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LONGITUDINAL HANDLING QUALITIES FOR HOVERING

by

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FOREWORD

The research in this report was conducted by the Department of Aeronautical Engineering, Princeton University, under the sponsorship of the United States Army Transportation Research Command, Fort Eustis, Virginia, as Phase 4 of work under the Alart program.

The work was performed under the supervision of Professor Edward Seckel, Department of Aeronautical Engineering, Princeton University, and was administered for the United States Army by Mr. Robert Graham.

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SYMBOLS

$C_{1/2}$	cyclic damping parameter, cycles to damp to 1/2 amplitude (cycles)
$CP = \frac{\partial M}{\partial \delta}$	control power derivative $(\frac{ft-lbs}{in})$
$CP_D = \frac{\partial X}{\partial \delta}$	derivative, "X" force component resulting from movement of the moment control $(\frac{lbs}{in})$
$CP_M = \frac{\partial M}{\partial \delta}$	control power derivative, moment resulting from movement of the moment control $(\frac{ft-lbs}{in})$
$\frac{CP}{I}$	moment control parameter $(\frac{rad/sec^2}{in})$
$D = \frac{\partial M}{\partial \dot{\theta}}$	aircraft angular damping derivative $(\frac{ft-lbs}{rad/sec})$
$\frac{D}{I}$	damping parameter $(\frac{ft-lbs}{rad/sec} \times \frac{1}{slug-ft^2})$ or $(\frac{1}{sec})$
$d = \frac{d}{dt}$	differential operator
g	acceleration due to gravity $(32.2 \frac{ft}{sec^2})$
I	moment of inertia $(slug-ft^2)$
I_x	moment of inertia of aircraft in roll $(slug-ft^2)$
I_y	moment of inertia of aircraft in pitch $(slug-ft^2)$
j	$\sqrt{-1}$
L	roll moment (ft-lbs)
$L_p = \frac{\partial L}{\partial p}$	roll damping derivative $(\frac{ft-lbs}{rad/sec})$

$L_v = \frac{\partial L}{\partial v}$	lateral velocity stability derivative $(\frac{ft\text{-}lbs}{ft/sec})$
$L_{\delta_\ell} = \frac{\partial L}{\partial \delta_\ell}$	roll control power derivative $(\frac{ft\text{-}lbs}{in})$
M	pitch moment (ft-lbs)
$M_u = \frac{\partial M}{\partial u}$	longitudinal velocity stability derivative $(\frac{ft\text{-}lbs}{ft/sec})$
$\frac{M_u g}{I}$	velocity stability parameter $(\frac{ft\text{-}lbs}{ft/sec} \times \frac{ft/sec^2}{slug\text{-}ft^2})$
$M_q = \frac{\partial M}{\partial q}$	pitch damping derivative $(\frac{ft\text{-}lbs}{rad/sec})$
M_δ	moment control parameter (Reference 8) $(\frac{deg/sec^2}{in})$
$M_{\dot{\theta}} = \frac{\partial M}{\partial \dot{\theta}}$	pitch damping derivative $(\frac{ft\text{-}lbs}{rad/sec})$
m	mass (slugs)
s	Laplace Transform Operator $(\frac{1}{sec})$
$T_{1/2}$	damping parameter, time to damp to 1/2 amplitude; if negative, time to double amplitude (sec)
T_2	damping parameter, time to double amplitude (sec)
t	time (sec)
u	longitudinal velocity (ft/sec)
V	mean wind velocity (meters/sec)
v	lateral velocity (ft/sec)
X	longitudinal force (lbs)
$X_u = \frac{\partial X}{\partial u}$	derivative $(\frac{lbs}{ft/sec})$

Z	altitude	(ft)
δ	control displacement	(in)
ζ	damping ratio	
θ	pitch attitude	(radians)
$\phi(\omega)$	power spectral density of the Eulerian time spectrum of turbulence	$(\frac{ft^2/sec^2}{rad/sec})$
Ω	reduced angular frequency, or wave number	(rad/ft)
ω	angular frequency	(rad/sec)
ω_n	undamped natural frequency	(rad/sec)

SUMMARY

A series of flight tests with a number of qualified pilots and a variable stability helicopter was conducted to determine the effect of certain stability parameters on precision hovering in atmospheric turbulence. A course was devised which would emphasize the precision control required to pick up sling loads, deliver litter patients, dunk Sonar buoys, etc., under gusty conditions.

The effect of velocity stability was determined to be of particular importance. The most important effect is that the pitching disturbances felt by the pilot due to turbulence are essentially proportional to this parameter. Secondary effects are the control gradient for trim at low speed, and the dynamic stability. The range of velocity stability variation was from practically zero, which was considered very favorable, to values that were unacceptable or even disastrous.

It was discovered, in the course of the above investigation, that certain pilot ratings did not correspond to previously published handling qualities criteria. Further investigation disclosed that somewhat higher angular damping and appreciably greater control effectiveness are desired by pilots for precision hovering than had previously been determined.

INTRODUCTION

During the past several years considerable interest has been shown in the prediction of handling qualities of V/STOL vehicles in hovering or low speed flight. Emphasis has been placed on establishing basic criteria for satisfactory handling qualities as determined by pilot opinion data obtained in ground simulators and actual flight. Previous studies determined the importance of angular velocity damping and control power. Although some studies have considered the effect of velocity stability on handling qualities, the exact and primary influence of this parameter was still relatively unknown. For the purposes of this research program, a series of flight tests with a number of qualified pilots and a variable stability helicopter was conducted in order to determine the effect of the velocity stability parameter on precision hovering in atmospheric turbulence. Changes in the gust response, dynamic stability and control displacement required for trim caused by the large changes in the velocity stability were investigated. Additional studies were made in order to re-examine the effects associated with changes in angular velocity damping and control power since large discrepancies with previously published data were noted during the course of the velocity stability investigation. A review of longitudinal handling qualities criteria as determined by other studies is included with the results of this research program.

DYNAMIC ANALYSIS

The dynamic stability and control of helicopters and VTOL aircraft in hovering depend principally on the velocity stability, angular rate damping, and moment control parameters.

The velocity stability parameter is peculiar to helicopters and V/STOL aircraft. It is the rate of change of pitching moment with velocity, other variables held constant. The parameter may be sensed by the pilot as a change in stick position to trim for changes in velocity while maintaining constant angle of attack. The latter restriction may be dropped at very low velocity where the angle of attack stability is near zero. The effect on the dynamics of increasing the velocity stability is to reduce the period and decrease the damping of the oscillatory mode. The magnitude of the velocity stability parameter also determines the level of aircraft response to atmospheric turbulence.

The effect of the pitch damping parameter is well known. Increases in pitch damping result in a longer period, more stable oscillatory mode and a more rapid convergence of the aperiodic mode.

The effects on the dynamics can be seen from a consideration of the equations of motion for hovering.

$$\left(\frac{X_u}{m} + d\right)u + (g)\theta = \left(\frac{CP_D}{m}\right)\delta + \left(\frac{X_u}{m}\right)u_{gust} \qquad (1)$$

$$(\frac{M_u}{I})u + (\frac{D}{I}d - d^2)\theta = (\frac{CP_M}{I})\delta + (\frac{M_u}{I})u_{gust} \tag{2}$$

The uncoupling or isolation of the vertical degree of freedom has been made since in hovering or at very low speeds the vertical component of motion does not influence the horizontal forces or the moments about the horizontal axes, while horizontal or tilting motion does not affect the thrust. The right hand sides of the equations contain pilot control and gust disturbance forcing functions. The effect of the drag equation terms $(\frac{X_u}{m})u$, $(\frac{CP_D}{m})\delta$, and $(\frac{X_u}{m})u_{gust}$ on the motions of the helicopter was practically negligible for the range of investigation of this report. The values of these terms varied linearly with their moment equation counterparts in the test program.

Expansion of the stability determinant gives the cubic:

$$d^3 + (\frac{X_u}{m} + \frac{-D}{I})d^2 + (\frac{X_u}{m} \times \frac{-D}{I})d + \frac{M_u g}{I} = 0 \tag{3}$$

For cases where the velocity stability or $M_u g/I$ is zero, the above differential equation may be solved exactly in terms of the two remaining parameters

$$d = D/I \qquad d = -X_u/m \qquad d = 0 \tag{4}$$

For other cases an approximate analytical solution can be made. If the value of X_u/m is negligible, the equation becomes:

$$d^3 + (-D/I)d^2 + M_u g/I = 0 \tag{5}$$

Approximate solutions are:

$$d \cong D/I, \qquad d^2 \cong M_u g/D \tag{6}$$

Using this first approximation, a better one can be obtained:

$$d \cong \frac{D}{I} \qquad d \cong -\frac{1}{2}\left[\frac{X_u}{m} - \frac{M_u g}{I}\left(\frac{I}{D}\right)^2\right] \pm \sqrt{\left(\frac{M_u g}{I}\right) \times \left(-\frac{I}{D}\right)}\, j \qquad (7)$$

From this one it can be seen that the oscillatory mode will always be unstable except for large values of X_u/m. The relative importance of the parameters D/I and $M_u g/I$ upon the dynamics also can be seen from this approximate equation or the following illustration based on it:

- - - - - - oscillatory damping (approx)
———— oscillatory period (approx.)
- —— - aperiodic damping (approx.)

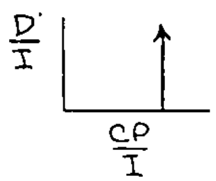
$$\frac{M_u g}{I} \sim \frac{(\text{ft-lb})(\text{ft/sec}^2)}{(\text{ft/sec})(\text{slug-ft}^2)}$$

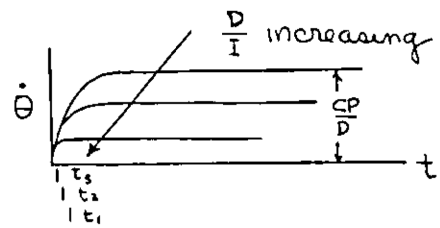
For the first few seconds of time following a step control input the aircraft velocity does not change. If we make this assumption, the equations of motion reduce to a single degree of freedom involving only the parameters D/I and CP/I. For this case the resultant aircraft motion is an aperiodic convergence to a steady angular pitch rate. The time t for the angular velocity to reach a characteristic percentage of the final steady state value is given by the illustration on page 4.

In terms of a time history of response to a step input, increasing CP/I produces an increase in the initial slope of the angular velocity curve. The effect of CP/I on the time history of pitch rate following a given control step input is as follows:

Since D/I is constant, the characteristic time t_1 has the same value for all typical time responses shown.

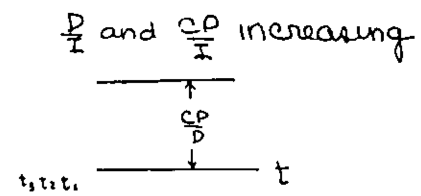
Changes in the value of D/I represent changes in the pitch damping ($M_{\dot{\theta}}$ or M_q). The effect of D/I on the initial time history of pitch rate following a control step input would appear as:





where the times t_1, t_2, t_3 have different values (Reference illustration on page 4).

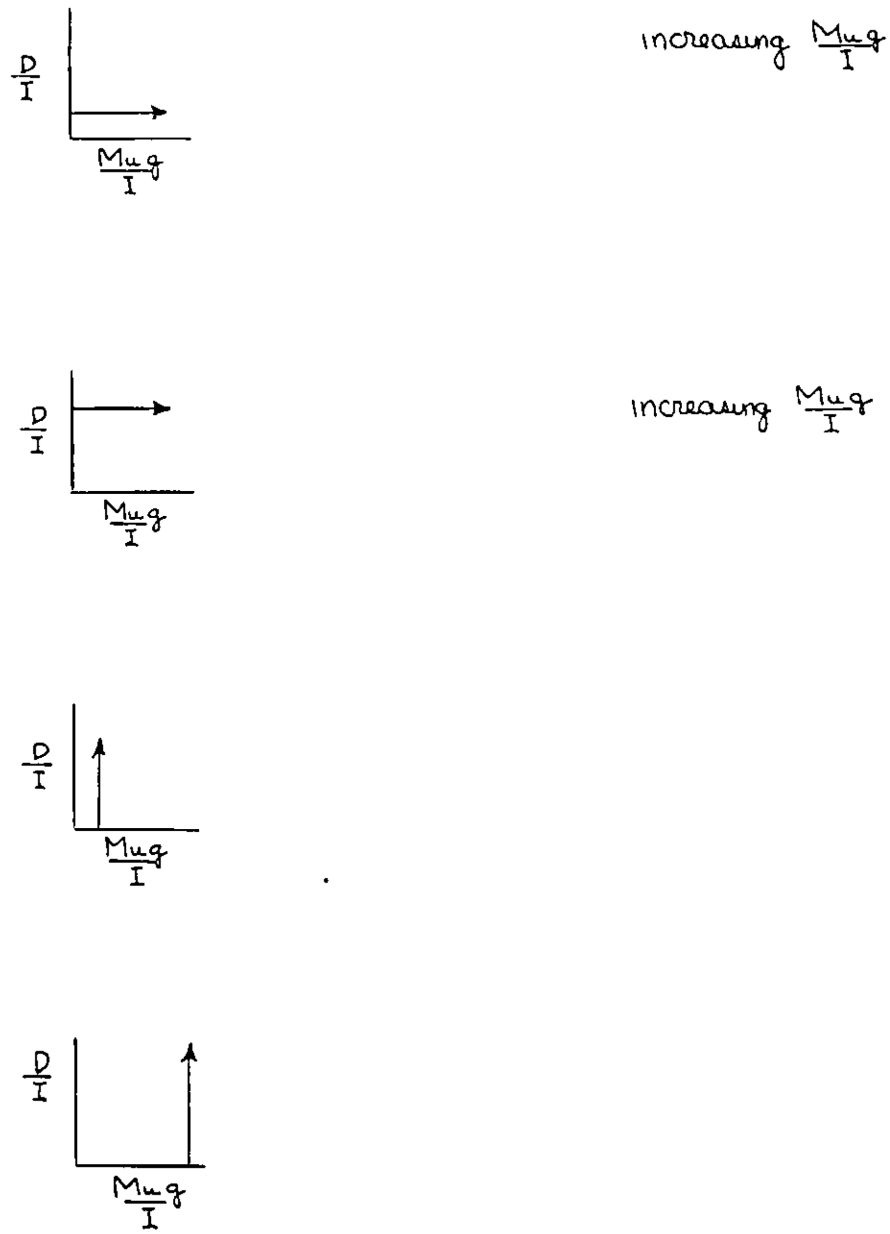
The steady state pitch rate depends on the ratio of CP/D. If this ratio is held constant, the time history for a given control step input would appear as:



This case is interesting since the commanded angular velocity for a given control deflection is always the same but the characteristic time t varies depending on the value of D/I (Reference illustration on page 4).

The characteristics of the oscillatory mode are visible later in the responses and occur because of the additional degree of freedom in velocity. The oscillatory mode is superposed on the aperiodic mode. The aperiodic characteristics, which have been previously discussed, are not altered appreciably by the additional degree of freedom.

Changes in the parameters D/I and $M_u g/I$, separately or both together, will have significant effects on the period and damping of the oscillation (Equation 7). Typical pitch rate time histories following a control step input for a given CP/I might appear as:



The initial response is principally the aperiodic mode. The period and damping of the subsequent oscillation for different D/I and $M_u g/I$ can be determined from the illustration on page 4 .

The aperiodic mode of motion is probably the one which is of most interest to the pilot since in turbulent air the characteristics of the oscillatory mode do not present themselves to him. Nevertheless, the velocity stability parameter is important since it determines the disturbance level and also the static stick deflections for trim.

EXPERIMENTAL PROCEDURE

1. Description of Variable Stability Helicopter and Inertial Velocity Sensor

A variable stability helicopter was used to provide the numerous stability configurations required in the test program. A modified autopilot installed in a HUP-1 tandem-rotor helicopter provided for variations in velocity stability, pitch and roll damping, and control power. Stability derivative values were effected by sensing a flight variable which activated a control servo in direct proportion to this signal, e.g., forward velocity activating the longitudinal servo to produce a pitching moment proportional to velocity, for an artificial velocity stability change.

An inertial measurement was used to determine the velocity of the aircraft. This method was chosen because of the problems of accurately measuring near-zero velocities in the vicinity of the rotors of the helicopter and the requirement for small time lags in the measurement. The system consisted essentially of an accelerometer mounted on a stabilized platform which was oriented parallel to the surface of the earth. The accelerations measured were therefore the inertial accelerations of the helicopter. These accelerations were integrated to give velocity. A more complete description and analysis of this velocity sensing system is contained in Reference 3.

2. Selection of Pilots

Five pilots were used for the collection of data. Since the findings would be based primarily on analysis and interpretation of pilot evaluations, the proper selection of the pilot subjects was of basic importance to the program. All of the pilots chosen are experienced test pilots with wide and diversified flying experience. In addition, three of the pilots are graduate engineers and the remaining two are graduates of the U.S.A.F. Test Pilot School. Their qualifications are summarized in Table 2. This flight test experience and technical background was considered necessary for comprehensive flight evaluations which could be used in the technical interpretation of the data.

3. Rating System

The Cooper rating scale was used by the pilots to evaluate the various configurations (Reference 5). This scale is shown in Table 1. Many rating scales have been used in the past by others and each has its own advantages, disadvantages, and limitations. This rating system was chosen primarily because of the pilots familiarity with it. Three of the pilots were totally familiar with it, had used it extensively, and were considered experts in its meaning and interpretation. The remaining two pilots (Army test pilots) were familiar with the scale but had not used it extensively. However, they commented that they had no difficulty in expressing their evaluation with this system.

Prior to evaluation flights, each pilot was asked to assign a Cooper rating to any production helicopter he had flown. General ratings were assigned and it was interesting to note that most of the machines were in the

3- to 4+ region of the rating scale. Although this was done just to check familiarity with the rating scale, the pilots also commented that any helicopter should be at least a 3.0 to be an acceptable machine for mission use.

4. Flight Problem

A flight program was set up to enable the pilots to have some standard basis of evaluating the various configurations. This consisted of a hexagon shaped flight course laid out on the airport grounds. The vertices of the hexagon were marked with pylons. The program required the pilots to hover at each pylon for approximately 20 seconds. Each hover was to be as precise as possible in terms of pitch, roll, yaw, and position over the ground. Flight between pylons was to be made as fast as possible, that is, accelerate rapidly to a moderate speed and decelerate rapidly to hover. The maximum speed between the pylons was limited to about 50 feet per second due to the placement of the pylons and the acceleration capability of the machine. This value was usually not reached except in the better configurations where the pilot had confidence in his machine. At one of the pylons the pilots were to execute rearward flight, reverse to forward flight, and return to the pylon. A limitation of 20 feet per second rearward velocity was imposed because of the limits of the velocity servo component of the inertial velocity sensor. Higher velocities would also result in the blades hitting the flapping stops. Again, the velocities in rearward flight were limited by the pilot's confidence and seldom exceeded 15 feet per second.

At the conclusion of the flight course, the pilots were to pick up hoops with a spear attached to the nose of the helicopter (Figure 3). Two hoops of approximately 1 foot and 2 feet in diameter were placed to permit engagement at about 5 feet above the ground. Pilots were instructed not to spear the hoops in slow forward flight but to hover and slowly engage the hoop. In the better configurations, the pilot was able to keep the spear centered in the smaller of the two hoops and pick up the hoop at will. In the poorer configurations, it was often impossible to pick up even the larger hoop except by luck or by lunging at it.

The hoop problem was not intended to be a measure of the worth of a configuration but merely a test to aid the pilot in his evaluation. The ability to pick up the hoops varied among pilots depending upon their individual technique. However, all felt that it was a precision task which required enough concentration to point up the weaknesses of the configurations which might not have been as evident during the first part of the flight problem. The pilots were not required to actually pick up the hoop, or even attempt it, if they felt they had sufficient data to evaluate the configuration without this problem. The same philosophy was applied to completion of the flight course.

During the entire flight of a configuration, the aircraft was disturbed by a simulated wind. The mean velocity of this wind was fixed at a constant value of 15 knots for all data configurations. The RMS value for gusts about the mean was 6.3 ft/sec. (Appendix 1). The same wind time history was used for all pilots to provide a standard problem. This does not mean that the aircraft disturbances felt by the pilot were constant, since the aircraft motions arising from the simulated wind depend on the value of M_u for the configuration. Flights were actually made in still air so that the only disturbances were those of the simulated wind. As mentioned before, the still air requirement was also necessary because of the method of determining the velocity by inertial means.

5. Range of Investigation

The parameters investigated were the velocity stability, pitch damping, and longitudinal control power. Ranges of the parameters $M_u g/I$, D/I, and CP/I were selected representing generous changes in the parameters and resulting dynamics so that the pilot would not be asked to evaluate subtle differences (Dynamic Analysis, Tables 3 and 4, Figures 4 and 5). Lateral parameters L_v, L_p, $L_{\delta \ell}$ were varied in a manner which would preserve the harmony of the longitudinal and lateral axes. The ability to simulate the dynamics with the helicopter was checked on the analog computer using analog models of the helicopter, autopilot-variable stability system, and the inertial velocity sensor (Reference 3). The dynamics of the autopilot-variable stability system and the helicopter control system were determined by frequency response techniques (Appendix 2). Representative configurations were also checked on the helicopter using dynamic flight test techniques.

Several qualified pilots, in addition to the evaluation pilots, were questioned on the apparent magnitude of the artificially induced turbulence on the basic configuration. All pilots felt that the aircraft responded realistically to what they considered to be a medium gusty day with approximately a 15 knot wind. The mean wind was established theoretically at 14.8 knots by Reference 13 (See Appendix 1). Some typical comments on the artificial turbulence by the evaluation pilots for the basic configuration were: "I would describe it as a 15 knot wind with a 5 to 10 knot spread, good summer day," "Nice warm summer day, moderate turbulent day. It is good realistic turbulence. You are working full time to maintain either hover speed or zero ground speed," "Not too bad a day, 8 to 12 or 8 to 17 knots, common ordinary turbulent day. It is not excessively turbulent."

6. Method of Extracting Data

The pilots were allowed to express freely their views on each configuration, both during the flight and the post-flight conferences. They were asked to comment and base their Cooper rating of the configuration on the longitudinal characteristics only, but to discuss any shortcomings of the lateral mode, particularly lack of harmony between the two axes. All pilot comments were recorded on tape for later use. Primary flight quantities were telemetered and recorded on tape. The telemeter data was used primarily to observe the operation of the inertial velocity sensor, autopilot-variable stability system, and the settings of the configuration variables. The pilot inputs and flight variables were monitored but no analytical study was conducted using the data. Motion picture films of all hoop engagements or attempts were taken to compare the performance of pilots on different configurations.

DISCUSSION

The experimental results obtained from the research of this program are illustrated in Figures 1 and 2. The results take the form of boundaries and zones of pilot opinion ratings of longitudinal flying qualities for precision hovering and low speed flight in the presence of atmospheric turbulence. The iso-opinion lines represent the numerical ratings consistent with the "description" and "adjective rating" of the frequently used Cooper Pilot Opinion Rating System (Reference 5 and Table 1).

Figure 1

In Figure 1, the results are plotted in terms of the commonly used ratios of damping moment to inertia (D/I) and control power to inertia (CP/I) for the longitudinal mode of motion. On this graph, the velocity stability M_u is relatively high and at a constant level corresponding to the value for the basic HUP. (For the basic HUP: static stability derivatives unaltered; configuration number 5; the value of $M_u g/l$ is equal to 1.13.) All flights were conducted in smooth, early morning calm air conditions. Also, the artificial gust inputs or canned atmospheric turbulence was held constant for this graph at a level representing a medium gusty day with approximately a 15-knot wind. Since the velocity stability is held constant, the disturbance level of the helicopter, for this medium gusty day, will remain constant also.

The iso-opinion curves are shown in Figure 1 for the Cooper pilot ratings of 3.5, 4.0, 4.5, 5.0, and 5.5. (The use of small increments or decimal Cooper rating units throughout the text is used only to aid in illustrating the trends or gradients of rating and should not be construed as decimal accuracy of the Cooper rating data.) The basic HUP is located by the circle symbol and it is rated slightly worse than a 4. Since the value of velocity stability and disturbance level were held constant on this graph, the variations of pilot opinion associated with changes in D/I or CP/I may be readily seen. In general, the pilots never had any trouble detecting changes in angular damping and all appeared to like heavy damping. It is interesting to note that the gradient of pilot opinion associated with changes in D/I is greater at the relatively low ratios of D/I as compared to the higher values of D/I. The test pilots stated that, once they received a reasonable, or good, amount of damping, further increases in D/I would not make appreciable improvements in Cooper rating. Whether the pilot opinion boundaries close for higher D/I cannot be determined from ranges covered in this research. Speculation in this regard may be of academic interest only since the rating lines seem to be spreading apart and rate of change of pilot opinion is decreasing for increasing D/I.

In contrast to the gradient of rating associated with changes in D/I, changes in CP/I revealed a broad or flat optimum <u>based solely on Cooper rating numbers</u>. During the in-flight conversations, as well as in the discussions that followed every flight, it was apparent that the evaluation pilots easily detected changes in control power (at constant D/I) and freely referred to these changes by remarks such as "too touchy," "too low control power," "good control but a little touchy," "sluggish" or "near optimum control power." However, and almost without exception, the large changes in CP/I (at constant D/I) were not accompanied by significant changes in Cooper rating. Some pilots, in an effort to show that there was a detectable difference, used quarter or tenths of a Cooper rating unit, but in general all agreed on the existence of flat optimums, large tolerance, and wide ranges of almost constant Cooper rating for the large changes in longitudinal control power in the regions shown (iso-opinion lines 4.0, 4.5, 5.0 for constant D/I). The optimum values of CP/I for a given D/I start out on the order of 0.45 and gradually increase toward 0.6 as the value of D/I increases. These values of optimum CP/I were obtained by individual pilot commentary during special control power optimization runs.

Attention is called to the fact that the velocity stability for these configurations is relatively high ($M_u g/I$ equal to 1.13) and that the atmospheric turbulence is equivalent to a medium gusty day. According to this graph, the best rating (optimum CP/I and D/I) that can be obtained for this amount of atmospheric turbulence and velocity stability, for precision hovering and low speed flight, is almost a 3 (at $D/I \approx 8$). The Cooper rating description for 3 is "Satisfactory, but with some mildly unpleasant characteristics" (Table 1).

The shaded area on Figure 1 represents the damping and control power minimums for the HUP as dictated by Military Specification H8501A of 7 September 1961 (Reference 15).

Figure 2

In Figure 2, lines of constant pilot opinion are plotted for various D/I and $M_u g/I$. The basic configuration (HUP with unaltered derivatives) is again located by the circle symbol. As mentioned before, (See Dynamic Analysis), the aircraft dynamics are varied as D/I or $M_u g/I$ are changed separately or together. The value of CP/I is held constant for this graph and at the approximate optimum value for the basic configuration, CP/I equal to 0.41. The atmospheric turbulence for this graph is also held constant and always approximates the same "medium gusty day." Canned turbulence or artificial gust inputs were utilized and all flights were conducted in smooth, early morning calm air conditions. The disturbance levels felt by the pilot vary with $M_u g/I$ since the level of the pitch response to gusts is proportional to this parameter. On Figure 2, the pilot always flies under the same simulated atmospheric turbulence conditions but the aircraft's pitch response does change according to the value of $M_u g/I$.

The graph illustrates pilot opinion rating for changes in velocity stability (M_u) and damping (M_q) for precision hovering and low speed flight in medium gusty turbulence. Again, pitch damping D/I (the stronger the better, given enough control power) is always desirable and pilot opinion improves with increasing D/I. A much stronger effect is evident for changes in the velocity stability M_u. The graph shows a change in Cooper rating of about 3 or 4 rating units for the range of $M_u g/I$ covered. For a constant D/I (the aperiodic root remains approximately constant), changes in M_u change the period and damping of the oscillatory mode (Equation 7). However, as mentioned in the Dynamic Analysis, changes in Cooper rating as M_u is varied (at constant D/I) may be caused by aircraft gust response and control displacement for trim as well as by changes in aircraft oscillatory dynamics.

In order to determine which of these three effects predominated in the deterioration of Cooper rating as $M_u g/I$ increased, special configurations (designated by *) with modified disturbance levels were compared to selected standard configurations. For this purpose, typical configurations such as numbers 2, 11 and 11* are discussed below. The longitudinal dynamics and values of D/I, CP/I, and $M_u g/I$ may be obtained from Table 4 for configurations 2 and 11. (Triangle and square symbols on Figure 2.) Configuration 11* is a special case of configuration 11 and is described below.

Configuration number 2. (Triangle symbol) The disturbance level was set at the correct and computed low level commensurate with the medium gusty day and the low value of $M_u g/I$ for this configuration. The general Cooper rating for configuration number 2 is about a 3.2. The pilots felt that this configuration was a considerable improvement over the basic HUP; (configuration number 5) "damping appeared quite good," "quite steady in hovering over the pylons," "response to gusts was very much reduced as compared to the basic HUP," and "gained a lot of confidence in maneuvering."

Configuration number 11. (Square symbol) The disturbance level was set at the correct and computed high level commensurate with the medium gusty day and the high value of $M_u g/I$ for this configuration. The general

Cooper rating for configuration number 11 is about 6.6. The pilots felt that this configuration represented a considerable deterioration in general; "very strong gust disturbances," "speed stability too high," "used very large control excursions," "probably could land aircraft in emergency without turning it over," "very poor configuration" and "slightly dangerous."

Configuration number 11*. The static and dynamic stability characteristics of this configuration are exactly identical to configuration number 11, but the disturbance level was set to a low level equal to that used in configuration number 2. However, the oscillatory period and damping between configuration number 2 and number 11* are considerably different (Table 4). Also, the stick displacement for trim is much larger for configuration 11* than for configuration number 2 because of the large difference in the values of the velocity stability. The general Cooper rating for 11* is approximately 3.2 for purely hovering conditions and a higher rating of approximately 4.5 for forward flight. In general, the pilots felt that there was not too much difference between configuration number 11* and number 2 in hovering. Configuration 11* was "a little bit less steady (than configuration number 2) but generally comparable," "could do a good job," and felt "it's not bad at all in hover." They said "it has excessive speed stability," "too much stick travel," "stick displacements are too large," "apprehension of running out of control in forward flight," "handling qualities are better in hover than in forward flight." When rating this configuration for the specific task of hovering, the pilots generally rated it the same as configuration 2. However, when in forward flight they changed their rating to the 4 - 5 region because of fear of running out of control and too much static stick displacement. Generally, they felt that the angular damping of configuration number 11* was adequate and were not too concerned with the oscillatory period and damping.

In adjacent flights which involved hovering only, configurations number 2 and 11* were practically indistinguishable whereas between 11 and 11* the differences were pronounced. From many sets of results similar to these, it was determined that essentially none of the change in pilot rating due to changes in $M_u g/I$ (Figure 2) could be charged against attending changes in oscillation period and damping. In hover, speed variations were small so that trim differences could not be noticed; however, when asked to rate 11* in forward flight, the pilots immediately objected to the large control displacements required for trim (associated with high M_u of 11*). This caused all pilots to rate 11* in forward flight an average of approximately one to one and a half units worse than 11* in hover due to this control displacement complaint. It seems that of the total change in rating between configurations 2 and 11 about a third of the effect of $M_u g/I$ on the rating is attributed to the undesirable stick position for trim. The remainder of rating change is clearly associated with the changes in gust sensitivity due to the variations in velocity stability. Very little change in rating is attributed to the change in aircraft oscillatory dynamics, although the oscillation period and damping varied significantly for the range covered (See table below).

Conf. No.	$\frac{CP}{I}$	$\frac{D}{I}$	$\frac{M_u g}{I}$	Dynamics Change Due to Changes in M_u			Disturbance Level (Normally Proportional to Velocity Stability.)	Pilot Rating For Hover Only	Pilot Rating For Hover And Slow Flight	Remarks
				Oscillatory Mode		Aper. Mode				
				Period	T_2	$T_{1/2}$				
2	0.41	1.98	0.28	17.1	14.5	0.34	Set at Low Level For Low M_u	Fig.2 3.2	Fig.2 3.2	General Rating of 3.2
11	0.41	1.98	3.38	5.6	3.4	0.27	Set at High Level For High M_u	Fig.2 6.6	Fig.2 6.6	General Rating of 6.6
11*	0.41	1.98	3.38	↓	↓	↓	Modified: Set at Level for Conf. #2	Approx Same as #2 $\approx$ 3.2	Approx. 4.5	Rating Incr. in Slow Flt. Due, Large Cont. Disp.

Some evaluation pilots offered the opinion that since they were constantly applying control inputs to counter gusts, they felt that only the initial response characteristics were important and that the period would have to be less than about 3 seconds before they would find it offensive and alter pilot rating significantly due to the period of the oscillatory mode. For such extreme variations giving oscillation periods of less than 3 seconds, certainly some influence could be expected. But, short periods like that would only occur in the very unfavorable areas of Figure 2 which are probably not of practical interest anyway. This can be seen from equation 7 and the illustration on page 4 , showing that lines of constant oscillation period on Figure 2 would be straight rays through the origin, and the one for a three second period goes almost through the point $M_u g/I = 4$; $D/I = 1$. Shorter periods are below this line in the unacceptable zone.

Review of Longitudinal Handling Qualities Data

The previous discussion represents the results of the research conducted for this program. Numerous other handling or flying qualities studies have been conducted by other companies and agencies.

Figure 6

In Figure 6, the Princeton data of Figure 1 are compared with Reference 8. The latter was a simulator study (visual flight) in which "...pilots rated...the longitudinal modes by evaluating the dynamic and control characteristics separately in still air and then giving an overall rating in slightly turbulent air." The ccordinates of the figure are control power M_δ and the damping of the oscillatory mode expressed in time $T_{1/2}$, rather than the frequency-dependent cyclic damping parameter $C_{1/2}$. Therefore, the exact manner in which M_u, M_q, and X_u is varied need not be specified except by the general relationships in the characteristic equation. The data of Figure 1 (iso-opinion lines 3.5, 4.0, 4.5, and 5.0) are located to the left of the neutral oscillation line or the unstable region in which most helicopters and V/STOL aircraft are located for the case of hovering and slow flight. The pilots used in the Princeton program seemed to be more tolerant of helicopter type configurations than the pilots of Reference 8. Eight pilots were used in the simulator program of Reference 8. Two were current helicopter pilots and the remaining were conventional aircraft pilots. A general interpretation of Reference 8 would rate many current helicopters in the region of Cooper rating 5, "Unacceptable for normal operation," and doubtful whether a primary mission can be accomplished. Although Reference 8 found no discernible shifts in the level of ratings given by their helicopter pilots and their conventional aircraft pilots, it would seem that airplane pilots would be less tolerant of unstable modes of motion than helicopter pilots. Also, it is difficult to determine from Reference 8, the exact use of turbulence or disturbance inputs for each configuration and their relative influence on pilot opinion ratings of the different configurations.

Figure 7

In Figure 7, a few configurations from Princeton data Figure 2 and Table 4 are plotted for comparison with Reference 8. Since the control power is held constant for Figure 2 (CP/I = 0.41 rad/sec^2/in or M_δ = 23.5 deg/sec^2/in) all configurations of Figure 2 fall on the value of M_δ equal to 23.5. The values of $1/T_{1/2}$ are obtained from Table 4. As $1/T_{1/2}$ increases negatively for configurations 2, 5, and 11, pilot rating increases from approximately 3.2 to 4.1 to 6.6 or decreases for configurations 12 and 1 from a rating of 5.9 to 3.7. It is important to note that the configuration located by the square symbol (as well as other identically located configurations of Figure 2) may have a variety of different ratings (for one location on Figure 7) depending on method of variation and value of M_u, M_q and disturbance level. Pilot opinion rating for hovering and slow flight in turbulence is influenced more directly by the gust sensitivity and control displacement than by changes in oscillatory damping ($T_{1/2}$) as M_u is being varied at a constant D/I.

In fact, if one studies the illustration on page 4 of the Dynamic Analysis section (where the dashed curves are lines of constant damping of the oscillatory mode, i.e., $1/T_{1/2}$ equals a constant, for configurations of Table 4 and Figure 2) it is evident that according to Figure 2 pilot opinion varies considerably for configurations located on a particular constant oscillatory damping line; but, according to Reference 8 they would all be located on Figure 7 at a single point and should not show any rating change.

The influence of angular damping on pilot opinion is important and already well known. Given enough control power, ratings always improve as D/I is increased for the range investigated in Figure 2.

The new results indicate that it is impossible to express pilot rating as a simple function of $T_{1/2}$ since Figures 1 and 2 indicate that pilot opinion is a function of all the quantities D/I, CP/I and $M_u g/I$ and the effects of atmospheric turbulence.

Figure 8

In Figure 8, the Princeton data of Figure 1 are compared with Reference 7. Reference 7 was a flight program conducted several years ago using an S-51 single rotor helicopter. Various precision tasks such as visual hovering and instrument approaches were flown. Atmospheric turbulence is not specified. Considerable reliance for the data was based on pilot performance of instrument approaches conducted at speeds between 25 and 45 knots. The value of velocity stability for the S-51 aircraft is an order of magnitude smaller than that used for Figure 1. Differences displayed in Figure 8 may presumably be attributed to these differences in velocity stability and the character of the task. Also, high values of control power were more difficult to achieve by cyclic control (single rotor S-51) than by differential collective (tandem rotor HUP).

Figure 9

In Figure 9, the Princeton data of Figure 1 are compared with Reference 9. Reference 9 was a visual flight condition, simulator study in which the pilot controlled strictly pitch attitude. The value of $M_u g/I$ of Reference 9 for this figure is 1.16. Disturbance inputs to the attitude presentation were in the form of occasional one second step inputs simulating preselected levels of pitching acceleration.

Although the levels of velocity stability are approximately equal for this comparison of data, the types of gust inputs to each system are completely different. Also, there is some question of task similarity since controlling pitch attitude in a flight simulator appears to be a considerably less complex task than actual precision hovering in helicopters or V/STOL aircraft.

Figure 10

In Figure 10, the Princeton data of Figure 1 are compared with Reference 10. Reference 10 presents the results of a stationary flight simulator study for a 40,000 pound, supersonic, VTOL fighter of the deflected jet type. The pilots evaluated configurations under simulated instrument hovering flight conditions and utilized a special presentation provided by an oscilloscope that displayed all position information, altitude, pitch and roll attitudes. Atmospheric turbulence was used. The velocity stability was equal to zero. Different definitions and units were utilized in Reference 10. It is important to note that Reference 10 places a relatively low limit on the commanded pitching acceleration (rad/sec^2) available to the pilot. Control sensitivity (rad/sec^2/in) and damping (1/sec) were varied. In reference 10, use was made of a non-linear control system in order to obtain different sensitivities within the limits of the pitching acceleration available (0.44 rad/sec^2). In the Princeton research program, a linear control system was used and the maximum angular acceleration available was of a relatively higher value (basic HUP: 2.7 rad/sec^2). In Reference 10, the boundaries close and ratings deteriorate quickly as damping is increased, presumably because of the maximum limit on the pitching acceleration available to the pilot. In the Princeton research program it was always possible to provide the pilots with sufficient angular acceleration capability (rad/sec^2) and an optimum level of sensitivity (rad/sec^2/in) for a given D/I, and the boundaries did not close for the range of parameters investigated in Figure 1.

The existence of flat or wide ranges of almost constant pilot opinion for changes in control sensitivity at constant damping is noted for the conditions used in Reference 10.

Figure 11

In Figure 11, the Princeton data of Figure 1 are compared to Reference 11. This was a two-axis, two degree of freedom, simulator study where the pilot controlled attitude only. Still air, visual flight conditions with no gust disturbances were assumed throughout the evaluation. With respect to disturbances, Reference 11 states, "Although disturbances from gust and ground effects were not included as quantitative inputs to the simulator, since they constitute disturbances to the airplane which vary with different airplane configurations and VTOL concepts, the pilots included these effects qualitatively in making their evaluations."

It is difficult to determine (as in Reference 9 also) what part of the complex and difficult task of precision hovering an actual vehicle in flight is simulated by the relatively simple requirement of controlling attitude only in a simulator. Also, in reference to disturbance inputs it is not clear what effect or influence is displayed or how the pilots altered their ratings by "including these (disturbance) effects qualitatively in making their (Cooper rating) evaluations." Discrepancies between the two sets of data are therefore to be expected.

CONCLUSIONS

The following general conclusions are made for the range of parameters and test conditions studied in this report:

1. The range of values of the control power parameter CP/I for satisfactory handling qualities is relatively large and does not exhibit the sharp optimum shown by certain other investigations. Appreciably greater control power and somewhat higher angular damping are desired by pilots for precision hovering than had previously been determined. Strong angular damping (given enough control power) is beneficial.

2. The velocity stability parameter $M_u g/I$ has an important influence on pilot opinion of handling qualities for precision hovering and low speed flight in turbulence. Increases in the value of this parameter cause rapid deterioration of rating, principally because of the undesirable response of the aircraft to gusts. A secondary detrimental effect is the increased stick deflection required for trim. Very little change in rating is associated with changes in the oscillatory dynamics.

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Operating conditions	Adjective rating	Numerical rating	Description	Primary mission accomplished	Can be landed
Normal operation	Satisfactory	1	Excellent, includes optimum	Yes	Yes
		2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
Emergency operation	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes	Yes
		5	Unacceptable for normal operation	Doubtful	Yes
		6	Acceptable for emergency condition only*	Doubtful	Yes
No operation	Unacceptable	7	Unacceptable even for emergency condition*	No	Doubtful
		8	Unacceptable - dangerous	No	No
		9	Unacceptable - uncontrollable	No	No
	Catastrophic	10	Motions possibly violent enough to prevent pilot escape	No	No

*Failure of a stability augmenter.

TABLE 1: Cooper Pilot Opinion Rating System

TABLE 2: Pilot Training and Experience Summary

Pilot A graduate aeronautical engineer, NASA test pilot

wide flying experience, diversified flying time, 45 helicopter and V/STOL types, 160 airplane types, single and multi-engine, reciprocating and jet propelled.

total flight time	5000 hours
total helicopter and V/STOL hours	1200 hours
total fixed-wing hours	3800 hours

Pilot B graduate U.S.A.F. Test Pilot School (Edwards Experimental Flight Test Center), U. S. Army test pilot

wide flying experience, diversified flying time, 15 helicopter and V/STOL types, numerous airplane types, single and multi-engine, reciprocating and jet propelled.

total flight time	3000 hours
total helicopter and V/STOL hours	1000 hours
total fixed-wing hours	2000 hours

Pilot C graduate engineer, Cornell Aeronautical Laboratory test pilot

wide flying experience, diversified flying time, 7 helicopter types, numerous airplane types, single and multi-engine, reciprocating and jet propelled.

total flight time	6000 hours
total helicopter hours	300 hours
total fixed-wing hours	5700 hours

Pilot D graduate aeronautical engineer, NASA test pilot

wide flying experience, diversified flying time, 20 helicopter and V/STOL types, 100 airplane types, single and multi-engine, reciprocating and jet propelled.

total flight time	7000 hours
total helicopter and V/STOL hours	1000 hours
total fixed-wing hours	6000 hours

TABLE 2 (Continued)

Pilot E	graduate of U.S.A.F. Test Pilot School (Edwards Experimental Flight Test Center), U. S. Army test pilot	
	wide flying experience, diversified flying time, 11 helicopter and V/STOL types, numerous airplane types, single and multi-engine, reciprocating and jet propelled.	
	total flight time	4600 hours
	total helicopter and V/STOL hours	900 hours
	total fixed-wing hours	3700 hours

Conf. Number	OSCILLATORY MODE Period Sec.	OSCILLATORY MODE T_2 Sec.	APERIODIC MODE $T_{1/2}$ Sec.	$\frac{D}{I}$ $\frac{\text{ft-lbs/rad/sec}}{\text{slug-ft}^2}$	$\frac{CP}{I}$ $\frac{\text{ft-lbs/in}}{\text{slug-ft}^2}$	$\frac{M_u g}{I}$ $\frac{\text{(ft-lbs)}}{\text{(ft/sec)}}\ \frac{(\text{ft/sec}^2)}{(\text{slug-ft}^2)}$
4	7.5	3.0	0.47	0.99	0.41	1.13
+ 5	8.9	6.6	0.31	1.98	0.41	1.13
6	13.4	21.8	0.14	4.95	0.41	1.13
13	15.4	27.4	0.10	6.65	0.41	1.13
15	15.4	27.4	0.10	6.65	0.63	1.13
16	13.4	21.8	0.14	4.95	0.63	1.13
17	8.9	6.6	0.31	1.98	0.63	1.13
18	7.5	3.0	0.47	0.99	0.63	1.13
19	7.5	3.0	0.47	0.99	0.21	1.13
20	8.9	6.6	0.31	1.98	0.21	1.13
21	13.4	21.8	0.14	4.95	0.21	1.13
22	15.4	27.4	0.10	6.65	0.21	1.13
23	15.4	27.4	0.10	6.65	0.82	1.13
24	7.5	3.0	0.47	0.99	0.82	1.13
25	8.9	6.6	0.31	1.98	0.82	1.13
26	15.4	27.4	0.10	6.65	0.72	1.13
27	8.9	6.6	0.31	1.98	0.72	1.13
28	7.5	3.0	0.47	0.99	0.72	1.13
+ Basic HUP						

TABLE 3: Configurations Tested for $\frac{D}{I}$ vs $\frac{CP}{I}$ Graph.

Conf. Number	OSCILLATORY MODE Period Sec.	T_2 Sec.	APERIODIC MODE $T_{1/2}$ Sec.	$\frac{D}{I}$ $\frac{\text{ft-lbs/rad/sec}}{\text{slug-ft}^2}$	$\frac{CP}{I}$ $\frac{\text{ft-lbs/in}}{\text{slug-ft}^2}$	$\frac{M_u g}{I}$ $\frac{(\text{ft-lbs})}{(\text{ft/sec})}\frac{(\text{ft/sec}^2)}{(\text{slug-ft}^2)}$
1	13.2	6.5	0.59	0.99	0.41	0.28
2	17.1	14.5	0.34	1.98	0.41	0.28
3	26.6	27.6	0.14	4.95	0.41	0.28
4	7.5	3.0	0.47	0.99	0.41	1.13
+ 5	8.9	6.6	0.31	1.98	0.41	1.13
6	13.4	21.8	0.14	4.95	0.41	1.13
7	5.7	2.2	0.40	0.99	0.41	2.25
8	6.6	4.3	0.29	1.98	0.41	2.25
9	9.5	17.4	0.14	4.95	0.41	2.25
10	4.9	1.8	0.37	0.99	0.41	3.38
11	5.6	3.4	0.27	1.98	0.41	3.38
12	7.8	14.8	0.13	4.95	0.41	3.38
13	15.4	27.4	0.10	6.65	0.41	1.13
14	31.0	25.9	0.10	6.65	0.41	0.28
+ Basic HUP						

TABLE 4: Configurations Tested for $\frac{D}{I}$ vs $\frac{M_u g}{I}$ Graph.

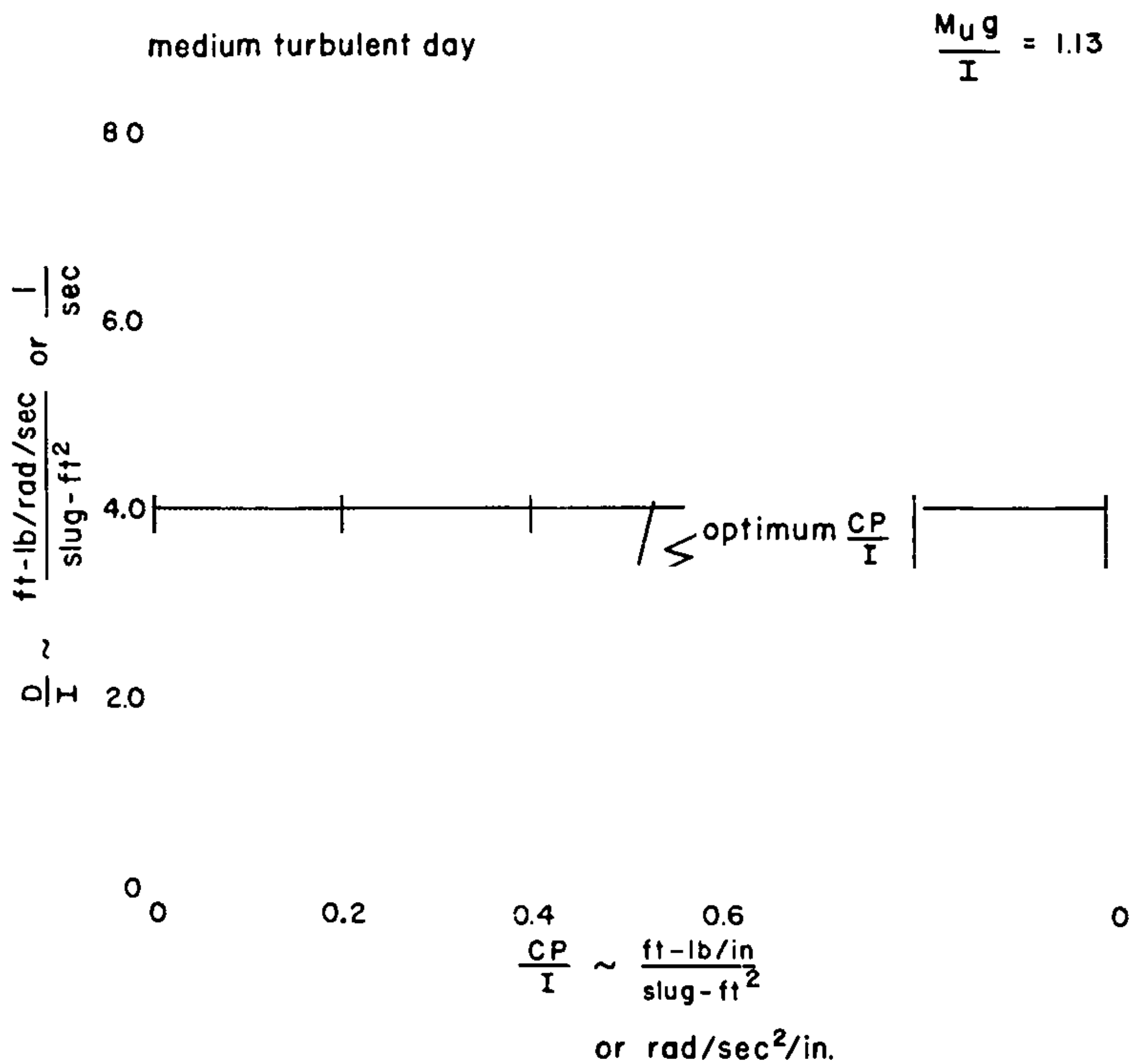


FIGURE I. LONGITUDINAL HANDLING QUALITIES BOUNDARIES

$\left(\frac{D}{I} \text{ vs } \frac{CP}{I}\right)$

medium turbulent day

$$\frac{M_u\, g}{I} \sim \frac{(ft-lb)}{(ft/sec)} \frac{(ft/sec^2)}{(slug\text{-}ft^2)}$$

FIGURE 2. LONGITUDINAL HANDLING QUALITIES BOUNDARIES

$$\left(\frac{D}{I} \text{ vs. } \frac{M_u g}{I}\right)$$

Config. ① 10°/sec

$\frac{M_u g}{I}$ increasing ↓

10°/sec.

$\frac{M_u g}{I}$ increasing ↓

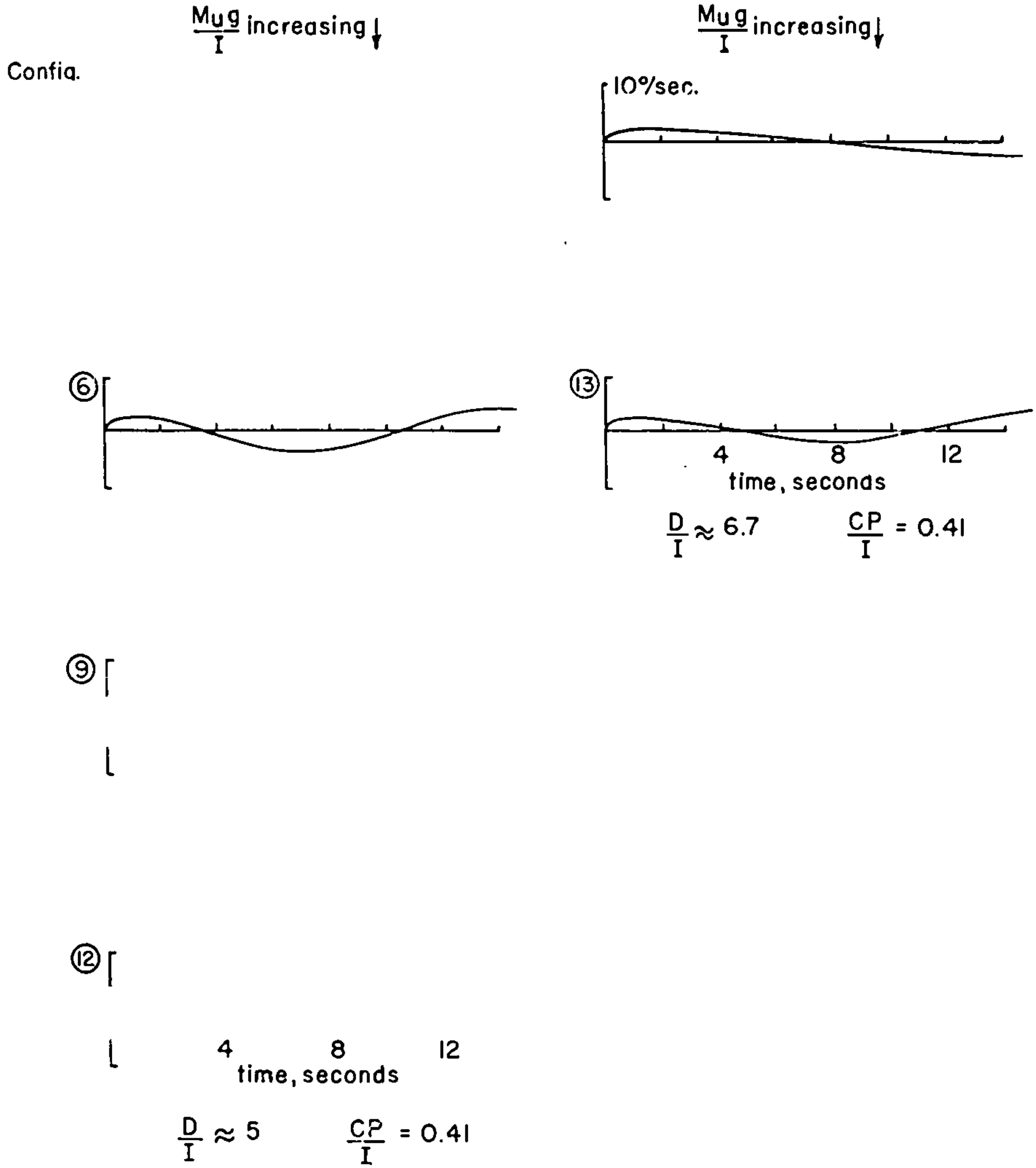
8 12
time, seconds

$\frac{D}{I} \approx 1.$ $\frac{CP}{I} = 0.41$

8 12
seconds

$\frac{D}{I} \approx 2.$ $\frac{CP}{I} = 0.41$

FIGURE 4A. ANALOG COMPUTER PITCH RATE RESPONSES TO STEP INPUT OF 1/2" LONGITUDINAL CONTROL



Mug/I increasing
Mug/I increasing
Config.
10%/sec.
6
13
4
8
12
time, seconds
D/I ≈ 6.7
CP/I = 0.41
9
12
4
8
12
time, seconds
D/I ≈ 5
CP/I = 0.41

FIGURE 4B

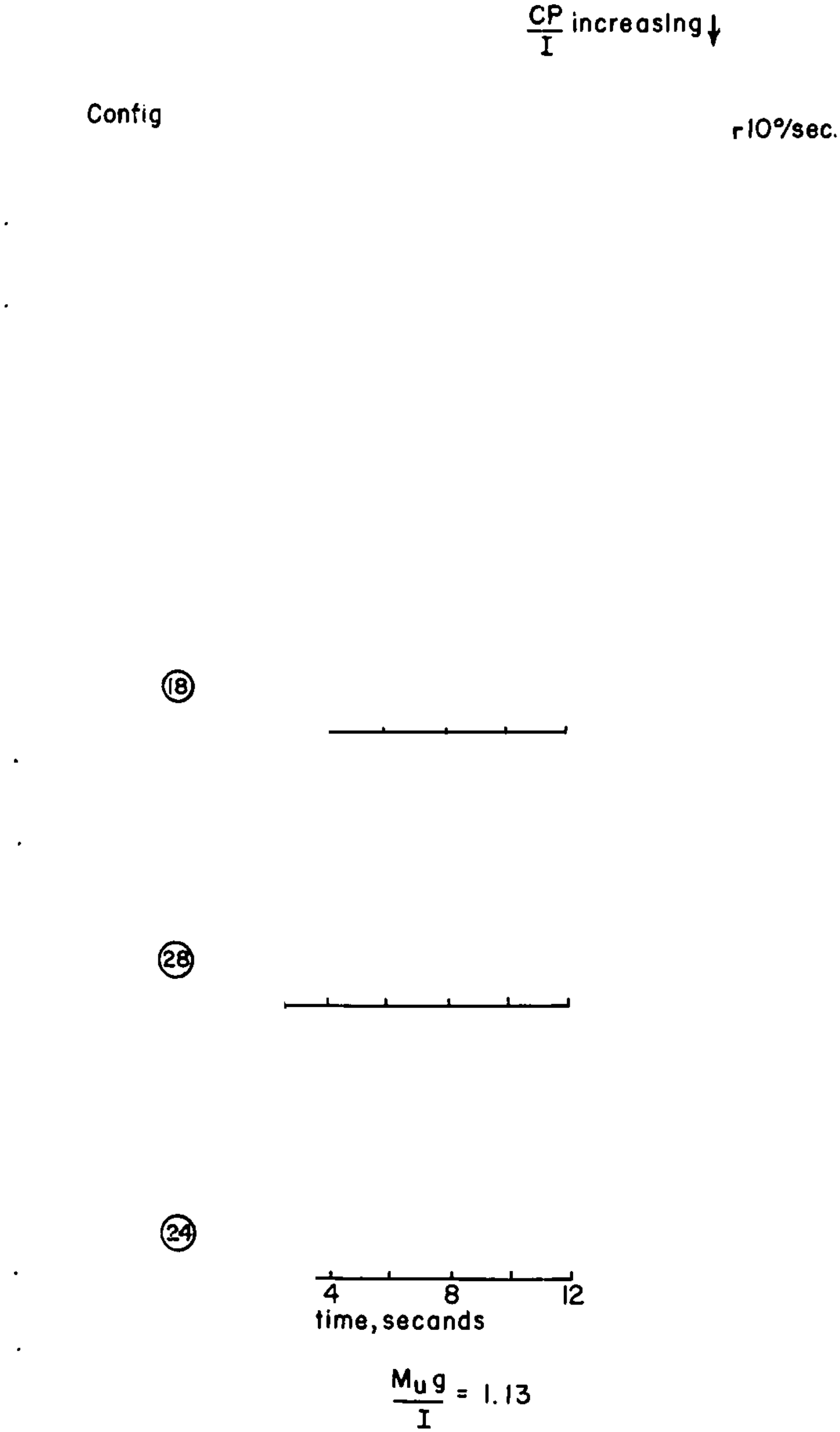

$\frac{CP}{I}$ increasing ↓
Config
r 10°/sec.
18
28
24
4
8
12
time, seconds
$\frac{M_u g}{I} = 1.13$

FIGURE 4C

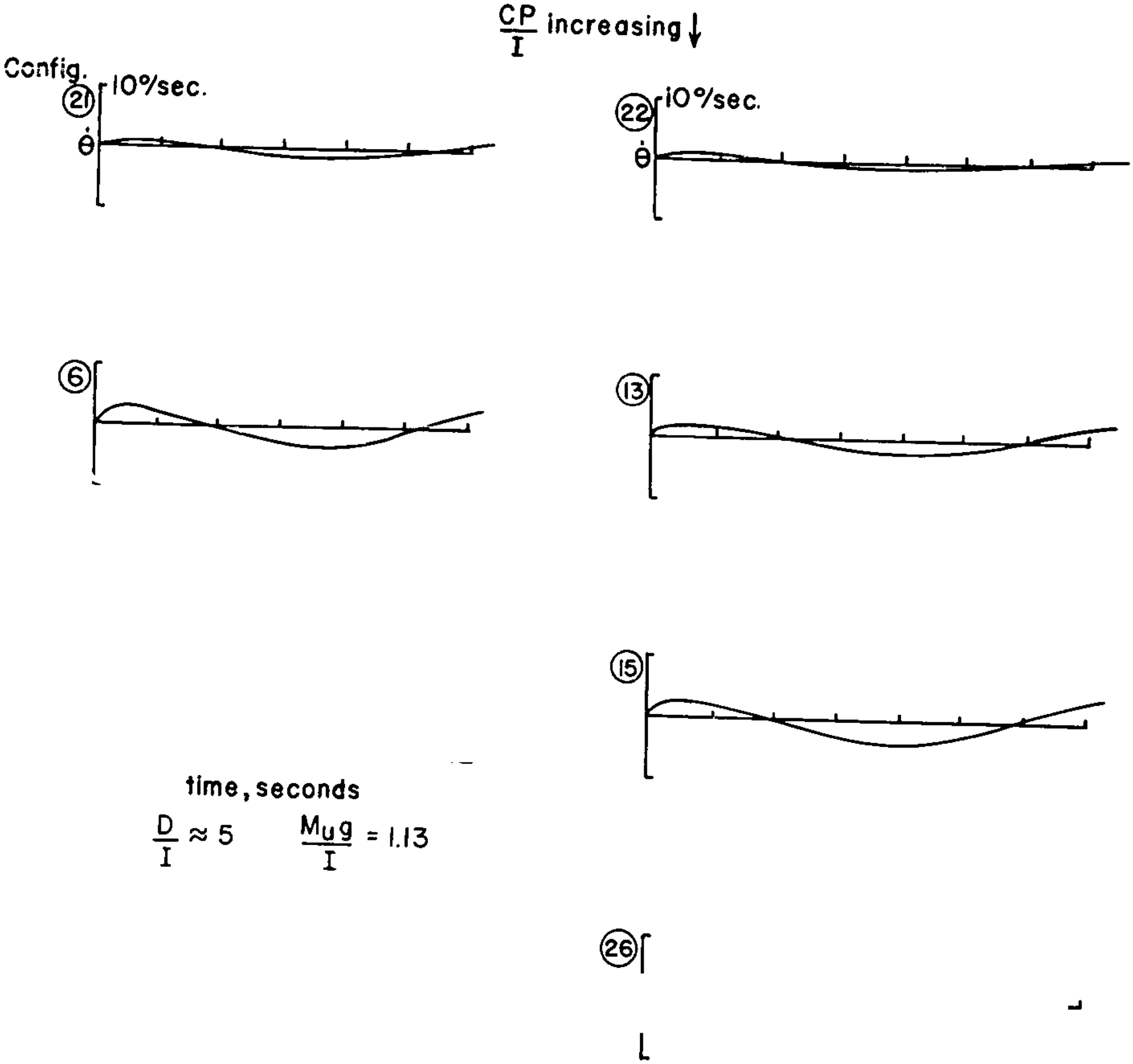

CP/I increasing ↓
Config.
21
10°/sec.
θ̇
22
10°/sec.
θ̇
6
13
15
26
time, seconds
D/I ≈ 5
Mug/I = 1.13

FIGURE 4D

$\frac{CP}{I}$ increasing

$\frac{M_u g}{I} = 1.13$

$\frac{D}{I} \approx 1$

$\frac{CP}{I}$ increasing

$\frac{M_u g}{I} = 1.13$

$\frac{D}{I} \approx 6.7$

$\frac{D}{I}$ increasing

$\frac{M_u g}{I} = 1.13$

$\frac{CP}{I} \approx 0.6$

FIGURE 5A. SUPERPOSED ANALOG COMPUTER PITCH RATE RESPONSES TO STEP INPUT OF 1/2" CONTROL FOR CONFIGURATIONS OF FIGURE 1.

increasing

$\frac{CP}{I} = 0.41$

$\frac{D}{I} \approx 1$

$\frac{D}{I}$ increasing

$\frac{CP}{I} = 0.41$

$\frac{M_u g}{I} \approx 0.3$

$\frac{D}{I}$ increasing

$\frac{CP}{I} = 0.41$

$\frac{M_u g}{I} \approx 3.4$

FIGURE 5B. SUPERPOSED ANALOG COMPUTER PITCH RATE RESPONSES TO STEP INPUT OF 1/2" CONTROL FOR CONFIGURATIONS OF FIGURE 2.

- - - - Princeton University (Data from Fig. 1)

Medium Gusty Day (Constant)

$M_u g/I = 1.13$ (Constant)

D/I, CP/I or (M_δ) varied as specified by Fig. 1

——— Fig. 5 of Ref. 8

M_u, M_q, X_u (varying but in unspecified manner)

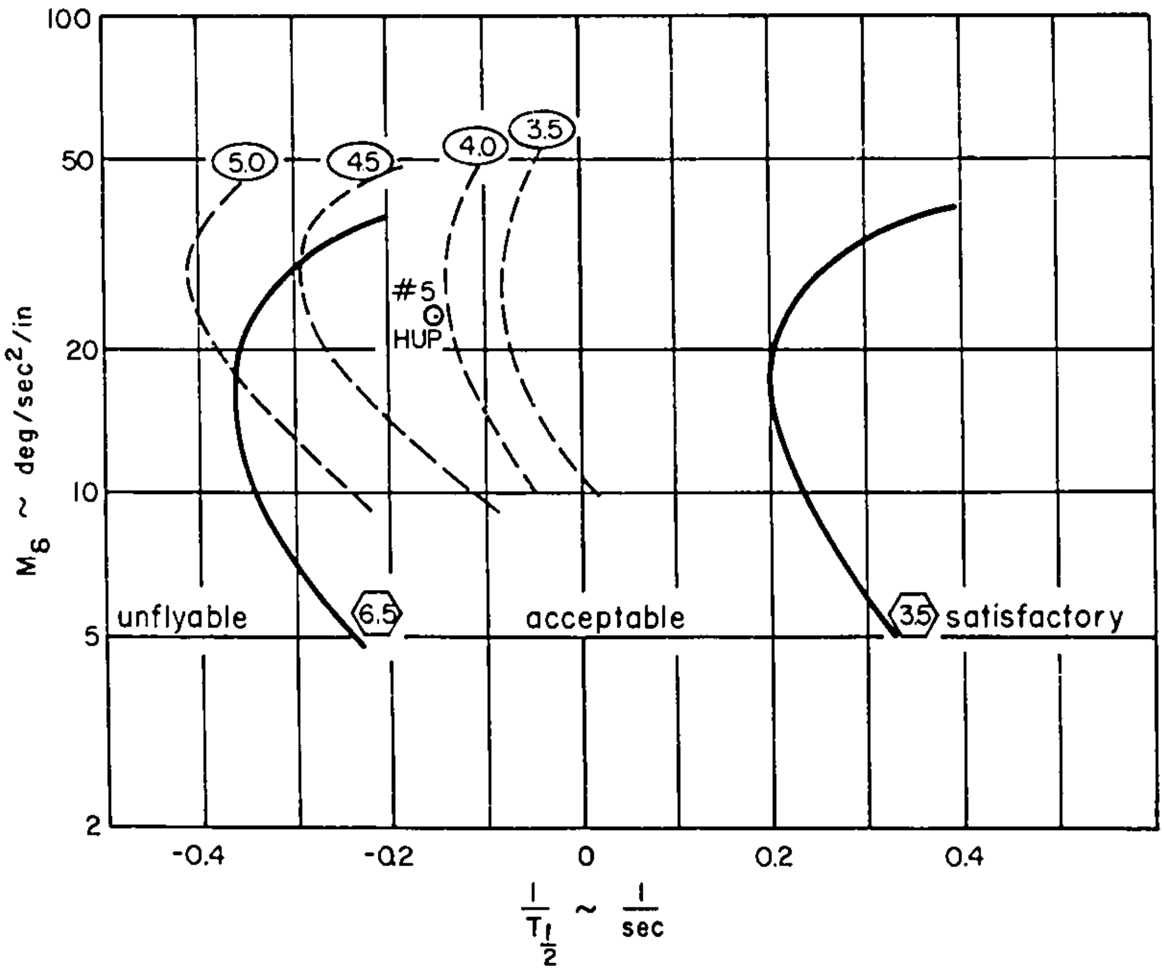


FIGURE 6. LONGITUDINAL HANDLING QUALITIES DATA

——— Fig. 5 of Reference 8

M_u, M_q, X_u (varying but in an unspecified manner)

Princeton University (data from Fig. 2 and Table 4)

Medium Gusty Day (Constant)

CP/I · 0.41 or M_δ 23.5 (Constant)

$M_u g/I$ varying

Conf.	$\frac{D}{I}$	COORDINATES M_δ	$\frac{1}{T_{1/2}}$	$\frac{M_u g}{I}$	Disturbance Level	Rating (Fig. 2)
C 1	0.99	23.5	0.15	0.28	low level for low M_u	3.7
C 5	1.98	23.5	0.15	1.13	medium level for basic HUP	4.1
C12	4.95	23.5	0.07	3.38	high level for high M_u	5.9
C 2	1.98	23.5	0.07	0.28	low level for low M_u	3.2
C11	1.98	23.5	0.29	3.38	high level for high M_u	6.6
C11*	1.98	23.5	0.29	3.38	MODIFIED: low level same as C 2	3.2 hover 4.5 low speed

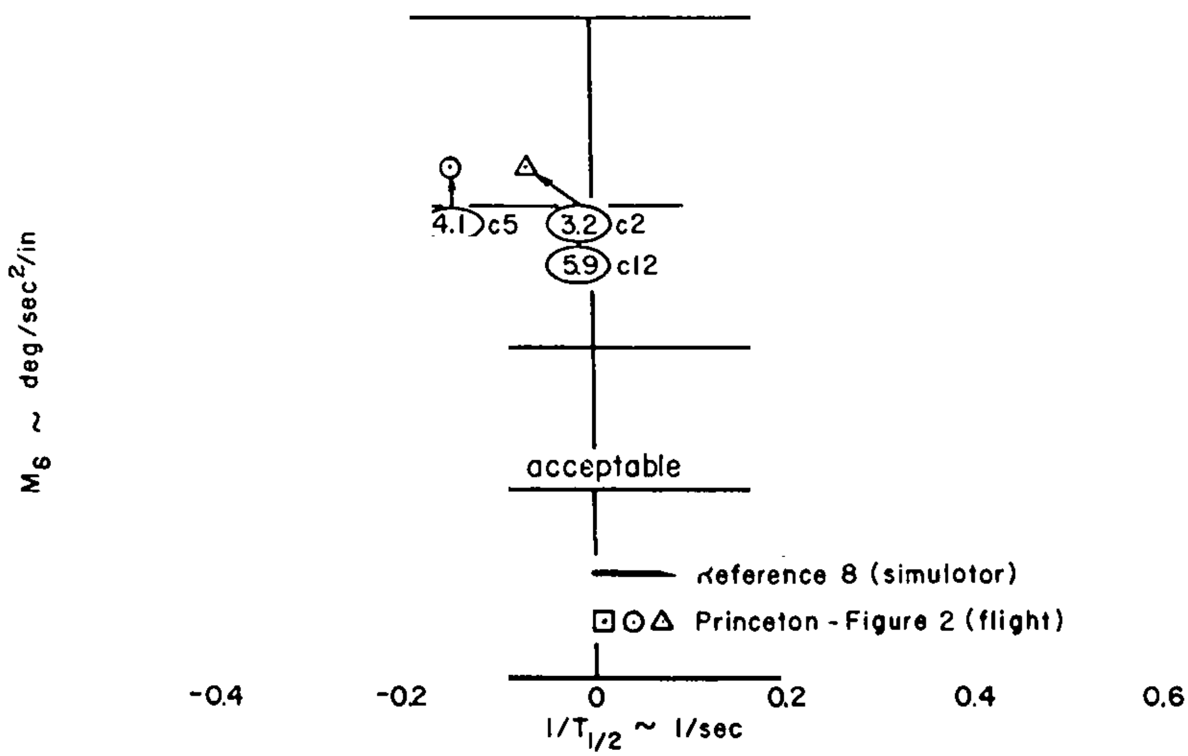


FIGURE 7. LONGITUDINAL HANDLING QUALITIES DATA

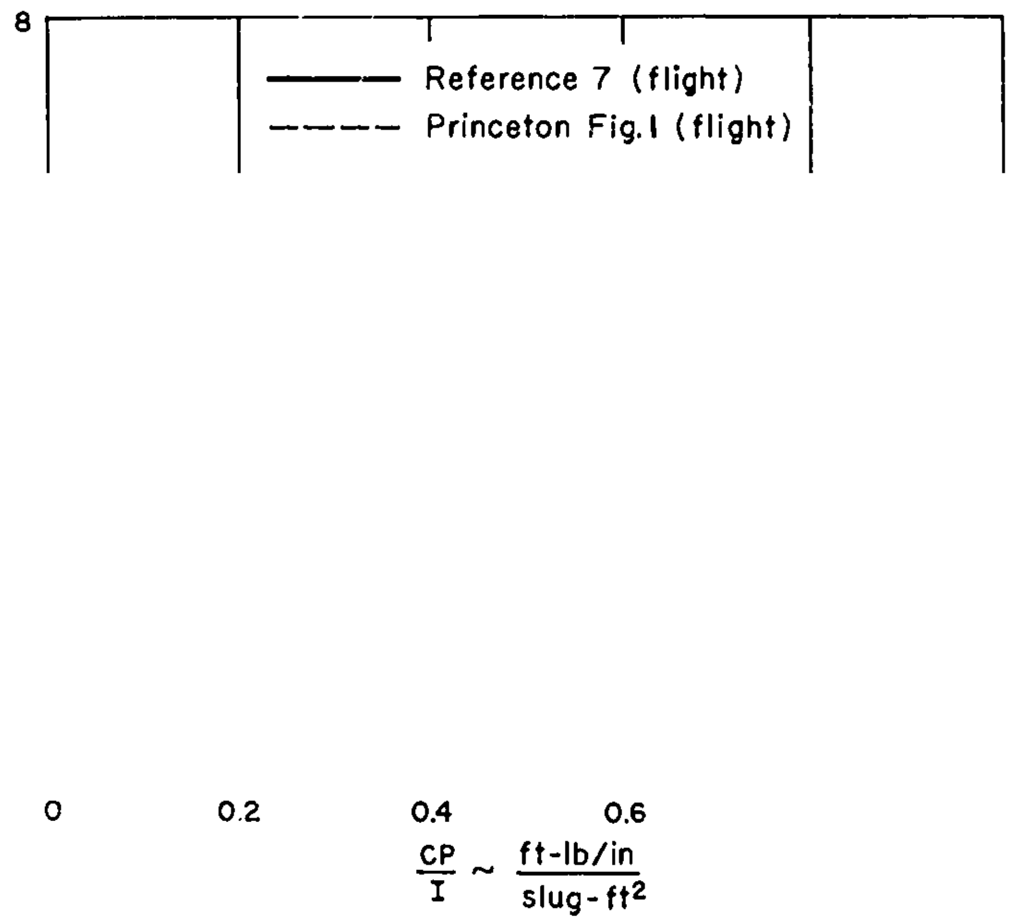


FIGURE 8. LONGITUDINAL HANDLING QUALITIES DATA

Reference 9, Fig.2, (simulator)

——— Princeton Fig.1 (flight)

slug-ft^2

FIGURE 9. LONGITUDINAL HANDLING QUALITIES DATA

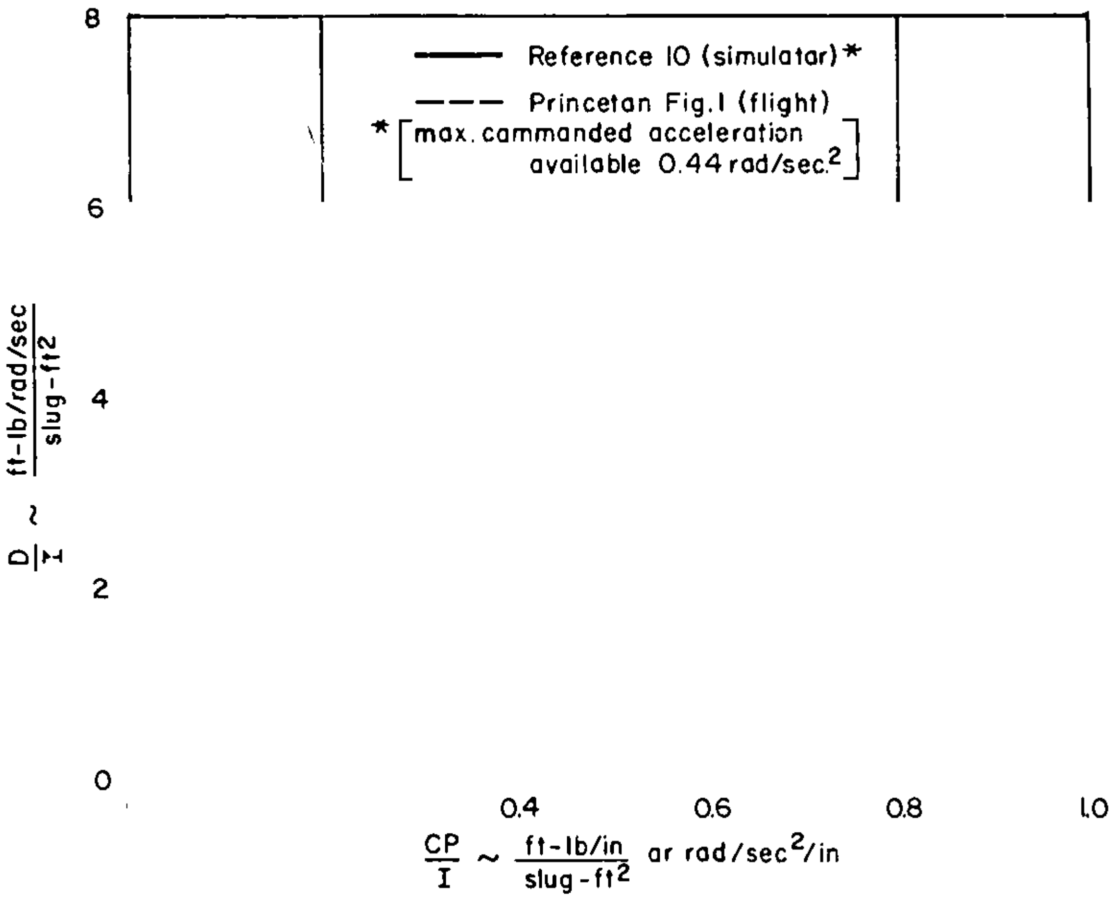


FIGURE 10. LONGITUDINAL HANDLING QUALITIES DATA

$\frac{D}{I} \sim \frac{\text{ft-lb/rad/sec}}{\text{slug-ft}^2}$

slug-ft^2

FIGURE II. LONGITUDINAL HANDLING QUALITIES DATA

APPENDIX 1

Turbulence Analysis

The handling qualities associated with flying in turbulent air were simulated by introducing a canned random input to the helicopter pitch and roll moment controls. The nature of this input was determined from the available atmospheric data. The proper turbulence spectrum was obtained by passing "white" noise through a first order filter with a transfer function of

$$\frac{1}{1 + \frac{1}{.314} S}$$

This signal was mechanically recorded and used for all flight configurations. The disturbance level was set to approximate a medium gusty day. Pilots familiar with the characteristics of the basic HUP-1 in turbulent air were also consulted to verify the degree of the simulated turbulence.

The root mean square (RMS) level of the gusts about the mean wind over the entire frequency spectrum is 6.3 feet per second. The maximum gust encountered about the mean wind is 12.5 knots and occurs once every 2 minutes, the period of the gust recording.

An analysis was conducted to more closely correlate the output of the gust generator with recent atmospheric turbulence data (Reference 13). A further objective of the analysis was to verify the designed output of the gust generator.

Reference 13 indicates that the power spectrum of the turbulence for horizontal gusts follows the empirical law

$$\varphi(\omega) = \frac{.139}{3.28} \times \frac{\tanh\left(20.8\frac{Z\Omega}{V}\right)}{\left(\frac{Z\Omega}{V}\right)^{2/3} \Omega}$$

where $\Omega = \frac{\omega}{3.28\,V}$

The above formula is based on a value of the mean wind (V) at 300 feet altitude and a roughness length of 3 feet (Reference 14). At the higher frequencies, the hyperbolic tangent is approximately one, and the power spectrum follows an inverse 5/3 power law with frequency The power spectrum obtained by passing "white" noise through a first order filter follows an inverse square law for frequencies above the corner frequency of the filter.

The power spectrum of the gust generator was obtained by passing the output through a band pass filter and squaring the result on an analog computer. The points determined in this manner are shown in Appendix Figure 1. The theoretical curve of the gust generator is also plotted. The RMS value of the power spectrum of the gust generator and that of atmospheric turbulence (Reference 13) were matched between the frequencies ω = .314 rad/sec. (corner frequency of gust generator) and ω = 6.28 rad/sec. This corresponds to gusts having periods of 20 seconds down to one second. Time histories of pilot motions for all configurations indicate that the maximum pilot frequency is about 1 C.P.S. Also, the energy level at frequencies greater than 1 C.P.S. is low.

The value of the mean wind for which the RMS values are equal is 14.8 knots. An altitude of 20 feet was assumed for the equations since this was the approximate rotor height above the ground while hovering. The power spectrum of turbulence at 20 feet for a 14.8 knot mean wind is also plotted in Appendix Figure 1.

An attempt was made to express the turbulence in terms of the mean wind at other altitudes and different roughness lengths. No definite results were obtained in the time available because of the voluminous amount of data, most of which is in raw form, additional parameters which were not considered in Reference 13, and the difficulty of the problem in general.

The movement of the moment control per unit of gust velocity was determined from the expression

$$\frac{CP_{long.\ basic}}{I_y} \times \Delta\delta_{long.} = \frac{M_u g}{I_y} \times \frac{1}{g} \times \Delta u_{gust}$$

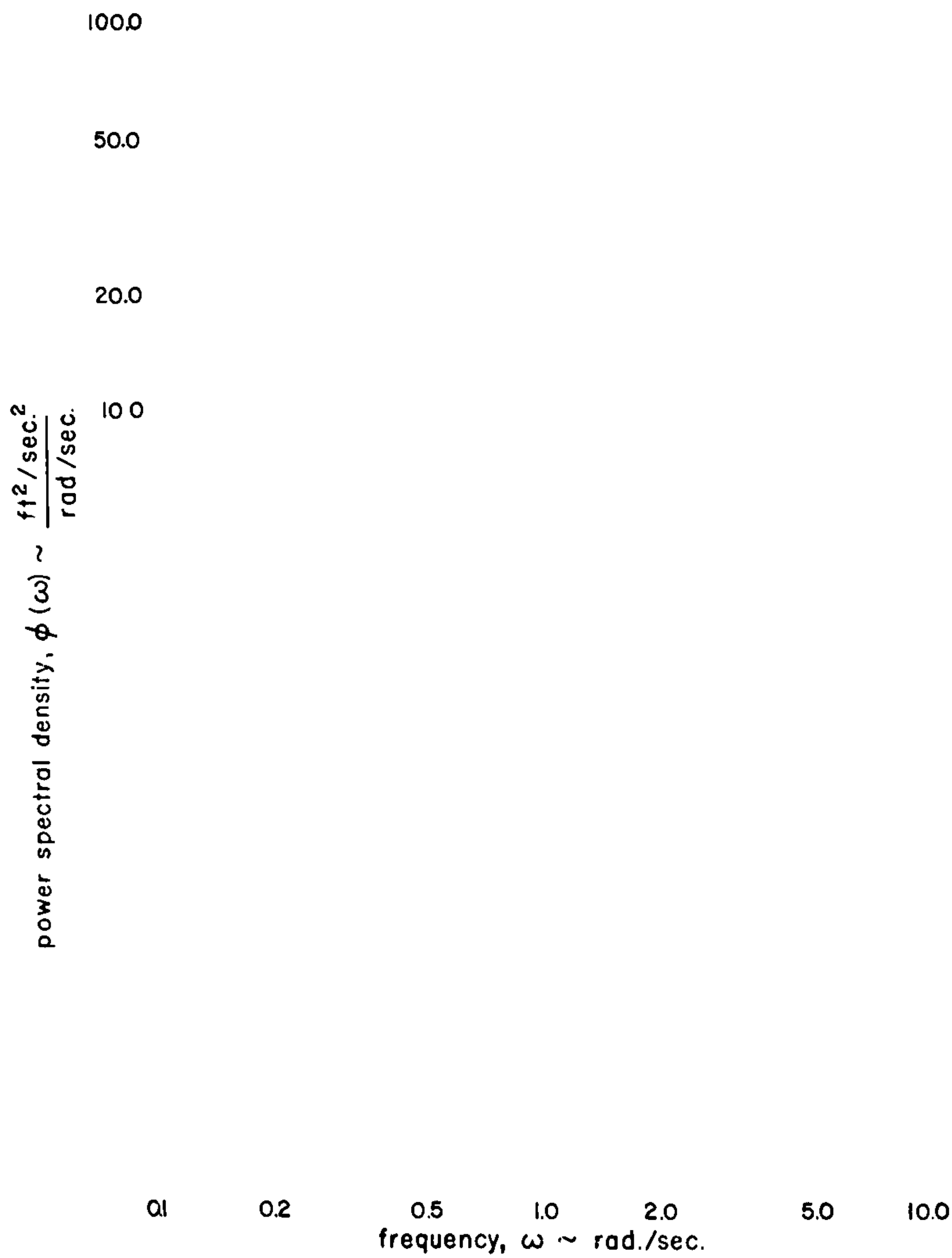
$$\Delta\delta_{long.} = \frac{M_u}{CP_{long.\ basic}} \times \Delta u_{gust}$$

A similar expression was used for the lateral mode

$$\frac{CP_{lat.\ basic}}{I_x} \times \Delta\delta_{lat.} = \frac{L_v g}{I_x} \times \frac{1}{g} \times \Delta v_{gust}$$

$$\Delta\delta_{lat.} = \frac{L_v}{CP_{lat.\ basic}} \times \Delta v_{gust}$$

In order to preserve harmony in the investigation, it was assumed that the value of L_v would change proportionally to changes in M_u. Therefore, the gust sensitivity in the two axes would be proportional. However, it was not possible to vary the dynamics resulting from changes in L_v from the basic value of the HUP-1 because of instrumentation limitations. The effect of changes in L_v was approximated by varying the lateral gust sensitivity while preserving the dynamics associated with the basic HUP-1 in the lateral mode. This technique is acceptable since the pilots were asked to evaluate only the longitudinal handling qualities, and the dynamics are of little interest to the pilot. The latter observation was determined from test configurations and is discussed in the text.

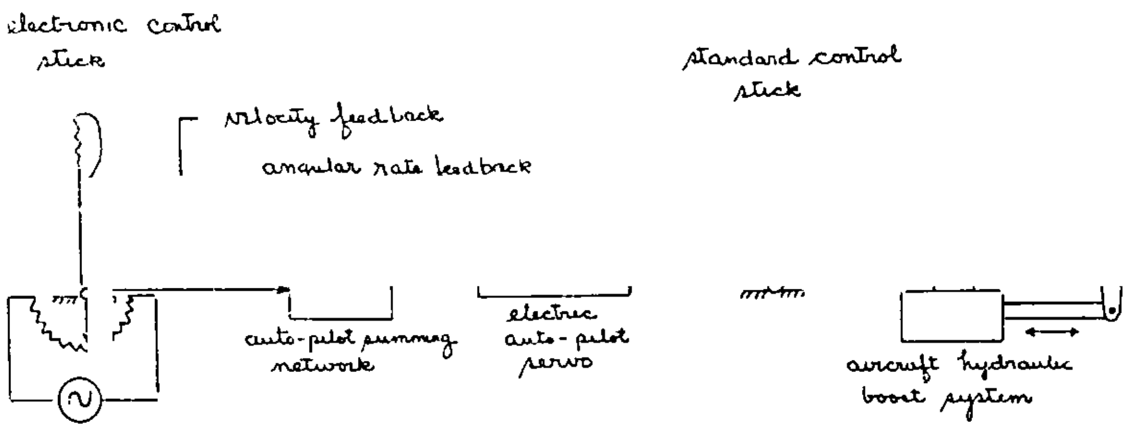


APPENDIX I FIGURE I. GUST GENERATOR POWER SPECTRUM

APPENDIX 2

Variable Stability Control System Response Analysis

The variable stability control system consists of the standard aircraft control system, a modified Minneapolis-Honeywell E-12 autopilot and its actuating servos, the pilot's electronic control stick, and the aircraft stability feedback elements, i.e., pitch rate gyros, velocity indicators, etc. As shown by the following schematic illustration, the inputs to the autopilot component (pilot's electronic control stick position, pitch rate, etc.) are summed algebraically, and the resulting output drives the electrical autopilot servo.



The standard control system is power boosted by the HUP-1 hydraulic system.

The pilot's electronic control stick is similar to the standard control stick in range of movement and general feel. There is no appreciable viscous damping, stiction, dead zone, or break-out force. The force gradients are constant and relatively light (gradient approximately 1 pound per inch for longitudinal and lateral electronic control stick).

The forward loop transfer function of the system (pilot's electronic stick position to rotor blade position) was determined by frequency response methods and approximated to a second order system of the form:

$$\frac{\omega_n^2}{s^2 + 2\zeta\omega_n + \omega_n^2}$$

The frequency response was conducted with the aircraft stability feedbacks disconnected. The electronic stick position was used as the input. The output was measured at the standard control stick and the rotor blade. Three complete frequency responses were obtained for standard control stick deflections of ± 1.9, ± 3.2, and ± 4.3 inches respectively. (The maximum travel of the standard control stick is 6.6 inches.) These amplitudes were adjusted at 0.1 cycles per second and the input displacements were held constant for each frequency response. Bode diagrams of the responses (electronic stick position to rotor blade position) are shown in Figures 1 and 2 of this appendix. Comparison of these curves with those of the electronic stick to standard control stick responses (not shown) indicated that the transfer function of the hydraulic boost system (or standard control system of the HUP-1) is essentially unity in the frequency range shown.

The damping factor, ζ, and the undamped natural frequency, ω_n, were determined from the gain frequency curve (Appendix 2, Figure 1). The rise time from 10% to 90% of the final value after a step input disturbance was derived from universal transient response curves and frequency response data. A step input disturbance was also applied to the system and the resultant rise time and damping factor is compared to the derived data in the following table:

Frequency Response			Step Response*		
Standard Control Stick Amplitude Inches	ω_n radians/sec	ζ	Computed Rise Time Secs	ζ	Measured Rise Time Secs
± 4.3	7.2	0.5	0.22	-	-
± 3.2	9.5	0.5	0.17	0.4	0.14
± 1.9	12.5	0.5	0.13	-	-

*Step input from zero to appropriate amplitude

The transfer function associated with input amplitudes of ± 1.9 inches was constructed from ω_n = 12.5 radians/second and ζ = .5:

$$\text{Transfer function} = \frac{156}{s^2 + 12.5s + 156}$$

$$= \frac{1}{0.0064s^2 + 0.08s + 1}$$

Flight test analysis of standard and electronic control stick displacements and frequencies for different configurations and pilots indicated that the <u>maximum</u> pilot input frequency is about 1 cps. During the flight experiments it was determined that the largest displacements of the standard control stick at this frequency are about ± 2.0 inches. These standard stick control displacements are much larger than the "normal" displacements used by the evaluation pilots (measured at the standard control stick) to stabilize the helicopter, and are probably associated with rapid recovery from gust disturbances, and, or other inputs, i.e., pitch rate and velocity feedback, etc. Also, the "normal" frequency of the pilot's inputs is somewhat lower. However, one pilot commented that at the higher control powers (large movement of rotor blade or standard control stick for small movements of electronic stick) he was beginning to detect what might have been objecticnable time lags in the control system.

It can be concluded that the transfer function associated with input amplitudes of $\pm$ 1.9 inches is a good representation of the control system for the evaluation flights. The characteristic time lag of the system is about 0.1 seconds. This "lag" was not noticeable to the pilots for most of the flight configurations.

gain, dbs

APPENDIX II FIGURE I. FREQUENCY RESPONSE OF SYSTEM FROM ELECTRONIC STICK TO ROTOR BLADE phase lag, deg.

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LONGITUDINAL HANDLING QUALITIES FOR HOVERING - E. Seckel, J. J. Traybar and G. E. Miller
Report No. 594, December 1961
64 pp. - illus.
Contract DA 44-177-TC-524
Project 9-38-01-000, Task 902
Unclassified Report

1. Airplanes, V/STOL handling qualities
2. Helicopters, handling qualities
3. Contract No. DA 44-177-TC-524

A series of flight tests with a number of qualified pilots and a variable stability helicopter was conducted to determine the effect of certain stability parameters.

The effect of velocity stability was determined to be of particular importance when hovering in atmospheric turbulence. The most important effect caused by the velocity stability is that the pitch disturbances felt by the pilot due to turbulence are essentially proportional to this parameter. Secondary effects are the control displacement and dynamics. The range of velocity stability variation was from practically zero, which was considered very favorable, to values that were unacceptable or even disastrous.

Also, additional investigations disclosed that somewhat higher angular damping and appreciably greater control effectiveness are desired by pilots for the precision hovering than had previously been determined.

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