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STUDY OF THE OPTIMUM VALUES OF SEVERAL PARAMETERS AFFECTING LONGITUDINAL HANDLING QUALITIES OF VTOL AIRCRAFT

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STUDY OF THE OPTIMUM VALUES OF SEVERAL PARAMETERS AFFECTING LONGITUDINAL HANDLING QUALITIES OF VTOL AIRCRAFT

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SUMMARY

Because of the many factors which influence handling qualities, a disparity often exists between the absolute pilot rating results obtained from various investigations. In this paper, longitudinal handling qualities data from three published studies have been analyzed and compared in terms of pilot rating trends associated with changes in each of several important parameters. Optimum values or points of diminishing returns for each of these parameters (pitch-rate damping, angle-of-attack stability, speed stability, and longitudinal control sensitivity) appear to be largely independent of changes in other parameters and operating conditions covered.

INTRODUCTION

Because of the many factors which influence handling qualities, a disparity often exists between the pilot rating results obtained from various investigations of a given parameter. Such a disparity can arise from the fact that all parameters simultaneously contribute to the pilot's overall assessment, even though only one parameter is under investigation. Clearly, then, the minimum satisfactory level of any handling-qualities parameter is a function of the base conditions, or the levels of the remaining parameters.

An examination of published longitudinal-handling-qualities data (refs. 1, 2, and 3) has indicated that even in the presence of gross changes in base conditions, the trends in pilot ratings (as opposed to the absolute pilot ratings) with changes in certain parameters were in relatively close agreement. For such parameters the designer can readily ascertain optimum values, points of diminishing returns, and estimates of the effect of changing the parameters. In this paper, pilot rating trends are presented for variations in pitch-rate damping, angle-of-attack stability, speed stability, and control sensitivity; and the optimum values are noted.

SYMBOLS

The units used in this investigation are given in both the U.S. Customary Units and the International System of Units (SI).

F_{X_u} rate of change of longitudinal force with respect to longitudinal velocity, $\frac{\text{lbf}}{\text{ft/sec}}$ $\left(\frac{\text{newton}}{\text{meters/sec}}\right)$

I_Y moment of inertia about body Y-axis, slug-ft^2 (kilogram-meters^2)

M_{Y_q} rate of change of pitching moment with respect to pitching angular velocity, $\frac{\text{lbf-ft}}{\text{rad/sec}}$ $\left(\frac{\text{newton-meters}}{\text{rad/sec}}\right)$

M_{Y_u} rate of change of pitching moment with respect to longitudinal velocity, $\frac{\text{lbf-ft}}{\text{ft/sec}}$ $\left(\frac{\text{newton-meters}}{\text{meters/sec}}\right)$

M_{Y_α} rate of change of pitching moment with respect to angle of attack, $\frac{\text{lbf-ft}}{\text{rad}}$ $\left(\frac{\text{newton-meters}}{\text{rad}}\right)$

M_{Y_δ} rate of change of pitching moment with respect to stick deflection, $\frac{\text{lbf-ft}}{\text{in.}}$ $\left(\frac{\text{newton-meters}}{\text{cm}}\right)$

m mass of aircraft, slugs (kilograms)

q pitching angular velocity, $\frac{\text{rad}}{\text{sec}}$

u longitudinal component of velocity, $\frac{\text{ft}}{\text{sec}}$ $\left(\frac{\text{meters}}{\text{sec}}\right)$

α angle of attack, rad

δ longitudinal control deflection, in. (cm)

Definitions:

Angle-of-attack stability, $\frac{M_{Y_\alpha}}{I_Y}$ (stable when negative), $\frac{1}{\text{sec}^2}$

Drag parameter, $\frac{F_{X_u}}{m}$ (stable when negative), $\frac{1}{\text{sec}}$

Longitudinal control sensitivity, $\frac{M_{Y_\delta}}{I_Y}$, $\frac{1}{\text{in.-sec}^2}$ $\left(\frac{1}{\text{cm-sec}^2}\right)$

Pitch-rate damping, $\frac{M_{Y_q}}{I_Y}$ (stable when negative), $\frac{1}{\text{sec}}$

Speed stability, $\frac{M_{Y_u}}{I_Y}$ (stable when positive), $\frac{1}{\text{ft-sec}}$ $\left(\frac{1}{\text{meters-sec}}\right)$

DESCRIPTION OF FLIGHT INVESTIGATIONS

The data analyzed in this report were obtained from three independent investigations (refs. 1, 2, and 3). During the NASA investigation reported in reference 1, a simulated (hooded) instrument-flight task was performed in a variable-stability helicopter at low speed (40 to 70 knots) in order to evaluate the effect of various combinations of angle-of-attack stability, pitch-rate damping, speed stability, and longitudinal control sensitivity on handling qualities. Princeton University conducted a visual-flight study of the longitudinal qualities while hovering with a variable-stability helicopter, the results of which are given in reference 2. Reference 3 reports the results of a fixed-base simulator study by United Aircraft Corporation during which visual-flight tasks were simulated using a contact analog display. The pilot rating system shown in table I was employed for all three investigations.

RESULTS AND DISCUSSION

Pitch-Rate Damping

The results of reference 1 were examined to determine pilot rating trends with pitch-rate damping in the presence of grossly different levels of angle-of-attack stability. In figure 1, pilot ratings are presented as a function of pitch-rate damping for various levels of angle-of-attack stability. It is apparent from this figure that for a given value of damping, there can be large differences in the absolute pilot ratings. The pilot rating trends with changes in damping, on the other hand, are seen to be relatively similar. A better comparison of the pilot rating trends may be obtained by shifting the curves of figure 1 along the pilot rating axis to form the narrowest possible envelope. The resulting envelope is shown in figure 2 which includes an insert to illustrate the maximum and minimum change in pilot rating that can occur for a given change in pitch damping while still remaining within the envelope.

The curve shifting process employed to obtain the envelope in figure 2 implies that the pilot rating scale is a linear measure of handling qualities. It is obvious, of course, that the pilot rating system is nonlinear at both ends since an aircraft cannot have a rating better than 1 or worse than 10; over the midportion of the rating system, the nonlinearity is less certain. Disregarding any further consideration as to whether some portion of the rating scale is linear, the shifting process appears to yield consistent

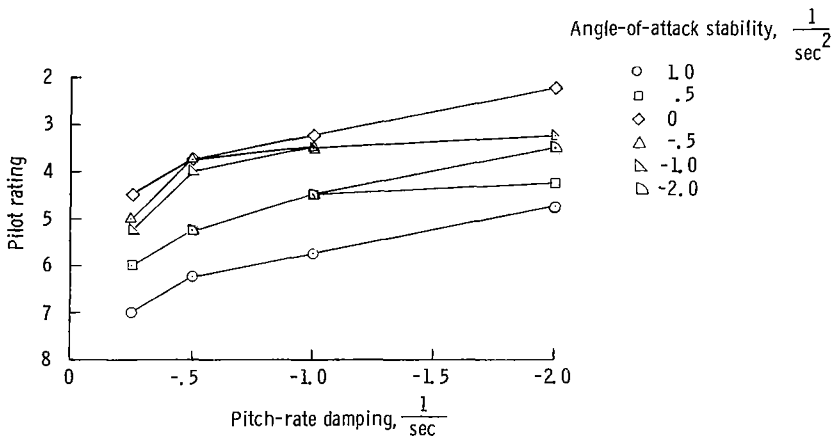

Figure 1.- Variation of pilot rating with pitch-rate damping. (Data from ref. 1.)

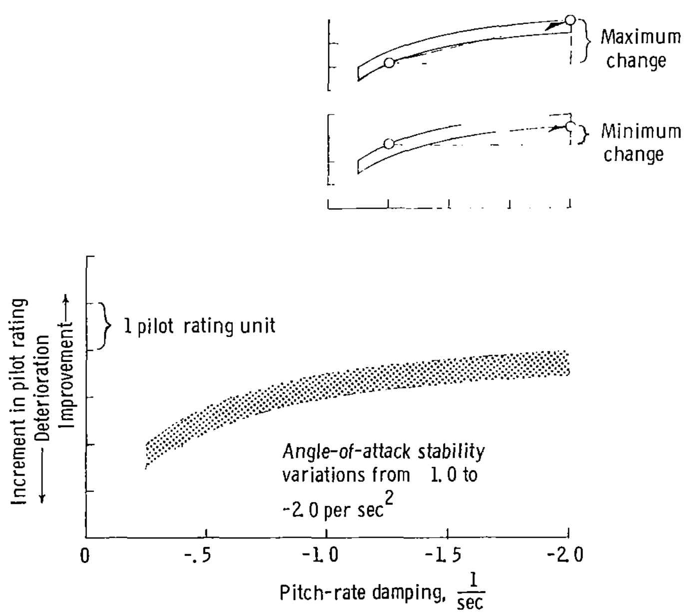

Figure 2.- Effect of pitch-rate damping on pilot rating in the presence of various levels of angle-of-attack stability.

results and is therefore used to obtain empirical relationships. Limitations on dealing with ratings at the extremities of the rating scale are discussed in a subsequent section.

Pilot rating increment plots were next constructed from the results of references 2 and 3 in order to determine whether the effect of pitch-rate damping on pilot rating also followed a consistent trend in the presence of gross changes in speed stability (ref. 2), control sensitivity (ref. 2), and the drag parameter (ref. 3). The resulting pilot rating increment plots are shown in figure 3. In all three cases narrow envelopes were obtained; this condition indicates that the effect of pitch-rate damping on handling qualities was relatively independent of the levels of speed stability, control sensitivity, and the drag parameter.

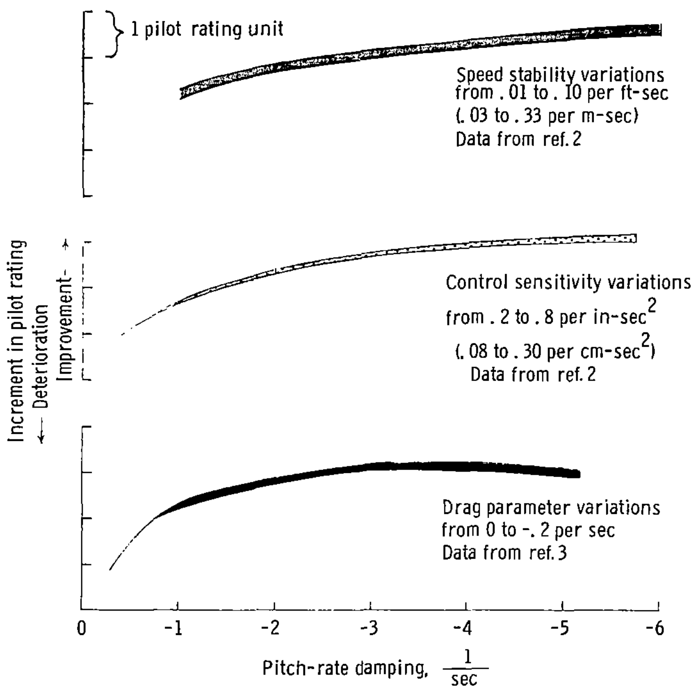

Figure 3.- Effect of pitch-rate damping on pilot rating in the presence of various levels of additional parameters.

The four envelopes of figures 2 and 3 are shown in figure 4 for comparison. An interesting implication arises from the fact that, in general, similar envelopes were obtained in each of the cases considered; that is, the relationship between pilot rating and pitch-rate damping appears to be essentially independent of the other parameters involved (both controlled and uncontrolled) as well as the tasks which were performed.

It may be noted from figure 4 that increasing pitch-rate damping up to about -1.0 per second results in a rapid improvement in handling qualities. The point of diminishing returns occurs at a damping value of approximately -2.0 per second. Above -2.0 per second further increases in damping result in relatively slight improvement.

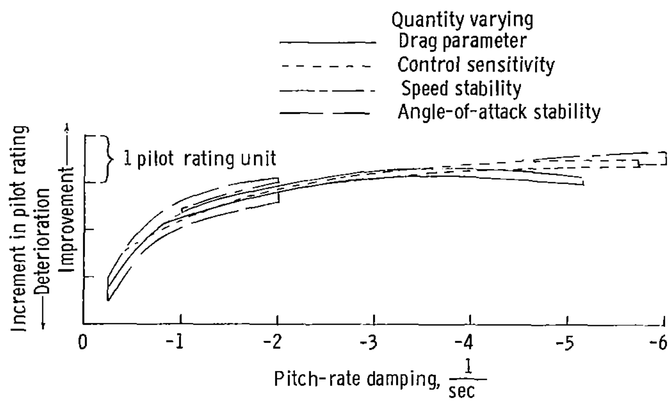

Figure 4.- Comparison of pilot rating increment envelopes from figures 2 and 3.

Angle-of-Attack Stability

Pilot rating trends with angle-of-attack stability in the presence of grossly different levels of pitch-rate damping were obtained from the data of reference 1. The resulting envelope of incremental pilot ratings is shown in figure 5 and was obtained in the presence of damping variations ranging from -0.25 to -2.0 per second. Figure 5 indicates that even though the damping varied over an order of magnitude, the pilot rating trend with angle-of-attack stability was consistent and the optimum angle-of-attack stability level occurred at a slightly stable value.

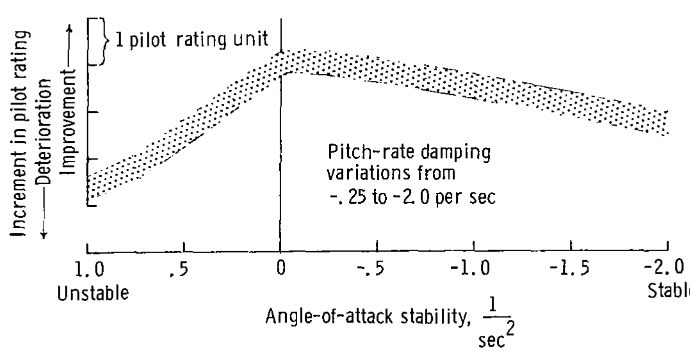

Figure 5.- Effect of angle-of-attack stability on pilot rating in the presence of various levels of pitch-rate damping. (Data from ref. 1.)

Speed Stability

Pilot rating trends with speed stability in the presence of grossly different combinations of pitch-rate damping and angle-of-attack stability were obtained from the data of reference 1. The effect of speed stability on pilot rating was obtained in the presence of four combinations of angle-of-attack stability and pitch-rate damping. The resulting envelope of incremental pilot ratings, together with the range of variables, is shown in figure 6. Only limited data were obtained over the dashed portion of the envelope.

Base conditions for speed stability variations

	1	2	3	4
Pitch-rate damping, 1/sec	-0.5	-2.0	-0.5	-1.0
Angle-of-attack stability, 1/sec^2	0	0.5	-1.0	-2.0

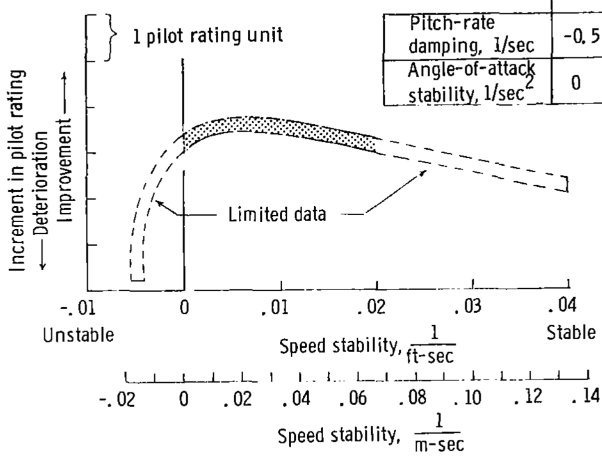

Figure 6.- Effect of speed stability on pilot rating in the presence of various combinations of pitch-rate damping and angle-of-attack stability. (Data from ref. 1.)

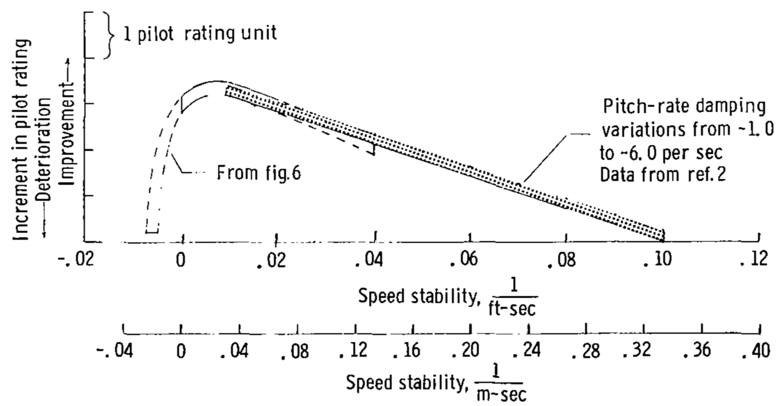

Figure 7.- Comparison of speed stability envelope obtained from data of reference 2 with envelope from figure 6.

The relationship between pilot rating and speed stability was further investigated by examining the data of reference 2, wherein speed stability was varied in the presence of several levels of pitch-rate damping. The resulting envelope of incremental pilot ratings is shown in figure 7 and compared with the envelope of figure 6. It is apparent that good agreement was obtained over the range where the tested values of speed stability overlapped.

Figure 7 indicates that the pilots preferred a slightly stable speed-stability level regardless of large differences in both pitch-rate damping and angle-of-attack stability.

Longitudinal Control Sensitivity

Pilot rating trends with longitudinal control sensitivity in the presence of grossly different combinations of pitch-rate damping and angle-of-attack stability were obtained from the data of reference 1. The four combinations of angle-of-attack stability and pitch-rate damping at which the sensitivity was investigated are noted in figure 8, which presents the resulting envelope of incremental pilot ratings.

Base conditions for longitudinal control sensitivity variations

	1	2	3	4
Pitch-rate damping, 1/sec	-2.0	-2.0	-0.5	-0.5
Angle-of-attack stability, $1/\text{sec}^2$	+0.5	-2.0	-0.5	+1.0

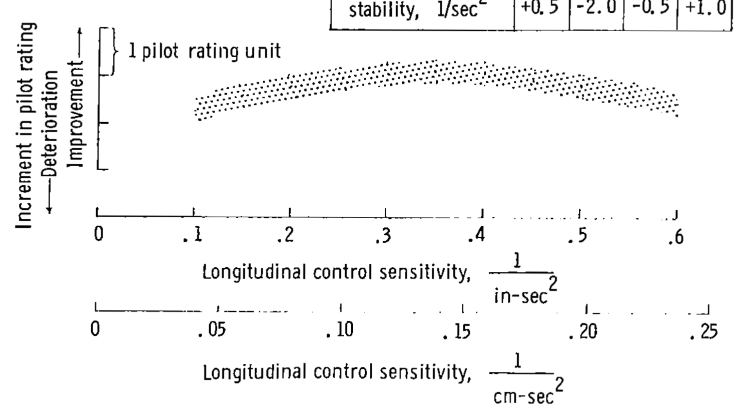

Figure 8.- Effect of longitudinal control sensitivity on pilot rating in the presence of various combinations of pitch-rate damping and angle-of-attack stability. (Data from ref. 1.)

The relationship between pilot ratings and longitudinal control sensitivity was further investigated by examining the data of reference 2, wherein control sensitivity was varied in the presence of several levels of pitch-rate damping. The resulting envelope of incremental ratings is shown in figure 9 and compared with the similar envelope of figure 8. Below a sensitivity of about 0.4 per in-sec^2 (0.16 per cm-sec^2) the agreement between the two investigations is good. Above this level of sensitivity, however, the results obtained from the data of reference 1 indicate a more rapid deterioration with increased sensitivity than those of reference 2. Reference 1 indicated that difficulty in maintaining an accurate stick trim position, aggravated by a deficiency in the stick-force trim system, contributed to the slight downrating at high sensitivities. In general, the optimum longitudinal control sensitivity level fell within a broad range which was centered about 0.4 per in-sec^2 (0.16 per cm-sec^2).

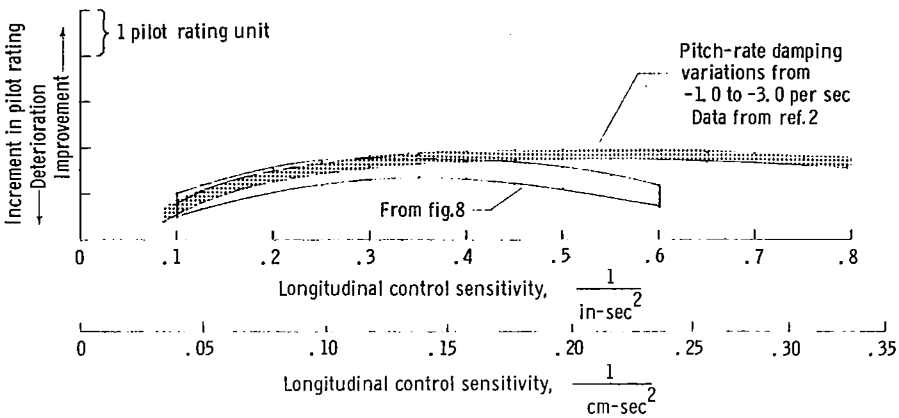

Figure 9.- Comparison of longitudinal control sensitivity envelope obtained from data of reference 2 with envelope from figure 8.

LIMITATIONS ON APPLICATION OF RESULTS

It has already been noted that the pilot rating envelope represents an empirical relationship and cannot be justified on a rigorous basis because of unknown nonlinearities of the pilot rating system. Caution should therefore be exercised in extending the results to conditions beyond the scope of this study; moreover, the results cannot be added unless the overall increment is reasonably small and avoids the ends of the pilot rating scale.

CONCLUDING REMARKS

In this paper, longitudinal handling qualities data from three published studies have been analyzed and compared in terms of pilot rating trends associated with changes in each of several important parameters. Optimum values or points of diminishing returns for each of these parameters (pitch-rate damping, angle-of-attack stability, speed stability, and control sensitivity) appear to be largely independent of changes in other parameters and operating conditions covered. Optimum angle-of-attack stability and speed stability levels were slightly stable. The optimum longitudinal control sensitivity level fell within a broad range which was centered about 0.4 per in-sec^2 (0.16 per cm-sec^2). An optimum pitch-rate damping level was not reached, but the point of diminishing returns occurred at a damping value of about -2.0 per sec.

The empirical relationships presented in this paper provide a means for estimating the effect on handling qualities due to changes in any of the four parameters surveyed. Since the relationships are empirical, caution should be exercised in applying these results where the additive effects are large or the estimates approach the ends of the pilot rating scale.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., February 16, 1968,
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TABLE I.- PILOT RATING SYSTEM

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[1]	Doubtful	Yes
No operation	Unacceptable	7	Unacceptable even for emergency condition[1]	No	Doubtful
		8	Unacceptable – dangerous	No	No
		9	Unacceptable – uncontrollable	No	No
	Catastrophic	10	Motions possibly violent enough to prevent pilot escape	No	No

[1]Failure of a stability augmenter.