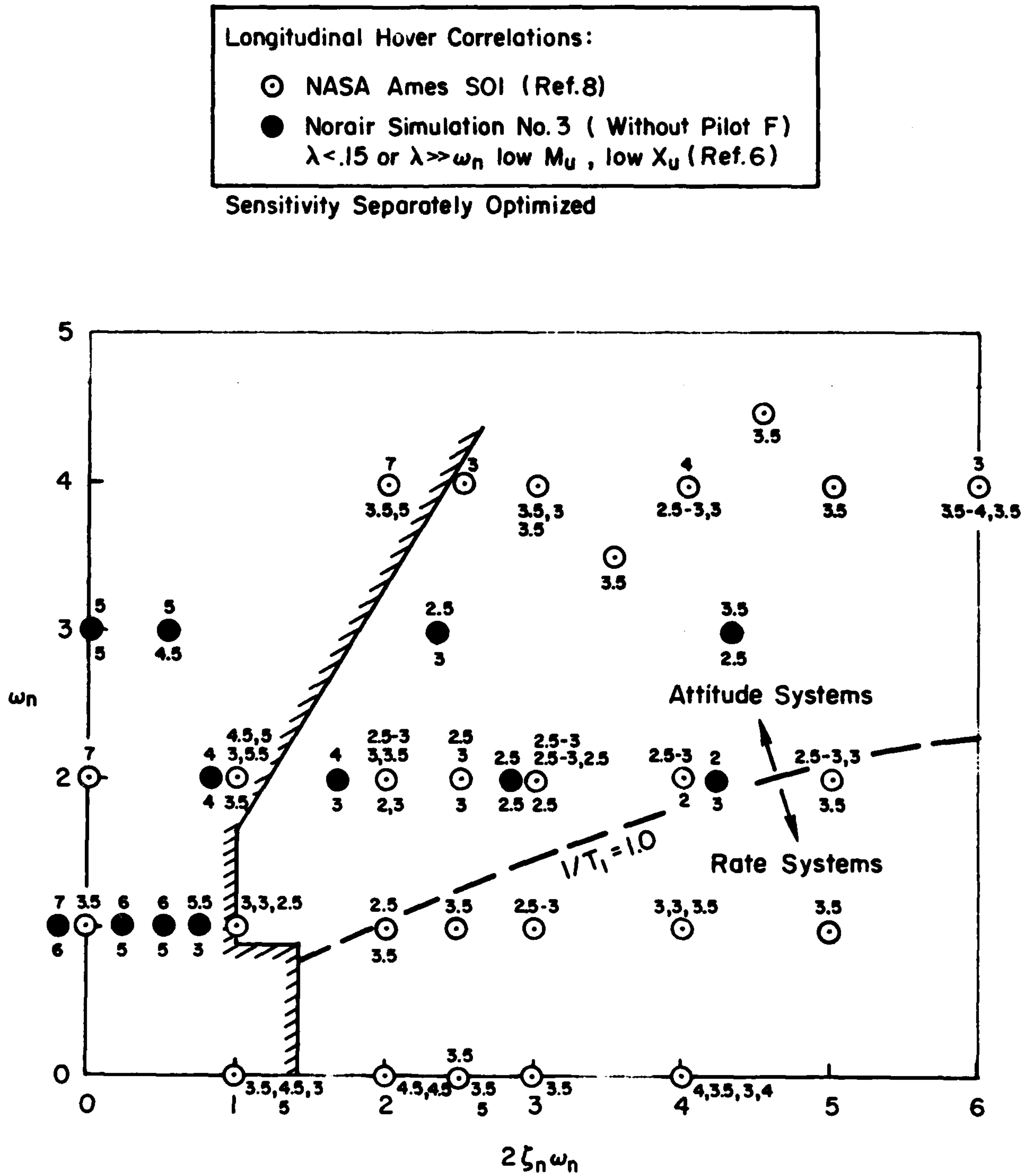


Figure 22. Pilot Rating Correlations With Ideal Second Order System Responses — Longitudinal Axis

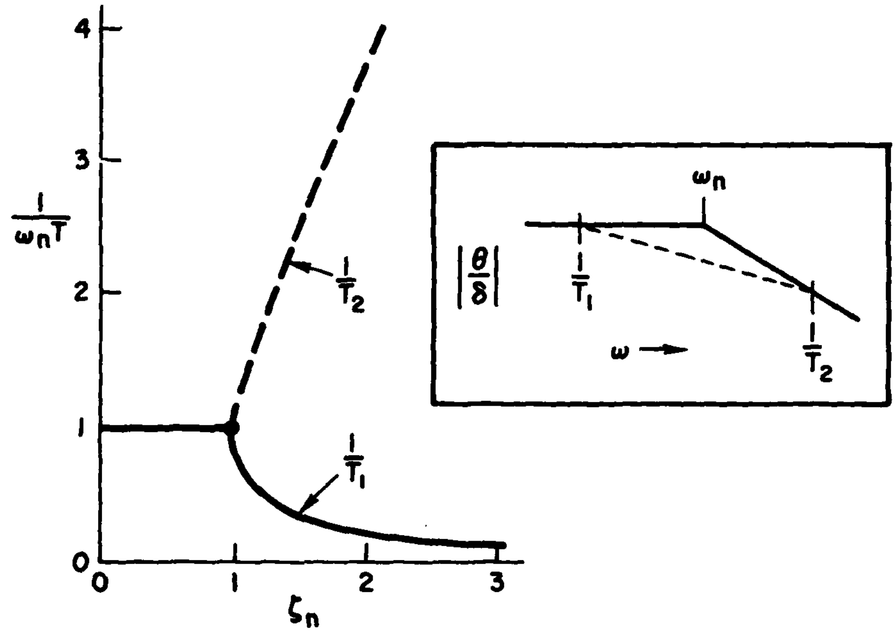


Figure 23. Transition From Attitude to Rate Response as ζ_n is Increased Beyond Unity

Such a limitation is consistent with the results obtained for pure rate systems (without low frequency attitude) in Section IVB-1. There it was noted that for $\zeta_n \geq 0$, the maximum value of ω_n must be limited to 0.9. This is equivalent to saying that the lower end of the −20 dB/decade slope (K/s) of the equivalent system must extend down to 0.9 rad/sec (see Fig. 2a). Specifying systems where $1/T_1 < 1.0$ as rate system in Fig. 21 implies a K/s slope down to 1.0 rad/sec. Hence the region below, $1/T_1 = 1.0$ in Figs. 21 and 22 are properly accounted for in the rate system criterion summarized at the end of Section IVB-1 and should be removed from the attitude criterion. This is accomplished via the modified attitude criterion plotted in Fig. 24. A lower boundary defined by $1/T_1 = 0.9$ is used (approximated by a straight line in Fig. 24) to be consistent with the $\omega_n \leq 0.9$ criterion utilized for rate systems. This lower boundary is somewhat redundant since rate systems should be culled out via the time response criterion in Fig. 3. It is included, however, to remove ambiguities which could arise from including rate systems in the attitude system criterion boundaries.

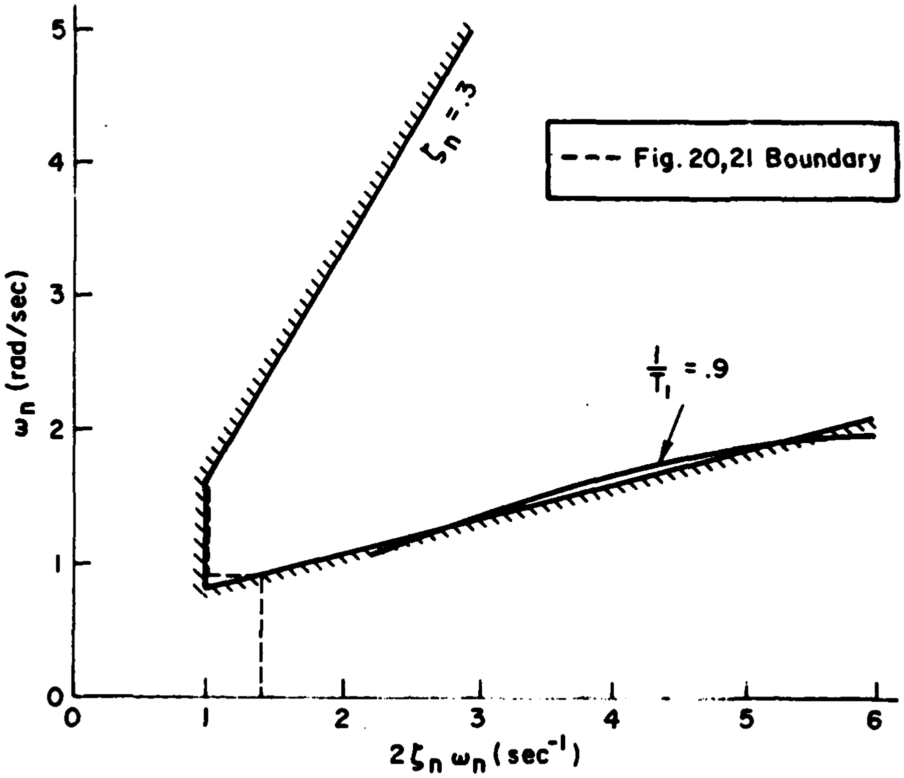


Figure 24. Tentative Criterion Boundary For Attitude Systems For Low Speed and Hover

It should be noted that the Fig. 21 and 22 boundaries are nearly identical to the low speed boundaries in the current MIL-F-83300 (Para. 3.3.2). One interpretation of these results is that pilots require equally good dynamics for hover as they do for forward flight. The current specification allows considerably degraded dynamics for hover. This is probably due to the lack of acceptance of augmentation systems at the time the specification was written. It is also a reflection of the fact that the specification is based on data taken primarily in VMC conditions.

1. Effect of Gain

The region of acceptable values for the gain, K_{φ_c} is obtained from the data plotted in Fig. 25. The majority of the data in Fig. 21 and all of the data in Fig. 25 were obtained from the raw simulation results of the Ref. 8 experiment. These data were made available to STI by Mr. Richard Greif of NASA Ames. The following observations apply to the data plotted in Fig. 25.

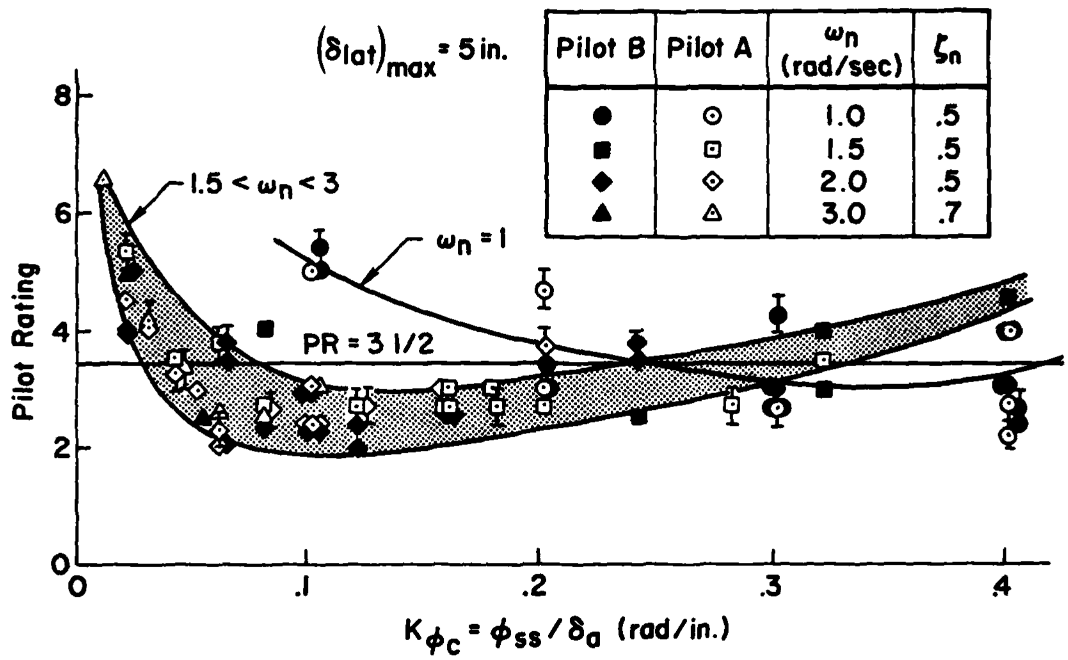


Figure 25. Pilot Ratings vs. Roll Attitude Gain

- For ω_n > 1.5 rad/sec the approximate region for satisfactory flying qualities (PR < 3-1/2) is defined by $0.03 \leq K_{\phi_c} \leq 0.33$ rad/in. The pilot ratings are relatively insensitive to K_{ϕ_c} in this region.

- There appears to be a requirement for higher values of K_{ϕ_c} when ω_n is low. For $\omega_n = 1$ satisfactory flying qualities are defined by $0.25 \leq K_{\phi_c} \leq 0.42$ rad/in.

The requirements on K_{ϕ_c} for low and high ω_n overlap slightly; and without additional data it is not clear how to set the K_{ϕ_c} boundaries for values of ω_n between 1.0 and 1.5. There does, however, seem to be an adequate number of data points to substantiate the requirement for increased K_{ϕ_c} when $\omega_n = 1.0$. Further experimental data are needed to determine the equivalent system gain requirements at values of ω_n above and below unity. Until such data are available it seems reasonable to assume a straight line variation as shown in Fig. 26. Note that according to these data a constant value of $0.25 < K_{\phi_c} < 0.33$ would be satisfactory for the range of ω_n tested.

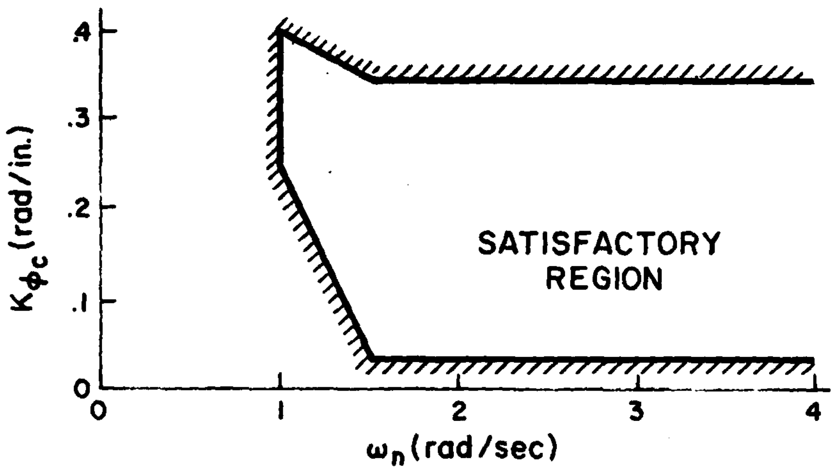


Figure 26. Limits on K_{ϕ_c} For Satisfactory Handling Qualities

2. Effect of λ

Increasing the value of λ has the effect of attenuating the low frequency response to control inputs (for example see Figs. 2b, d and e). This would be expected to cause problems relative to low frequency trimming and increased pilot workload due to a tendency for the aircraft attitude to wander. Large values of λ can be achieved in combination with moderate values of ω_n via augmentation or through very large values of M_u. None of the low speed and hover experiments run to date have considered the generic effects of augmentation and hence the only data for large λ is also for large M_u (see Ref. 6). These data are plotted on the tentative damping vs. frequency criterion boundaries in Fig. 27. Both the effect of increased M_u and increased λ on the boundary are seen to be negligible; i.e., the points correlate well with the low M_u, low λ boundary.

Considering that this conclusion is based on only two data points (Cases 101 and 104) it must be considered tentative at best. In fact, the acceptable pilot ratings for the two configurations which plot inside the criterion boundaries are somewhat unexpected considering the shapes of the frequency

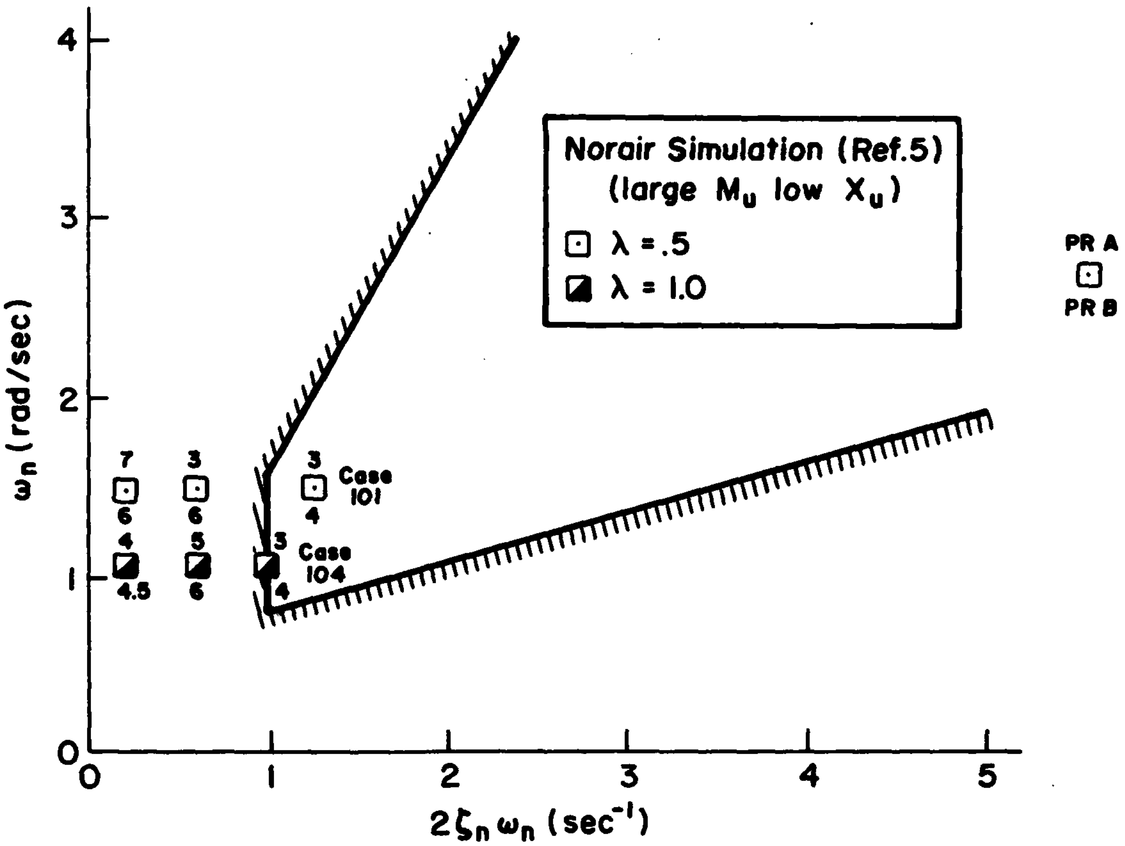


Figure 27. Comparison of Configurations With Large λ With the Attitude System Criterion Boundaries

and time responses for these cases shown in Fig. 28. The extreme non-attitude-like shape of these responses stems from values of λ which are near ω_n. Because of the significance of these configurations, the pilot commentary is included as Table 3. Pilot A seemed to be completely satisfied with both configurations whereas Pilot B noted some problems with precision hover (underlined in Table 3). The key question, of course, is whether these problems would become more dramatic in low visibility conditions and with increased winds and turbulence (the Ref. 6 simulation included steady winds of 10 kt with gusts having an rms value of 3.4 ft/sec).

Finally, large values of λ arise from large M_u or feedback of speed to a longitudinal control. Both of these effects start looking like a translational rate command (TRC) system. Perhaps configurations where λ approaches

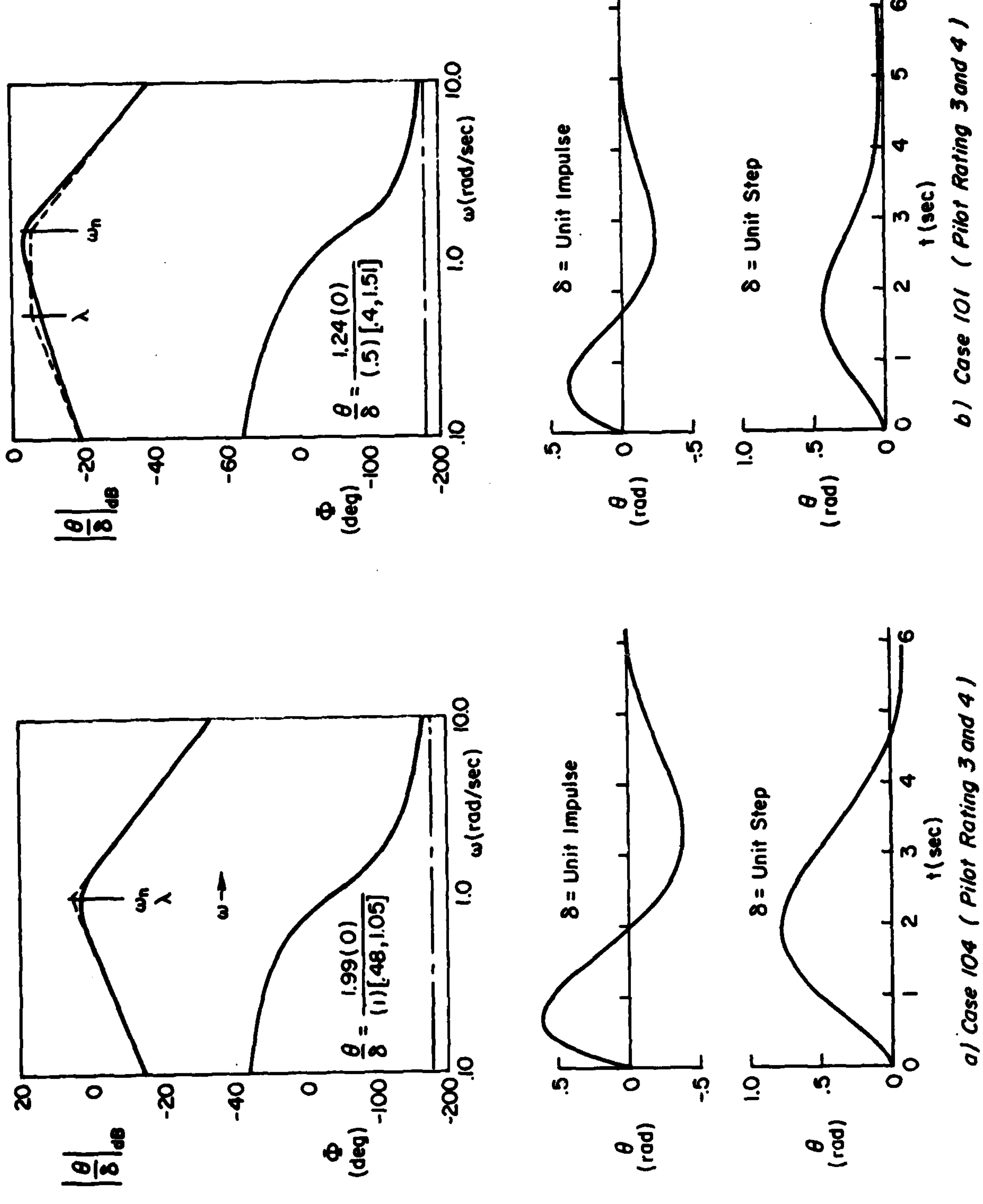


Figure 28. Frequency and Time Responses For Two Configurations With Large λ From Norair Simulation (Ref. 6) N_{ug} = 1.0

TABLE 3. PILOT COMMENTARY FOR CONFIGURATIONS WITH LARGE λ

---

a. Case 104 (λ = 1.0; ω_n = 1.05)

PILOT A: PR = A3 M_δ = 1.99

Control sensitivity was good.

No problem on square or hovering turn.

Quick stop was good.

Lateral-directional and height dynamics did not affect evaluation.

PILOT B: PR = A4 M_δ = 0.71

Compromise in control sensitivity because of abrupt longitudinal pitch response. Probably this response was due to M_u. Almost constant hunting in pitch.

Air taxi was pretty good. Hover was fair.

Turn over a spot, fairly good. Probably had low X_u.

360-degree turns and stopping on heading were not problems.

Crosswind turns were not too bad.

Precision of hover was not as good as it should be. Took too long but fairly good hover could be achieved. Lack of real precision in hover.

Quick stop was okay. Didn't achieve much speed. Fair to poor stop.

Attitudes seemed moderate and acceptable.

(Concluded on next page)

TABLE 3. (CONCLUDED)

b. Case 101 ($\lambda = 0.5$, $\omega_n = 1.51$)

PILOT A: PR = A3 $M_\delta = 1.24$

Smooth control. No worry about overcontrolling. Quick stop easy; no feeling of slowing down. A certain pitch attitude resulted in the airplane going along as desired.

PILOT B: PR = A4 $M_\delta = 0.87$

Control sensitivity was a compromise between what was desired and what could be stood because of abruptness in response. May have been better off with a lower sensitivity because of small abrupt kicks.

Attitude slightly nose-down, but pretty level. Probably small X_u.

Able to achieve fairly stable velocity and stop fairly well.

Precision of hover not great but adequate for a landing. Sometimes hover seemed pretty good. Could manage hover all right. Not really solid, but fair.

Turn over a spot was pretty good. Crosswind turn not too bad; pretty fair performance.

Attitude changes fairly mild in quick-stop maneuver. Collective requirements also fairly mild.

Felt sort of loose laterally (lateral axis was a good rate system, e.g., $\lambda = 5.0$, $\omega_n = 0.18$, $\zeta_n = 0.26$)

ω_n should be classified as TRC systems and correlated via the criterion in Figs. 35 and 36. More data is required to pursue this hypothesis.

More experimental data are clearly required to resolve the effect of large λ on attitude systems. It should be noted that the basic characteristics of these systems is a large initial response with respect to the steady state which looks like low damping in the time domain. This is well illustrated by the impulse responses in Fig. 28. Attitude systems with large values of $1/T_\theta$ (see Eq. 3 and Fig. 2e) also have this basic deficiency and should be included in the experimental matrix of systems with large λ.

If systems with values of λ near ω_n are ultimately found to be acceptable, some method for accounting for their apparent low damping will have to be included in the attitude system identification criterion developed in Section IIC. The systems in Fig. 28 would not meet the criterion since their overshoot exceeds that which would be equivalent to a damping ratio of 0.2 (equivalent second order system damping ratio is less than 0.1 for Cases 101 and 104 based on measuring peaks of the impulse responses).

3. Model Following Attitude Systems

A model following attitude system is defined here as a system where the command/response dynamics are different from the responses due to external (disturbance) inputs. The basic concept is to utilize a high bandwidth closed loop system for gust suppression while avoiding the concomitant abrupt responses to control inputs via stick shaping. An example model following attitude system was discussed in Section IIA. A good deal of the existing data for model following attitude systems comes from the NASA Langley CH-46 variable stability helicopter, e.g., see Refs. 15, 33, and 34.

Based on the Ref. 8 results, ω_n was initially set to 2 rad/sec. However, when mechanized on the CH-46 helicopter, the pilots complained of excessive abruptness and ω_n was reduced to 1.43 rad/sec except for the yaw mode where it was left at 2.0 rad/sec. Analysis of pilot comments from the Grief data (plotted in Fig. 21) taken on the S01 simulator (one-to-one motion and real world visual) did not reveal any problems with abruptness for ω out to 4 rad/sec. Furthermore, the X-22 model following attitude system was set at ω_n = 2 rad/sec (Ref. 14) which supports the simulator results from both programs. It, therefore, appears that the command/response abruptness

problem is somehow unique to the CH-46 helicopter. Discussions with personnel at NASA Ames indicated that rotor mode problems were encountered when mechanizing a UH-1H helicopter with an attitude SCAS. The experience is consistent with some recent flight tests involving the optimization of helicopter autopilot gains. Increasing the gains to provide attitude stiffness resulted in very abrupt large amplitude motions of the rotor tip path plane. It is possible that the "abruptness" referred to is a rotor mode in the CH-46 and does not represent a basic limitation for attitude control. Finally, the pilot sits 20 ft ahead of the center of gravity in the CH-46, which may account for the abruptness comments.

It appears that there is currently no published data from which the upper boundary on ω_n can be derived.

The majority of the pilot ratings in Fig. 21 are dominated by command response piloting tasks with little emphasis on turbulence regulation. Hence, this data is felt to be appropriate to defining specification boundaries for the lower limits of frequency and damping of the model portion of the model following system (G_i in Fig. 1).

4. Rate Command Attitude Hold (RCAH)

Rate command/attitude hold (RCAH) systems represent a special case of a model following attitude system where the stick shaping is simply an integrator. It would, therefore, seem logical to utilize experimental data involving command response tracking with rate systems to correlate RCAH systems as well. It follows that the criterion boundaries developed in Section IV-B-1 should apply for the command response characteristics of the RCAH system.

The fixed base simulation results of Ref. 18 showed that the use of RCAH for both axes was less than satisfactory for low speed and hover in full IMC conditions (see Table 2). Turbulence was not a factor in the evaluations. The displays consisted of a 3 cue mechanical flight director and a moving map display.

The X-22 control display experiments (Ref. 14) indicated that RCAH could be acceptable for hover if used only in the lateral axis and with a sophisticated integrated display (position plus velocity plus flight director), e.g.,

Config. ED3, ATT/RATE) in Fig. 6. The pilot commentary indicates that control problems in the lateral axis were the primary reason why less sophisticated displays (no flight director bars) were not acceptable for this configuration. Even with the satisfactory display, the pilots commented that the lateral control seemed "very light" and "a bit more attention to bank angle control is required than I would like." One of the runs rated as a 3 included a 22 kt headwind, a 13 kt crosswind, and moderate turbulence. It therefore seems reasonable to tentatively allow RCAH in the lateral axis as long as the longitudinal axis is at least a model following attitude system; and an integrated display including position, velocity and flight director command bars is employed. Inasmuch as the above conclusion is based on a single run with one pilot, further substantiating data are required. Until more data becomes available, the minimum allowable frequency and damping for the attitude hold equivalent system should be tentatively set to the values used in the X-22 experiment, e.g., ω_d = 2.1 rad/sec and ζ_d = 0.5.

Based on the Ref. 18 results (Table 1) RCAH would be acceptable as a backup system for full IMC, e.g., Level 2 flying qualities. The required displays should include a flight director command bars as a minimum and preferably a moving map display. More data is required to determine the necessity of the latter for level 2 flying qualities.

E. TRANSLATIONAL RATE COMMAND

The nature of translational rate command (TRC) systems is such that they are easily identified and do not require a separate classification criterion.

A simplified block diagram which illustrates the key features of a generic TRC SCAS is given in Fig. 29. Lower order equivalent systems (LOES) forms derive from considerations of the various combinations of feedback and feedforward gains as follows:

- TRC with attitude only (K_{DFC} = 0).
- TRC with direct force control independent of attitude (K_{θ_c} = 0).
- TRC with a combination of direct force control and attitude.

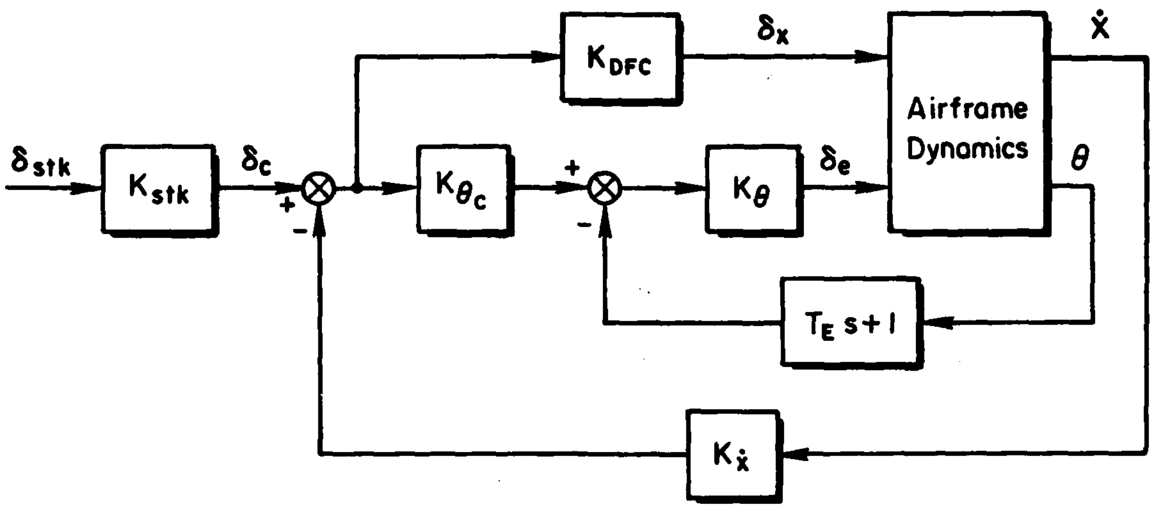


Figure 29. Generic Block Diagram For TRC Systems

In addition to the above, it is expected that a split axis concept which utilizes any one of the above in combination with an attitude system will be appropriate in many cases.

1. Translational Rate Control (TRC) With Attitude Only ($K_{DFC} = 0$)

The generic root locus characteristics of TRC systems which utilize pitch or roll attitude to provide the force required to translate are presented in Fig. 30. The attitude-augmented airframe characteristics are designated by the single prime notation in Fig. 30 and represent the starting point for this example which utilizes XV-15 characteristics. The root locus shown in Fig. 30 shows the effect of $K_{\dot{X}}$ on the dominant system modes. The effect of the values of $K_{\dot{X}}$ shown in Fig. 30 on the path and attitude time responses to a 1 in. step longitudinal control input is shown in Figs. 31a and 31b, respectively. It can be seen from Figs. 30 and 31 that the generic effect of increasing $K_{\dot{X}}$ is to improve the path response at the expense of larger attitude excursions. An experiment was conducted on the NASA Ames FSAA simulator to investigate the effect of increasing path mode bandwidth on pilot opinion (Ref. 44).

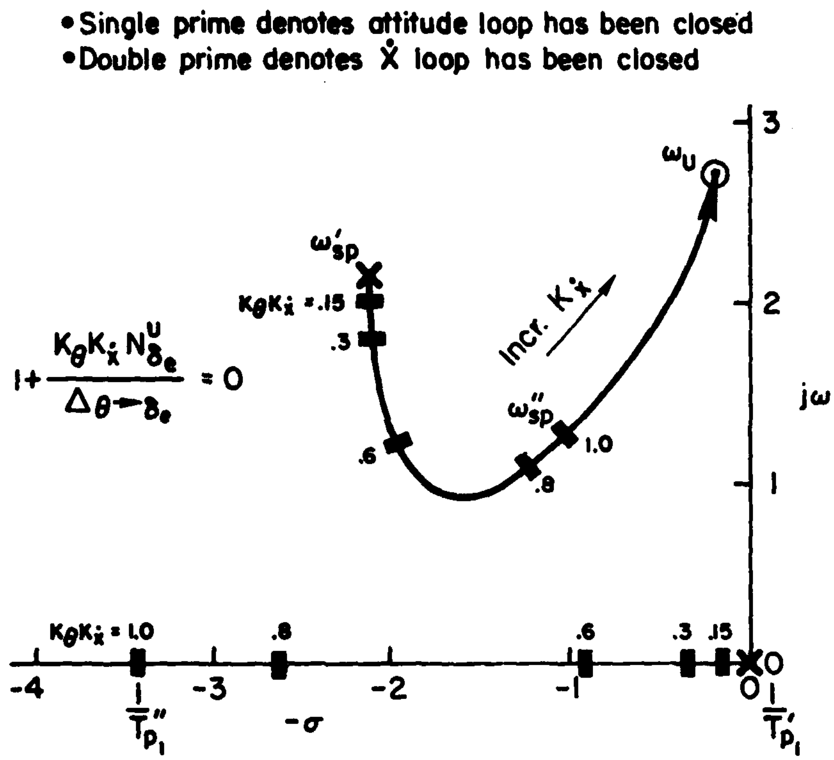
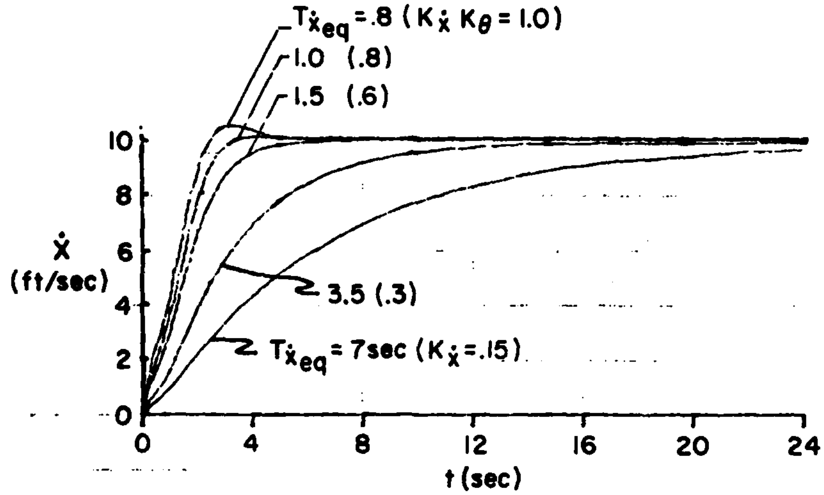


Figure 30. Effect of $K_{\dot{X}}$ on Dominant System Modes

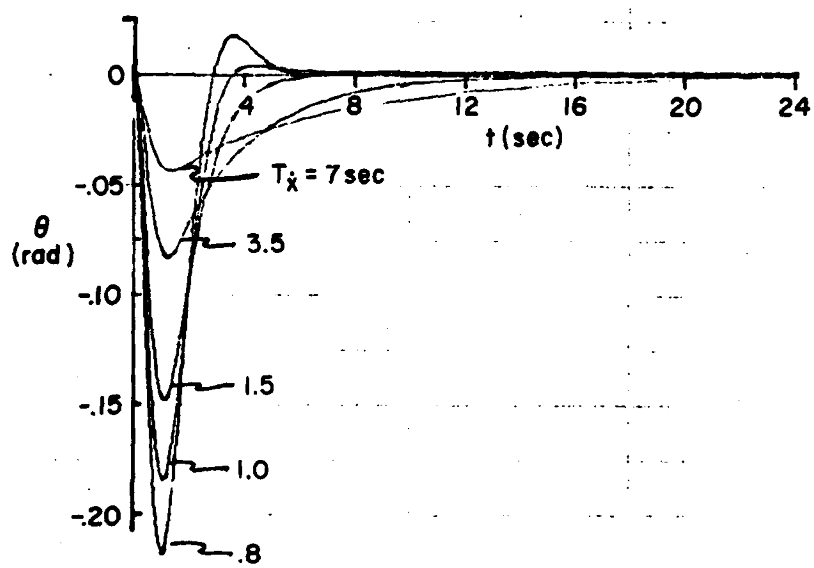
Preliminary pilot ratings are given in Fig. 32 where path mode bandwidth is quantified as the −3 dB point on a $|\dot{X}/\delta_{stk}|$ frequency response plot. The task was to fly as rapidly as possible to various points on a terrain board and hover at each point. These results indicate that a path mode bandwidth of 0.6 rad/sec is about optimum. It should be noted that due to the visual display problems discussed in Section IV-A, precision hovering was very difficult. A loose interpretation of these results is that they represent hovering over the deck in poor visibility at night where the visual cues are minimal.

As would be expected, pilot comments on the lower bandwidth systems in Fig. 32 centered on poor hover position control. This was most critical when decelerating to hover since it was possible to drift into a fixed

Note: $T_{\dot{X}_{eq}}$ *is obtained by assuming a first order form equation.*
$T_{\dot{X}_{eq}} = t$ *when X is 63% of steady state*
Note that $1/T_{\dot{X}_{eq}} \doteq 1/T''_{p_1}$ *when* $1/T''_{p_1} << \omega''_{sp}$



a) Path Response



b) Pitch Attitude Response

Figure 31. Time Responses to a 1 in. Step Longitudinal Control Input

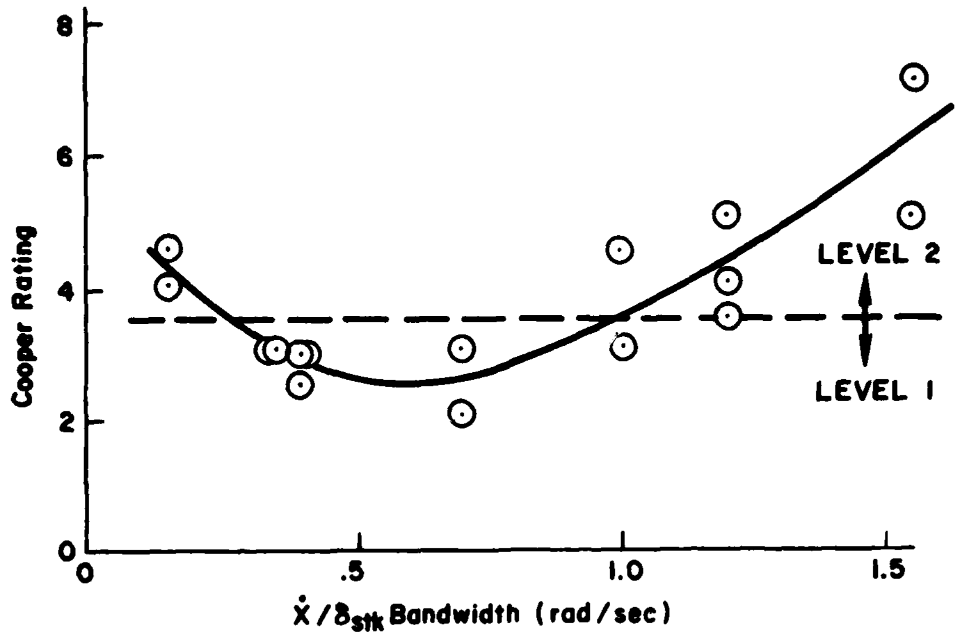


Figure 32. Preliminary Pilot Ratings vs. Path Mode Bandwidth

object. On the other hand, the pilots found the higher bandwidth systems to be too abrupt and complained of extreme pitch attitudes.

Figure 31a reflects the fact that $1/T''_{p_1}$ dominates the path response (see Fig. 30) as long as $1/T''_{p_1} < \omega''_{sp}$. This leads to more general definitions of competing lower-order equivalent system path responses for TRC systems using attitude, e.g., Eqs. 6-8 (T''_p has been generalized to $T_{\dot{X}}$ and ω''_{sp} to ω_n in these equations):

$$\frac{\dot{X}}{\delta_{stk}} = \frac{K_{\dot{X}}}{T_{\dot{X}}s + 1} \tag{6}$$

or

$$\frac{\dot{x}}{\delta_{stk}} = \frac{K_{\dot{x}}\left(\frac{s^2}{\omega_n^2} + \frac{2\zeta_u}{\omega_n} s + 1\right)}{(T_{\dot{x}}s + 1)\left(\frac{s^2}{\omega_n^2} + \frac{2\zeta_n}{\omega_n} s + 1\right)} \tag{7}$$

or

$$\frac{\dot{x}}{\delta_{stk}} = \frac{K_{\dot{x}}}{(T_{\dot{x}}s + 1)\left(\frac{s^2}{\omega_n^2} + \frac{2\zeta_n}{\omega_n} s + 1\right)} \tag{8}$$

Equation 7 is the most general equivalent system but suffers from undue complexity since six variables exist ($K_{\dot{x}}$, $T_{\dot{x}}$, ζ_n, ω_n, ζ_u, and ω_u). Reference 35 suggests that the form of Eq. 8 is an adequate representation of the TRC system path response. However, from Figs. 30 and 31 it can be surmised that an appropriate equivalent system form is simply a first order response when the first order pole $1/T''_{p_1}$ is less than ω''_{sp}. In fact, good pilot rating correlations result by assuming a first order form and using the equivalent time constant $T_{\dot{x}_{eq}}$ defined in Fig. 31a. These correlations are shown in Fig. 33. The data in Fig. 33 indicate that the responses for cases where $T_{\dot{x}_{eq}} < 1$ sec are rated very poorly (because of overly abrupt attitude motions). Figure 31 indicates that the responses look reasonably first order for configurations with acceptable pilot ratings, e.g., $T_{\dot{x}_{eq}} > 1$ sec. The implication of these data is that if a third order equivalent system is required to match the response, the system is probably unacceptable due to abrupt pitch and roll attitude responses to pilot commands. On this basis it seems reasonable to assume a first order equivalent system form for the path response of TRC systems of this type (i.e., attitude to translate). The data in Fig. 33 was obtained from the FSAA simulator tests on the XV-15 in addition to flight test points corresponding to the TAGS (Ref. 12) and the HLH (Ref. 23) helicopters.

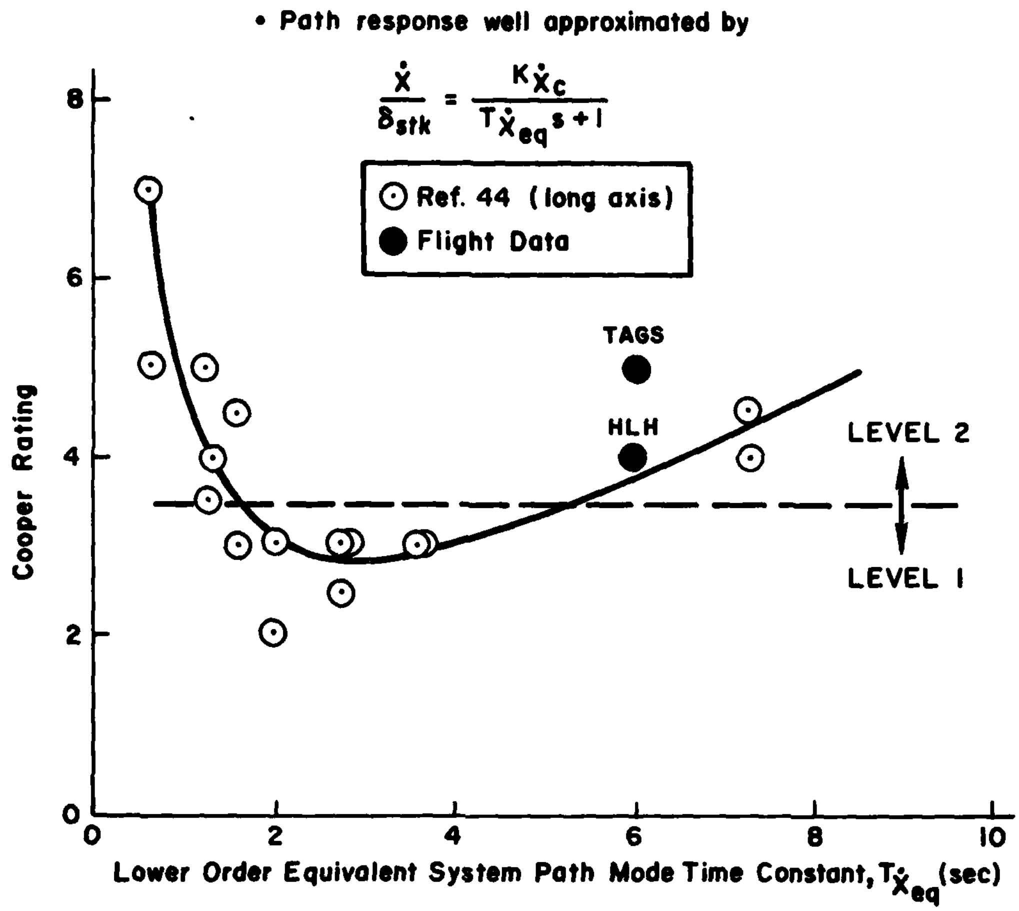


Figure 33. Translational Rate System Parameters

a. Stick Sensitivity

A general complaint on all the TRC systems tested on the FSAA was that the maximum velocity was too low (approximately 24 kt). This would indicate the need for a controller with significantly increased travel or blending to a different SCAS for high-speed flight. Problems with the former approach have been documented in the TAGS program (Ref. 22). Possible criteria for SCAS blending are discussed in Section VIII.

Forward loop nonlinear stick shaping was attempted in the heavy lift helicopter (HLH) program to allow low sensitivities for small deflections. However, problems associated with mechanizing this nonlinearity in the

presence of a parallel trim system made it impractical because the stick sensitivity became a function of trim stick position (functions of wind and CG) see Ref. 23, Fig. 22. Nonlinear shaping was used for the HLH load controlling crewman controller (LCCC) where trim was not a factor, i.e., zero groundspeed always represented zero controller position. The lateral and longitudinal stick shaping functions used for the LCC (Ref. 23) are presented in Fig. 34. These functions were developed during the HLH flight tests (using a modified CH-47) primarily to eliminate undesirable load excitation and may not be applicable to tasks where a sling load is not a factor. A maximum velocity of 15 ft/sec was felt to be too low during the HLH evaluations.

b. Tentative Criterion Format For TRC with Attitude

Based on the above discussions, it appears that the Eq. 6 equivalent system form will be adequate for specifying criterion boundaries for TRC systems, e.g., it may be assumed that,

$$\frac{\dot{x}}{\delta_{stk}} = \frac{K_{\dot{x}_c}}{T_{\dot{x}_{eq}} s + 1}$$

The pilot rating data of Fig. 33 are plotted on a grid of $K_{\dot{x}_c}$ vs. $T_{\dot{x}_{eq}}$ in Fig. 35 for center stick controllers and in Fig. 36 for sidearm controllers. Approximate lines of constant peak attitude to a step control input are also plotted on these figures. This was done to account for pilot comments which indicated that the upper limits on system bandwidth (lower limit on $T_{\dot{x}_{eq}}$) are strongly influenced by the secondary attitude responses to translational rate commands. Although the data base is very limited, some trends may be identified in Figs. 35 and 36.

- Larger steady state velocities per unit control input are acceptable as the system response becomes more sluggish (increased $K_{\dot{x}_c}$ at increased $T_{\dot{x}_{eq}}$). This is implied by the data in Fig. 36 and suggested by the lines of constant peak attitude.

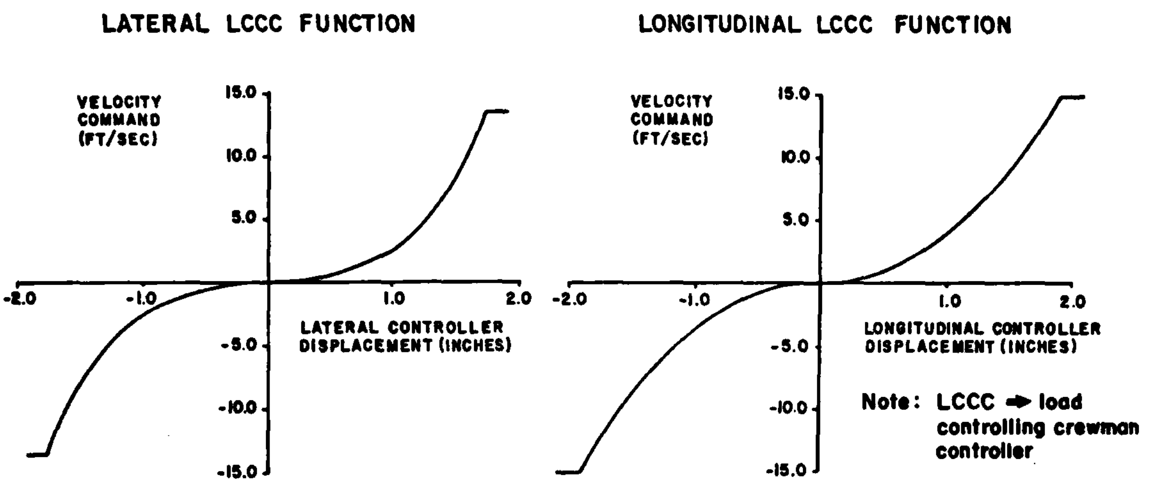


Figure 34. Comparison of Lateral and Longitudinal Control Response with 4-Axis Finger/Ball Controller

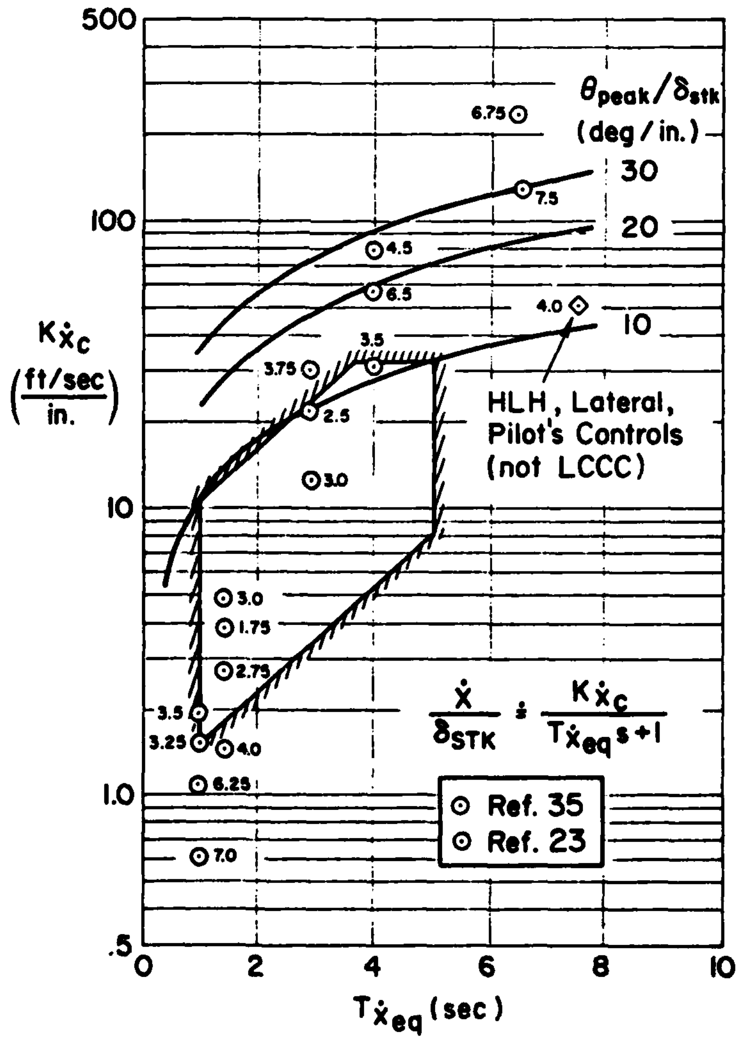


Figure 35. Pilot Rating Correlations for TRC Systems — Center Stick Controllers

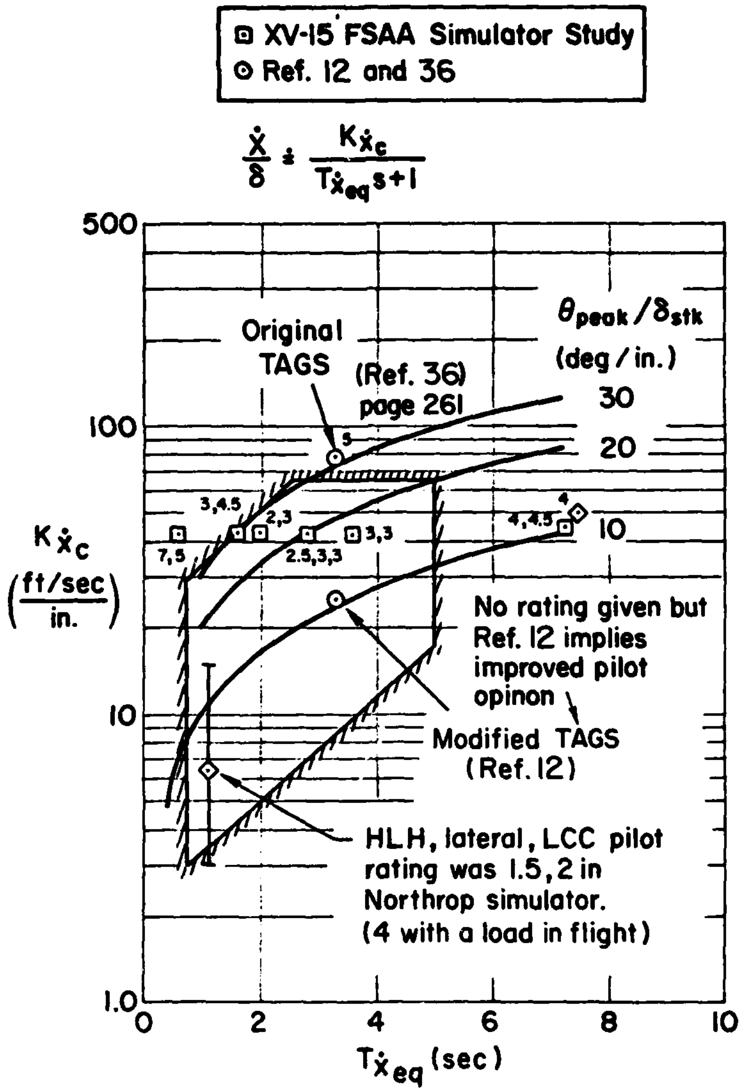


Figure 36. Pilot Rating Correlations For TRC Systems — Sidearm Controls

- Increased peak attitudes per inch of controller deflections are acceptable for sidearm controllers when compared to center stick controllers.

The Level 1 boundaries shown in Figs. 35 and 36 are estimates based on the existing data and on the premise that the peak attitude per inch of controller ($\theta_{peak}/\delta_{stk}$) represents a limiting condition. The data correlations shown in Figs. 35 and 36 are sufficiently encouraging to warrant

consideration of $K_{\dot{X}_c}$ and $T_{\dot{X}_{eq}}$ as key variables in forthcoming simulator and/or flight test experiments.

2. Translational Rate Command (TRC) With Direct Force Control (DFC)($K_{\theta_c} = 0$)

The prime theoretical advantage of direct force control (DFC) lies in its ability to decouple the aircraft responses to control inputs; its disadvantage is the ability to impose lateral and longitudinal ("uncoordinated") accelerations on the pilot. There is some evidence that complete decoupling between attitude and horizontal translation is not necessarily superior. In fact, the simulator studies of Ref. 37 showed slightly better ratings for attitude TRC systems (PR = 1 when $K_{DFC} = 0$). Similar results were obtained in the X-14A flight test where a vane was used to generate direct force control (Ref. 38). In those tests the use of DFC for translation was preferred over bank angle only when a low value of roll control power was available. With a satisfactory level of roll-control power the two methods were equally acceptable.

The basic X-14A augmentation consisted of a roll rate feedback; also the tests did not utilize linear velocity feedback ($\dot{X}$, $\dot{Y}$) and therefore amounted to a comparison of acceleration command techniques. It is felt however that the results pertaining to the decoupling of attitude and horizontal translation have direct application to TRC augmentation. For low speed maneuvering around a prescribed course the X-14A direct force control was not preferred because it introduced another input into the system and could easily be misapplied (pilot controlled bank with a center stick and direct force with a proportional "thumb cradle").

Further experimental results are clearly required to establish the advantages and disadvantages of TRC systems using DFC vs. attitude to translate, and to define handling quality boundaries on DFC systems.

3. Translational Rate Command With a Combination of Direct Force Control and Attitude

Experience with this type of TRC system is limited to the HLH longitudinal axis. The advantages of such a system accrue from being able to set the peak

attitude per inch of stick (θ_{peak}/δ) and $K_{\dot{X}_c}$ (see Figs. 35 and 36) independently a simulated response of the HLH to a 100 percent LCCC input is given in Fig. 37 (taken from Ref. 23). The pitch attitude changes are seen to be quite small (less than 1 deg). TRC in the lateral axis was accomplished with pure attitude control. The pilot ratings for precision hover were 1.5 in the longitudinal axis indicating a distinct preference for the combination DFC plus attitude mode. Unfavorable comments regarding the lateral axis indicated that the sling load was disturbed by bank angle excursion resulting from lateral translation commands.

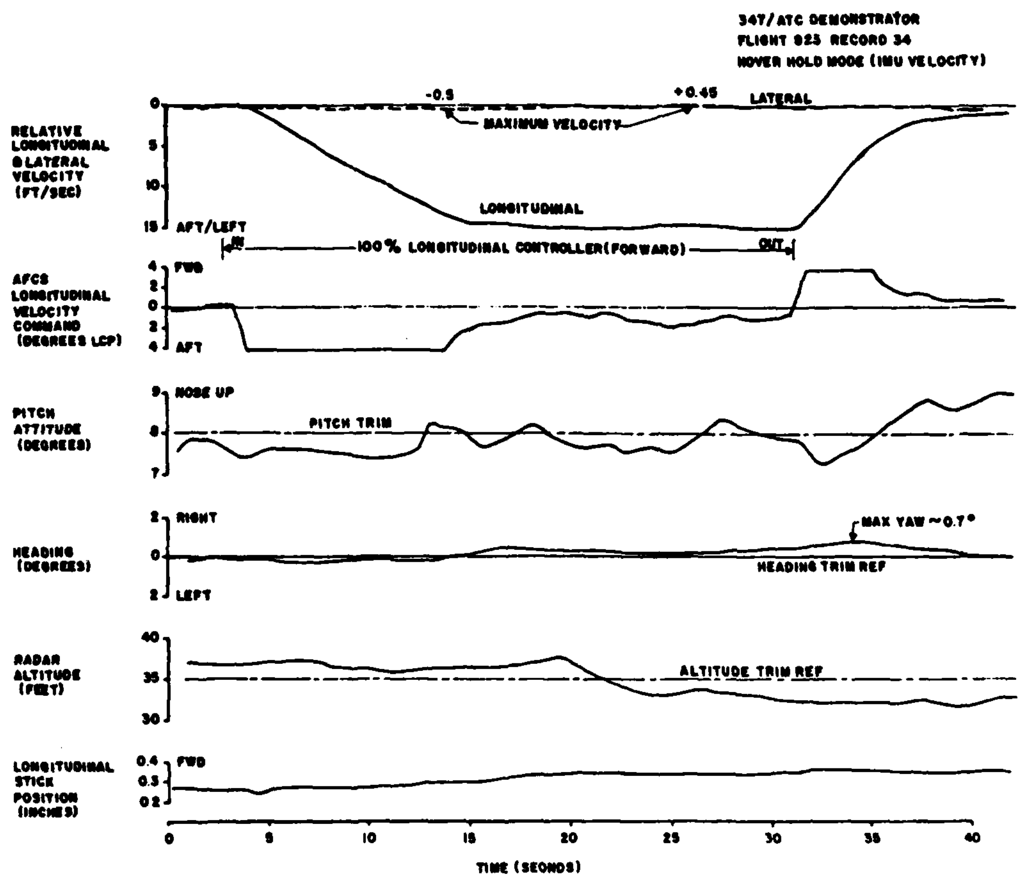


Figure 37. Response of HLH to 100 Percent LCC Input (from Ref. 20)

SECTION V

EVALUATION OF EXISTING DATA BASE AND SUGGESTED CRITERIA DEVELOPMENT PROGRAMS FOR LONGITUDINAL AND LATERAL AXES

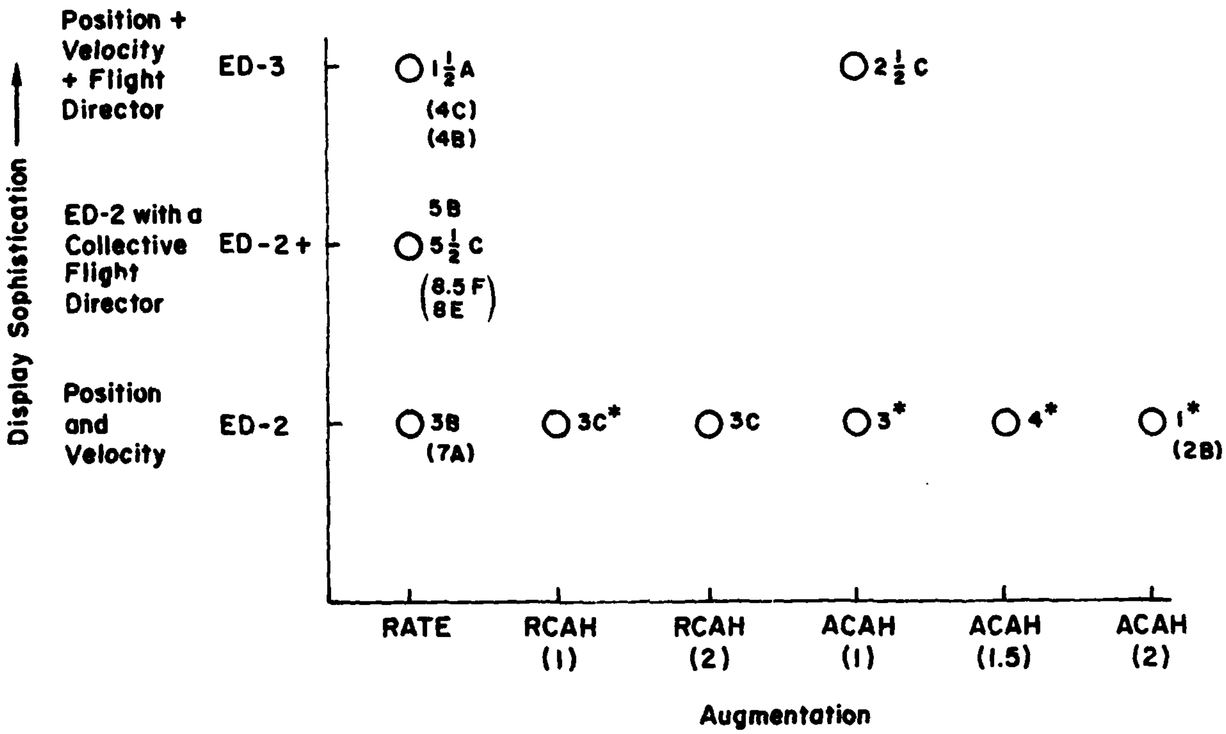
A primary objective of the work reported in sections III and IV has been to gather, evaluate, and correlate all the available data for the lateral-directional and longitudinal axes in low speed and hover. A natural byproduct of this effort has been the identification of gaps in the data base requiring further piloted simulator and flight experiments. Each of the areas identified are summarized below.

A. CONTROL-DISPLAY TRADEOFF

The data in Table 2 is primarily based on the results of the control-display experiments performed on the X-22 at Calspan and the CH-46 at NASA Langley (Refs. 14, 15, and 20 respectively). The X-22 results consist of only one pilot who flew one or two runs per configuration and, therefore, must be considered as tentative. The CH-46 results of Ref. 20 indicated that full IMC approaches to hover in IMC conditions (Visual Level 5) were unreasonably demanding. This is in conflict with later results with apparently the same system (Ref. 15) which indicate satisfactory pilot opinion. Discussions with the authors of these reports indicate that they are uncertain as to why the pilot opinion was more favorable for the later control display experiment. It is strongly suspected, however, that the constant attitude deceleration profile used in the later experiment (Ref. 15) had a major positive influence on the ratings.

There is a serious discrepancy between Ref. 14 and Ref. 15, e.g., the pilot rating of 3 vs. 7 discussed for configuration ED-1/FD in Section III-B. Another discrepancy which needs to be resolved is the recent X-22 data published in Ref. 21. These data (shown in Fig. 38) are at significant odds with <u>all</u> the results reviewed and correlated in Section IV. The primary discrepancies noted are summarized below.

- Rate systems were found to be acceptable for approach and hover in IMC conditions in Ref. 21 and were unacceptable in all the data discussed in Section IV.



Notes: 1) Numbers in parenthesis on abcissa indicate system bandwidth, e.g., RCAH (1) implies a rate command attitude hold system with bandwidth of 1 rad/sec.

2) Pilot ratings in parenthesis indicate data from previous X-22 experiment (Ref. 14, also Fig. 6).

3) Pilot ratings with a star indicate 100 percent authority SCAS. All other ratings have a 20 percent authority SCAS.

Figure 38. Recent X22A Control Display Results (Ref. 14)

- Improving the augmentation from a rate system to a 2 rad/sec bandwidth attitude system had a negligible effect on the ratings. Reference 14 and 15 indicate that progressing from a rate system to an attitude system should result in a dramatic improvement in pilot rating.

These data were taken from an experiment where the X-22A was configured to simulate the AV-8B. The data shown in Fig. 38 utilized the same cockpit display (with minor improvements) as the earlier X-22 experiment except it was presented on a headup display (HUD). Discussions with the author of Ref. 21 indicated that the reason for the discrepancies noted above are not apparent to the investigators at this time. However, it should be noted that the data are still being analyzed by Calspan.

The above noted discrepancies between the Calspan and Langley results as well as between the two Calspan experiments need to be explained before a handling quality criterion can be defined. While no definitive explanation can be made at this time, we can offer the following insights and possible solutions.

The simpler deceleration profile used in Ref. 21 certainly has some impact as discussed in Section IIIC (Fig. 10). However, this does not explain the drastic improvement for the entire task including hover in OVC 5 (IMC) conditions. It is possible that the discrepancies noted are a result of too few runs with not enough pilot subjects. This is compounded by the lack of control of environmental conditions inherent to in-flight testing. Inasmuch as the extremely high cost of running variable stability flight tests precludes a more intensive test program, it appears that simulation is the logical solution. Of course, the visual display problems discussed in Section IV-A will have to be resolved on any simulation used to gather data for low speed and hover. Assuming that this can be accomplished (e.g., use NASA/Ames S01 or resolve Redifon problems) each control/display configuration should be run a sufficient number of times to allow the pilots to get up on the learning curve as well as to investigate the more subtle points such as pilot abuses and the effect of discrete wind shears and gusts. At least three pilots should be utilized to minimize the unavoidable effect of per- [illegible] pilot preferences dominating the results. The role of flight test [illegible] to concentrate on a few key configurations defined in the

simulation to validate or expose problems with the simulator data; and 2) to expose the evaluation pilots to the real world situation. This last point implies that the same pilots should participate in the flight test and in the simulation.

The pilot tasks for which ratings are to be given should be better defined, e.g., one rating for constant speed ILS tracking, deceleration, hover and vertical descent tells very little about the problems encountered. Each of these phases should be considered as a separate task and rated accordingly.

Finally, the outside visual cues can be quantitatively varied in the simulator to make it possible to obtain data for Table 2 directly instead of by inference as was done in the current study. NASA/Ames has been successfully using a variable runway visual range (RVR) on the Redifon display for a number of years. This feature would be of significant value for obtaining data for Table 2.

B. EFFECT OF LARGE λ ON ATTITUDE SYSTEMS

All the data (6 points in Fig. 27) for large λ also involves large M_u. The negligible effect of large λ on pilot rating shown in Fig. 27 is unexpected and should be further investigated.

C. EFFECT OF WIND DISTURBANCES AND GUST SENSITIVITY

There is very little comprehensive data of the effect of gusts and/or discrete windshears as a function of gust sensitivity. The simulation experiments reported in Ref. 6 varied the primary gust derivatives (X_u, M_u, Y_v, and L_v) but held the turbulence level constant. These results are discussed in Section IV (see Fig. 20). Further work along these lines is required with emphasis on the following areas:

- Investigate the effect of providing a secondary controller to alleviate the large aircraft attitudes required when X_u or Y_v are large. Determine acceptability of specific mechanizations, e.g., additional manipulators, automatic trim followup with a direct force control, etc.

- Investigate the effect of large discrete shears.

- Investigate the effect of disturbances when direct force is used as a primary control either alone or in combination with attitude.
- Investigate, systematically, the effect of increasing system bandwidth in the presence of turbulence and discrete shears. Do for all systems listed in Table 1. Measure hands off rms attitude disturbances for various turbulence levels and attempt to correlate with pilot ratings.
- Use ship wake model from Ref. 39 as a discrete turbulence input.
- Using points which represent the minimum acceptable configuration/turbulence combinations, determine the effect of decreased visibility. Use the Fig. 5 visibility scale as a guide.

D. STICK FORCE GRADIENTS

It seems to be well established that pilots desire very low stick force gradients for low speed and hover. Stick force gradients were used in several of the experiments cited in Section IV. However, there is no record of why these gradients were picked or of any parametric variation of the gradients which would allow us to establish boundaries. Reference 6 notes that if large trim attitude changes are required (due to large X_u or Y_v) even moderately low force gradients become objectionable.

Experimental data is required to establish upper and lower bounds for stick force gradients for each of the systems in Table 2.

E. EQUIVALENT SYSTEM MISMATCH

If the flying quality criteria are to be couched in terms of lower order equivalent systems (LOES), the degree of allowable mismatch must be established. The frequency range of interest must also be defined. Finally, an experiment is required to test the hypothesis that VTOL pilots in the low speed and hover flight condition require lower order responses in attitude velocity and position to control inputs and will reject more complicated higher order responses. Evidence that this is indeed the case has been published by Hodgkinson, et al. (Ref. 3) for fighter aircraft, e.g., the Neal Smith data (Ref. 40). Such an experiment would involve a series of generic configurations for each equivalent system type in Table 2. These configurations should range from a "pure" lower order system to higher

order systems which depart significantly from the LOES. These departures should be made to occur at various frequencies to determine the frequency range of interest.

A large majority of the data generated to date (and correlated in Section IV) represents more or less pure lower order system forms. This is either a consequence of using very simplified equations in a ground based simulator (for example, Refs. 6, 8 and 35) or of using high gain model following systems which suppress all higher order dynamics (e.g., Refs. 14, 15 and 20).

F. EFFECT OF TIME DELAY

There is evidence that pure time delays ($e^{-\tau_e s}$) have a considerably larger effect on pilot opinion than would be predicted from the phase contribution ($\Delta\varphi = \tau_e\omega_c$) at the crossover frequency ω_c. Some idea of the effect of τ_e on longitudinal attitude control can be obtained from work by Hodgkinson, et al. (Ref. 3) where a regression analysis showed a degradation of one pilot rating for every 50 ms of τ_e. As an extension of the Ref. 3 work, an attempt was made to predict pilot ratings as a function of the mismatch between the controlled element and a pure rate response in attitude, e.g., $\theta/\delta = Ke^{-\tau_e s}/s$. The results of this analysis for the Ref. 40 data gave the following function.

$$\text{Pilot Rating} = 3.4 + 0.0966\ M + 11.21\ \tau_e \qquad (9)$$

The coefficient variable, M, is the mismatch function which is obtained by calculating the sum of the squares of the differences in magnitude and phase between the lower order system (LOS) and the higher order system (HOS) at a number of frequencies between 0.1 and 10 rad/sec, i.e.,

$$M = \Sigma \left\{(\text{gain}_{HOS} - \text{gain}_{LOS})^2 + (\text{Phase}_{HOS} - \text{Phase}_{LOS})^2\right\} \qquad (10)$$

Where gain is in decibels, phase is in radians and LOS refers to $(K/s)e^{-\tau_e s}$. This function was found to account for 85 percent of the variance in the data. The standard deviation in the error estimate was one pilot rating point. A plot of estimated vs. actual pilot rating is given in Fig. 39.

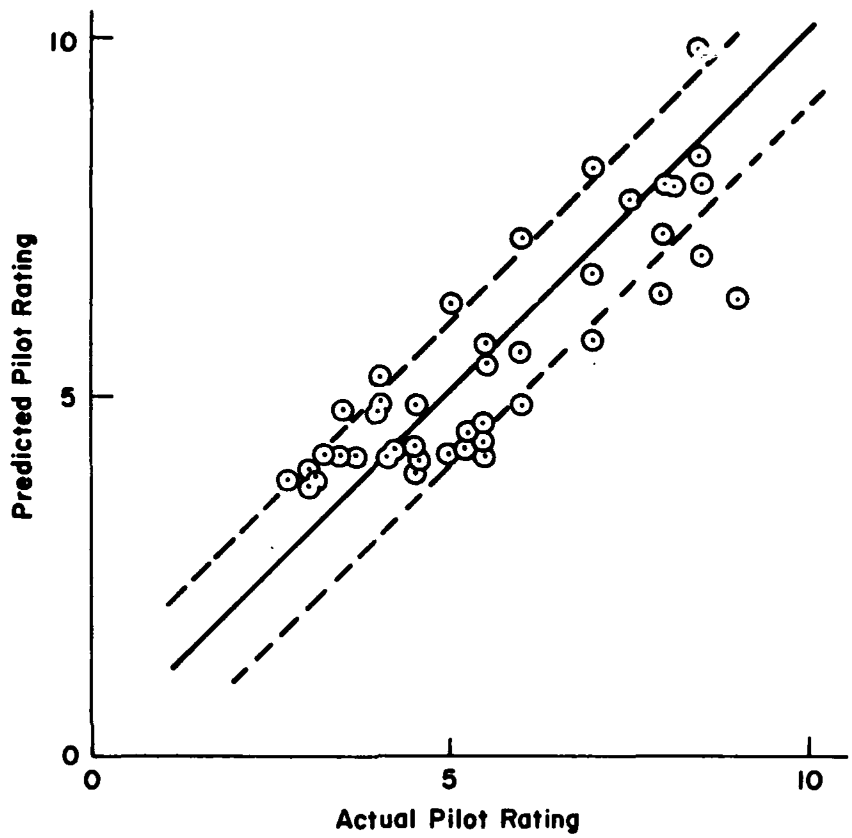


Figure 39. Actual vs. Estimated Pilot Rating
Using Equation 9

The predicted degradation in pilot rating due to τ_e is seen to be one pilot rating pcr 89 ms of τ_e (from Eq. 9) which is unexpectedly large on the basis of phase lag, e.g., a τ_e of 0.089 is equivalent to only 10 degrees of phase lag for a 2 rad/sec crossover frequency. These data were taken for a precision pitch tracking task (Ref. 40) for fighter aircraft configurations in up and away flight using the variable stability T-33 aircraft. Conventional attitude systems for such configurations are rate systems in the region of crossover. However, the extreme difference in task and environment preclude using the data as a criterion boundary for rate systems in low speed and

hover. Nonetheless, the data indicate a need for separately specifying boundaries on τ_e. Whether this need is real or an artifact of the data base used in Ref. 3 needs to be determined. In fact, data correlated in Ref. 41 indicates that the effects of time delay and phase lag are equivalent (see Fig. 40). A carefully contrived experiment which would reveal differences, if any, between time delays and phase lags is required to resolve the issue.

G. CLASSIFICATION OF ATTITUDE AND RATE SYSTEMS

As noted in Section III and in Ref. 42, a key issue with the use of equivalent systems for handling quality criteria is the ability to quantify the distinction between rate systems and attitude systems. The scheme proposed in Section II is felt to have considerable merit but is in need of experimental verification. Such an experiment should occur in two phases.

1) Ask the pilots to classify a series of systems as attitude or rate and see if their opinions correlate with the Fig. 3 criterion.

2) Establish a hover task that can only be satisfied with an attitude system via an appropriate combination of visibility, displays, and turbulence.

The proposed experiment would involve testing a large number of configurations in the first phase. Selected configurations would then be subjected to the second evaluation technique to insure that the basic intent of classifying these systems is satisfied.

H. ADDITIONAL DATA FOR MODEL FOLLOWING SYSTEMS

The model following systems tested in Refs. 14 and 15 were developed by setting the feedback loop gains at their maximum value without exciting a limit cycle or instability (based on informal discussions with the investigators in these experiments). There is a need to parametrically vary the feedback loop gains to determine maximum and minimum values of disturbance bandwidth for acceptable flying qualities.

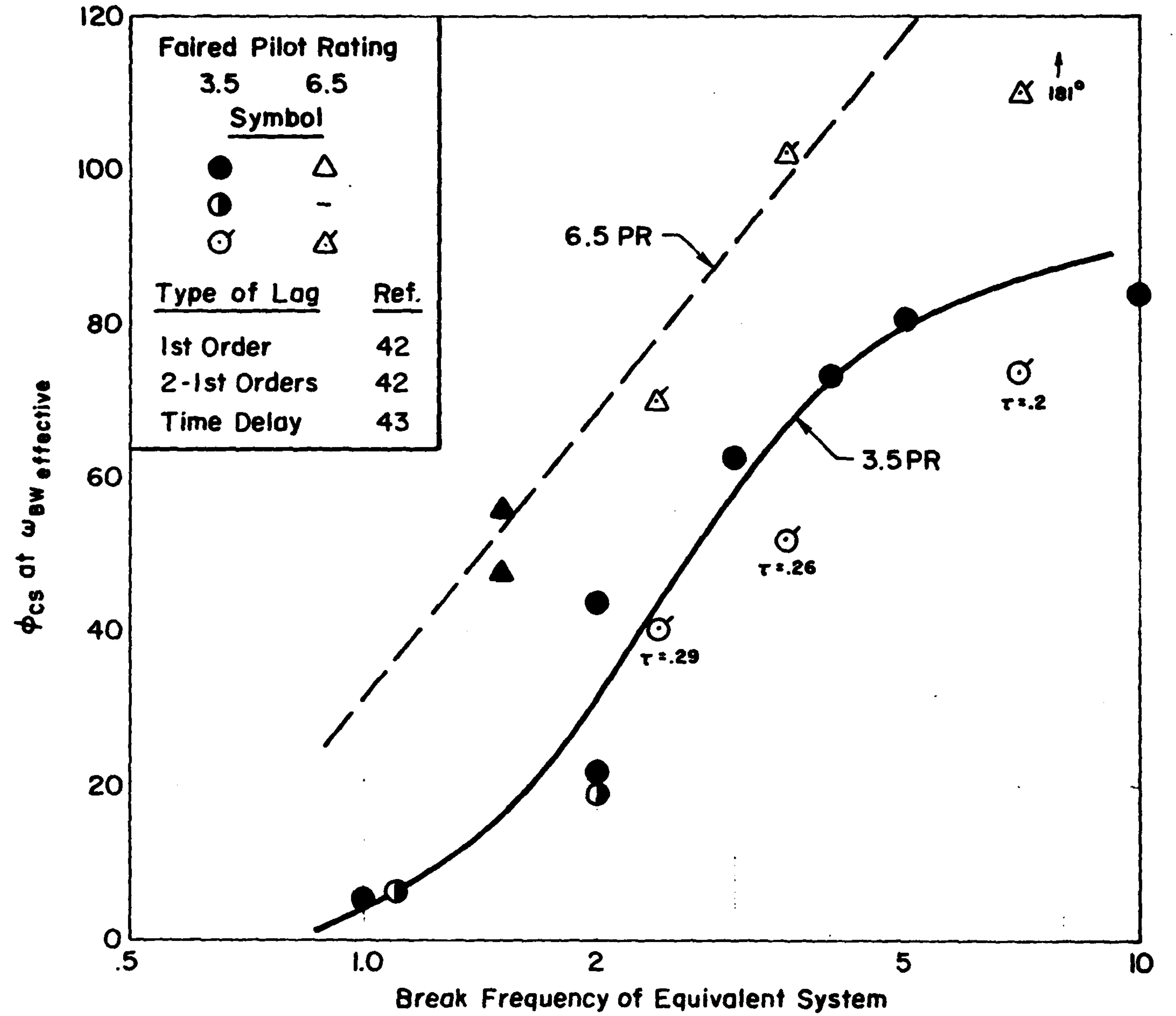


Figure 40. Control System Lag Requirements Correlation of Data (see Ref. 39)

There is some discrepancy between Refs. 14 and 15 regarding the model break frequency. Reference 14 (X-22) used 2 rad/sec which is in agreement with the Ref. 8 results, whereas Ref. 15 (CH-46) tried 2 rad/sec and found it to be too abrupt. Reference 15 ultimately used 1.43 rad/sec, which seems low.

It is clear that a parametric variation of the disturbance and model bandwidths is required to establish flying qualities boundaries for model following systems.

I. ADDITIONAL DATA FOR TRANSLATIONAL RATE SYSTEMS

The data base for parametric variation of translational rate system variables is limited to Refs. 35 and 44. Both of these involve systems without direct force control capability. The Ref. 35 data was taken on the NASA/Ames S01 simulator which has six degrees of freedom with one to one motion and real world outside visual cues. The pilot subjects were highly qualified. It follows that the confidence level in the data is high. It is the primary source for the data correlations shown in Fig. 35. As can be seen in Fig. 35, more data is required to better define the boundaries between acceptable and unacceptable handling. The primary source of data for sidearm controllers (Fig. 36) was the FSAA simulator experiments of Ref. 44. Because of the limitations in the visual display (see Section IV-A for discussion) these data must be considered as trend information only. Finally there is no data for vehicles with direct force control (DFC). Such data is required and should include the spectrum from pure DFC to pure attitude (e.g., vary K_{DFC} and K_{θ_C} in Fig. 29). The experiments should include using DFC for closed loop tracking as well as for low frequency trimming. If taken on a simulator, the fore/aft and lateral motion cues should be accurate.

SECTION VI

CONTROL POWER

A comprehensive solution to the control power problem is beyond the scope of the present study. What we have done is to systematically review alternative approaches to a criterion development as well as to summarize and analyze existing data. Based on this work recommendations for further research are made.

A. REQUIREMENTS

It is convenient to establish gross qualitative requirements for control power as a basis for evaluation of different criterion formats. Such requirements may be summarized as follows. There must be adequate control power to:

1) maintain vehicle attitudes, velocities and/or position in the presence of steady winds, random gusts, and discrete shears.

2) maneuver as required by the mission

3) avoid cockpit control or actuator limiting in either of the above situations which would be objectionable to the pilot.

In order to satisfy the first of these requirements it will be necessary to define the gust/shear environment. Examples would include specific airwake models for shipboard landings, atmospheric turbulence spectra as a function of altitude, wind, terrain character, etc., and design windshear conditions.

The maneuver requirement is difficult to generalize and may have to become part of the type specification for each individual case. Nearly all available VTOL control power data are based on maneuvering tasks; quick stops being the most critical one. The qualitative nature of these maneuvers makes it impossible to compare different sets of experiments. This is evidenced by a wide variation in required control power in the experimental data (see Section VI-D).

The third requirement depends on qualitative pilot opinion. Available data needs to be analyzed to define what is acceptable and what is not. The data generated during the simulation experiment conducted by STI and Vought (see Ref. 16) on the FSAA should be analyzed in this context. These data include approaches to a moving ship with three different augmentation systems and a head up display. Incidentally, the problems with the visual system on the FSAA (noted in Section IV) are not felt to be a primary factor in the Ref. 16 experiment inasmuch as the pilots utilized the HUD for tracking. The visual scene was mainly utilized for status information.

B. DISCUSSION OF POTENTIAL CRITERIA

The pros and cons of potential control power criteria are discussed in this subsection. The objective is to summarize existing experience to provide a starting point for the development of a comprehensive control power criterion.

1. Current MIL-F-83300 Criterion

The current MIL-F-83300 criterion specifies control power in terms of the ability to change attitude by a specified amount in one second. Paragraph 3.2.3.1 is repeated below for convenience.

> 3.2.3.1 Control power. With the wind from the most critical directions relative to the aircraft, control remaining shall be such that simultaneous abrupt application of pitch, roll and yaw controls in the most critical combination produces at least the attitude changes specified in Table IV within one second from the initiation of control force application.

TABLE IV. ATTITUDE CHANGE IN ONE SECOND OR LESS (DEGREES)

LEVEL	PITCH	ROLL	YAW
1	±3.0	±4.0	±6.0
2	±2.0	±2.5	±3.0
3	±2.0	±2.0	±2.0

One reason why the achievable attitude in a given time interval is felt to be a poor candidate is that it does not account for the presence of direct force control. Another equally important reason is that it is independent of the vehicle gust sensitivity. These deficiencies are felt to be severe enough to eliminate aircraft attitude in a given time interval as a viable approach to specifying a control power criterion. It is, however, a valuable design guide for vehicles without direct force control or that use direct force control for trim only. As such, it may have potential as a part of a more general criterion.

2. Maximum Control Moment ($M_\delta \delta_{max}$)

This is certainly the most direct method of specifying control power. In fact, many researchers take for granted that maximum installed moment is synonymous with control power (for example, see Refs. 8, 26-28, and 45 through 47). In addition to the above noted deficiencies related to the attitude in one second requirement, control moment has the deficiency of not being uniquely related to the ability to make large rapid controlled attitude changes. Such changes depend on damping or stiffness as well as maximum control moment. This is illustrated in Fig. 41 where it is shown that the achievable attitude in one second can vary over a large range for a fixed value of maximum moment.

While not suitable as a comprehensive criterion for control power, the installed moment is a valuable design guide. This is especially true regarding the effect of random horizontal gusts on pitching activity (M_u). For example, Ref. 48 showed that for a conventional hovering helicopter in the presence of Gaussian random turbulence, the required rms control deflection is approximately related to the rms gust input as follows:

$$\left(\frac{\sigma_\delta}{\sigma_{u_g}}\right)^2 \doteq \left(\frac{M_u}{M_\delta}\right)^2 \left[\frac{1 + \frac{2\zeta''\omega''}{\omega_{u_g}} + (T_{L_\theta})^2(\omega'')^2}{2\zeta''\frac{\omega_{u_g}}{\omega''} + 2\zeta'' + \frac{\omega''}{\omega_{u_g}}}\right] \tag{11}$$

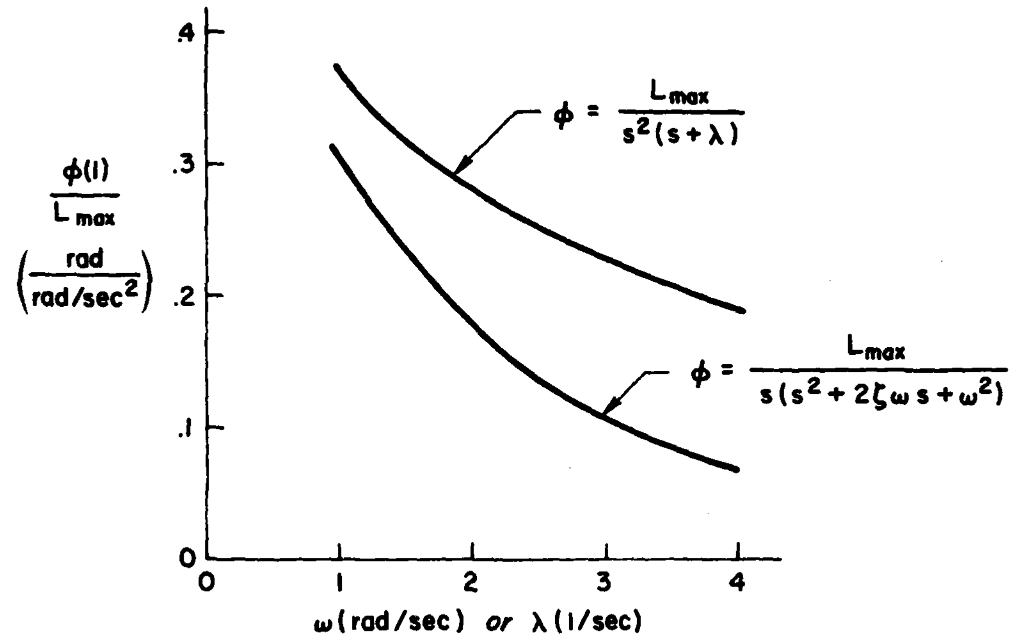


Figure 41. Illustration of How the Attitude In One Second Requirement Varies With Aircraft Dynamics

where double primes indicate the attitude and position loops have been closed and

T_{L_θ} = lead in attitude loop closure

ω_{u_g} = gust break frequency = 1.0 rad/sec (Ref. 48 page 134)

ζ'' = closed loop attitude mode damping

ω'' = closed loop attitude mode frequency

The term in brackets is plotted in Fig. 42 where it is seen to be relatively strong function of the tightness of the attitude loop closure, the amount of lead (pilot generated or augmentation) that is required to provide the necessary damping, as well as the gust sensitivity M_u. Reference 48 suggests that the term in brackets may be represented as a constant value of 1.4, consistent with "optimized" nominal closures which compromise among σ_x, σ_θ, and σ_δ, as shown below; Ref. 29 uses 1.75.

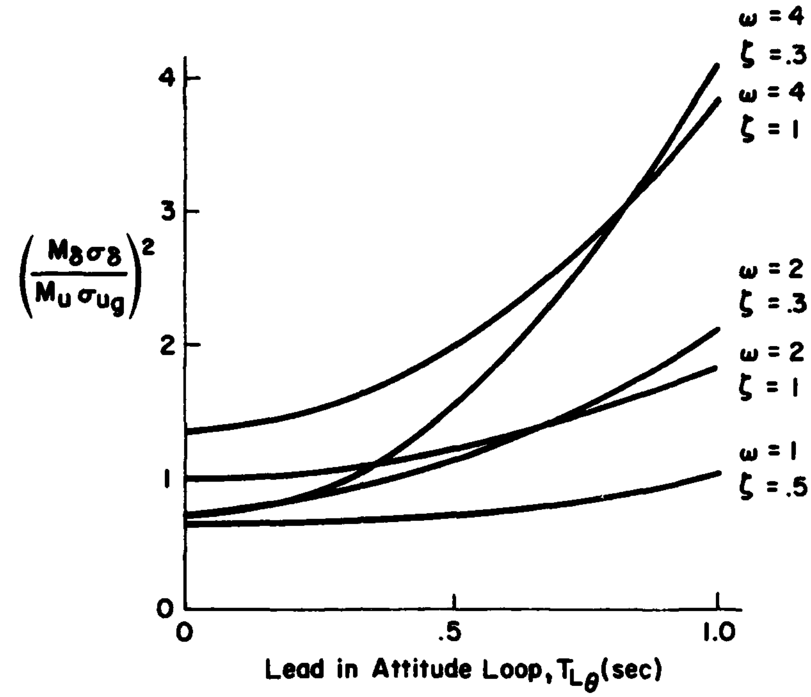


Figure 42. Control Requirements in Gusts (Plot of Eq. 11)

3. Control Power In Terms of Surface or Actuator Travel

The most direct way to specify control power is to simply dictate that the control surfaces and actuators shall not hit the limits of their travel for specified disturbances and command inputs. Calculation of the surface and actuator motions tends to get quite involved as it requires assumptions on the pilot loop closure characteristics including remnant; as well as modeling of the aircraft plus augmentation system.

Nonetheless, there appears to be no alternative which meets the requirements in Section VIA. In the following paragraphs we shall outline the considerations which are involved in the development of such a specification.

a. Pilot Model

In order to establish a baseline from which all aircraft can be compared it is necessary to specify a standard automatic or pilot-vehicle loop closure characteristic. An example of the effect of the variation in required control power (in terms of installed moment) as a function of the pilots' attitude and position loop gains is calculated in Ref. 48 and repeated here as Fig. 43. For the two cases considered in Fig. 43, the required control power is relatively invariant with the position loop gain but is shown to be somewhat sensitive to large values of attitude gain, at least for the high M_u case. The nominal gains shown are a reasonable compromise which minimizes the aggregate of the variables. For reference to Fig. 43, these nominal gains resulted in $\zeta_p'' \doteq 0.3$ and 0.33, and $\omega_p'' = 2.2$ and 3.8 for low and high M_u respectively.

b. Acceptable Level of Saturation

It is probably overly conservative to require that the controls shall never hit their limits. Consequently, it may be necessary to identify a metric which adequately quantifies levels of saturation. Vinje and Miller in Ref. 24 utilized the levels exceeded some given small percent of the time with unlimited moment available. Five percent was selected as a reference ($\overline{CM}_5$) and the control moment limits used in the experiment were varied by changing this reference in increments of 10 percent (e.g., $0.8\overline{CM}_5$, $0.9\overline{CM}_5$, $1.1\overline{CM}_5$, etc.). The pilot rating data which resulted from this experiment are shown in Fig. 44 (taken from Ref. 24). These data indicate that the required control moment depends on the type of augmentation as well as the level of gust sensitivity. It is interesting to note that in most cases considerably more control moment than $\overline{CM}_5$ was required for satisfactory pilot ratings. The question of how much control system saturation is acceptable to the pilot remains as an important unknown in the determination of a control power criterion.

C. ANALYSIS AND DISCUSSION OF EXISTING CONTROL POWER DATA

The data from the Ref. 8 (S01 simulator) and Ref. 26 (X-14A) flight test experiments were correlated in terms of $\phi(1)$ for rate systems and attitude

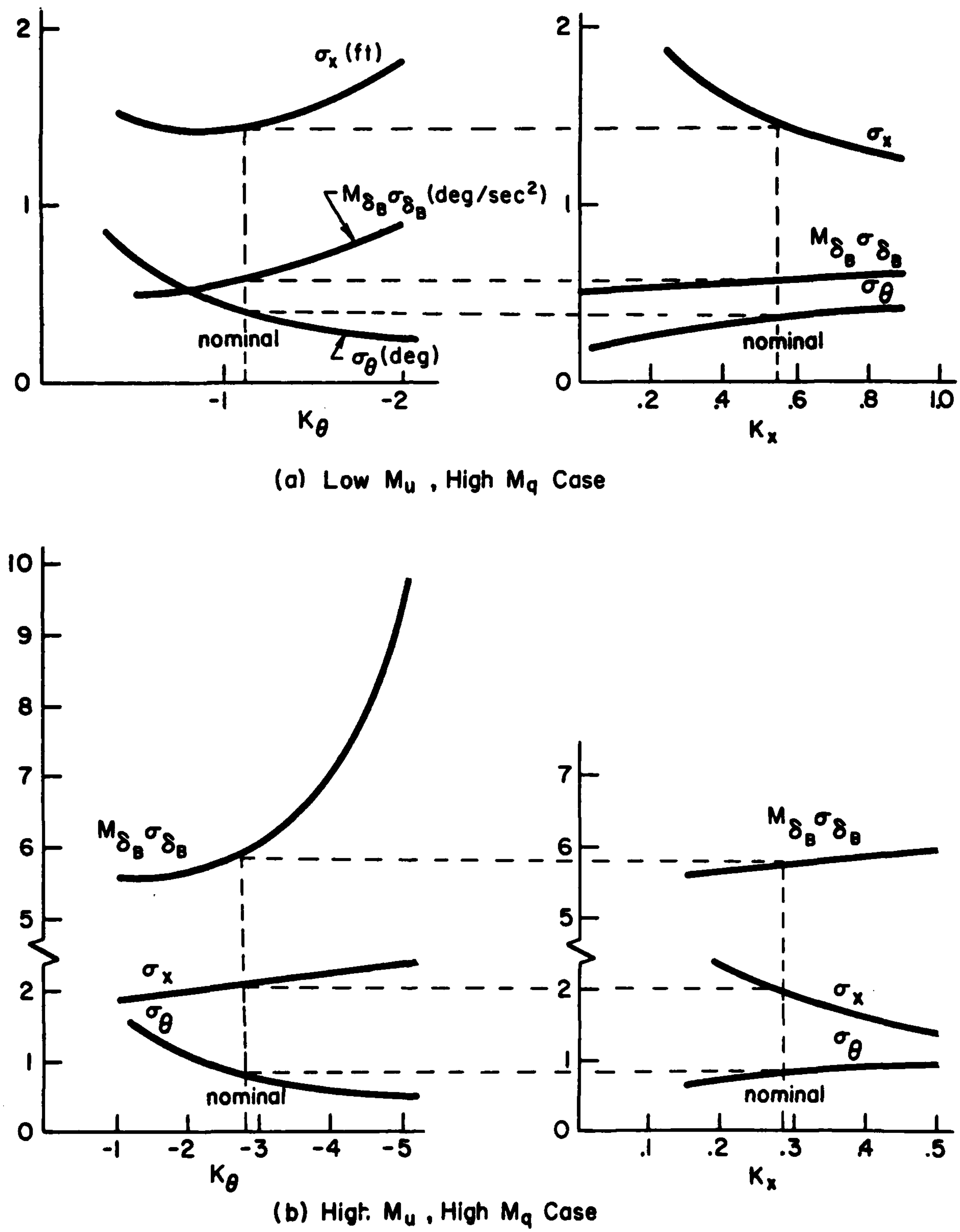


Figure 43. Variations of Gust Responses with Pilot Gains

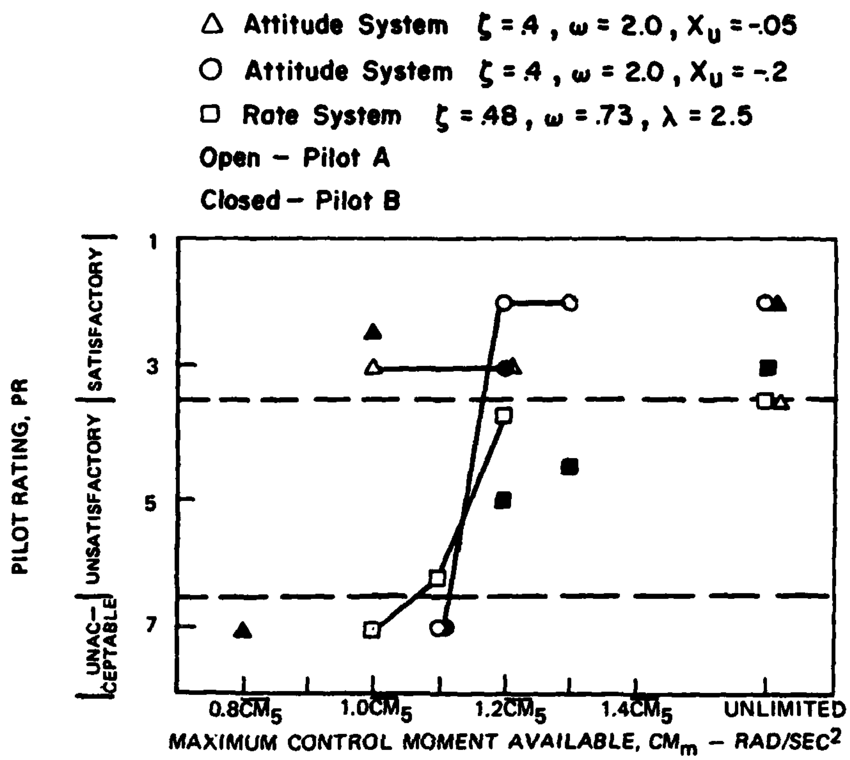


Figure 44. Pilot Rating Results for Control Moment Limits from UARL Study (taken from Ref. 24)

systems. These correlations are shown in Figs. 45 and 46. They indicate that significantly higher values of $\phi(1)$ are required than would be expected from the current specification (e.g., $\phi(1) = \pm 4$ deg). It is suspected that this discrepancy is more a function of the limited maneuvering room of the simulator (±9 ft cube) and the qualitative nature of the quick stop maneuver than a basic deficiency in $\phi(1)$. An attempt was made to repeat the quick stop maneuvers performed in the Ref. 8 experiments during a short session in the NASA/Ames S01 simulator. The author of Ref. 8 and the author of this report both flew the simulator and agreed that the maneuver could be classified as "very abrupt". Perhaps the most important outcome of this exercise was the realization of the very qualitative nature of the quick stop maneuver. It can be performed very rapidly or very smoothly with equal correctness. It is conceivable that this may "explain" the very large

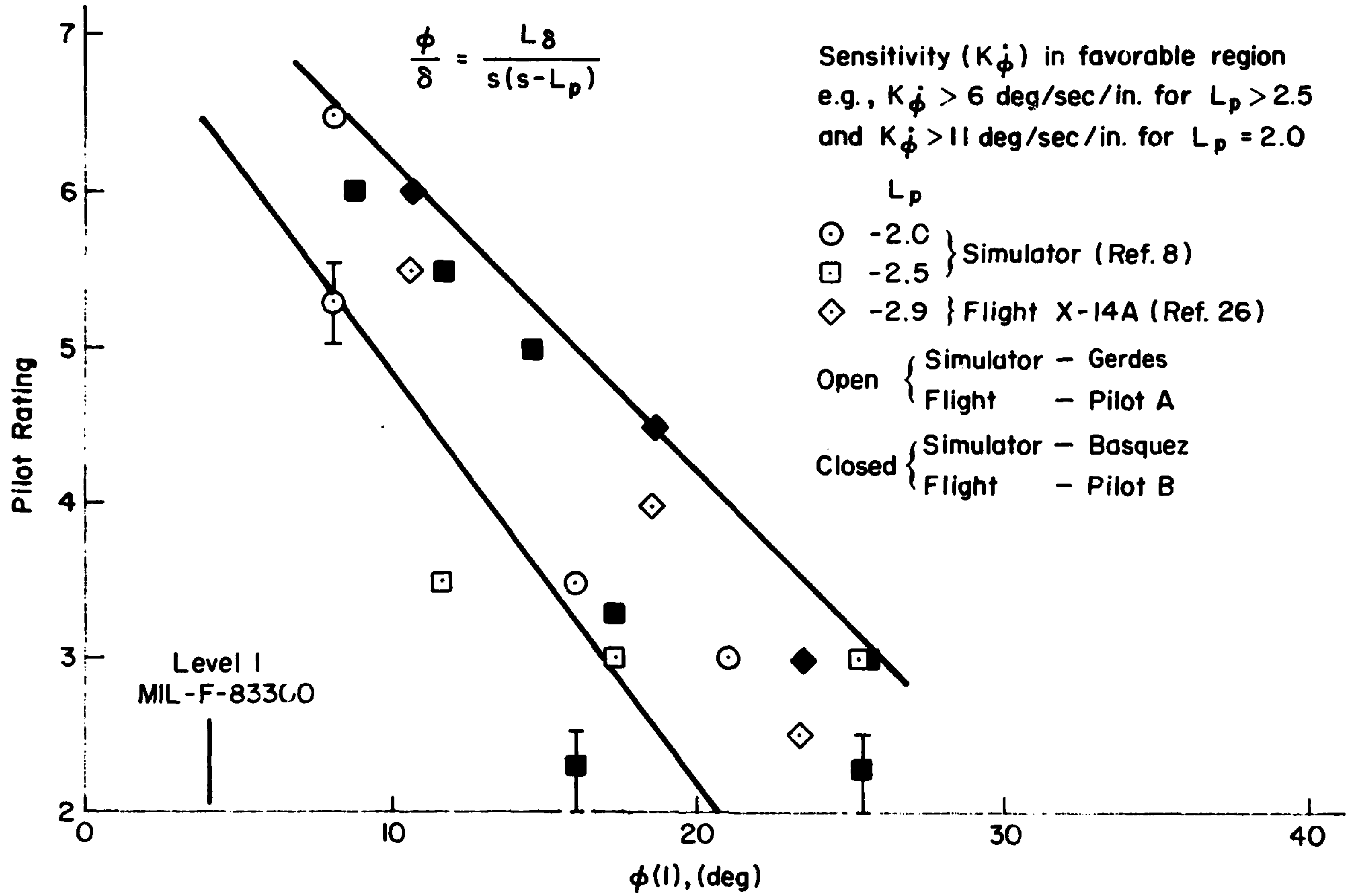


Figure 45. Control Power Correlations for Rate Systems from SO1 (Ref. 8) Experiment

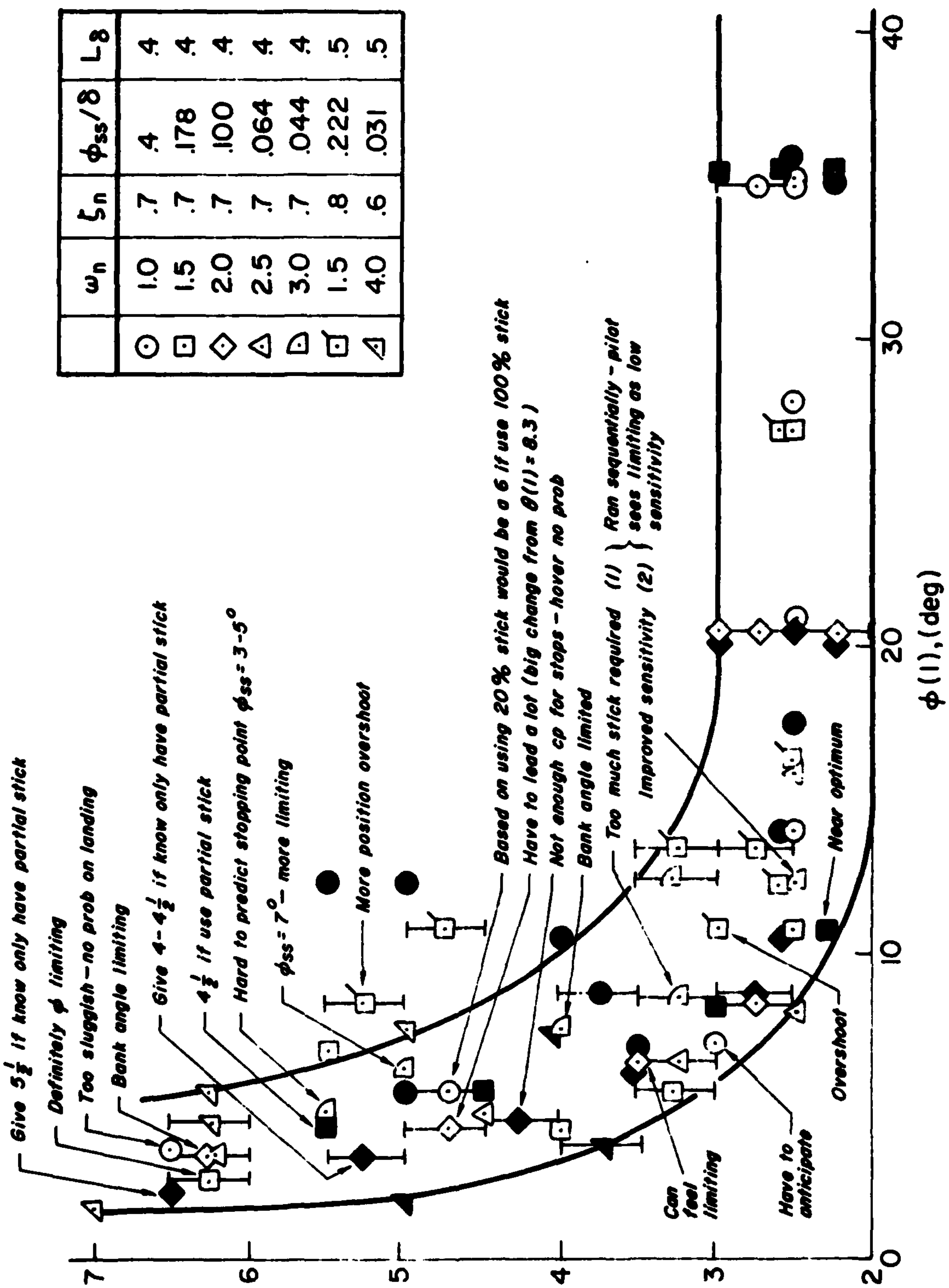


Figure 46. Control Power Correlations for Attitude Systems From S01 Experiment (Ref. 8)

intra experimental spread in control power results that exists even though there is good agreement within each experiment. That is, if the project pilot demonstrates the maneuver to each subject pilot in a given experiment, it is likely that the abruptness and corresponding control power required, will be set for that experiment. Hence the control power data which is currently available may be a function of the background of the project pilot in each experiment. A good deal of this data is summarized in Table 4 in terms of maximum achievable angular acceleration (the most common metric). The vast discrepancies noted in Table 4 have been particularly difficult to reconcile in light of the reasonably good pilot to pilot rating variation within each experiment. It is notable, however, that even though several maneuvers were usually utilized, the quick stop nearly always set the limiting values on control power.

The control power required to execute a precision hover involving precise small position changes is typically much less than that for maneuvering. An example of this is the Ref. 27 (CH-46) experiment where the control power to execute a constant heading square was found to be factors of 2 to 5 less than required for the quick stop (see Table 4). Equally dramatic evidence was obtained from the Ref. 8 data plotted in Fig. 47. These data indicate that when the pilots were asked to evaluate hover only, the value of $\phi(1)$ required for an attitude system was reduced from about 8 deg (Fig. 45) to less than 1.5 deg (e.g., Fig. 47 shows that the pilot ratings for $\phi(1)$ = 9 deg for quick stops were essentially identical to $\phi(1)$ = 2 deg for the precision hover task).

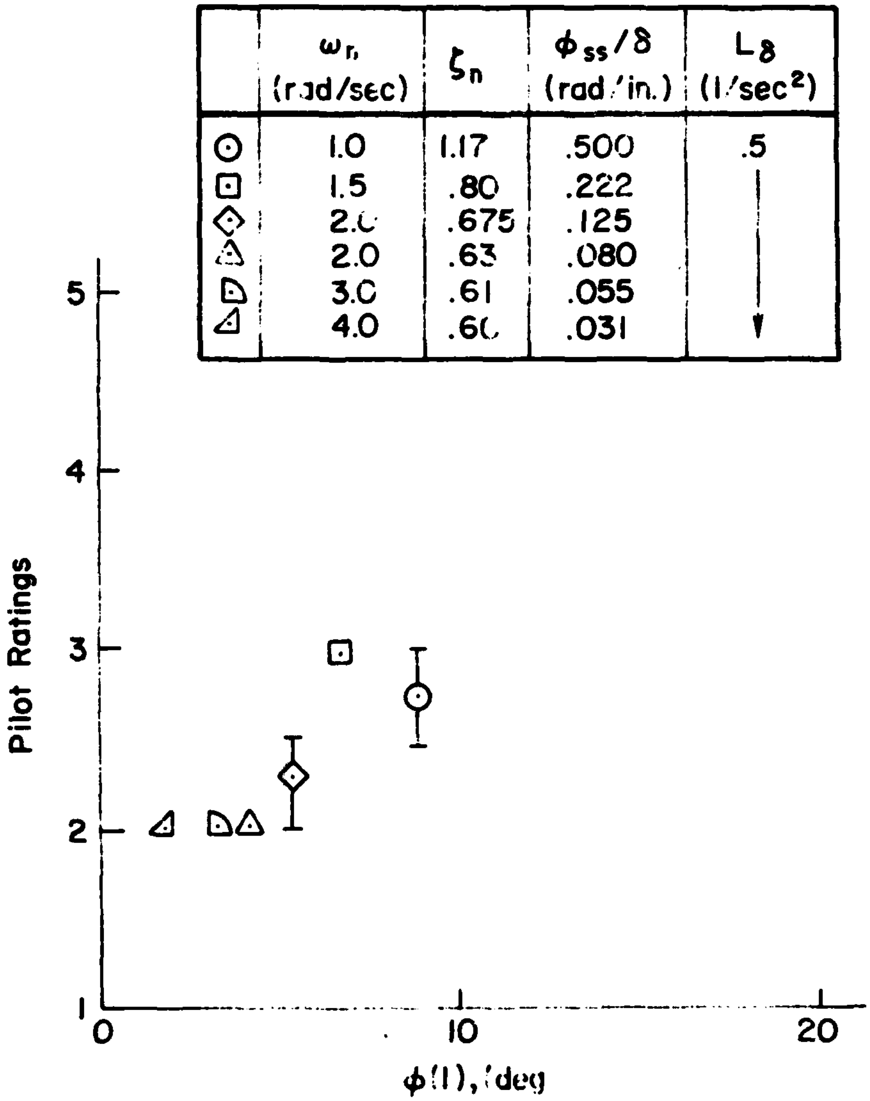
1. Control System Saturation

The classical context of control power infers the maximum linear or angular acceleration that can be achieved when a control surface is mechanically at its full travel or 100 percent thrust is applied. Inasmuch as the effects on vehicle motion are identical whether the saturation is mechanical or electrical, a viable criterion should account for each type of saturation.

For augmented systems, the question of what constitutes δ_{max} arises when both a mechanical path (parallel actuator) and an electrical path (series

TABLE 4. CONTROL POWER REQUIRED FOR PILOT RATING ≤ 3.5 IN TERMS OF ANGULAR ACCELERATION

SOURCE			COMMAND RESPONSE										
			ACCELERATION			RATE			ATTITUDE			TRC	
REFERENCE	SIMULATOR OR FLIGHT TEST VEHICLE	GOVERNING MANEUVER	L_δ	M_δ	N_δ	L_δ	M_δ	N_δ	L_δ	M_δ	N_δ	L_δ	M_δ
8	S01 6 degree of freedom simulator (NASA Ames)	Quick stops	Not acceptable with infinite control power			1.30	0.90		0.80	0.50		0.40	0.40
27	CH-46 Variable Stability Helo (NASA Langley)	Quick stops Pedal turns				0.75	0.47	(Approx) 0.4					
		Constant heading square pattern				< 0.20	< 0.20	0.18					
26, 49	X-14A flight test	Quick stops				1.75	0.55	0.5					
48	Bell Variable Stability Helo	Quick stops				0.50	0.25	0.2					
50	Fixed base Simulator-Boeing	Quick stops				0.50	0.22	—	0.29	0.31	—		
24	Moving base Simulator-UARL	Quick stops				0.79	1.07	0.23	0.40	0.40	0.15		
45	AGARD		.30 – .60	.20 – .40	.10 – .50	.20 – .40	.10 – .30	.10 – .50	.20 – .40	.10 – .30	.1 – .5		



	ω_n (rad/sec)	ζ_n	ϕ_{ss}/δ (rad/in.)	L_δ (1/sec^2)
⊙	1.0	1.17	.500	.5
⊡	1.5	.80	.222	↓
◇	2.0	.675	.125	
△	2.0	.63	.080	
D	3.0	.61	.055	
◿	4.0	.60	.031	

Figure 47. Control Power Required for Precision Hover (from Ref. 8 data base)

actuator) are utilized, e.g., not fly by wire. This is shown schematically in Fig. 48.

If the aircraft in Fig. 48 is neutrally stable or less (as most VTOL's are), the primary requirement on the series actuator is to cancel the constant δ_p which occurs when the pilot commands a step attitude change. Hence the control power is dictated by the series actuator authority in this example. An example of series actuator limiting was cited in Ref. 18. There it was shown that a large windshear required very little surface deflection, but that the series actuator requirements were significantly greater than the available travel. This is illustrated in Fig. 49 (taken from Ref. 18) for the XV-15 Tilt Rotor aircraft with attitude augmentation. Because of the limited authority series actuator, the SCAS was remechanized as a rate command attitude hold system with the results shown in Fig. 50. The block diagram for the rate command attitude hold system is identical to Fig. 48 except that there is an integrator at the output of δ_{stk}. Figure 50 shows that the series servo travel is well within its travel limits for this type SCAS for the same large windshear input. The point

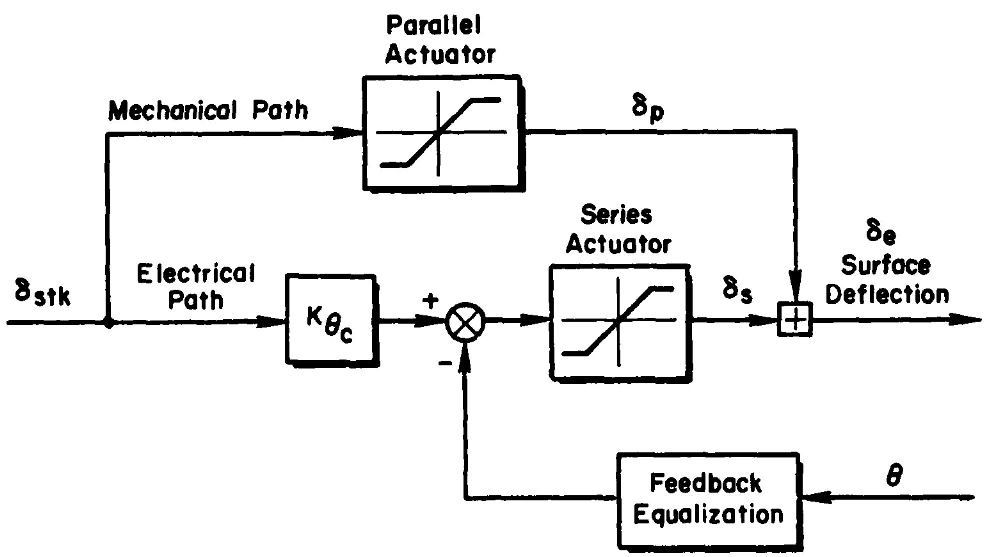


Figure 48. Typical System With Parallel and Series Servos

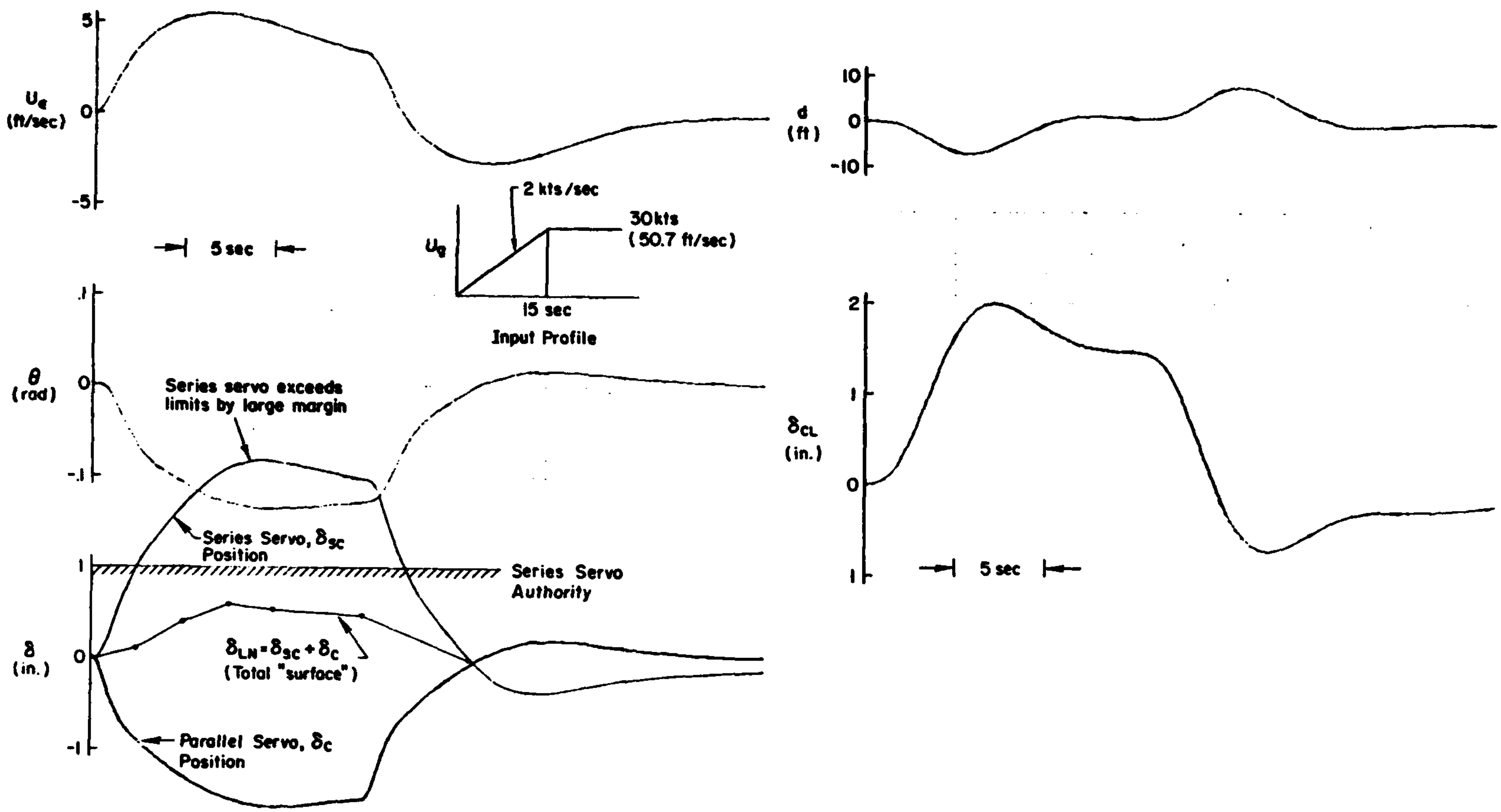


Figure 49. Time Response Characteristics for a Large Horizontal Wind Shear Input with Attitude Command/Attitude Hold SCAS, V = 60 kt (Taken from Ref. 18)

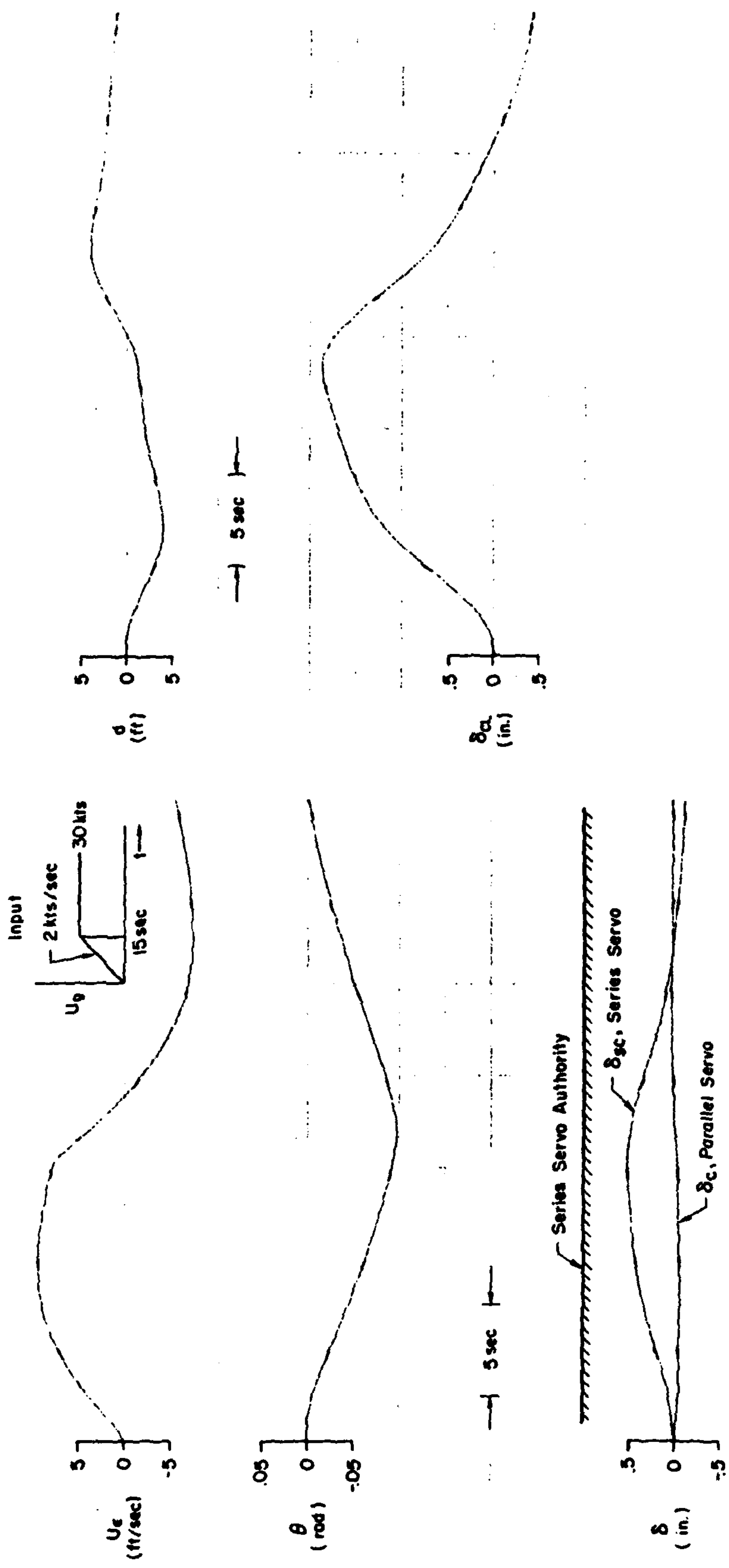


Figure 50. Time Response Characteristics for a Large Wind Shear Input at V = 60 kt (from Ref. 18)

is that the available "control power" may depend on the detailed characteristics of the augmentation such as the signal split between the series and parallel servos. It is also interesting to note that the critical disturbance input sometimes depends on the details of the augmentation system mechanization. For example, the XV-15 time response shown in Fig. 49 exhibits no saturation to large random gust inputs. The windshear used in Fig. 49 was selected based on the knowledge that a long term step-like stick input was required to saturate the series servo.

The authors of Ref. 50 noted that larger steady state aircraft attitudes could be achieved without increasing control power by saturating the available control. This concept takes advantage of the fact that the θ/δ response of unaugmented VTOLS tends to be rate or acceleration-like and hence have essentially infinite values of low frequency gain (e.g., the open loop attitude response to a step control is unbounded or at least very large). Control system saturation rates were defined as shown in Fig. 51. The fixed base simulation results of that study strongly supported their original hypothesis as shown in Fig. 52. These results are augmented by the moving base S01 simulator results presented in Ref. 8. Figure 53 (taken from Ref. 51) shows that increasing SR is beneficial for attitude systems with

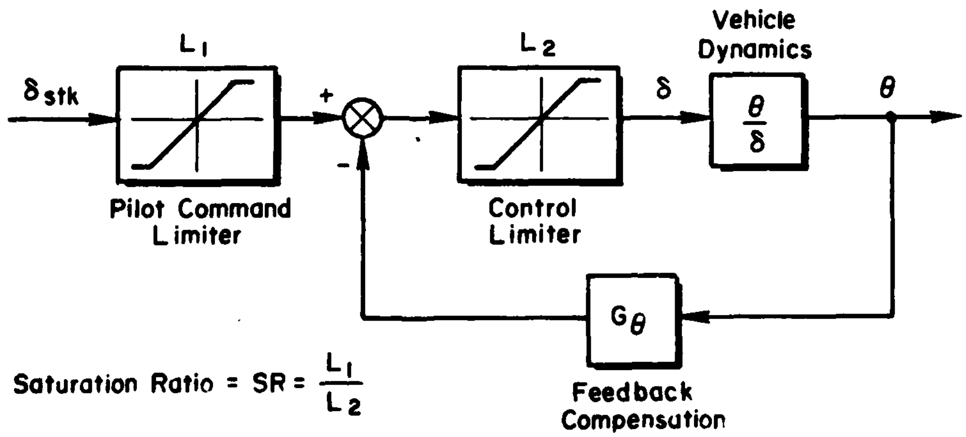


Figure 51. Definition of Saturation Ratio

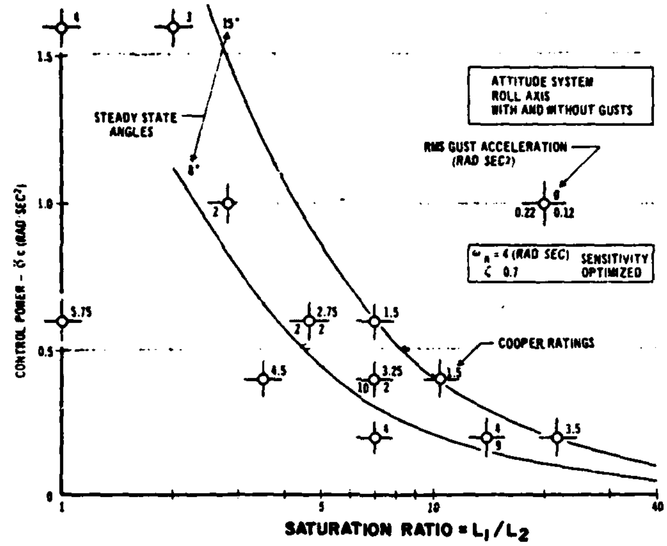


Figure 52. Effect of Saturation Ratio on Lateral Control Power — Attitude System

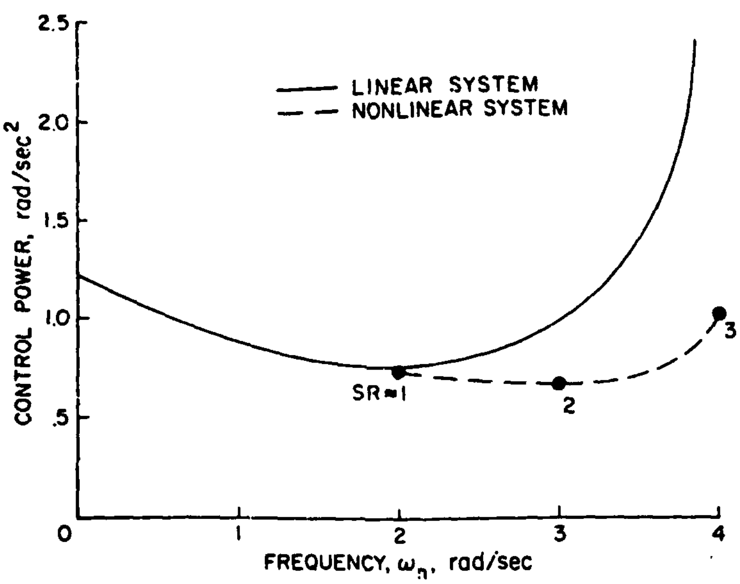


Figure 53. Effect of Saturation Ratio on Required Control Power as a Function of Equivalent System Frequency (Ref. 51)

ω_n > 2 rad/sec. It is suspected that these results are primarily due to the response feedback mechanization used wherein the maximum attitude decreases with increasing frequency, i.e.,

$$(\varphi_{ss})_{max} = \frac{L_\delta \delta_{max}}{\omega_n^2} = \frac{\text{max command moment}}{\omega_n^2}$$

If so, the advantages of increasing saturation ratio shown in Fig. 52 may well be realized by simply moving the feedback compensation to the forward loop.

The effect of increasing saturation ratio at constant frequency (ω_n = 2 rad/sec) was investigated using the basic data from Ref. 8 (S01 6 DOF simulation). A configuration with marginal control power was picked to see if increasing saturation ratio would move it into the satisfactory range. As shown in Fig. 54, increasing values of the saturation ratio increases the maximum steady state bank angle (φ_{ss}) as expected. However,

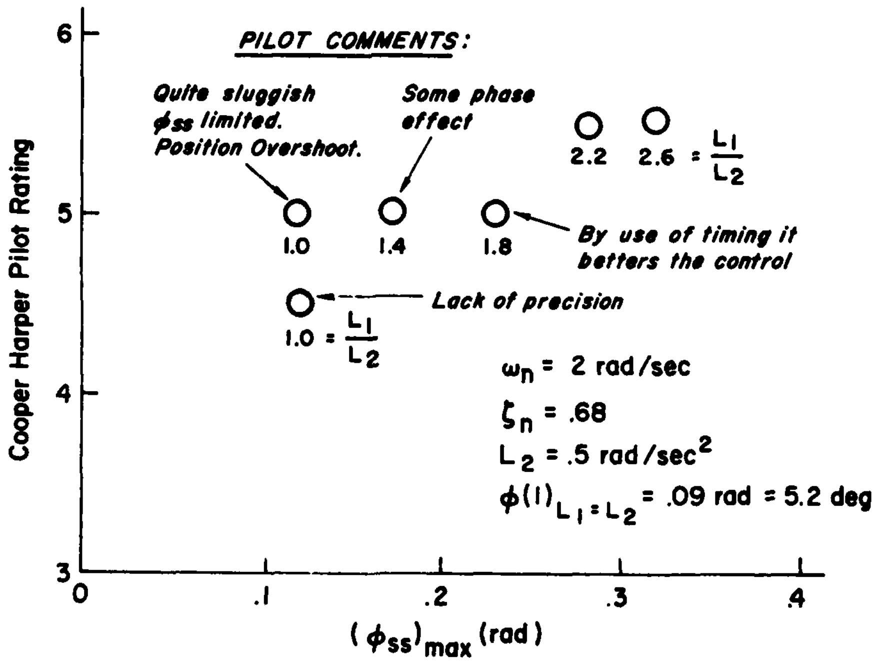


Figure 54. Effect of Saturation Ratio on an Attitude System With Marginal Control Power

the pilot ratings actually degrade slightly. Pilot comments indicate that phase effects are responsible. Comments made by the authors of Ref. 8 indicate that the general consensus of the subject pilots was that the adverse phase effects caused by increased saturation ratio more than offset any advantages of increased achievable attitudes.

The drastic reduction in required control power with increasing saturation ratio shown in Fig. 52 probably is influenced by the high natural frequency used (ω_n = 4 rad/sec) and may be an artifact of the lack of motion and non real world visual scene in the simulator.

D. SUMMARY

Of all the methods discussed for setting control power limits, it appears that establishing the actual required surface or control-effector limiting characteristics is the only approach that is general enough to insure adequate control authority without overdesigning the system. The steps which must be taken to set the maximum levels of surface and actuator travel (or maximum control thrust) are given below.

1. Steps to Develop Control Power

a. Establish operating environment

- steady winds
- random turbulence
- airwake model
- descrete wind shear
- ground effect

b. Compute steady trim control power required

c. Settle on loop closure characteristics

- Augmentation and/or automatic control analysis and/or unmanned simulation
- Human pilot manned simulation
- Acceptable performance, e.g., for a given disturbance from Step a, how large may the attitude and position errors be? Obtain from pilot ratings and commentary.

d. Establish how much control saturation is acceptable from simulation

- based on performance
- based on pilot acceptance (ratings and commentary in simulation)

e. Check that adequate maneuvering can be accomplished with the control power obtained from Steps a through c.

To develop better, more solidly acceptable crossover and exceedance criteria requires a control power development program which includes a moving base manned simulation. As discussed in Section IV, the simulator visual requirements for low speed and hover are quite stringent. However, there appears to be no viable alternative to obtaining the data needed to develop what are and what are not allowable levels of control saturation and what is and what is not an acceptable level of performance for the Navy mission.

2. Recommended Control Power Criteria Development Program

A two phase criteria development program is recommended. Phase 1 consists of analysis and development of a simulation experimental plan. Phase 2 is the simulator experiment and analysis thereof to generate the data required to set the specification boundaries.

The underlying concept of the research is the recognition that at one extreme — a fully automatic system — the determination of required control power is simply a matter of specifying command/disturbance inputs and acceptable system performance. Further, such input/performance specifications are related to and stem from the appropriate mission/task structure. Complicating factors enter the picture when, rather than under fully automatic control, the system is partially or totally controlled by a human pilot; these complications are:

- The degree of saturation which the pilot will tolerate is not known.
- The precision of control required by the pilot in hover is not well established.
- The minimum maneuver/control desired/required by the pilot in hover is not well-defined.

The following program is designed to answer the above questions and thereby unify control power specification whether for manual or for fully automatic systems.

a. Phase 1

The data base generated by the Ref. 16 experiment should be analyzed to gain insight into the following areas:

- RMS and peak values of control utilization as a function of disturbance inputs, i.e., deck motion, steady wind vector, and wind turbulence over the deck for rate, attitude, and velocity-command/position-hold augmentation.
- The extent to which pilots were willing to operate in the saturated region for each system.
- Levels of system and stationkeeping performance acceptable to the pilots.

Based on analysis of the time histories, approximate pilot models should be defined. Of particular interest will be cases where saturation occurred, although linear pilot models should also be developed. Inasmuch as pilots frequently modify their tracking behavior in the presence of control system limiting, the objective of such modeling will be to quantify the behavior modification.

Closed-loop analyses should be performed on the following generic augmentation schemes:

- Rate systems
- Rate-command/attitude-hold systems
- Response feedback attitude systems
- Model-following attitude systems
- Translational rate command (TRC) with attitude
- TRC with direct force control (DFC)
- TRC with combination DFC and attitude

Using appropriate pilot models, the required control power to "just barely" avoid saturation for each of the above systems should be determined and compared for the following selected inputs:

- The latest version of the airwake model
- Random turbulence
- Large discrete shear

The probability of exceedance level which constitutes "just barely" avoiding saturation for the random turbulence will be based on analysis of existing simulation data and should be refined during the Phase A simulation effort discussed subsequently. Additionally, the degradation in performance can be calculated for specific levels of saturation. Based on the insights gained from analysis of the Ref. 16 data, it should be possible to estimate acceptable levels of saturation and performance degradation. These estimates should form the basis for the final simulator investigation.

The final part of Phase 1 will utilize all of the above data to define a simulation program. Minimum requirements for a simulation facility will be established and certain specific simulators identified. Once the tradeoffs between cost, schedule, and technical requirements are established, and a facility selected, Phase 1 will be complete.

b. Phase 2

Phase 2 consists of a carefully designed comprehensive simulation program to generate the data required to set control power criterion boundaries for low speed and hover. Based largely on the Phase 1 analysis and the existing data review contained in this report, the "full" experimental matrix [which consists of seven generic augmentation schemes, three disturbance models, and varying levels of gust sensitivity (X_u, Y_v and M_u, L_v)] should be reduced to fewer, more "critical" and instructive cases. The nominal level of control power for each configuration will be set by the value determined from closed-loop analysis. Selected perturbations from these values should be tested until the Level 1 and Level 2 boundaries have been established for several levels of external disturbance.

Feel system and control sensitivity characteristics should be separately optimized for each of the generic test configuration.

The control power relief afforded by secondary controls will also be investigated. Especially important in this regard is the additional workload required to operate the secondary control. Specific cases to be tested are:

- Retrimming nozzles when attitude is the primary translation control.
- Retrimming attitude when DFC is the primary translation control.

Both manual and automatic trim followup should be considered.

Detailed pilot ratings and commentary will be obtained for each of the following subtasks.

1. Transition to hover
2. Hover
3. Vertical descent
4. Takeoff and initial climb

The time spent on each of these areas should depend on their relative importance for each system tested based on initial pilot commentary and ratings. These tasks will be simulated separately to allow the subject pilots to concentrate on a single well-defined task. Finally, the entire maneuver should be simulated to allow the pilots to make an overall evaluation. At least three subject pilots should be utilized.

Primary considerations for simulator selection are expected to be the pilot's outside visual cues, and requirements for linear and rotational motion.

It is suggested that the simulation be conducted in two phases. Phase A would consist of a one-pilot checkout of each of the configurations, disturbance models, auxiliary controls, and task scenarios to establish control system dynamic and gain characteristics for each configuration. The data obtained during Phase A will be utilized to refine the analysis, which in turn will result in better information upon which to base the final test plan for Phase B.

Phase B would consist of actual data taking with a minimum of three subject pilots. Any trends not supported by the closed-loop analysis should be subjected to additional testing and when proven valid, incorporated into the theory by the end of the program. Hence, the boundaries established at the end of the experiment will, by definition, be supported by the analysis. Such an approach allows filling in the blank spaces in the original "full" test matrix through analytic extension of the experimental data obtained.

SECTION VII

VERTICAL AXIS

A. BASIC CONSIDERATIONS

With the aircraft pitch attitude loop closed by the pilot (or by augmentation) the vertical velocity response to a vertical thrust input may be expresses as follows (see Ref. 4).

$$\frac{\dot{h}}{\delta_T} = \frac{N^{h}_{\delta_T} + Y_\theta N^{\dot{h}\ \theta}_{\delta_T \delta_e}}{\Delta + Y_\theta N^{\theta}_{\delta_e}} \tag{12}$$

Experience has shown that for Y_θ's consistent with normal piloted attitude control, or SCAS practice, the effective gain is sufficiently high so that,

$$\frac{\dot{h}}{\delta_T} \doteq \frac{N^{\dot{h}\ \theta}_{\delta_T \delta_e}}{N^{\theta}_{\delta_e}} \doteq \frac{-Z_{\delta_T}}{s + (1/T_{\theta_2})} \tag{13}$$

$1/T_{\theta_2}$ is approximately equal to the aircraft heave damping, $-Z_w$, and $Z_{\delta_T}\delta_T = -g(T/W - 1)$ so that

$$\dot{h} = \frac{g(\frac{T}{W} - 1)}{s - Z_w} \tag{14}$$

B. DYNAMIC RESPONSE CONSIDERATIONS

For high disk loading VTOL's, the aerodynamic heave damping tends to be very low. The implications of this on piloted control of altitude can be seen from the Bode asymptotes in Fig. 55. The well-developed theory of pilot vehicle analysis states that the pilot will provide equalization such that the open loop dynamics (h/h_ϵ) have a K/s response in the region of piloted crossover. (For example, see Ref. 13). Furthermore, if the

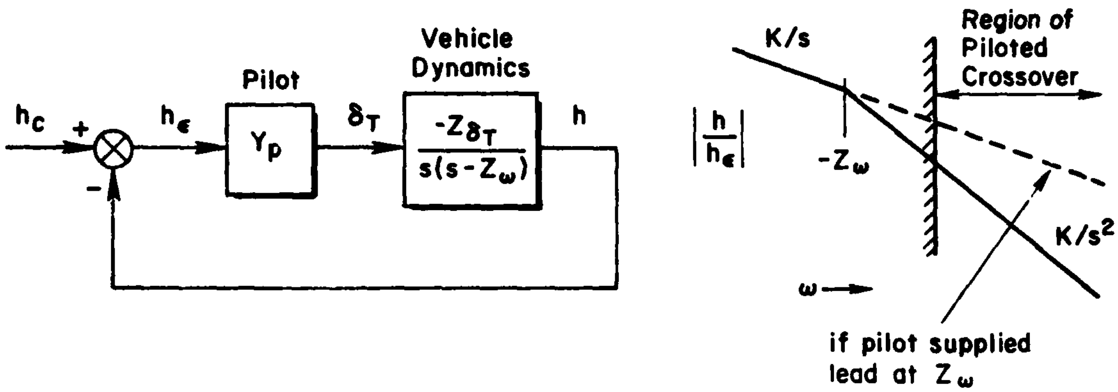


Figure 55. Piloted Control of Altitude in Low Speed and Hover

required pilot lead equalization, T_L, is greater than one second, the aircraft will be rated as less than satisfactory. The very low values of Z_w which occur with high disk loading VTOL's (see Fig. 56) would therefore be expected to be unsatisfactory without heave axis augmentation.

Examination of the data from several flight experiments (see Fig. 57) shows, however, that zero heave damping can result in satisfactory pilot commentary if the thrust to weight (T/W) is at least 1.1. The discrepancy between this result and the extremely large data base which supports the desirable range of T_L is explainable on the basis of pilot task and environment. All of the experiments represented in Fig. 57 were accomplished with very light or no turbulence and with negligible winds, thus minimizing the need for moderate to high bandwidth. Conversely, there is experimental evidence, discussed below, indicating that a K/s height response to moderate frequencies is required for satisfactory ratings in a disturbed environment.

1. **STI/Vought Simulation** (Ref. 16)

In this simulation, the baseline (attitude command) system was augmented to K/s out to 1 rad/sec in the vertical axis. However, the backup (attitude rate) system had no vertical axis augmentation resulting in a K/s^2 response throughout the region of piloted control. With low levels of wind over the

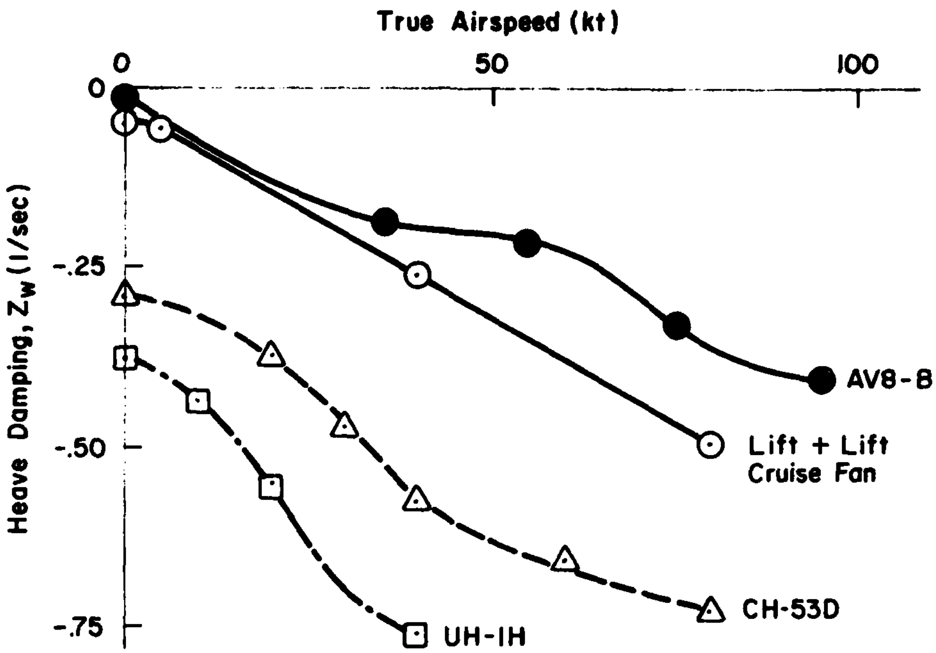


Figure 56. Comparison of Aerodynamic Heave Damping of High and Low Disk Loading VTOLs

deck (WOD) the two systems were rated approximately equally (Cooper Harper rating 3 to 4). With a 25 kt WOD, and correspondingly high turbulence, the backup system was rated a 9 whereas the baseline system was still acceptable (average rating = 4-1/2). Pilot commentary indicated that the extremely poor rating for the backup system in the presence of disturbances was primarily due to problems with height control. (See Fig. 11 for pilot ratings).

2. XV-5A Flight Test

During piloted evaluations of the XV-5A it was noted that height control was satisfactory (Pilot rating = 2) when hovering out of ground effect. However, disturbances due to ground effect resulted in pilot ratings for height control of 5-1/2 (Ref. 52). Attempts to achieve soft touchdowns were unsuccessful. It was, therefore, necessary to set up a sink rate until ground contact occurred with "no attempt to flare or cushion the landing with the lift stick." (Ref. 53). The aerodynamic height damping of the XV-5A is

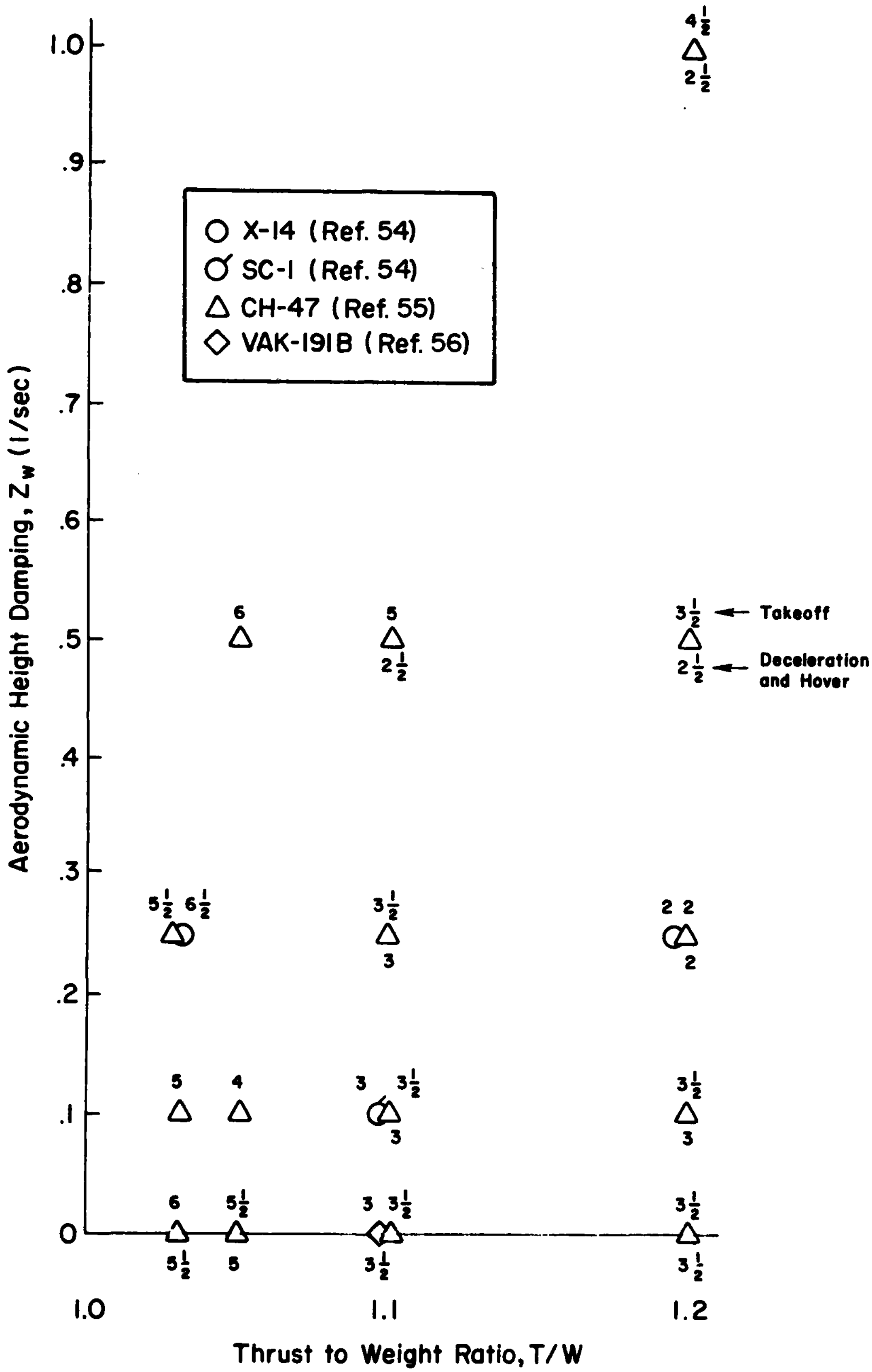


Figure 57. Flight Data for Vertical Axis Control

approximately zero in hover. As noted above, this was satisfactory until operation was attempted in a disturbed environment; further evidence that zero height damping may not be practical. It should also be noted that the XV-5A was restricted to operation in winds of less than 5 kts.

3. Vinje, Miller Simulation Data (Ref. 24)

As discussed in Section IV, these data have certain limitations and are considered useful for trend information only. However, they do show that when operating in a generally disturbed environment (10 kt mean wind with 3.4 ft/sec rms gust along the X and Y axes) the ratings for three pilots were all unsatisfactory for vertical axis damping less than 0.35 even with $T/W > 1.1$. These pilots commented that "it would probably be impossible to perform any other task, such as lateral air taxi, in addition to controlling height" with lower height damping. An example of these data is shown in Fig. 58. It is interesting to note that zero vertical axis damping results in pilot ratings which do not even meet the Level 2 requirements.

There is also some evidence that finite values of heave damping are required, even in a nondisturbed environment. These are given below.

a. A'Harrah/Kwiatkowski Simulation Data (Ref. 57). These data were generated during an early attempt to establish handling qualities criteria for low speed and hover for VTOL's. Height damping vs. control sensitivity boundaries were derived from fixed base simulation pilot rating data as shown in Fig. 59. The atmospheric turbulence was zero during these tests. These data were generated with effectively unlimited control power ($T/W = 1.5$). They are in agreement with the Ref. 24 data in that finite values of heave damping in the neighborhood of $-Z_w \doteq 0.3$ are required for satisfactory ratings.

b. Navy Carrier Landing Experience. The need for finite levels of heave damping during precision height control tasks was demonstrated in Ref. 58 for the carrier approach task. In that study it was shown that a minimum level of $1/T_{\theta_2}$ of 0.35 was required for satisfactory pilot opinion.

C. HEAVE AXIS AUGMENTATION

Based on the above considerations it can be seen that there is strong evidence that heave axis augmentation may be a practical necessity for operational VTOL's. The effects of such augmentation have been investigated in

PILOT	CALSPAN B*	UARL	
SIMULATOR MODE	MB	FB	MB
SYMBOL	●	□	■

* NO SIMULATED WINDS FOR CALSPAN PILOT EVALUATION

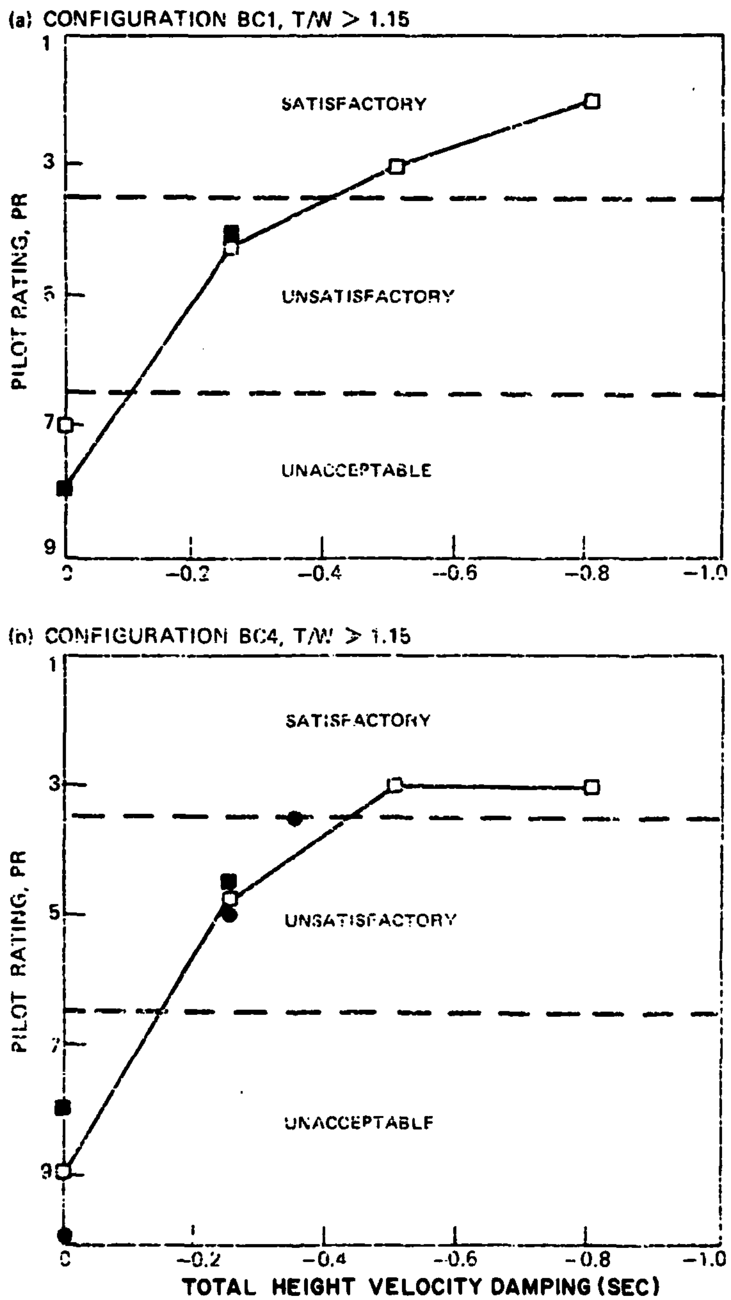


Figure 58. Change in Pilot Rating of Height Control with Height Velocity Damping from Ref. 24.

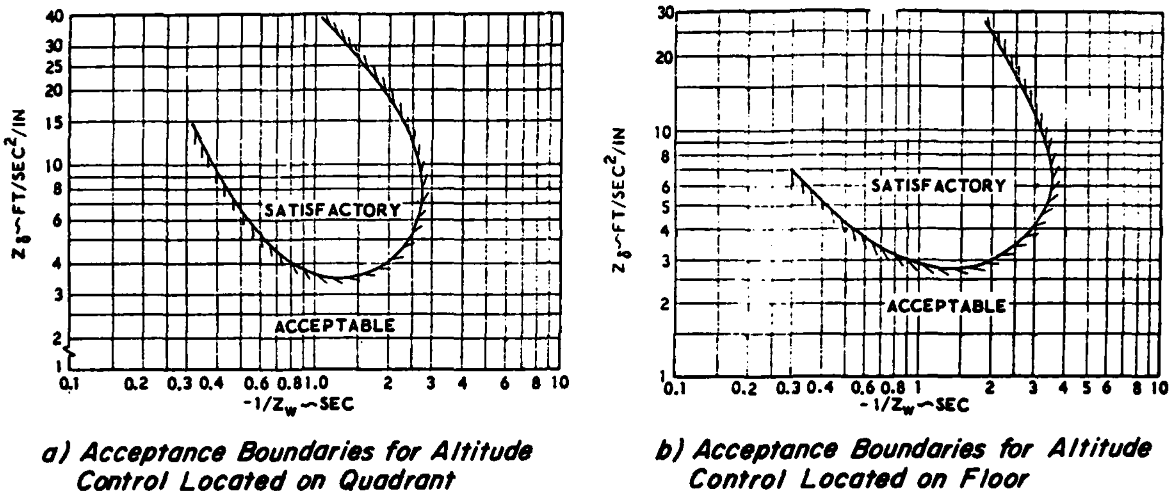


Figure 59. Fixed Base Simulation Data (T/W = 1.5)
(From Ref. 57)

two separate programs at NASA Langley utilizing the variable stability CH-47 (Refs. 19 and 55). The data from Ref. 55 are plotted in Fig. 57. They indicate that for acceleration from hover, i.e., takeoff, there is a penalty for increasing the vertical velocity damping at constant T/W. Pilot comments for the large $-Z_w$ cases tend to indicate an overly sluggish response. This was also true for the vertical velocity command system tested in Ref. 19 as shown in Fig. 60. Another interesting feature of this plot is that pilot opinion is not constant along lines of constant steady climb rate to collective ($\dot{h}/\delta_c$). This is somewhat at odds with the MIL F-83300 (Ref. 59) and AGARD 577 criteria which are given in terms of constant $\dot{h}/\delta_c$ boundaries.

The reasons for the above noted discrepancies are rooted in the details of the mechanization of vertical axis augmentation. Most of the existing experimental data are based on response feedback type augmentation wherein the equalization is placed in the feedback path. The effect of this on the $\dot{h}/\delta_c$ response is identical to increasing the aerodynamic heave damping, Z_w; i.e., the steady state response to a collective input is reduced. This short-coming can be overcome by placing the equalization in the forward loop; frequently termed command augmentation. Utilization of command augmentation removes the dependency of the steady response on the level of heave damping. This is illustrated in Fig. 61.

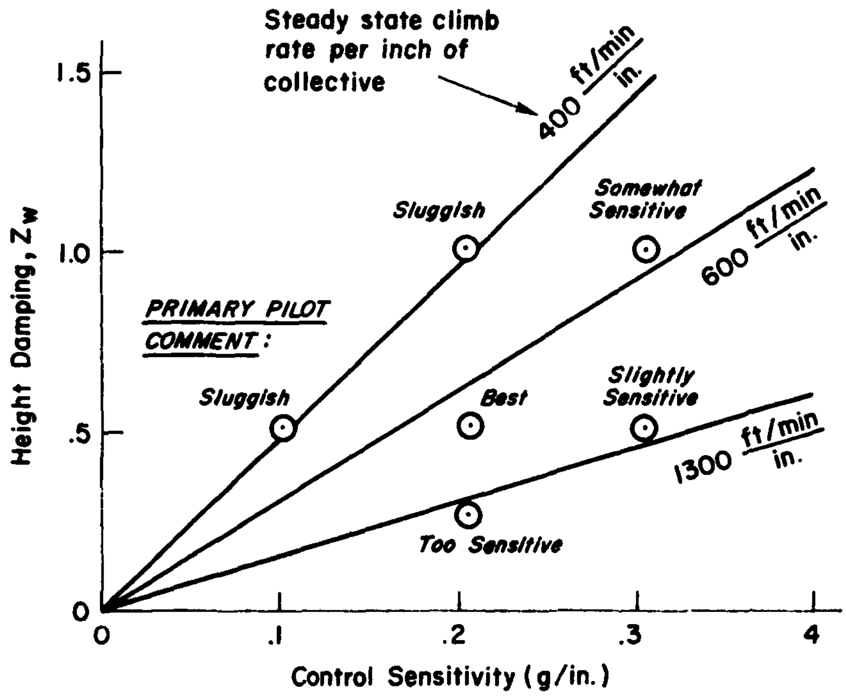


Figure 60. Primary Factor for Downrating Various Combinations of Control Sensitivity and Height Damping (Ref. 19)

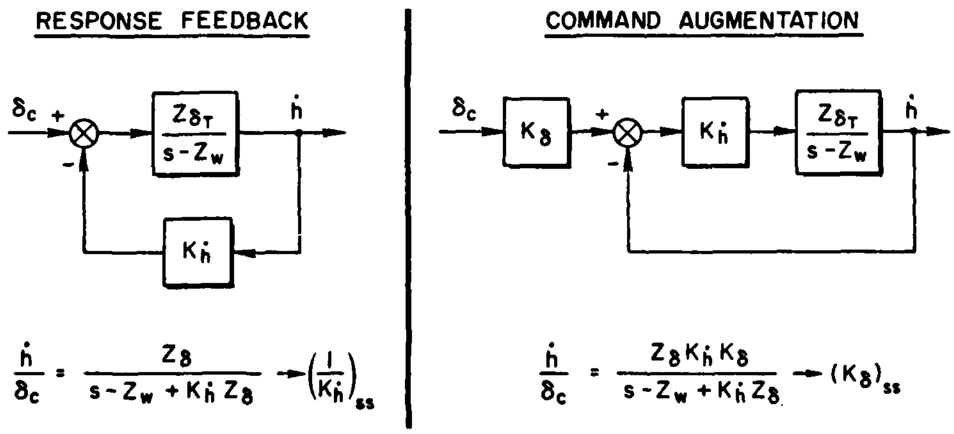


Figure 61. Effect of Different Implementations of Vertical Axis Augmentation

From Fig. 61 it can be seen that in each case, increasing $K_{\dot{h}}$ has the same effect on the <u>dynamics</u>, i.e., the heave damping is augmented so that $1/T_h = Z_w + K_{\dot{h}} Z_\delta$. However, in the response feedback mechanization such augmentation tends to suppress the steady response, $(\dot{h}/\delta_c)_{ss} = 1/K_{\dot{h}}$, resulting in pilot commentary of "sluggish". Thus it can be appreciated that the lines of constant $(\dot{h}/\delta_c)_{ss}$ utilized in Refs. 19 and 55 may really be only an artifact of the SCAS mechanization and not a fundamental property of vertical axis control.

Based on the above observations and issues, more experimental data are required to:

1. Establish the effects of external disturbances in longitudinal and lateral axes on vertical axis damping requirements.
2. Isolate the effects of vertical axis damping from steady state climb rate to collective input, $(\dot{h}/\delta_c)_{ss}$.
3. More closely delineate the vertical axis requirements for deceleration to hover as distinct from acceleration from hover using command augmentation.

D. NONLINEARITIES

Nonlinearities in the thrust response were shown to seriously degrade pilot opinion of height control in the VAK-191B flight tests reported in Ref. 56. More specifically, the pilot had two throttles; one for the "lift" engines, the other for the main engine. These throttles were nominally operated together in hover (where the diverted main engine thrust is also lifting) to achieve control of altitude or sink rate. The nonlinear thrust response occured due to automatic restriction of main engine thrust to avoid exceeding design limits. At the heavier aircraft weights ($T_{max}/W \leq 1.05$), the resulting nonlinearity in the working region of throttle displacement contributed heavily to very poor pilot opinion (Cooper Harper pilot rating = 8). At lighter aircraft weights ($T/W \geq 1.1$) where limiting was not encountered, the height control was judged to be satisfactory (pilot rating = 3). These rating differences are much higher than those attributable directly to the difference in T/W — e.g., see Fig. 57. Clearly, thrust

non-linearities can have overriding impact and deserve investigation to determine limits for acceptable operation.

E. EFFECT OF LIFTING SYSTEM RESPONSE DYNAMICS

The response dynamics of the lifting system introduce additional phase lags in the $\dot{h}/\delta_c$ response. Degradations in pilot opinion due to phase lags are easily predicted from pilot vehicle analysis techniques as outlined in Ref. 13. If we approximate the dynamic response by a first order lag in the lifting system, the resulting $\dot{h}/\delta_c$ response is well represented by (see Eq. 13).

$$\frac{\dot{h}}{\delta_c} = \frac{K_{\dot{h}} e^{-\tau_{\dot{h}} s}}{(s + \frac{1}{T_{\dot{h}}})(s + \frac{1}{T_L})} \qquad (13)$$

Where $1/T_{\dot{h}}$ is the augmented vertical axis heave damping ($1/T_{\dot{h}} \approx -Z_w$ for zero augmentation).

The current specification (Ref. 59) places an effective limit on the magnitude of T_L by requiring that it "be possible to achieve 63 percent of a commanded incremental thrust of at least 0.05W in not more than 0.3 seconds". Such a requirement erroneously assumes that the allowable lifting system lag is independent of vertical axis heave damping. An attempt to account for the combined effects of T_L and $T_{\dot{h}}$ by formulating a dynamic height control criterion in terms of total phase angle vs. frequency was reported in Ref. 60. This work was considered during the development of the current MIL F-83300 (see Ref. 43) but was rejected on the grounds that further substantiation was required. This was a reasonable conclusion considering that the Ref. 60 work was done on a fixed base simulator. However, it is our opinion that the data represents a valid starting point for further experiments as well as a tentative specification for the height control LOES. The criterion proposed in Ref. 60 is shown in Fig. 62. The simulated turbulence environment consisted of an rms level of 5.1 ft/sec in the longitudinal axis and 1.28 ft/sec in the lateral axis. The pilots described the simulation as a medium turbulent day.

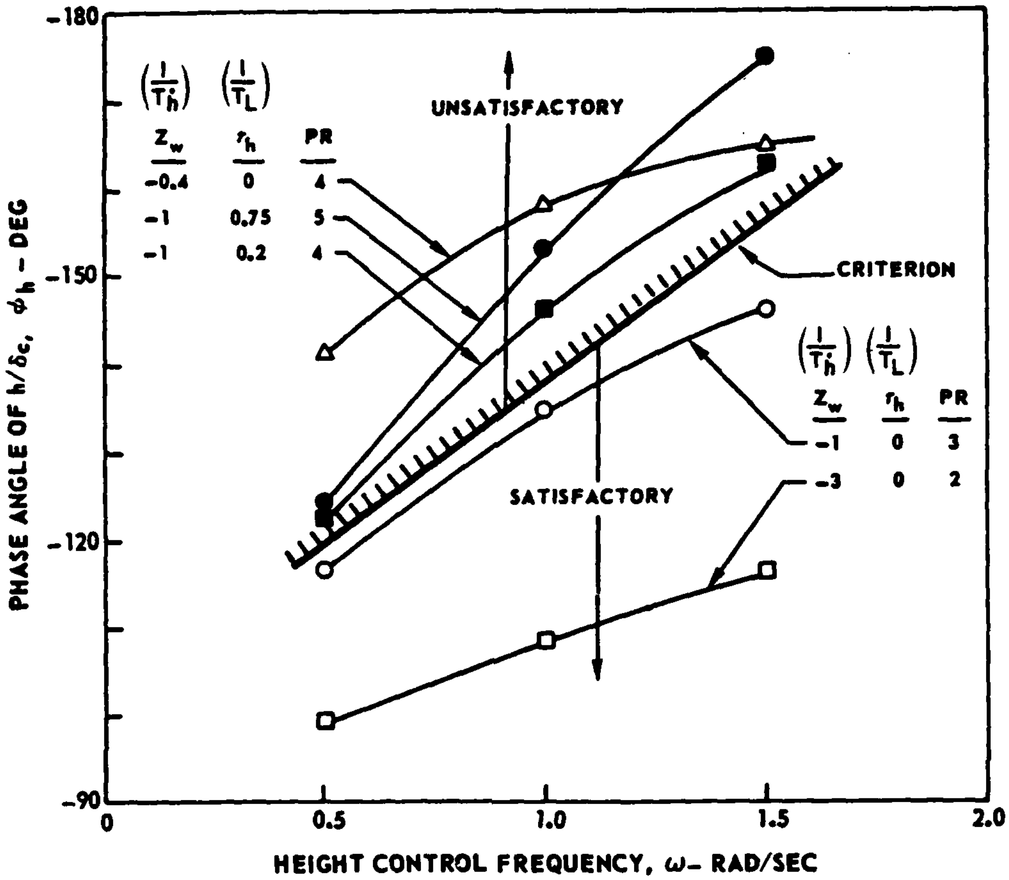


Figure 62. Dynamic Height Control Criterion in Terms of Phase Angle of Height Response (taken from Ref. 60)

The criterion shown in Fig. 62 represents a fairly stringent height control requirement. In way of illustration, if all the system lags are zero ($1/T_L = 0$), the criterion in Fig. 62 indicates that the minimum acceptable value of $1/T_{\dot{h}}$ would be about 0.9 sec^{-1}. While in our opinion this does not seem unreasonable, it does represent a significant increase from the current MIL-F-83300 which requires only that $1/T_{\dot{h}} > 0$. In support of the Fig. 62 criterion, it is consistent with a wide body of pilot vehicle analysis which indicates that a requirement for the pilot to generate lead greater than one second will result in unsatisfactory pilot opinion. Values of $1/T_{\dot{h}} < 1$ would result in such a requirement (see Ref. 13).

F. RECOMMENDED CRITERIA DEVELOPMENT PROGRAM FOR HEIGHT CONTROL

The requirements for height control have been shown to be influenced by the workload in the lateral and longitudinal axis. Visual and motion cues available to the pilot are also major factors. The following criteria development program is based on investigating these, as well as more direct effects.

1. Limited Pilot Vehicle Analysis

A limited amount of pilot vehicle analysis work is required to

- Quantify pilot equalization requirements as a function of the equivalent system parameters.
- Establish tentative criterion boundaries based on pilot vehicle analysis rules (Ref. 13) and on limited available simulation data.
- Investigate the effect of nonlinear engine response using describing function analysis procedures.

The analytic results will be useful in scoping and detailing specific desirable additional simulation experiments.

2. Piloted Experiment

The desirability of generating translational disturbances in the horizontal plane as well as simulating levels of lateral and longitudinal augmentation from rate to TRC essentially rules out the use of any existing flight test facility. The selected simulation facility would preferably have a real world visual scene (e.g., pilot looks out at simulator bay) as well as one to one motion (no washouts).

It is expected that the variation in height control requirements with increasing levels of external disturbance will be most apparent for the less sophisticated augmentation. A logical test sequence would therefore include the two augmentation schemes which occur at the extreme ends of the spectrum; rate and TRC. The TRC system would be included primarily to test the conclusion from existing data that the requirements on height damping

can be relaxed to nearly zero if the lateral and longitudinal axis workload is low.

Each height control configuration would be tested under the following conditions

LATERAL/ LONGITUDINAL AUGMENTATION	EXTERNAL DISTURBANCE
Rate	Low Moderate High
TRC	High

Height control power (T_{max}/W) should also be a variable in the experiment to test existing results which indicate a tradeoff between control power and height damping. The planned experiment would extend these results to include the effects of secondary tasks and external disturbances. In this regard the height damping should be inherent (aerodynamic) or generated via response feedback augmentation. Approach to hover and hover tasks should be evaluated separately from liftoff and acceleration tasks. The purpose of emphasizing these separately is to evaluate the results of Ref. 55 which indicate that takeoff is most critical from a minimum T/W standpoint. Configurations which utilize response feedback and command augmentation should be separately tested as well.

Configurations with a nonlinear thrust response to simulate limiting of some components of the lifting system (a là VAK 191B) should be tested. Results of these tests would allow specification of allowable nonlinearities in the lifting system.

Combinations of height damping and lifting system lag should be tested to determine limiting values of the lower order equivalent system (LOES) parameters (Eq. 13). In addition, several higher order systems (HOS) should be tested to determine the allowable departure from the LOES form before pilot ratings show a degradation.

SECTION VIII

BLENDING BETWEEN AUGMENTATION MODES

There is considerable evidence that augmentation schemes which are appropriate for hover are inappropriate for up and away flight (see Refs. 14 and 15). More specifically, attitude command/attitude hold (ACAH) or translational rate command (TRC) systems are required for adequate pilot ratings in hover (when visual cues are lacking) whereas rate command/attitude hold (RCAH) is in many cases more desirable for up and away flight. Hence, it is necessary to consider the blending between these augmentation systems. There is very little data which covers the limiting aspects of SCAS blending. This section describes the development of several SCAS blending schemes as well as the results of moving-base piloted evaluations on the NASA Ames Flight Simulator for Advanced Aircraft (FSAA)*. The aircraft dynamics programmed on the simulator were representative of the XV-15 tilt rotor VTOL aircraft.

A. DESCRIPTION OF AUGMENTATION SYSTEMS

The longitudinal control system utilized conventional feedbacks for rate command/attitude hold (RCAH), attitude command/attitude hold (ACAH) and translational rate command (TRC) as shown in Fig. 63. Figure 63 includes some blending functions which will be discussed shortly.

The lateral SCAS was of identical form to the longitudinal SCAS (e.g., feedback of φ, $\dot{\varphi}$, and $\dot{Y}$).

B. SUMMARY OF BLENDING SCHEMES

1. RCAH/ACAH

The variables defining blending between RCAH and ACAH are the length of the blending interval and the logic which initiates the blend. Two methods

---

*This work was sponsored by the NASA Ames Research Center and was conducted under the supervision of Dr. James R. Franklin and W. J. Brigadier. STI participated in a consulting role. As of the present time it has not been published.

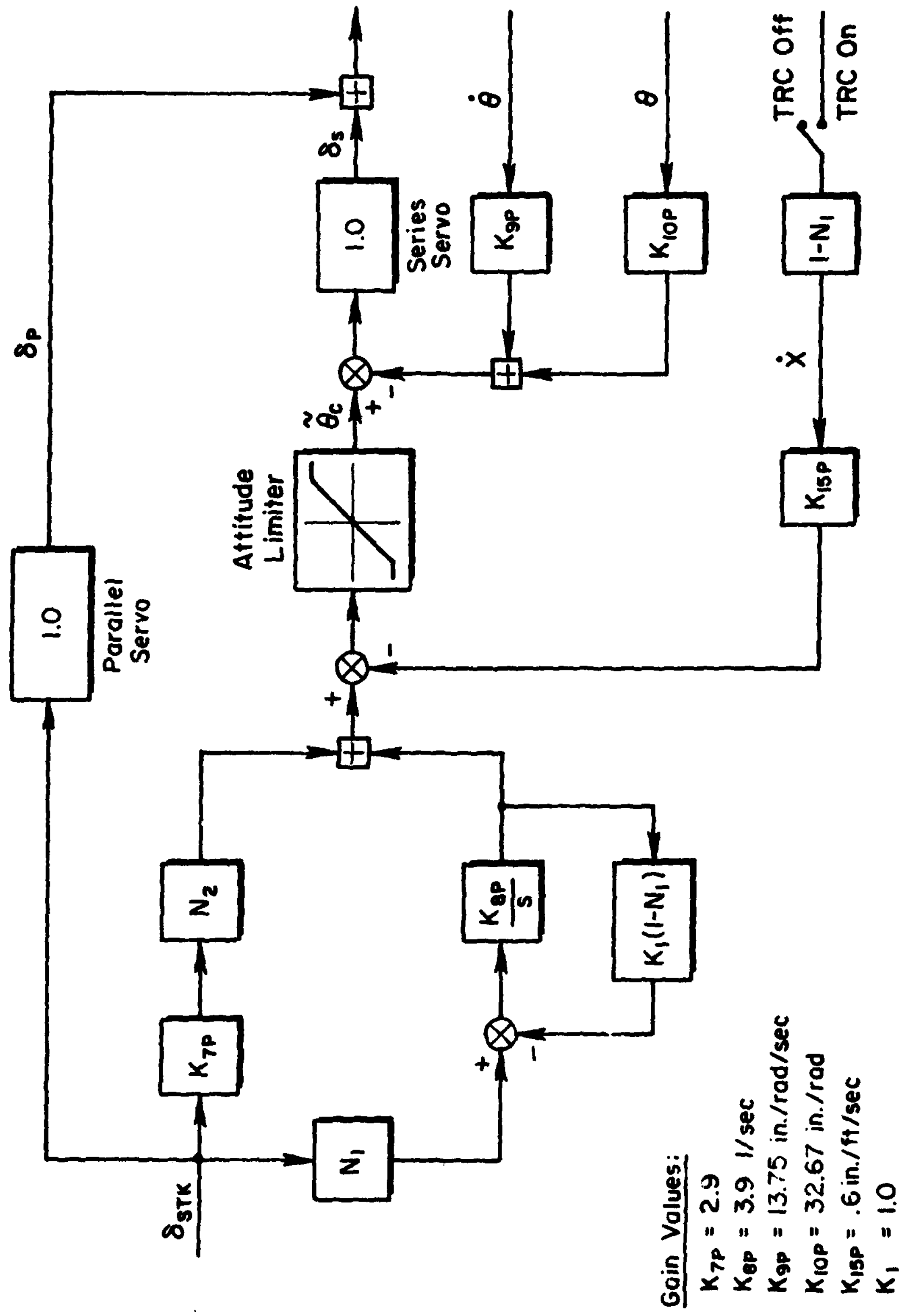


Figure 63. Longitudinal Augmentation System Block Diagram

of initiating the SCAS blend were tested — an automatic blend initiation based on airspeed, and a manual switch located on the collective control. It was hypothesized that it would be desirable to switch into ACAH approaching hover at a different airspeed than when switching into RCAH during acceleration out of hover. Hence, the logic includes RCAH — ACAH at V_a and ACAH — RCAH at V_b. Additionally, the automatic blend was initiated only if the airspeed criterion was met for more than 3 seconds. This was done to avoid switching back and forth in gusty air.

The blending interval is based on time rather than air or ground speed since the deceleration/acceleration rates are expected to vary depending on the pilot and task.

The primary blending function is N_1 (see Fig. 63). A plot of the general shape of N_1 is given below in Fig. 64. From Fig. 63 it can be seen that when N_1 is equal to unity, the forward loop integrator is phased in, thereby providing the rate command input to the SCAS. Two types of rate command SCAS stick shaping were tested. In one case N_2 was left at unity, which results in the shaping shown in Fig. 65. In other cases N_2 was set to $-1/K_{7P}$ so that the proportional signal was zero (e.g., no high frequency asymptote in Fig. 65). For these cases, the logic controlling N_2 was as follows:

$$N_2 = 1 \qquad \text{when } N_1 < .95 \qquad \text{RCAH} \rightarrow \text{ACAH}$$

$$N_2 = -\frac{1}{K_{7P}} \qquad \text{when } N_1 \geq .95 \qquad \text{ACAH} \rightarrow \text{RCAH}$$

Due to an error in the computer program, N_2 was set equal to zero (instead of $-1/K_{7P}$) for RCAH in nearly all of the blending runs. The effect on the stick shaping in Fig. 65 was to increase the break frequency from 1 rad/sec to 3.9 rad/sec. This effectively eliminates the high frequency asymptote since it occurs well above the piloted crossover frequency.

2. RCAH/TRC — Longitudinal

As shown in Fig. 63 the blend from RCAH to TRC was identical to RCAH to ACAH except the $\dot{X}$ feedback was blended in as $1-N_1$. Some thought was given to synchronizing on $\dot{X}$ to eliminate transients when switching to TRC at some forward speed (e.g., at the completion of the blend to TRC, zero

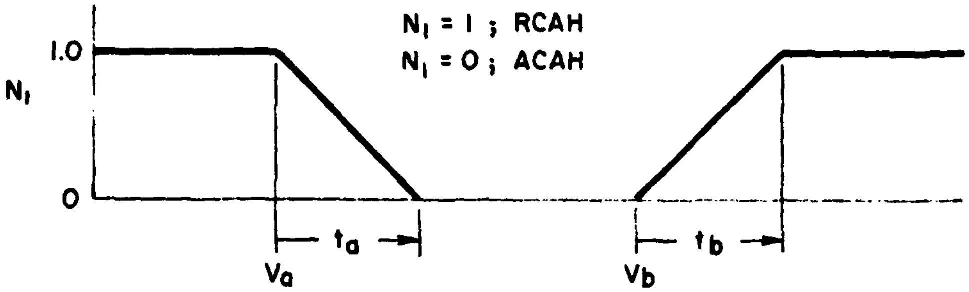


Figure 64. N_1 Blending Function

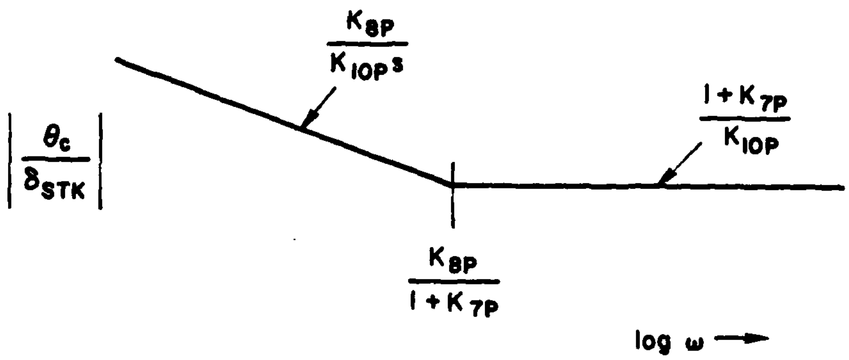


Figure 65. Stick Shaping

control position commanded the velocity existing at the switch point). This option was abandoned early in the program due to the undesirability of losing correspondence between zero control position and zero inertial velocity. The correspondence between control position and velocity turned out to be a significant asset of the TRC system because of limited visual cues in hover with the simulator visual flight attachment (Redifon).

The correspondence between zero control position and zero ground speed also requires that inertial velocity as opposed to airspeed be used as a feedback. Attempts to use airspeed feedback in steady winds were rated as unacceptable. Hence the block diagram in Fig. 63 shows $\dot{X}$ as the outer loop (as opposed to air velocity).

3. RCAH/TRC — Lateral

There was not time in the simulation to set up and test lateral TRC blending. However, the primary consideration for lateral RCAH/TRC blending is the inner-loop SCAS. This arises from the fact that RCAH is primarily a turn-following mode (control heading with bank angle), whereas lateral TRC is a constant heading mode. The blending between these different augmentation schemes must be handled on a case by case basis since the feedbacks depend on the basic vehicle deficiencies. Fortunately, most blending will be done when in coordinated, or at least nearly coordinated, flight. In such cases there will be no transients at the switch point.

C. SIMULATION SCENARIO

A six degree of freedom moving base simulator (NASA Ames FSAA) was used with a Redifon visual flight attachment (VFA). A terrain board developed for nap of the earth (NOE) maneuvering was utilized to implement tasks which could exercise critical aspects of the blending. The piloting task was to start at 200 feet altitude at an airspeed of 60 knots and to come to hover at a specified point. Next the aircraft was accelerated at maximum rate to 60 kt at a very low altitude (following a road) and then brought to hover again. The final transition from hover involved an accelerating climbing left turn. This maneuver was set up to insure that the blend would occur during the turn.

1. Pilot Commentary and Ratings on RCAH/ACAH Blend

The pilot commentary and Cooper-Harper ratings for the RCAH/ACAH blends (see Table 5) lead to the following conclusions.

- The most critical aspect of blending is in the lateral axis while simultaneously turning and blending from ACAH to RCAH.
- There is a tendency to bobble pitch attitude during acceleration from hover while blending from ACAH to RCAH.
- A 10 second blend which occurs at 10 kt seemed about optimum for acceleration and deceleration.
- Additional workload imposed by having the pilot manually switch the SCAS was noticeable.

TABLE 5. RCAH/ACAH BLENDS

PILOT	RUN	t_a*	t_b	AUTOMATIC SWITCH V_a	AUTOMATIC SWITCH V_b	PILOT SELECT	PILOT COMMENTS AND RATINGS
		sec	sec	kt	kt		
CH	25-42	5	5	20	40	no	Cannot feel change in SCAS coming into hover. Felt it pitch down when accelerating and felt it roll in the climbing turn. PR = 3
	25-43	0	0	20	40	no	Real noticeable abrupt change in pitch attitude coming into hover. PR = 4
	25-44	10	10	20	40	no	Have to add considerable left pedal when switching from ACAH to RCAH in climbing left turn. Hardly noticeable otherwise. PR = 3
	25-45	0	0	—	—	yes	Selected ACAH after stopping in hover. Selected RCAH before starting acceleration out of hover; worked good. Automatic switch is probably better because less work for pilot. PR = 3
	25-46	0	0	10	10	no	Changeover more noticeable here but not objectionable.
	25-48	10	10	—	—	yes	Change is more noticeable if you are in a turn when it occurs. However it is not objectionable. PR = 3
	25-49	10	10	10	10	no	Cannot detect change coming into hover. Seems like this is about optimum. Get ACAH quick enough in hover and airspeed is not that critical during the acceleration transient. PR = 2
RG	26-35	10	10	40	20	no	Like this blend. However I got a little impatient holding the nose down in the climbing turn waiting for the blend. PR = 2.5
	26-36	0	0	40	20	no	Pitch down transient during acceleration which is unsatisfactory. Could be disastrous if close to ground. PR = 7-8
	26-37	10	10	—	—	yes	Pitch bobble during blend when accelerating (ACAH → RCAH). PR = 4 due to bobble. Had extra task of switching.
	26-38	0	0	—	—	yes	My criterion there is to leave it in RCAH unless in hover to minimize transients. PR = 3

*See Fig. 64 for definition of t_a, t_b, V_a, and V_b.

The most noticeable problem was a tendency for the bank angle to increase when accelerating from hover in a turn. This was due to the large amount of left stick required to hold a bank angle in the attitude command mode. The stick deflection changes from a bank angle to a bank angle rate command during the blend to RCAH. This was aggravated by the fact that the lateral stick sensitivity and control power were low in the ACAH system (full stick was only 30 deg of bank). These results indicate that lateral control power requirements for ACAH systems should be set, in part, by the SCAS blending (ACAH → RCAH) in a turn.

The tendency to bobble pitch attitude while accelerating is attributable to the same basic phenomenon as the turn problem, i.e., large stick displacement at blend initiation. There is a requirement to convert from a large forward stick displacement to zero stick displacement when converting from ACAH to RCAH while accelerating. As with the turn, increased stick sensitivity in the ACAH system tends to minimize the problem. Decreased stick sensitivity in the rate system would have the same effect.

Since the pilot rating for the best system was a 2 (Run 25-49, Table 5), the above problems do not appear to be severe as long as the proper blending times and speeds are observed (10 sec and 10 kt).

It is doubtful if airspeed could actually be used as an automatic blend initiation variable because of the obvious problems in steady winds. Airspeed was used in this program because the tactical mission of the XV-15 would not allow derivation of inertial speed, and it was initially thought that larger blending speeds would be appropriate. However, since the blending runs were made without wind, the effect went unnoticed.

In general, an automatic blend initiation at an inertial speed of 10 kt should be used when possible (PR = 2). Manual selection of the SCAS mode is acceptable (PR = 3-4) when inertial velocities are not available.

2. Pilot Commentary and Ratings on RCAH/TRC Blend

The pilot commentary and Cooper-Harper ratings for the RCAH/TRC blends (see Table 6) lead to the following conclusions.

TABLE 6. TRC/TCAH BLENDS (LONGITUDINAL)

PILOT	RUN	t_a^*	t_b	AUTOMATIC SWITCH V_a	AUTOMATIC SWITCH V_b	PILOT SELECT	PILOT COMMENTS AND RATINGS
		sec	sec	kt	kt		
TW	26-9	10	10	—	—	yes	Blending while coming into hover is good because stick is in a good position (centered). During acceleration I can have problems if stick is way forward. PR = 4
	26-10 -11	0	0	—	—	yes	Extremely abrupt pitchup when TRC is selected coming into hover. Selected TRC at 40 kt on first run and 10 kt on second run. Unacceptable in both cases. PR = 10
	26-12 -13	10	10	—	—	yes	Worked great coming into hover. Slight pitch bobble during acceleration. Have to move stick a lot (3 to 4 in.) during blend (TRC to RCAH). Seems like a nonlinear blend during acceleration. I get impatient and put in lots of stick. It seems like I get RCAH all at once at that point. Tried to switch RCAH to TRC at 50 kt. I can control attitude during the blend but it takes lots of stick. (Note: the TRC stick sensitivity was found to be too low later in the simulation.) PR = 3
	26-15	10	3	—	—	yes	Acceleration from hover is easier because it is over quicker.
	26-16	10	0	—	—	yes	Get abrupt pitch bobble during acceleration — no good.
	26-17	10	1.5	—	—	yes	OK if I switch early in the acceleration. Get a pitch bobble if I delay switch to RCAH; old problem of stick too far forward.
	26-18	10	1.5	10	10	no	Beautiful on deceleration to hover. Not as good going out of hover. Too abrupt. PR = 3
	26-20	10	10	10	10	no	Still get a PIO on acceleration. Would rather get it over a shorter period. Like last case better. PR = 3 but it is a better 3 than pilot select (Run 13). Reason I like it better is that airspeed blend keeps me from getting into trouble by switching too late during acceleration.

*See Fig. 64 for definition of t_a, t_b, V_a, and V_b.

- There is a tendency to bobble pitch attitude during acceleration from hover.
- A 10 second blend during deceleration and a 3 second blend during acceleration represent the best compromise. These blends should be initiated at a speed of about 10 kt.
- Initiating the blend at high speeds can result in large abrupt pitch attitudes, especially for the RCAH — TRC blend. As a result, the use of manual SCAS selection with the attendant possibility of inadvertant high speed switching is not desirable. As discussed in Section 2, inertial speed will be available for blend initiation since it is required as a feedback on TRC systems.

To even a greater extent than the ACAH — RCAH blend, the stick position of the TRC system is at or near its maximum forward limit during a rapid acceleration. It is therefore not surprising that a large nose down pitch rate can develop as the TRC SCAS blends to RCAH. The solution lies in performing the blend from TRC to RCAH at as low a speed as possible (or even just prior to leaving hover) and to perform the bulk of the acceleration in RCAH.

Unlike the RCAH — ACAH blend, the best solution for the RCAH — TRC blend is to use a longer time decelerating than accelerating. A longer blend is required when going from RCAH to TRC to avoid a very abrupt commanded pitch up due to a sudden speed error. This effect was dramatically exhibited in Runs 26-10 and 26-11 (blend time = 0) where the pilot gave a rating of 10. Shorter blend times are desirable when accelerating to minimize the stick retrimming time, e.g., stick needs to go from forward to zero when going from TRC to RCAH. A zero time switch tended to be too abrupt, whereas a 3 second blend seemed like the best compromise.

SECTION IX

SUMMARY

The work presented in this report is summarized through presentation of proposed modifications to certain paragraphs of MIL-F-83300 (Ref. 59). In some of the areas studied, the necessary data were not available to define quantitative limits or boundaries. In these cases paragraph numbers were assigned and the reader referred to the appropriate section of the report to review the proposed experiments as well as the recommended form of the flying qualities criterion. In most cases only Level 1 boundaries are specified.

A. DYNAMIC RESPONSE REQUIREMENTS (3.2.2)

The dynamic response requirements shall be defined in accordance with the outside visual cues (OVC) required to complete the specified mission and the cockpit displays available to the pilot (see Fig. 5 and Table 2).

1. Requirements for Attitude Systems (3.2.2.1)

If an attitude system is indicated in Table 2, the requirements for compliance (e.g., to show that the response is attitude-like as opposed to rate or acceleration) are defined in Fig. 3. As indicated in Section IIC some experimental data is required to finalize the numerical values to be used in Fig. 3.

Both rate and attitude systems shall be compatible with the following lower order equivalent system (LOES) form

$$\frac{\text{Attitude}}{\text{Control Displacement}} = \frac{K(s + \frac{1}{T})e^{-\tau s}}{(s + \lambda)(s^2 + 2\zeta_n\omega_n s + \omega_n^2)}$$

The mismatch function, M, used to fit this equivalent system form is tentatively defined as

$$M = (\text{gain}_{HOS} - \text{gain}_{LOS})^2 + (\text{Phase}_{HOS} - \text{Phase}_{LOS})^2$$

where phase is in radians.

The frequency range over which this function should be evaluated and maximum allowable levels of M are currently under study by Hodgkinson, et al. Until more results are obtained, a frequency range of 0.1 to 10 rad/sec and a maximum value of M = 200 has been suggested in Ref. 2. The possibility of weighting M more heavily in the region of piloted crossover should be seriously considered.

a. LOES Boundaries for Rate Systems (3.2.2.1.1)

If the value of M is within the specified limits, acceptable rate systems are defined when

$$\omega_n < 0.5 \text{ rad/sec} \qquad -0.22 < \zeta_n < 0$$

$$\omega_n < 0.9 \text{ rad/sec} \qquad \zeta_n \geq 0$$

$$\lambda \geq 1.0$$

$$20 > K > 5 \text{ deg/sec/in}$$

These requirements also apply to the response to control inputs of rate command attitude hold systems.

b. LOES Boundaries for Attitude Systems (3.2.2.1.2)

If the value of M is within the specified limits, the equivalent system damping and frequency boundaries are defined in Fig. 24. The equivalent system gain limits are defined in Fig. 25. Maximum allowable values of λ cannot be specified without further experimental data. If the mission requirement and cockpit displays dictate a model following attitude system (Table 6) a frequency of at least 4 rad/sec shall be required. If a rate command attitude hold system is indicated in Table 2, the allowable frequency and damping for the attitude hold equivalent system shall be set by the boundaries in Fig. 24.

c. LOES Boundaries for Translational Rate Command Systems (TRC) (3.2.2.1.3)

The LOES form for TRC systems is given as

$$\frac{\text{Translational Velocity}}{\text{Control Displacement}} = \frac{K_{\dot{x}_c}}{T_{\dot{x}_{eq}} s + 1}$$

The appropriate frequency range for matching this LOES and the maximum acceptable value of mismatch function, M, for TRC systems is not yet defined. Tentative boundaries for $K_{\dot{x}_c}$ and $T_{\dot{x}_{eq}}$ are given in Figs. 35 and 36 for center stick and sidearm controllers respectively. These boundaries are based on experiments where attitude alone was used for translation. Further experiments are required to validate the boundaries in Figs. 35 and 36 and to extend these results to include direct force control.

B. CONTROL POWER (3.2.3)

As discussed in Section VI, a viable control power criterion cannot be established without additional experimentation which was beyond the scope of the present study. The present status and required work is discussed in detail in Section VI.

1. Response to Control Input (3.2.3.2)

This subparagraph should be deleted since specification of the equivalent system sets the control sensitivity.

C. CONTROL LAGS (3.2.4)

Control lags are inherent to the LOES response and do not need to be separately specified.

D. VERTICAL FLIGHT CHARACTERISTICS (3.2.5)

The LOES form for height control is given as

$$\frac{\dot{h}}{\delta_c} = \frac{K_{\dot{h}} e^{-\tau s}}{(s + \frac{1}{T_{\dot{h}}})(s + \frac{1}{T_L})}$$

As with the previous LOES forms the maximum allowable value of the mismatch function, M, and the appropriate frequency range need to be defined.

1. Dynamic Response for Height Control (3.2.5.1)

A tentative requirement on the maximum allowable phase lag due to $1/T_{\dot{h}}$, $1/T_L$, and $\tau_{\dot{h}}$ is given in Fig. 62. However, because the data were taken on a fixed base simulator and because they indicate a fairly stringent height control requirement, it is felt that additional data is required. The experiments required to obtain the necessary data are outlined in Section VI-F. It is likely that the limiting value of phase lag will be somewhat dependent on the level of lateral and longitudinal augmentation.

2. Sensitivity (3.2.5.2)

Levels of $K_{\dot{h}}$ which represent Level 1 and Level 2 flying qualities also need to be established from the experiments defined in Section VI-F. Considerations of the type of manipulator should be included since sensitivity is highly manipulator dependent.

3. Height Control Power (3.2.5.3)

There is some experimental evidence that the required height control power depends on the dynamic height response. These results were inherent to the mechanization used response feedback and therefore should not be generalized into a specification. Further experiments are required to obtain more general height control power boundaries. (See Section VI-F).

4. Linearity of Lifting System Response (3.2.5.4)

The vertical thrust response shall not exhibit objectionable nonlinearities in the region where

$$0.95 \leq T/W \leq (T/W)_{max}$$

Exactly what constitutes the maximum acceptable nonlinearity is not currently known and should be investigated as discussed in Section VI-F.

REFERENCES

1. Hoh, R. H., R. H. Klein, and W. A. Johnson, Development of an Integrated Configuration Management/Flight Director System for Piloted STOL Approaches, NASA CR-2883, August 1977.

2. Hodgkinson, J. and K. A. Johnston, "Initial Results of an Inflight Simulation of Augmented Dynamics in Fighter Approach and Landing," AIAA Paper No. 79-1783, presented at the AIAA Guidance and Control Conference held in Boulder, Colorado, 6-8 August, 1979.

3. Hodgkinson, J., W. J. LaManna, and J. L. Heyde, "Handling Qualities of Aircraft with Stability and Control Augmentation Systems —A Fundamental Approach," The Aeronautical Journal, Vol. 80, No. 782, Feb. 1976, pp. 75-81.

4. McRuer, Duane, Irving Ashkenas, and Dunstan Graham, Aircraft Dynamics and Automatic Control, Princeton University Press, Princeton, N. J., 1973.

5. Heffley, Robert K., Wayne F. Jewell, John M. Lehman, and Richard A. Van Winkle, Compilation of Helicopter Handling Qualities Data, Systems Technology, Inc., TR-1087-1, Oct. 1977.

6. McCormick, R L., VTOL Handling Qualities Criteria Study Through Moving-Base Simulation, AFFDL-TR-69-27, Oct. 1969.

7. Lebacqz, J. V., Summary Documentation of AV-8B Model Development and X-22A Simulation of AV-8B, Calspan Corp. Rept. X-22A TM No. 98, 20 July 1977.

8. Greif, Richard K., Emmett B. Fry, Roland M. Gerdes, and Terrence D. Gossett, Effect of Stabilization on VTOL Aircraft in Hovering Flight, NASA TN D-6900, Aug. 1972.

9. Miller, R. J., and E. R Tribken, "Automatic Flight Control System for a Helicopter Night Landing System," The Guidance and Control of V/STOL Aircraft and Helicopters at Night and in Poor Visibility, AGARD-CP-148, May 1975, pp. 25-1 to 25-9.

10. Traskos, R., USN/FMOD FRG VAK-191B Joint Flight Test Program Final Report. Volume No. 1, Summary, NAVAIR-1R-76, Aug. 1976.

11. Seckel, E., J. J. Traybar, and G. E. Miller, Longitudinal Handling Qualities for Hovering, Princeton Univ., Dept. of Aero Eng., Rept. No. 594, Dec. 1961.

12. Bryant, William B., James J. Cattel, William A. Russell, and Ralph B. Trueblood, VTOL Advanced Flight Control System Studies for All-Weather Flight. Vol. I: Task I Report, USAAMRDL-TR-75-13A, July 1975.

13. McRuer, D. T., and E. S. Krendel, Mathematical Models of Human Pilot Behavior, AGARD-AG-188, Jan. 1974.

14. Lebacqz, J. V., and E. W Aiken, A Flight Investigation of Control, Display, and Guidance Requirements for Decelerating Descending VTOL Instrument Transitions Using the X-22A Variable Stability Aircraft, Calspan Corp. Rept. AK-5336-F-1, Sept. 1975.

15. Niessen, Frank R., James R. Kelly, John F. Garren, Jr., Kenneth R. Yenni and Lee H. Person, The Effect of Variations in Controls and Displays on Helicopter Instrument Approach Capability, NASA TN D-8385, Feb. 1977.

16. Stapleford, Robert L., Warren F. Clement, Robert K. Heffley, George C. Booth, and Robert L. Fortenbaugh, Flight Control/Flying Qualities Investigation for Lift/Cruise Fan V/STOL. Vol. II: Piloted Simulation, Systems Technology, Inc. TR-1122-1, Aug. 1979.

17. Winn, Albert L., Warren E. Griffith II, and Carl F. Mittag, Instrument Flight Evaluation OH-6A Helicopter, Part 1, USAASTA Project No. 72-16, Nov. 1973.

18. Hofmann, L. G., Roger H. Hoh, Wayne F. Jewell, Gary L. Teper and Pradip D. Patel, Development of Automatic and Manual Flight Director Landing Systems for the SV-15 Tilt Rotor Aircraft in Helicopter Mode, NASA CR-152040, Jan. 1978.

19. Kelly, James R., Frank R. Niessen, Kenneth R. Yenni, and Lee H. Person, Jr., Flight Investigation of a Vertical-Velocity Command System for VTOL Aircraft, NASA TN D-8480, July 1977.

20. Kelly, James R., Frank R. Niessen, Jerry J. Thibodeaux, Kenneth R. Yenni, and John F. Garren, Jr., Flight Investigation of Manual and Automatic VTOL Decelerating Instrument Approaches and Landings, NASA TN D-7524, July 1974.

21. Lebacqz, J. V., and R. C. Radford, "An Experimental Investigation of Control-Display Requirements for a Jet-Lift VTOL Aircraft in the Terminal Area," A Collection of Technical Papers, AIAA Atmospheric Flight Mechanics Conference, Palo Alto, California, Aug. 7-9, 1978. pp. 243-252.

22. Bryant, William B., James J. Cattel, William A. Russell and Ralph B. Trueblood, VTOL Advanced Flight Control System Studies for All-Weather Flight. Vol. II: Task III Report, USAAMRDL-TR-75-13B, July 1975.

23. Davis, J., T. Garnett, and J. Gaul, Heavy Lift Helicopter Flight Control System. Vol. III: Automatic Flight Control System Development and Feasibility Demonstration, USAAMRDL-TR-77-40C, Sept. 1977.

24. Vinje, Edward W. and David P. Miller, Flight Simulator Experiments and Analyses in Support of Further Development of MIL-F-83300-V/STOL Flying Qualities Specification, AFFDL-TR-73-34, June 1973.

25. Corliss, L., R. K. Greif, and R. M. Gerdes, "Comparison of Ground-Based and In-Flight Simulation of VTOL Hover Control Concepts," AIAA Journal of Guidance and Control, Vol. 1, No. 3, May-June 1978, pp. 217-221.

26. Rolls, L. Stewart, Fred J. Drinkwater III, and Robert C. Innis, Effects of Lateral Control Characteristics on Hovering a Jet Lift VTOL Aircraft, NASA TN D-2701, Mar. 1965.

27. Kelly, James R., John F. Garren, and John P. Reeder, A Visual Flight Investigation of Hovering and Low-Speed VTOL Control Requirements, NASA TN D-2788, Apr. 1965.

28. McGregor, D. M., The Influence of Aircraft Size on Control Power and Control Sensitivity Requirements. A Comparison of Results From Two Variable Stability Helicopters, NRC Aero Rept. LR 459, July 1966.

29. Craig, Samuel J. and Anthony Campbell, Analysis of VTOL Handling Qualities Requirements: Part I Longitudinal Hover and Transition, AFFDL TR-67-179, Oct. 1968 and Samuel J. Craig, Anthony Campbell, and R. H. Klein, Analysis of VTOL Handling Qualities Requirements. Part II. Lateral-Directional Hover and Transition, AFFDL-TR-67-179, Feb. 1970.

30. Morello, Samuel A., Lee H. Person, Jr., Robert E. Shanks and Richard G. Culpepper, A Flight Evaluation of a Vectored-Thrust-Jet V/STOL Airplane During Simulated Instrument Approaches Using the Kestrel (XV-6A) Airplane, NASA TN D-6791, May 1972.

31. Ashkenas, I. L., Some Open- and Closed-Loop Aspects of Airplane Lateral-Directional Handling Qualities, AGARD Report 533, May 1966.

32. Tapscott, Robert J. and Robert W. Sommer, A Flight Study with a Large Helicopter Showing Trends of Lateral and Longitudinal Control Response with Size, NASA TN D-3600, Sept. 1966.

33. Garren, John F. Jr., James R. Kelly, Robert W. Sommer, "VTOL Flight Investigation to Develop a Decelerating Instrument Approach Capability," SAE Paper No. 691693, Oct. 6-10, 1969.

34. Garren, John F. Jr., James R. Kelly, Rober W. Sommer, and Daniel J. DiCarlo, Flight Investigation of VTOL Control and Display Concept for Performing Decelerating Approaches to an Instrument Hover, NASA TN D-6108, Feb. 1971.

35. Corliss, Lloyd D. and Daniel C. Dugan, A VTOL Translational Rate Control Systems Study on a Six-Degrees-Of-Freedom Motion Simulator, NASA TM X-62,194, Oct. 1972.

36. Tactical Aircraft Guidance System Advanced Development Program Flight Test Phase Report, Vol. I, USAAMRDL-TR-73-89A, Apr. 1974.

37. Merrick, Vernon K., "Study of the Application of an Implicit Model-Following Flight Controller to Lift-Fan VTOL Aircraft," NASA Technical Paper 1040, Nov. 1977.

38. Feistel, Terrell W., Ronald M. Gerdes, and Emmett B. Fry, An Investigation of a Direct Side-Force Maneuvering System on a Deflected Jet VTOL Aircraft, NASA TN D-5175, Apr. 1969.

39. Fortenbaugh, R. L., Mathematical Models for the Aircraft Operational Environment of DD-963 Class Ships, Vought Corporation Rept. No. 2-55800/8R-3500, 26 Sept. 1978.

40. McFadden, Norman M., Richard F. Vomaske, and Donovan R. Heinle, Flight Investigation Using Variable-Stability Airplanes of Minimum Stability Requirements for High-Speed, High-Altitude Vehicles, NASA TN D-779, Apr. 1961.

41. Craig, S. J. and I. L. Ashkenas, Background Data and Recommended Revisions for MIL-F-8785B(ASG), "Military Specification-Flying Qualities of Piloted Airplanes," Systems Technology, Inc. TR-189-1, Mar. 1971.

42. DiFranco, Dante A., In-Flight Investigation of the Effects of Higher-Order Control System Dynamics on Longitudinal Handling Qualities, AFFDL TR-68-90, Aug. 1968.

43. Chalk, Charles R., David L. Key, John Kroll, Jr., Richard Wasserman, and Robert C. Radford, Background Information and User Guide for MIL-F-83300- Military Specification — Flying Qualities of Piloted V/STOL Aircraft, AFFDL-TR-70-88, Mar. 1971.

44. Brigadier, W. J., forthcoming NASA TM (Ames Research Center).

45. V/STOL Handling-Qualities Criteria, AGARD Report No. 577, Dec. 1970. 52 pgs.

46. Matranga, Gene J., Harold P. Washington, Paul L. Chenoweth, and William R. Young, Handling Qualities and Trajectory Requirements for Terminal Lunar Landing, as Determined from Analog Simulation, NASA TN D-1921, Aug. 1963.

47. Garren, John F. Jr., Daniel J. DiCarlo, and Norman R. Driscoll, Flight Investigation of an On-Off Control for V/STOL Aircraft Under Visual Conditions, NASA TN D-3436, Jun. 1966.

48. Walton, R. P., and I. L. Ashkenas, Analytical Review of Military Helicopter Flying Qualities, Systems Technology, Inc. TR-143-1, Aug. 1967.

49. Rolls, L. Stewart and Fred J. Drinkwater III, A Flight Determination of the Attitude Control Power and Damping Requirements for a Visual Hovering Task in the Variable Stability and Control X-14A Research Vehicle, NASA TN D-1328, May 1962.

50. Lollar, Thomas E. and Gerhard K. L. Kriechbaum, "VTOL Handling Qualities Criteria and Control Requirements — Analysis and Experiment," in J. of the AHS, Vol. 13, No. 3, July 1968, pp. 20-30.

51. Greif, Richard K., Emmett B. Fry, Ronald M. Gerdes, and Terrence D. Gossett, VTOL Control System Studies on a Six-Degree-Of-Freedom Motion Simulator, NASA TM X-59065, 1966.

52. Preliminary Pilot Qualitative Evaluation of the XV-5A Research Aircraft, Letter Report, Army Aviation Test Activity (no number), Edwards AFB, California, Oct. 28, 1965.

53. La Plant, Porter II and Robert L. Baldwin, Flight Evaluation of the XV-5A VSTOL Aircraft, Air Force FTC-TR-66-30, Mar. 1967.

54. Gerdes, Ronald M., A Piloted Motion Simulator Investigation of VTOL Height-Control Requirements, NASA TN D-2451, Aug. 1964.

55. Kelly, James R., John F. Garren, Jr., and Perry L. Deal, Flight Investigation of V/STOL Height-Control Requirements for Hovering and Low-Speed Flight Under Visual Conditions, NASA TN D-3977, May 1967.

56. Obermeier, L., and J. Iles, USN/FMOD FRG VAK-191B Joint Flight Test Program, Vol. 3, Pilot Evaluations, NAVAIR-3R-76, Aug. 1976.

57. A'Harrah, R. C., and S. F. Kwiatkowski, "A New Look at V/STOL Flying Qualities," in Aerospace Engineering, Vol. 20, No. 7, July 1961, pp. 22-23, 86-92.

58. Cromwell, C. H., and I. L. Ashkenas, A Systems Analysis of Longitudinal Piloted Control in Carrier Approach, Systems Technology, Inc. TR-124-1, Jun. 1962.

59. Flying Qualities of Piloted V/STOL Aircraft, Military Specification, MIL-F-83300, 31 Dec. 1970.

60. Vinje, Edward W., and David P. Miller, Analytical and Flight Simulator Studies to Develop Design Criteria for VTOL Aircraft Control Systems AFFDL-TR-68-165, Apr. 1969.

DISTRIBUTION LIST

NADC-77052-30

PE 62241N/WF 41-421

Copies	Address
13	Commander Naval Air Development Center Warminster, PA 18974 Attn: Mr. J. W. Clark, Jr. (6053) - (10) Attn: Library (8131) - (3)
7	Commander Naval Air Systems Command Department of the Navy Washington, DC 20361 Attn: Mr. D. Kirkpatrick (AIR-320D) - (1) Attn: Library (AIR-954) - (2) Attn: Mr. D. Hutchins (AIR-530112) - (1) Attn: (PMA-269) - (1) Attn: Mr. H. Andrews (AIR-03PA) - (1) Attn: Mr. G. Tsaparas (AIR-340D) - (1)
2	Commander Naval Ship Research and Development Center Carderock, MD 20034 Attn: Mr. R. Williams (Code 1660) - (1) Attn: Mr. J. Martin - (1)
1	Chief Office of Naval Research 1800 N. Quincy St. Arlington, VA 22217 Attn: Mr. R. VonHusen - (1)
1	Superintendent Naval Postgraduate School Monterey, CA 93940 Attn: Dr. L Schmidt - (1)
1	Commander Naval Weapons Center China Lake, CA 93555
2	Commander Naval Air Test Center Patuxent River, MD 20670 Attn: Mr. R. Traskos (SA-43) - (1) Attn: Mr. A. Rossetti (SA-71) - (1)
1	Commanding General Army Aviation Systems Command St. Louis, MO 63102

(continued inside cover)

4 Director
National Aeronautics and Space Administration
Ames Research Center
Moffett Field, CA 94035
Attn: Mr. S. Anderson - (1)
Attn: Mr. J Franklin - (1)
Attn: Dr. J. V. Labacqz - (1)
Attn: Mr. I. Statler (AMRDL) - (1)

1 Director
National Aeronautics and Space Administration
Flight Research Center
Edwards AFB, CA 93523

1 Director
National Aeronautics and Space Administration
Langley Research Center
Hampton, VA 23365
Attn: Mr. L. Taylor - (1)

1 Director
ASD/ENFTC
WPAFB
Dayton, OH 45433

12 Administrator
Defense Documentation Center
Bldg. No. 5, Cameron Station
Alexandria, VA 22314

3 McDonnell Aircraft Co.
PO Box 516
St. Louis, MO 63166
Attn: Mr. T. Lacey (AV-8B Project) - (1)
Attn: Mr. R. Konsewicz (D338) - (1)
Attn: Mr. J. Hodgkinson - (1)

1 General Dynamics
Convair Division
PO Box 80986
San Diego, CA 92138

1 The Boeing Co.
Seattle, WA 98101
Attn: Mr. D. West (MS41-11) - (1)

1 Vought Corp.
PO Box 225907
Dallas, TX 75265
Attn: Mr. R. Fortenbaugh - (1)

1 Rockwell International
Columbus, OH 43216
Attn: Mr. W. Palmer - (1)

1 Rockwell International
Los Angeles, CA 90053

1 General Dynamics Corporation
Ft. Worth, TX 76108
Attn: Mr. G. Joyce - (1)

1 Fairchild-Republic Corporation
Farmingdale, NY 11735

1 Lockheed California Co.
PO Box 551
Burbank, CA 91503
Attn: Mr. A. Byrnes - (1)

1 Northrop Corp.
Hawthorne, CA 90250
Attn: Dr. W. Martin - (1)

1 Lockheed Georgia Co.
Marietta, GA 30061
Attn: Mr. M. Jenkins - (1)

2 Grumman Aerospace Corp.
Bethpage, NY 11714
Attn: Mr. A Whitaker - (1)
Attn: Mr. R. Martorella - (1)

1 Royal Aeronautical Establishment
Bedford, England UK
Attn: Mr. O. P. Nicholas - (1)

1 Boeing Vertol Co.
PO Box 16858
Philadelphia, PA 19142
Attn: Mr. B. Blake - (1)

1 Systems Technology Inc.
13766 S. Hawthorne Blvd.
Hawthorne, CA 90250

1 Dept. of Aero and Mechanical Sciences
Princeton University
Princeton, NJ 08540
Attn: Dr. R. Stengel - (1)

1 Bell Helicopter
PO Box 482
Ft. Worth, TX 76101

2 Calspan Corp.; Advanced Technology Center
Flight Research Branch
PO Box 400
Buffalo, NY 14225
Attn: Mr. C. Chalk - (1)
Attn: Mr. R. Radford - (1)