Research on VTOL Aircraft Handling Qualities Criteria

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Analytical and flight simulator studies were conducted to examine the effects on selection of optimum longitudinal control sensitivity of 1) the oscillatory mode dynamics, 2) the stability derivatives M_q/I_y, X_u/m, and M_ug/I_y, and 3) the level of turbulence. An improved method for presenting handling qualities criteria was developed which permits construction of the optimum longitudinal control sensitivity line on a plot of pitch rate damping vs longitudinal control sensitivity (i.e., Tapscott's form of presentation) for any aircraft for which X_u/m and M_ug/I_y are known or can be estimated. In this method a constant slope is assumed for the optimum line; for each of three reference levels of turbulence, contours of constant intercept with the zero-damping axis are presented on the X_u/m vs M_ug/I_y plane, and contours of constant Cooper pilot rating are presented on the M_q/I_y vs M_ug/I_y plane for three values of X_u/m. Predictions of the optimum longitudinal control sensitivity line made using contours established in the United Aircraft Corporation (UAC) flight simulator are in good agreement with published flight-test data for the NASA X-14A VTOL research airplane and the Princeton HUP-1 variable stability helicopter.

Nomenclature

g = gravitational constant, 32.2 ft/sec²
I_x = moment of inertia in roll, slug-ft²
I_y = moment of inertia in pitch, slug-ft²
L_p = rolling moment due to roll rate, lb-ft/(rad/sec)
L_v = rolling moment due to lateral velocity, lb-ft/fps
L_δ = rolling moment due to unit lateral control stick displacement, lb-ft/in.
m = mass of aircraft, slugs
M_q = pitching moment due to pitch rate, lb-ft/(rad/sec)
M_u = pitching moment due to longitudinal velocity, lb-ft/fps
M_δ = pitching moment due to unit longitudinal control stick displacement, lb-ft/in.
$(M_\delta/I_y)_0$ = longitudinal control sensitivity at which the extended optimum line crosses the zero-damping axis (rad/sec²)/in.
PR = Cooper pilot rating, Table 1
T_2 = time to amplify to double amplitude, $0.693/-\zeta\omega_n$, sec
u, v = velocity components in x, y directions of stability axis system, fps
u_g, v_g = longitudinal and lateral components of gust velocity, respectively, fps
u_m = mean wind speed, fps
x, y = longitudinal and lateral coordinates in stability axis system, respectively, ft
X_u = longitudinal force due to longitudinal velocity, lb/fps
Y_v = side force due to lateral velocity, lb/fps
δ_P = longitudinal displacement of control stick from center of travel, in.
δ_R = lateral displacement of control stick from center of travel, in.
$(\Delta u)_{rms}$ = rms gust velocity fluctuation, $(\Delta u)_{rms} = 0.257\ u_m$, fps
ζ = damping ratio
θ = pitch attitude relative to horizon, rad
ϕ = roll attitude relative to horizon, rad
ω = damped frequency of oscillation, $\omega = \omega_n(1 - \zeta^2)^{1/2}$, rad/sec
ω_n = undamped natural frequency of oscillation, rad/sec

Superscripts

$(\dot{\ })$ = first derivative with respect to time, d/dt
$(\ddot{\ })$ = second derivative with respect to time, d^2/dt^2

Presented as Preprint 64-618 at the AIAA Transport Aircraft Design and Operations Meeting, Seattle, Wash., August 10–12, 1964; revision received November 30, 1964.
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Introduction

AT the present time, the most widely used method for presenting handling qualities criteria for VTOL aircraft in hovering and low-speed flight is the method generally accredited to Tapscott of NASA.[1] In this form of presentation, satisfactory regions are defined on a plot of rate damp-

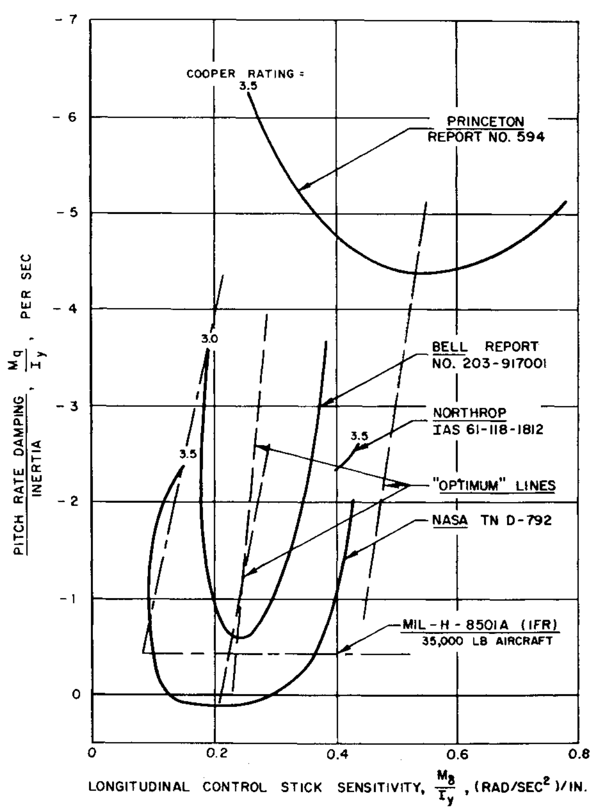

Fig. 1 Typical criteria for longitudinal handling qualities in hover.

ing vs control sensitivity. For example, Fig. 1 shows the results of several longitudinal handling qualities studies[2-5] on a plot of pitch rate damping M_q/I_y vs longitudinal control stick sensitivity M_δ/I_y. Combinations of damping and control sensitivity within the Cooper pilot rating 3.0 and 3.5 boundaries (Table 1) were found to be satisfactory in each particular study. The nearly vertical dashed lines within these satisfactory regions indicate the corresponding variations of optimum control sensitivity with damping.

It is apparent from Fig. 1 that considerable disagreement exists among the boundaries and corresponding optimum lines established by the various investigators. It was recognized by Tapscott[1] that differences in the mass and moment of inertia of the aircraft might cause some diagreement, and in a more recent flight-test study[5] the strong influence of the speed-stability derivative M_ug/I_y was clearly demonstrated. The experience of the authors in conducting a number of handling qualities studies led them to believe that, in addition to these factors, the oscillatory mode dynamics, the longitudinal stability derivative X_u/m, the level of actual or simulated turbulence, and the precision of the piloting task required were also important factors that had not been given adequate attention in previous studies. It was believed that, if the most important of these factors could be identified and shown to have significant and systematic effects on handling qualities, then improved methods for presenting criteria could subsequently be developed.

Accordingly, exploratory analytical and flight simulator studies have been undertaken at the UAC Research Laboratories to investigate comprehensive methods for presenting handling qualities criteria. The research reported in this paper has been concerned specifically with the factors that affect optimum longitudinal control sensitivity criteria. Further studies are planned in which both optimum and minimum satisfactory (Cooper pilot rating 3.5) criteria will be investigated.

V/STOL Aircraft Flight Simulator

The experimental program was conducted in the V/STOL aircraft flight simulator located in the Analog Computation Laboratory at the UAC Research Laboratories. This facility, which consists of a full-scale fixed-base Sikorsky S-61 helicopter cockpit with a Norden contact analog display system, is used by the Research Laboratories and the Sikorsky Aircraft Division of UAC for studying the performance and handling qualities of a wide range of helicopter and V/STOL aircraft configurations. Figure 2 shows the interior of the cockpit, the conventional helicopter-type controls, and the contact analog display.

The Norden contact analog system provides the pilot with an inside-out video picture of the motion of the aircraft relative to the earth. A number of different displays are possible, since in addition to the earth elements (the ground grid, horizon, and sky) a commandable pathway, two earth position markers, and two general-purpose screen elements are available. Figure 3 shows the contact analog display for the VTOL hovering and low-speed flight task. The cross indicated the position of the nose of the aircraft relative to the ground and hence remained fixed at the center of the viewing screen. The square traversed vertically on the screen and was used as a sensitive longitudinal position indicator. When the square was at the center of the screen (coinciding with the cross) the aircraft was located directly over a reference hovering position, such that the ground position indicator (also shown in Fig. 3) was approximately 135 ft ahead of the aircraft for the simulated hovering altitude of 40 ft. As the aircraft maneuvered 50 ft forward and rearward, with respect to the nominal reference hovering position, the square traveled to the bottom and top edges of the screen, respectively.

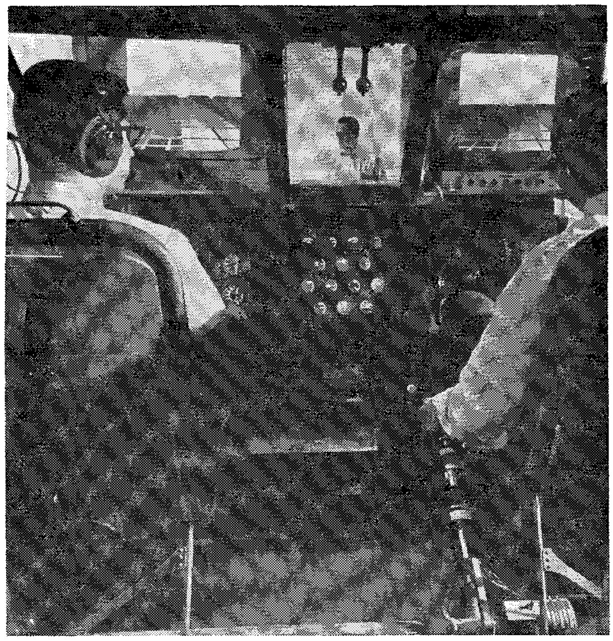

Fig. 2 United Aircraft Corporation V/STOL aircraft flight simulator.

Initial Basic Studies of Pursuit Tracking Task

Initial studies of a rather basic nature were conducted to investigate the effects of changes in the longitudinal oscillatory mode dynamics and the external disturbance on the opti-

Table 1 Cooper pilot rating system

	Adjective rating	Numerical rating		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[a]	Doubtful	Yes
No operation	Unacceptable	7	Unacceptable even for emergency condition[a]	No	Doubtful
		8	Unacceptable—dangerous	No	No
		9	Unacceptable—uncontrollable	No	No
	Catastrophic	10	Motions possibly violent enough to prevent pilot escape	No	No

[a] Failure of a stability augmenter.

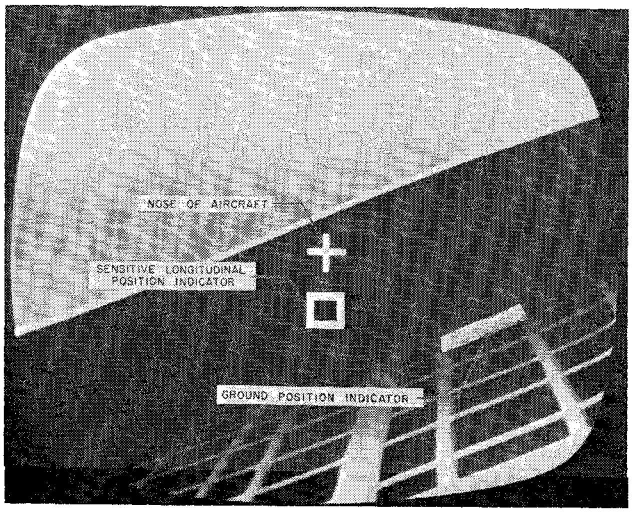

Fig. 3 Contact analog display for VTOL hovering task.

mum longitudinal control sensitivity line.[6] For these studies, the pilot was required to perform a pursuit tracking task of a randomly moving target using a more simplified contact analog display than that shown in Fig. 3. A generalized unstable system was simulated in which the equations of motion programed on the analog computer had the same mathematical form as the longitudinal equations of motion for a VTOL aircraft in hover. The following pertinent conclusions were drawn regarding the effects of the oscillatory mode dynamics on the optimum control sensitivity line on a plot of pitch rate damping M_q/I_y vs longitudinal control sensitivity M_δ/I_y:

1) For the wide range of oscillatory mode dynamics of interest in VTOL aircraft (frequency $0 \leq \omega \leq 1.0$ rad/sec and time to double amplitude $3.5 \leq T_2 \leq \infty$ sec), changes in frequency and time to double amplitude cause the slope of the optimum line and its intercept with the zero-damping axis to vary significantly and in a systematic manner. The slight decrease in slope with increasing frequency and the increase in intercept with decreasing time to double amplitude are illustrated in Fig. 4a.

2) More important, however, is the fact that, for the limited range of oscillatory mode dynamics that result in satisfactory handling qualities, i.e., Cooper pilot ratings less than 3.5, changes in frequency and time to double amplitude have a negligible effect on the slope and intercept of the optimum line. These dynamic characteristics are within the approximate ranges $0 \leq \omega \leq 0.5$ rad/sec and $7.0 \leq T_2 \leq \infty$ sec.

3) Increasing target speed in the tracking task (analogous to increasing the level of turbulence in the VTOL hovering flight task) causes a small increase in the slope of the optimum line and a very large increase in its intercept (see Fig. 4b); moreover, within the limited range of oscillatory mode dynamics that result in satisfactory handling qualities, changes in the optimum line due to changes in target speed are much greater than those due to changes in frequency and time to double amplitude.

4) The addition of a roll control compensatory task requiring lateral motions of the control stick in addition to those longitudinal motions required for the pitch task has a negligible effect on the slope of the optimum line, but causes a very large decrease in its intercept (typically, a decrease by a factor of 4 from the levels shown in Fig. 4).

Studies of VTOL Hovering Flight Task

After the initial basic studies had indicated that the oscillatory mode dynamics are of minor importance within the satisfactory range of handling qualities, attention was directed toward investigating the influence of the stability derivatives X_u/m and $M_u g/I_y$ and the level of turbulence. For these and all subsequent studies, a VTOL hovering task that required both precision hovering and low-speed maneuvering was simulated. The principal experimental results and an improved method for presenting optimum longitudinal control sensitivity criteria are discussed in the remainder of the paper.

Equations of Motion and Simulation of Turbulence

Equations governing the pitch, longitudinal velocity, roll, and lateral velocity degrees of freedom of a VTOL aircraft in hovering and low-speed flight were programed on an analog computer. The equations had the general form

$$\left.\begin{aligned} M_u u + M_q\dot{\theta} - I_y\ddot{\theta} &= -M_\delta\delta_P - M_u u_g \\ X_u u - mg\theta - m\dot{u} &= -X_u u_g \\ L_v v + L_p\dot{\phi} - I_x\ddot{\phi} &= -L_\delta\delta_R - L_v v_g \\ Y_v v + mg\phi - m\dot{v} &= -Y_v v_g \end{aligned}\right\} \quad (1)$$

where u_g and v_g are the longitudinal and lateral components of the turbulence, respectively (u_g and v_g consisted of a mean wind u_m plus filtered random fluctuations with time). The transfer functions for the pitch attitude response to a control input for both the VTOL hovering task and the previously discussed pursuit tracking task had the same zero and pole configuration; hence, the attitude response to a control input for both tasks was dynamically similar. Along with the addition of longitudinal velocity, roll, and lateral velocity degrees of freedom, the other major difference incorporated in the VTOL hovering flight equations was the manner in which the gust disturbances were introduced. For an actual aircraft, the gust disturbances upset the equilibrium of the aircraft through the stability derivatives X_u, M_u, Y_v, and L_v. Therefore, unlike the pursuit tracking task where the disturbances were presented on the contact analog screen and were independent of the controlled system dynamics, for the VTOL hovering task the gusts were inseparably linked to the zero and poles through the stability derivatives X_u, M_u, Y_v, and L_v. For all experimental data presented in this paper,

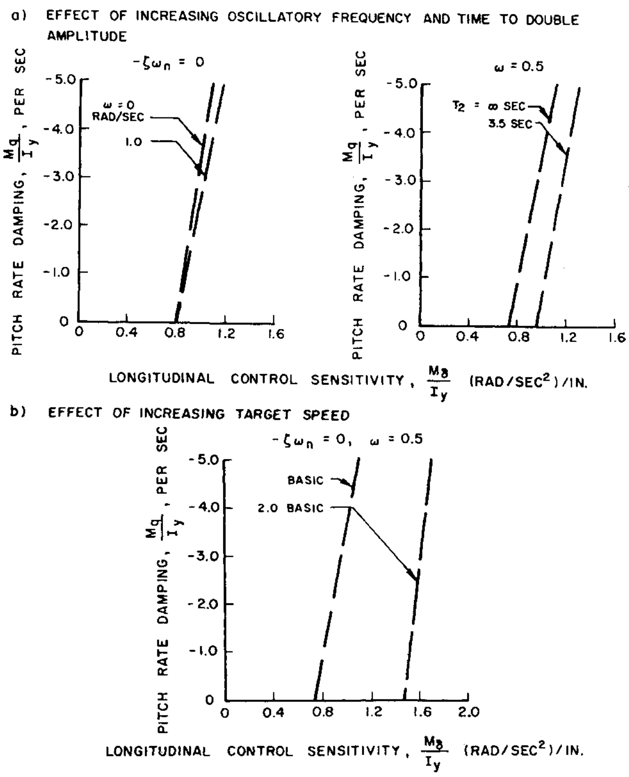

Fig. 4 Effects of oscillatory dynamics and target speed on optimum line.

the lateral stability derivatives were held constant at the following values: $Y_v/m = -0.20$, $L_v/I_x = -0.002$, $L_p/I_x = -4.0$, and $L_\delta/I_x = 0.556$.

The random component of the wind was generated by passing the output of a low-frequency random noise generator through a first-order filter having a break-point frequency of 0.314 rad/sec. This method is identical to that used for generating artificial turbulence for the flight tests of Ref. 5. In Ref. 5, it is shown that a filter of this form used in conjunction with a random noise generator having a uniform power spectrum at low frequencies produces artificial turbulence that correlates well with measured atmospheric turbulence. In the present study the level of turbulence was varied by varying the mean wind u_m while holding the rms value of the random component constant at approximately 25% of the mean wind $[(\Delta u)_{\text{rms}} = 0.257u_m]$.

Hovering and Low-Speed Flight Task

The pilot was required to maneuver about the hover point and to maintain position with respect to a point ahead of the aircraft marked by the ground position indicator on the contact analog ground plane (Fig. 3). The nominal reference position of the ground position indicator was 135 ft ahead of the aircraft and the hovering altitude was 40 ft. The maneuvers required rapid translation followed by momentarily holding position at points within an area bounded by distances approximately ± 50 ft longitudinally and ± 50 ft laterally from the nominal reference hovering position.

The pilot controlled longitudinal and lateral acceleration by tilting the thrust vector through pitching and rolling of the aircraft. Both the mean and random components of the wind were introduced into the pitching moment circuit, whereas only the random component of the wind was introduced into the longitudinal translation circuit. Thus it was assumed that the pilot would use auxiliary means, such as partial wing tilt or thrust deflection, to trim the mean headwind U_m while maneuvering around the hover point. This is an important consideration, since the nose-down pitch attitudes required to trim by tilting the entire aircraft become unacceptably large even at relatively low wind speeds. For example, a nose-down attitude of 7° would be required to trim an aircraft having $X_u/m = -0.20$ in a steady wind of only 20 fps.

In performing rapid maneuvers, the maximum longitudinal and lateral velocities developed were about ± 20 fps. Maximum pitch accelerations occurred at low values of damping; accelerations up to about ± 0.5 rad/sec^2 were recorded. Maximum translational accelerations were approximately $\pm 0.25\,g$.

Procedure for Selecting Optimum Control Sensitivity

Before discussing the results that are directly applicable to developing improved methods for presenting criteria, it is believed worthwhile to discuss the results of a brief study of the considerations that influence the pilot's selection of optimum control sensitivity. The stability derivatives of the HUP-1 helicopter were used for this particular study. The pilot was required to hover as precisely over the reference point as he could in a mean wind of 24.5 fps for periods of 100 sec. Damping was held constant, and a series of runs were made at each of five levels of control sensitivity. Figure 5 shows the resulting variations with control sensitivity of Cooper pilot rating, rms pitch attitude angle, rms pitch acceleration, rms longitudinal displacement from the hovering point, and rms longitudinal control displacement.

With increasing control sensitivity, pilot rating (Fig. 5a) improved up to M_δ/I_y of 0.5 to 0.6 (rad/sec^2)/in. and then deteriorated at higher control sensitivities. It was readily apparent to the pilot that the high pilot rating at low control sensitivities was attributable to the large control displacements required (Fig. 5e) and his inability to hold hovering position (Fig. 5d). Although the pilot continued to maintain hovering position accurately at control sensitivities higher than that where the best rating occurred, pilot rating increased because of the increased pitch accelerations (Fig. 5c) and to some extent because of the inadvertent upsetting pitch control inputs introduced when applying lateral control. The bandwidth of control sensitivities which the pilot would consider as "optimum" for the given level of damping is shown to be about ± 10 to 15% of the control sensitivity at the best rating.

The major conclusion to be drawn from Fig. 5 is that, whereas the lower limit of the bandwidth of control sensitivities that the pilot would consider as "optimum" is readily determinable from visual cues and level of pilot effort, the upper limit is more difficult to judge. Without motion cues, the pilot must rely on his visual impression of the "touchiness" of the aircraft (i.e., his visual impression of pitch accelerations) in setting the upper limit. Therefore, since these studies were conducted in a fixed-base simulator, the pilots were instructed to approach the final selection of optimum control sensitivity from the lower side of the bandwidth. On the basis of the close agreement between the UAC flight simulator data and flight-test data (discussed subsequently), it is concluded that this method of selecting optimum control sensitivity is fully appropriate for use in fixed-base simulators

Results of Studies of X_u/m, M_ug/I_y, and Level of Turbulence

Flight simulator data were obtained for nine combinations of X_u/m and M_ug/I_y within the ranges $-0.2 \leq X_u/m \leq 0$ and $0 \leq M_ug/I_y \leq +1.0$ for a mean wind $u_m = 20$ fps. For each combination, the pilot selected optimum control sensitivity and recorded his pilot rating for four or five levels of damping M_q/I_y in order to determine the slope and intercept of the optimum line and the associated variation of pilot rating. The results are summarized in Figs. 6 and 7, where the systematic variation of the data is quite apparent. It was found that straight lines having a slope $\partial(M_q/I_y)/$

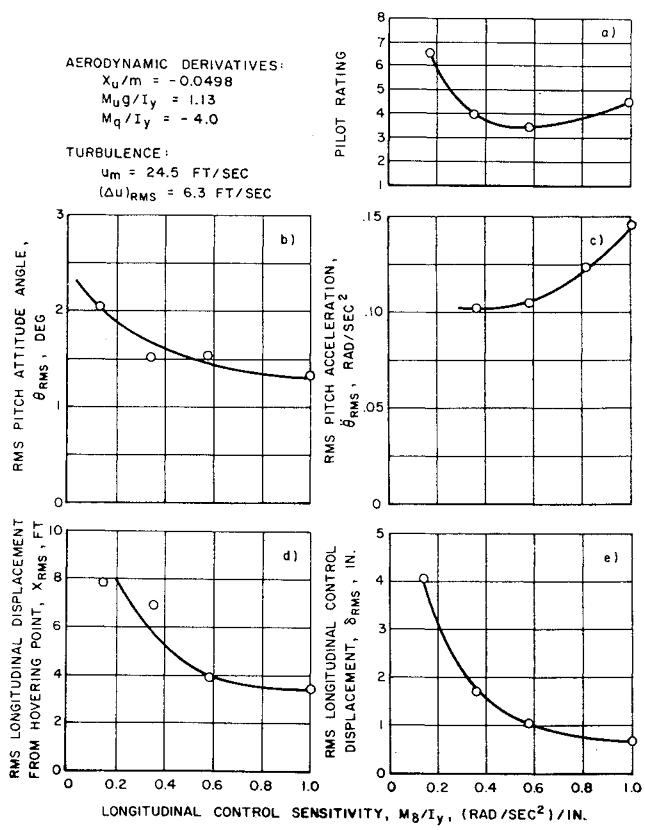

Fig. 5 Effects of varying longitudinal control sensitivity on factors that influence pilot rating.

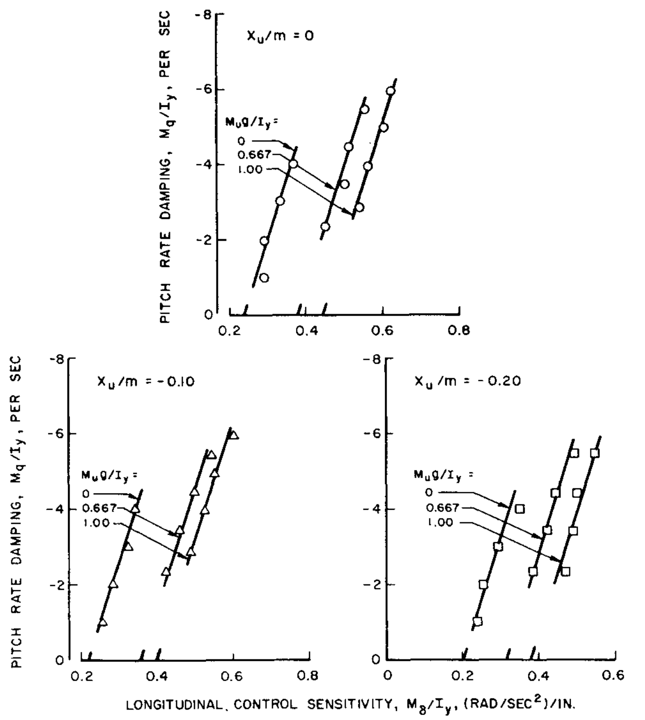

Fig. 6 Summary of effects of M_ug/I_y on optimum control sensitivity line [average slope $\partial(M_q/I_y)/\partial(M_\delta/I_y) = -32.29$, mean wind $u_m = 20$ fps].

$\partial(M_\delta/I_y) = -32.29$ could be faired through all of the data and extended to the zero-damping axis to obtain the intercepts $(M_\delta/I_y)_0$. This value of the slope was later found to be independent of level of turbulence as well, and it is also in fairly good agreement with the flight-test data of Refs. 2 and 5.

Contours of constant intercept

By crossplotting the experimentally determined intercepts with the variables X_u/m and M_ug/I_y, a set of contours of constant intercept $(M_\delta/I_y)_0$ on the X_u/m vs M_ug/I_y plane was constructed (Fig. 8). It is evident, from both the contours of Fig. 8 and from the actual data on plots of M_q/I_y vs M_δ/I_y in Fig. 6, that optimum control sensitivity exhibited a very strong and systematic dependence on M_ug/I_y; increasing M_ug/I_y from 0 to 1.0 at constant damping required an increase in control sensitivity of nearly a factor of 2. In Fig. 7 the derivative X_u/m is seen to exhibit a smaller, but still significant influence on optimum control sensitivity; increasing X_u/m from 0 to -0.20 resulted in a decrease in control sensitivity of about 0.10 to 0.15 at a constant level of damping. The qualitative effects of these two stability derivatives on handling qualities are discussed in the Appendix.

Contours of constant pilot rating

Contours of constant Cooper pilot rating derived from the flight simulator data are presented in Fig. 9 on plots of M_q/I_y vs M_ug/I_y. Since pilot rating exhibited a dependence on X_u/m, it is necessary to present contours for three separate values of X_u/m. It can be seen in Fig. 9 that there was a substantial deterioration of pilot rating with increasing M_ug/I_y at a constant level of M_q/I_y. Although there were only small differences in rating between X_u/m of -0.20 and -0.10 at a constant value of M_ug/I_y, it is noted that significantly poorer ratings were assigned as X_u/m approached zero because of the lack of translational damping during maneuvering flight (see Appendix). The important results are that 1) although the parameter M_ug/I_y was previously recognized as being important, the parameter X_u/m must also be considered, and 2) characteristics of the optimum line and pilot rating vary in a systematic manner with changes in the stability derivatives X_u/m and M_ug/I_y.

Effects of turbulence

Results showing the effects of varying the level of turbulence on the optimum line are presented in Fig. 10 for one combination of X_u/m and M_ug/I_y. Flight simulator data were obtained for levels of turbulence corresponding to mean wind velocities of 0, 20, 30, and 40 fps. In general, the level of turbulence has a strong and systematic influence on both optimum control sensitivity and pilot rating. For this combination of stability derivatives, increasing the mean wind from 0 to 20 fps resulted in only a relatively small increase in optimum control sensitivity, because the level of control sensitivity required for counteracting the effects of the increased gusts only slightly exceeded that required for maneuvering. However, the deterioration of pilot rating at a mean wind of 20 fps resulted in a substantial increase in the level of pitch rate damping required to obtain a satisfactory rating (pilot rating 3.5). As the mean wind was further increased to 30 and 40 fps, an additional deterioration of pilot rating resulted, and the pilot required a large increase in

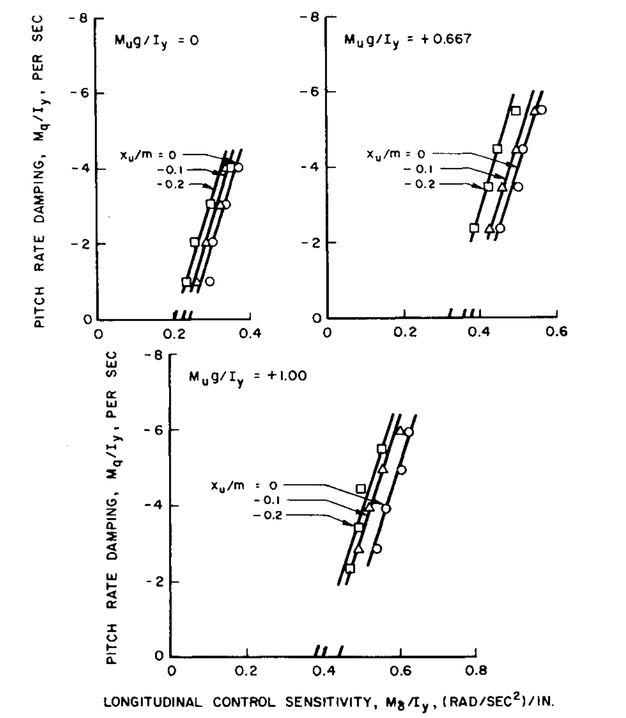

Fig. 7 Summary of effects of X_u/m on optimum control sensitivity line [average slope $\partial(M_q/I_y)/\partial M_\delta/I_y) = -32.29$, mean wind $u_m = 20$ fps].

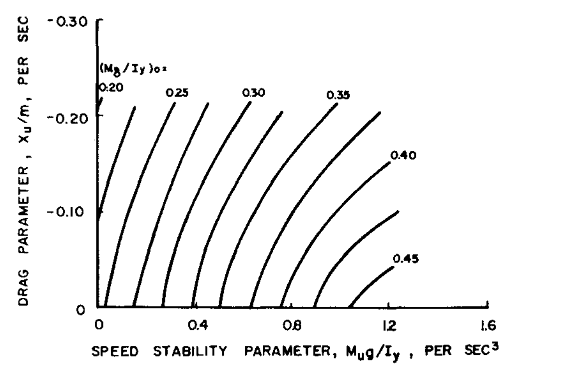

Fig. 8 Contours of intercept of optimum line derived from flight simulator data (average slope of optimum line = -32.29, mean wind $u_m = 20$ fps).

control sensitivity to cope with the effects of the larger gusts. As in the case of varying X_u/m and $M_u g/I_y$, varying the level of turbulence had a negligible influence on the slope of the optimum line. Qualitative aspects of the effects of turbulence on handling qualities are also discussed in the Appendix.

Discussion of Improved Method

Using the data previously discussed, an improved (although admittedly more cumbersome) method for presenting optimum handling qualities criteria was devised, and preliminary comparisons with published flight-test data were made.

Format for presenting criteria

It is suggested that criteria be presented using a series of figures, each having the format shown in Figs. 8 and 9. Examination of Figs. 8 and 9 will show that sufficient information is given to define completely the optimum line on Tapscott's plot of M_q/I_y vs M_δ/I_y for any existing or proposed aircraft for which the mass m, moment of inertia I_y, and aerodynamic derivatives X_u and M_u are known. Specifically, the intercept $(M_\delta/I_y)_0$ of the optimum line with the zero-damping axis may be obtained from the contours of Fig. 8. The slope $\partial(M_q/I_y)/\partial(M_\delta/I_y)$ is assumed constant (independent of X_u/m, $M_u g/I_y$, and level of turbulence) at the value of -32.29 previously discussed. The optimum line may then be constructed on a plot of M_q/I_y vs M_δ/I_y as shown in Fig. 11. Then the contours of pilot rating in Fig. 9 may be used (with interpolation with respect to X_u/m if necessary) to determine the variation of pilot rating along the optimum line. This procedure has been illustrated in Figs. 11a and 11b for two hypothetical aircraft having widely different combinations of X_u/m and $M_u g/I_y$.

Contours for the single level of turbulence corresponding to $u_m = 20$ fps (approximately equivalent to a "medium turbulent day," according to Ref. 5) are probably adequate for presenting criteria for normal VTOL operating conditions and for correlating flight-test results. A series of either three or four groups of plots, each having the format shown in Figs. 8 and 9, would be required to cover adequately the range of turbulence associated with mean winds from 0 to about 35 knots.

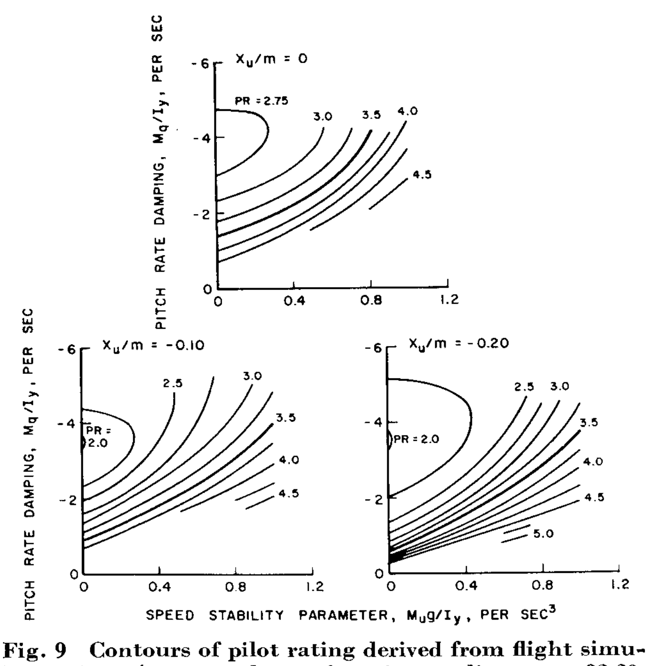

Fig. 9 Contours of pilot rating derived from flight simulator data (average slope of optimum line = −32.29, mean wind u_m = 20 fps).

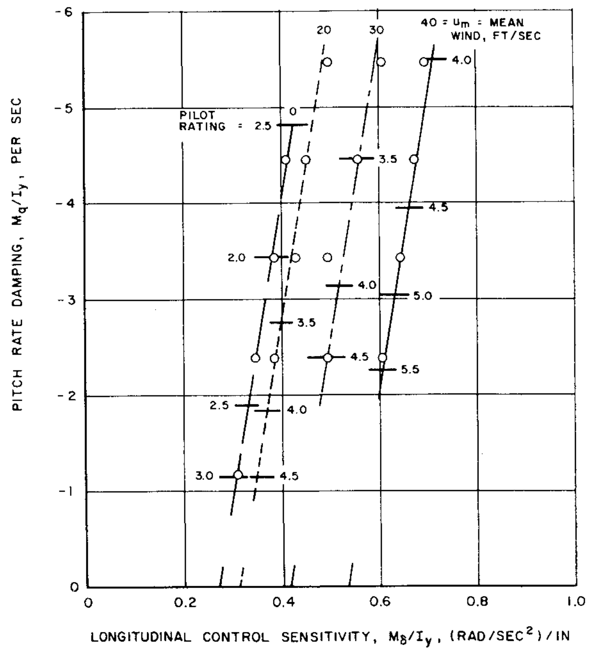

Fig. 10 Effects of varying level of turbulence on optimum line [X_u/m = −0.20, $M_u g/I_y$ = 0.667, $(\Delta u)_{rms}/u_m$ = 0.257].

The principal features of the method described may be summarized as follows:

1) The presentation is restricted to within the satisfactory and unsatisfactory range of handling qualities as defined by the Cooper pilot rating system (pilot ratings from 1.0 to about 4.5).

2) Since the changes in airspeed which are associated with maneuvering and precision hovering in the presence of turbulence affect the control and damping requirements through the stability derivatives X_u/m and $M_u g/I_y$, these stability derivatives are used as parameters to form the basis for presenting criteria.

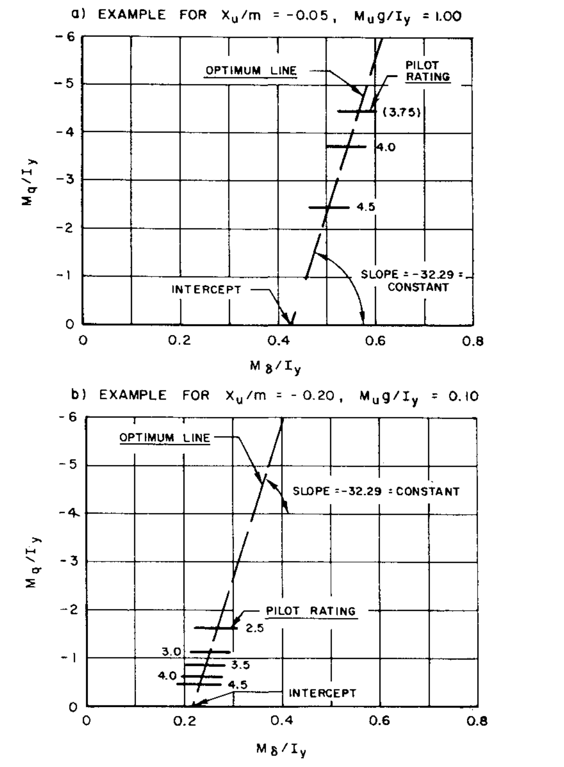

Fig. 11 Construction of optimum line [turbulence: u_m = 20 fps, $(\Delta u)_{rms}$ = 5.2 fps].

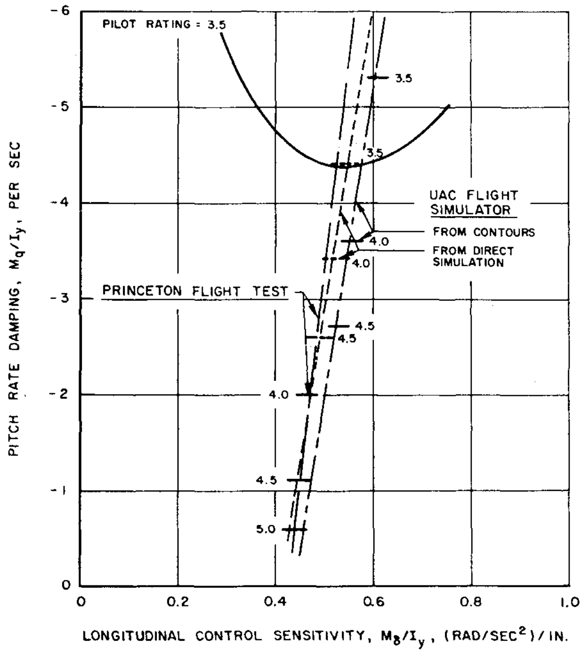

Fig. 12 Comparison of United Aircraft Corporation flight simulator data with Princeton flight-test data (HUP-1 tandem-rotor helicopter).

3) For each of several reference levels of turbulence, the optimum line on a plot of M_q/I_y vs M_{δ}/I_y is therefore completely defined by presenting contours of constant intercept on plots of X_u/m vs M_ug/I_y and by the assumed constant slope. The variation of pilot rating along the optimum line is defined by presenting contours of constant pilot rating on plots of M_q/I_y vs M_ug/I_y for three values of X_u/m.

Correlation with flight-test data

Preliminary comparisons of predictions made using the contours of Figs. 8 and 9 with flight-test data are shown in Figs. 12 and 13. Figure 12 presents a comparison with flight-test data for the Princeton HUP-1 variable stability helicopter.[5] Both the prediction made using the contours of Figs. 8 and 9 and the optimum line established on the UAC flight simulator by direct simulation of the HUP-1 (i.e., simulation of the HUP-1 stability derivatives and the exact artificial turbulence characteristics used in the flight-test program) are shown. Examination of Fig. 12 indicates that both optimum lines from the UAC studies are very close to the flight-test line. Furthermore, the levels of damping at which the boundaries of the satisfactory regions (pilot rating 3.5) occur are identical for the flight-test data and the direct simulation data, and the level determined from the contours is close. The differences in the unsatisfactory region (pilot ratings 4.0 and 4.5 in Fig. 12) were expected because of the lack of motion cues in the fixed-base simulator; as shown in Ref. 7, the effect of motion cues under low-damping conditions is to cause a decrease (improvement in pilot rating) from the ratings determined in fixed-base simulators. The fact that the gradient of pilot rating along the optimum line is small, and hence that small differences in pilot rating appear as large differences in level of damping, should also be considered in comparing results.

A similar comparison with flight-test data and single-axis, movable-base flight simulator data for the NASA X-14A VTOL research airplane[2,8] is shown in Fig. 13. The prediction based on the contours of Figs. 8 and 9 for $X_u/m = 0$ and $M_ug/I_y = 0$ is remarkably close to the optimum line determined in the NASA studies, even though the prediction is based on stability derivatives and a level of turbulence that must differ somewhat from the actual flight-test values. The agreement between the levels of damping at which pilot rating 3.5 occurs appears somewhat poor at first glance and may also be attributable to the lack of motion cues in the fixed-base simulator. In addition, although the actual values of X_u/m and M_ug/I_y for this aircraft are not known at this time, the actual value of X_u/m is certainly larger (more negative) than zero. Increasing X_u/m has a small decreasing effect on pilot rating which would also tend to drive the 3.5 level determined from the contours downward toward the NASA data. Further consideration must also be given to the possibility that differences in the relative precision of the hovering and maneuvering tasks in the two studies might contribute to the differences in pilot rating shown in Fig. 13.

Concluding Remarks

This research has led to several conclusions regarding the factors that influence optimum longitudinal control sensitivity criteria. First, the oscillatory dynamics per se have a negligible influence within the region of satisfactory handling qualities, i.e., within the Cooper pilot rating 3.5 boundary. Second, the stability derivatives X_u/m and M_ug/I_y and the level of turbulence all have significant and systematic effects. Finally, it is concluded that more comprehensive methods of presenting criteria which include these important factors can be developed. One improved method for presenting optimum control sensitivity criteria has been discussed in this paper, and it has been shown to have promise as a means for correlating flight-test data for aircraft having widely different aerodynamic, mass, and inertia characteristics.

This research has been concerned with only one of the many handling qualities problems facing designers of VTOL aircraft. Further studies are planned at the UAC Research Laboratories in which this approach will be used to develop methods for presenting criteria for minimum satisfactory control sensitivity and minimum satisfactory control power. As part of these studies, it is planned to evaluate the theory of handling qualities proposed by Lynn[9] with some modifications and to compare the experimental results with the minimum control sensitivity and minimum damping requirements of Secs. 3.2.13 and 3.2.14 of Military Specification MIL-H-8501A.[10]

Appendix: Qualitative Discussion of Effects of Stability Derivatives and Level of Turbulence

Longitudinal Force Derivative, X_u/m

The stability derivative X_u/m is a measure of the change in longitudinal force on the aircraft caused by small changes in airspeed. Consequently, X_u/m serves both as translational damping when performing longitudinal maneuvers and as a means by which gusts impart longitudinal accelerations to the aircraft. Note in Fig. 8 that, as X_u/m became more negative (increasing drag), less control sensitivity was required, especially at high values of M_ug/I_y. The qualitative influence of X_u/m may be summarized as follows:

1) At values of X_u/m near zero, relatively high levels of control sensitivity are required because of the lack of translational damping. Once the aircraft is set in motion either directly by maneuvering or indirectly by gusts through M_ug/I_y, the aircraft has a tendency to continue translating until arrested by rapid tilting of the thrust vector (i.e., rapid pitch up or pitch down of the aircraft). Therefore, the high values of control sensitivity at low values of X_u/m are primarily required in order to stop with precision at the end of rapid maneuvers between preselected hovering points.

2) High values of X_u/m are preferable because of the improved translational damping, even though the aircraft is more susceptible to longitudinal accelerations due to gusts. Although the increased susceptibility to gusts was noticeable at the higher values of X_u/m studied ($X_u/m = -0.20$), it was not objectionable.

3) For the range of values of X_u/m which was investigated, changes in the oscillatory dynamics caused by changes in X_u/m had a relatively small effect on the selection of optimum sensitivity and pilot rating.

Speed-Stability Derivative, $M_u g/I_y$

The speed-stability derivative $M_u g/I_y$ is a measure of the change in pitching moment on the aircraft caused by small changes in airspeed. This derivative is important because it determines the displacements of the longitudinal control stick which are required to trim changes in airspeed, and it determines the pitch acceleration response to gusts. Changes in $M_u g/I_y$ also cause appreciable changes in the oscillatory dynamics of the aircraft. As shown in Fig. 8, large increases in control sensitivity were required as $M_u g/I_y$ was increased. The qualitative influence of $M_u g/I_y$ on handling qualities requirements may be summarized as follows:

1) As $M_u g/I_y$ is increased, the most important factor causing the large increase in control sensitivity required is the increased pitching response of the aircraft to gusts. As was also reported in Ref. 5, this pitch excitation accounted for most of the deterioration in pilot rating at a constant level of damping.

2) As $M_u g/I_y$ is increased, the second most important factor is the larger excursions in the position of the longitudinal control stick required to trim during maneuvers and to trim the long period components of gusts.

3) For combinations of high level of turbulence and large $M_u g/I_y$, high levels of damping are desirable in order to reduce the effects of the short-period (less than about 5 sec) components of gusts on the pitching motions of the aircraft. However, it was found that providing enough damping to relieve the pitch excitation problem often caused the pitch response of the aircraft to be too sluggish for maneuvering. Because of this, satisfactory pilot ratings were not attainable at one test point in this program ($X_u/m = 0$, $M_u g/I_y = +1.0$; Fig. 9).

4) At the higher values of $M_u g/I_y$, it was observed that the speed stability of the aircraft relieved to some extent the low translational damping problem associated with low values of X_u/m. When translational motion was initiated either intentionally or unintentionally, the change in pitching moment on the aircraft was such as to rotate the thrust vector in the proper direction to oppose the motion.

5) As in the case of X_u/m, the influence of changes in the oscillatory dynamics caused by changes in $M_u g/I_y$ on the selection of optimum control sensitivity and pilot rating was small as compared to the other considerations noted.

Level of Turbulence, u_m

For one combination of stability derivatives ($X_u/m = -0.20$, $M_u g/I_y = +0.667$), turbulence was varied by varying the mean wind velocity from $u_m = 0$ to 40 fps while holding $\Delta u_{\text{rms}}/u_m$ constant at 0.257. These data have been discussed previously and are presented in Fig. 10. Qualitative results for this one combination of stability derivatives are as follows:

1) The addition of low levels of turbulence ($u_m < 20$ fps) resulted in only a small increase in optimum control sensitivity because the control sensitivity required for trimming the gusts did not significantly exceed that required for maneuvering. The rate of change of optimum control sensitivity with level of turbulence would be expected to be strongly dependent upon $M_u g/I_y$.

2) At higher levels of turbulence ($u_m > 20$ fps), the selection of optimum control sensitivity is primarily determined by the gust response of the aircraft rather than by maneuvering considerations.

3) As the level of turbulence is increased, a very large increase in damping is required to obtain a satisfactory rating (pilot rating 3.5). The increased damping is beneficial for reducing the response of the aircraft to short-period gusts but tends to make control response too sluggish.

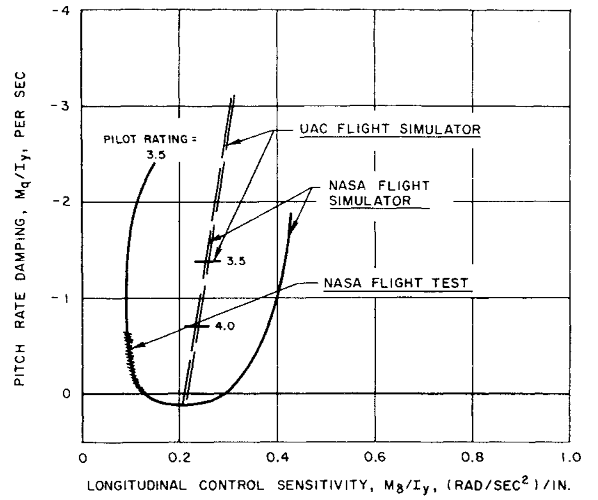

Fig. 13 Comparison of United Aircraft Corporation flight simulator data with NASA flight simulator and flight-test data (X-14A VTOL research airplane).

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