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SIMULATOR STUDY OF MINIMUM ACCEPTABLE LEVEL OF LONGITUDINAL STABILITY FOR A REPRESENTATIVE STOL CONFIGURATION DURING LANDING APPROACH

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16. Abstract

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SIMULATOR STUDY OF MINIMUM ACCEPTABLE LEVEL OF LONGITUDINAL STABILITY FOR A REPRESENTATIVE STOL CONFIGURATION DURING LANDING APPROACH

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SUMMARY

A fixed-base simulator study was conducted to determine the minimum acceptable level of longitudinal stability for a representative turbofan STOL (short take-off and landing) transport airplane during the landing approach. Real-time digital simulation techniques were used. The computer was programed with equations of motion for six degrees of freedom, and the aerodynamic inputs were based on measured wind-tunnel data. The primary piloting task was an instrument approach to a breakout at a 60-m (200-ft) ceiling.

The results of the study correlate reasonably well with some of the most recently published STOL longitudinal handling qualities criteria. They showed that the pilot would accept, for emergency use, a decidedly unstable airplane. Pilot ratings of 6.5 or better were assigned to many conditions having positive (destabilizing) values of C_{m_α} (pitching-moment coefficient due to angle of attack) and negative (stabilizing) values of C_{m_q} (pitching-moment coefficient due to rate of pitch). The degree of tolerable instability was a function of the amount of damping present. Pilot opinion was found to be related to divergence time rather than to the degree of static instability. It was concluded that, when a STOL airplane was unstable and required 2.5 seconds or longer to diverge to double amplitude in pitch, it could be safely controlled (a pilot rating of 6.5 or better). Any boundary or boundaries that may be drawn from the results of this study should be presented in dimensional, not coefficient, form since the coefficients are independent of airplane size. Hence, aircraft size did not affect the conclusions drawn.

INTRODUCTION

The requirement for STOL (short take-off and landing) transport airplanes has emphasized the need for high lift to reduce approach and landing speeds. However, some STOL designs may be subject to a loss of static longitudinal stability because of the large

downwash associated with high-lift systems. Although it is probable that in normal operations STOL transport airplanes will have the benefit of sophisticated stability and control augmentation systems (see ref. 1, for example), a requirement will still exist for acceptable flying qualities in the emergency state resulting from failure of various components of the augmentation system. Since the problem of providing adequate inherent longitudinal stability may be greater for some STOL aircraft than for conventional aircraft, there is a question as to what is the minimum acceptable level of longitudinal stability.

Studies in the area have indicated that there may be instances in which the longitudinal handling qualities of certain STOL airplanes having static longitudinal instability will be acceptable if an adequate maneuver margin is provided. Both ground-based and in-flight simulation studies have been previously conducted, as in references 2 and 3, wherein conventional airplanes (both fighters and transports) having unstable static longitudinal characteristics were simulated. However, results have varied appreciably as to the degree of static instability that was classified as being tolerable in an emergency situation. Such variation should be expected since the class of airplanes and the piloting tasks simulated differed. For example, reference 2 (p. 17) simulated a typical fighter aircraft at high airspeeds and concluded that "the maneuver neutral point was a reasonable aft center of gravity limit" at which acceptable controllability could be expected without the assistance of stability augmentation. In contrast, reference 3 (p. 10) simulated a lightweight transport flying at low airspeeds (V = 135 knots; 1 knot = 0.51 m/sec) and concluded that "neutral or very slightly unstable static stability was tolerable."

STOL airplanes operating in the terminal area will fly at very low airspeeds (V = 75 knots, for example); they will fly steep approach angles, will have very good normal acceleration capability on the approach with powered lift, and will be flown using piloting techniques normally associated with aircraft flying on the "backside" of the thrust-required curve. Therefore, the present piloted simulation study was conducted to provide data on the effects of large reductions in static longitudinal stability on the handling qualities of a representative externally blown flap STOL transport configuration during the landing approach. Specifically, the program was directed toward the definition of a minimum acceptable level of static longitudinal stability. This objective was accomplished by a systematic variation of the static longitudinal stability derivative C_{m_α}, the pitch-damping derivative C_{m_q}, and the pitching-moment-due-to-thrust coefficient $C_{m_{C_T}}$. In addition, information was provided on the effects of atmospheric turbulence, airplane size, and automatic airspeed control.

The study was conducted with a fixed-base simulator and utilized real-time digital simulation techniques. The computer was programed with equations of motion for six degrees of freedom, and the aerodynamic input quantities were based on the wind-tunnel

data reported in references 4 and 5. The primary piloting task was an instrument approach in a breakout at a 60-m (200-ft) ceiling. No attempt was made to establish a complete handling qualities criteria from this limited study; its aim was simply to generate information that could be of use in design evaluations of the flying qualities of STOL airplanes that may be longitudinally unstable within the normal flight envelope.

SYMBOLS

In order to facilitate international usage of the data presented, dimensional quantities are given in both the International System of Units (SI) and U.S. Customary Units. The measurements and calculations were made in U.S. Customary Units. Dots over symbols denote differentiation with respect to time.

C_L lift coefficient

C_m pitching-moment coefficient

$C_{m_{C_T}} = \frac{\partial C_m}{\partial C_T}$

$C_{m_q} = \frac{\partial C_m}{\partial \frac{q\bar{c}}{2V}}$, 1/radian

$C_{m_\alpha} = \frac{\partial C_m}{\partial \alpha}$, 1/radian

$C_{m_{\dot{\alpha}}} = \frac{\partial C_m}{\partial \frac{\dot{\alpha}\bar{c}}{2V}}$, 1/radian

C_T thrust coefficient

$\bar{c}$ mean aerodynamic chord, meters (feet)

g acceleration due to gravity, meters/second^2 (feet/second^2)

h altitude, meters (feet)

I_X, I_Y, I_Z moment of inertia about X, Y, and Z body axis, respectively, kilogram-meters^2 (slug-feet^2)

I_{XZ} product of inertia, kilogram-meters^2 (slug-feet^2)

$M_q = \frac{\rho V^2 S \bar{c}^2}{4VI_Y} C_{m_q}$, 1/second

$M_\alpha = \frac{\rho V^2 S \bar{c}}{2I_Y} C_{m_\alpha}$, 1/second^2

n/α steady-state normal acceleration change per unit change in angle of attack for an incremental horizontal-tail deflection at constant airspeed, gravity units/radian

q angular velocity about aircraft Y body axis, radians/second

S wing area, meters^2 (feet^2)

T thrust, newtons (pounds force)

t time, seconds

t_2 time to double amplitude, seconds

V airspeed, knots (feet/second)

X,Y,Z coordinate body axes

α angle of attack, degrees or radians

δ_c control column displacement, degrees

ζ damping ratio

θ pitch angle, degrees

ρ air density, kilograms/meter^3 (slugs/foot^3)

ω_d longitudinal short-period damped frequency, radians/second

ω_n longitudinal short-period undamped natural frequency, radians/second

Abbreviations:

ADI attitude director instrument

CTOL conventional take-off and landing

IFR instrument flight rules

ILS instrument landing system

STOL short take-off and landing

DESCRIPTION OF SIMULATED AIRPLANE

The simulated STOL transport configuration was a four-engine subsonic jet with a high wing and high-bypass-ratio turbofan engines. The engines were mounted in such a manner that the jet exhaust impinged directly on the trailing-edge flap system in order to induce high values of C_L. This type of design is normally referred to as an externally blown flap STOL configuration.

The aerodynamic data used as inputs for the simulation were identical to the data used and presented in reference 1, with the exception of the pitching-moment data. The pitching-moment data of reference 1 were nonlinear with angle of attack and thrust coefficient; for the present study, however, the aerodynamic pitching-moment data were linearized in order to simplify the interpretation of the effects of these derivatives. The basic simulated airplane had a gross weight of 245 kN (55 100 lbf), a wing loading of 3142 N/m^2 (65.4 lbf/ft^2), and a thrust-weight ratio of 0.60 for the maximum thrust condition. A larger airplane was also evaluated in order to determine the effects of airplane size. The large airplane had a gross weight of 578 kN (130 000 lbf) and a wing loading of 3831 N/m^2 (80 lbf/ft^2). The engine characteristics used for the basic airplane were uprated in order to maintain a maximum thrust-weight ratio of 0.60 for the large airplane. The mass and dimensional characteristics of both the basic and the large airplane are presented in table I.

The transport-type cockpit was equipped with conventional flight and engine-thrust controls and with a flight-instrument display representative of those found in current transport airplanes. (See fig. 1.) A conventional cross-pointer-type flight director instrument was used, and the command bars (cross-pointers) were driven by the main computer program. (See ref. 1 for a description of the flight director system used in this study.) One unique feature of the attitude director instrument (ADI) used in the present study, but not used in reference 1, was the fast-slow feature of this instrument. During the present investigation the fast-slow indicator (fig. 1) was used to provide the pilot with information regarding the airspeed of the aircraft as compared with the desired airspeed.

The control forces were provided by a hydraulic servosystem and were functions of control displacement and rate. The control characteristics are defined in table II.

TESTS AND PROCEDURES

To obtain valid flying qualities data in the form of pilot ratings and comments, one must carefully define, for the evaluation pilot, the mission which the aircraft-pilot combination will perform and the conditions under which it will be performed. For the present study, the simulated airplane was defined as an all-weather STOL transport which was to make landing approaches; the task was considered a two-pilot operation to the extent that no allowance was made for typical additional duties, for example, flap setting, communications, and so forth. Other factors such as passenger comfort were not considered by the pilot in making his evaluations.

The piloting task was an ILS approach, using a 6° slope, to break out at 60-m (200-ft) altitude. The approach was initiated with the airplane in the power-approach configuration (power for level flight), on localizer, at an altitude below the glide slope, $h \approx 610$ m (2000 ft), and approximately 3.5 n. mi. from the runway threshold. The pilot's task was to capture the glide slope and to track the localizer and glide slope as closely as possible, while maintaining an airspeed of 75 knots under IFR conditions. Simulated landing approaches were made wherein various combinations of values of C_{m_α}, C_{m_q}, and $C_{m_{C_T}}$ were used as inputs in an attempt to define the minimum acceptable level of longitudinal stability. The range of these coefficients was: $C_{m_\alpha} = -2.0$ to 2.4; $C_{m_q} = -100$ to 10; and $C_{m_{C_T}} = 0$ to -0.2. Only three values of $C_{m_{C_T}}$ were tested (0, -0.1, and -0.2), $C_{m_{C_T}} = -0.1$ being the base value. However, a sufficient number of combinations of C_{m_α} and C_{m_q} were evaluated to define the pilot opinion boundaries.

The effects of automatic airspeed control, airplane size, and atmospheric turbulence were also considered. The turbulence model used was a Dryden model and included scale lengths of 183 m (600 ft) for the longitudinal and lateral turbulence and 9 m (30 ft) for the vertical turbulence. The root-mean-square gust intensities used for the longitudinal, lateral, and vertical turbulence were 2.5, 1.6, and 1.5 knots, respectively. This simulated turbulence was described by the pilot as representative of "light to moderate" turbulence.

The only pilot to take part in this program was a NASA research pilot who has participated in numerous STOL studies over the past years. (See ref. 1.)

RESULTS AND DISCUSSION

As stated previously, the intent of this study is to present information that should be of use in design evaluations of the flying qualities of STOL transport airplanes that may be longitudinally unstable within the normal flight envelope. No attempt is made here to establish detailed handling qualities criteria.

Although six degrees of freedom were simulated, the results of the study are presented and discussed in relation to pilot ratings and opinions of the longitudinal characteristics. (See table III for pilot rating system.) The lateral-directional characteristics remained constant for each flight condition; although they were not specifically optimized, the pilot's comments indicated that the lateral-directional characteristics were such that they did not influence the ratings obtained in the longitudinal evaluations.

The basic piloting technique for flying the landing approach was to control airspeed with pitch attitude and to control the flight path (rate of descent) with thrust. During landing approaches with this simulated powered-lift STOL airplane, it has been found that pilots tended to use rapid and frequent control inputs rather than prolonged, slow control inputs. Thus, the pilot's awareness of controllability and maneuverability was influenced primarily by the short-term attitude response of the airplane to control inputs. The pilot ratings obtained in this study and in former studies (for example, ref. 1) reflected primarily the amount of difficulty the pilot had in controlling pitch attitude; the ratings were affected by the responsiveness of the airplane to pitch control inputs, to the level of apparent pitch damping, and to the amount and direction of pitch-attitude change ($\Delta\theta$) due to a change in thrust (ΔT).

Pilot Opinion Boundaries

One of the primary objections to the unaugmented longitudinal handling qualities of this STOL airplane was the low pitch damping. (See ref. 1.) Also, since damping in pitch causes an "apparent" increase in the static stability of the airplane in maneuvering

(fig. 2) because of the classical maneuver margin, the damping-in-pitch parameter C_{m_q} was varied from -100 to 10 for values of C_{m_α} ranging from -2.0 to 2.4. The pilot was asked to evaluate the longitudinal flight characteristics for each combination of derivatives while performing IFR landing approaches. As expected, the results indicated that the larger negative values of C_{m_q} (positive damping) produced the better pilot ratings for all the test values of C_{m_α}.

The basic value used for $C_{m_{C_T}}$ was -0.1. The pilot opinion boundaries obtained when various magnitudes of C_{m_α} and C_{m_q} were used in combination with the basic value of $C_{m_{C_T}}$ are presented in figure 3. The chief reason why the region of high damping and high stability was given only an "acceptable" rating, as opposed to a "satisfactory" rating, was that there were large pitch-attitude excursions associated with changes in thrust. The region of high damping and positive C_{m_α} was given an "acceptable" rating, as opposed to a "satisfactory" rating, because of (a) the direction and magnitude of the quantity $\Delta\theta/\Delta T$ and (b) the magnitude of the static stability. The remainder of the "acceptable" region was not assigned "satisfactory" ratings primarily because of the lack of adequate pitch damping.

An aircraft is usually referred to as being statically unstable if it has a positive value of C_{m_α}. In this simulation study, however, when $C_{m_{C_T}} = -0.1$, the pilot did not observe any evidence of static instability until C_{m_α} was increased to values larger than 0.5. This phenomenon the pilot observed was due to the effects of the derivative $C_{m_{C_T}}$ on the overall speed stability of the airplane. That is, the product $C_{m_{C_T}} C_T$ in the pitching-moment equation can cause a change in the total pitching-moment coefficient even if thrust is held constant, because $C_T = \frac{2T}{\rho V^2 S}$ and C_T can change as a result of change in airspeed. This characteristic is similar to the "Mach tuck" exhibited at transonic speeds by conventional aircraft as described in reference 6. The fact that the effective C_{m_α} can be stable (negative) when the actual C_{m_α} is unstable (positive) is illustrated in figure 4. Because of the effect of $C_{m_{C_T}}$ on the overall stability of the airplane, the "effective" neutral static stability boundary for the precision configuration would be at $C_{m_\alpha} = 0.548$. (See fig. 4.) Similarly, the "effective" neutral maneuver stability boundary is affected by the magnitude of $C_{m_{C_T}}$. (See fig. 3.)

In an attempt to relate the pilot ratings to the response characteristics of the airplane, the computer-generated time histories of figure 5 were obtained wherein the control column was pulsed and the ensuing pitch attitude response recorded for the various combinations of C_{m_q} and C_{m_α}. As shown in figure 5(a), when the value of static stability was $C_{m_\alpha} = -0.5$, the pilot ratings varied from 2.5 (acceptable) for $C_{m_q} = -100$ to 7.0 (unacceptable) for $C_{m_q} = 0$. There is a similar correlation of pitch damping with pilot rating when $C_{m_\alpha} = 0.2$ (fig. 5(b)) or when $C_{m_\alpha} = 0.8$ (fig. 5(c)). This correla-

tion of lower pilot rating with lower damping in pitch is understandable because of the obvious increase in the oscillatory nature of the motion as the pitch damping is reduced. However, the data show little correlation of pilot rating for a specific response; for example, compare the responses shown in figures 5(a) and 5(b) for a pilot rating of 4.5. It is obvious, then, that something other than pitch damping is affecting pilot opinion $\left(\text{these factors being } C_{m_\alpha} \text{ and/or } C_{m_{C_T}}\right)$, regardless of whether the airplane is statically stable $\left(-C_{m_\alpha}\right)$ or unstable $\left(+C_{m_\alpha}\right)$.

If the airplane has sufficient pitch damping, it might be assumed that the pitch response is the factor which affects pilot rating as the static stability is varied. With $C_{m_q} = -100$ (very high damping), a 1° step input to the horizontal tail was made for values of C_{m_α} ranging from -2.0 to 2.4, and the pitch-attitude response was measured. (See fig. 6.) As can be seen from these data, there is again no definite correlation between pilot rating and any specific pitch response. (Compare the time histories obtained for $C_{m_\alpha} = -2.0$ and $C_{m_\alpha} = 0.80$, and note that both conditions were assigned a pilot rating of 5.5.) Therefore, something other than pitch response and pitch damping must affect the pilot's opinion of the longitudinal characteristics.

The pilot observed that one of the major factors that influenced the ratings of the longitudinal characteristics was the amount and direction of pitch-attitude change ($\Delta\theta$) brought about by a change in thrust (ΔT). With $C_{m_q} = -100$ (very high damping), a step reduction of thrust, with a magnitude approximating that required to capture a 6° glide slope, was made for values of C_{m_α} ranging from -2.0 to 2.4, and the pitch-attitude response was measured. (See fig. 7.) It can be seen from these data that for a large negative value of C_{m_α}, the airplane has a fairly large nose-down pitch for a step reduction in thrust. Also, with a C_{m_α} of -0.5 it is seen that essentially zero-pitch attitude change is experienced when the thrust is reduced for glide-slope capture. (This was the configuration assigned the best pilot rating.) For values of $C_{m_\alpha} > -0.5$, the airplane pitches nose-up for a reduction in thrust, the rate of pitch increasing as the C_{m_α} is increased. The direction of pitch-attitude change ($\Delta\theta$) associated with a change in thrust $\left(\Delta C_T\right)$ depends upon the sign of the sum of $\left(C_{m_{C_T}} \Delta C_T + C_{m_\alpha} \Delta\alpha\right)$. The effect of $C_{m_{C_T}}$ on the magnitude of "effective" C_{m_α} was discussed earlier in this section. The pilot preferred to have zero-pitch change associated with changes in thrust, but he preferred a nose-down change over a nose-up change for a reduction in thrust. The major reason for such a preference was that it would be bothersome and dangerous to have the airplane pitch nose-down when thrust was added for the landing flare.

All the time histories shown in figure 7 were obtained for a very high value of C_{m_q} $\left(C_{m_q} = -100\right)$. As shown in figure 5, however, the magnitude of C_{m_q} greatly affects the pitch-attitude response when the column is deflected. Likewise, the magnitude of C_{m_q} affects the pitching motion experienced when thrust is varied. (See fig. 8.)

As indicated in figure 9, the magnitude of $C_{m_{C_T}}$ can also affect the control of pitch attitude. Figure 9 presents the pitch responses caused by a reduction in thrust for several values of $C_{m_{C_T}}$, and it can be seen that a larger $\Delta\theta$ was experienced for the larger negative value of $C_{m_{C_T}}$. (It should be mentioned that the small $\Delta\theta$ indicated for the condition where $C_{m_{C_T}} = C_{m_\alpha} = 0$, is attributed to the effect of $C_{m_{\dot{\alpha}}}$.)

Pilot evaluations were also obtained for the previously discussed C_{m_q} and C_{m_α} matrix, where $C_{m_{C_T}}$ was set equal to 0 as well as -0.2, and the resulting pilot opinion boundaries are presented in figures 10 and 11, respectively. After comparing figures 10, 3, and 11 ($C_{m_{C_T}} = 0$, -0.1, and -0.2, respectively), it can be seen that (a) there was no definite trend regarding the magnitude of $C_{m_{C_T}}$, insofar as the likelihood of being within the "satisfactory" region is concerned, and (b) it appears that the likelihood of being within an "acceptable" region would be greater for $C_{m_{C_T}} = -0.1$ than for $C_{m_{C_T}} = 0$ or -0.2. However, it can be concluded from these pilot opinion boundaries (figs. 3, 10, and 11) that the pilot would accept, for emergency use, a decidedly unstable aircraft.

Comparison of Results With Dynamic Stability Requirements and Criteria

The results presented in figure 3, wherein the base value of $C_{m_{C_T}}$ was used, were compared with some commonly used criteria for longitudinal handling qualities. These criteria are presented in figure 12, and the comparisons of the results of figure 3 with these criteria are shown in figure 13. (The requirements of minimum damping for "acceptable" operation have also been included where applicable.) As can be seen in figure 13, the correlation of results of the present study with the criterion presented in reference 7 is good. The correlation of these results with the criterion set forth in reference 8 is fair for the positive values of C_{m_α} tested. Note that no attempt is made to correlate the present results with the criterion of reference 8 for the negative values of C_{m_α} tested. No specific criterion is given in reference 8 for an "acceptable" level of minimum damping; only a "satisfactory" level of minimum damping is presented there. The correlation of the results of this study with the criterion proposed in reference 9 appears to be very good for the entire range of C_{m_α} tested, and the correlation with the criterion presented in reference 10 appears to be poor for most of the C_{m_α} range of the test. (Typical values of C_{m_q} and C_{m_α} for the simulated STOL aircraft, as well as for a typical CTOL jet transport are presented in fig. 13.)

It is concluded that the results of the present study correlated reasonably well with the published STOL handling qualities requirements. The best correlation was with the most recently published requirements. In addition, the results of the present STOL simulation correlated poorly with the most recently published longitudinal handling qualities requirements for CTOL aircraft. (See ref. 10.)

Autospeed Control Operative

The autospeed system which was used drove a segment of the wing flap to maintain a selected airspeed (75 knots for this study) as described in reference 1. The piloting technique used to fly the approach when the autospeed control was operative was first to use the throttles (thrust) to capture the glide slope while an attempt was made to maintain a constant nose-up pitch attitude. The thrust was then held constant for the remainder of the approach, and the pilot tracked the glide slope with the column and/or the pitch trim control (pitch attitude).

The pilot opinion boundaries obtained when various magnitudes of C_{m_α} and C_{m_q} were used in combination with $C_{m_{C_T}} = -0.1$ and the autospeed operative are presented in figure 14. After a comparison of the results of figure 14 with those of figure 3, which were also obtained with $C_{m_{C_T}} = -0.1$ but with no autospeed, it could generally be said that they compare very well, particularly the "acceptable" boundaries. It may be noted that the boundaries shown in figure 14 tend to shift upward (higher damping required) from those boundaries presented in figure 3. The most probable explanation for this effect is that the pilot desires higher damping when he uses pitch attitude for tracking the glide slope (fig. 14) than when he uses pitch attitude for airspeed control (fig. 3).

Past investigations of CTOL aircraft, for which pitch attitude is used predominantly to track the glide slope, have often related the pilot's willingness to accept the longitudinal stability and control of a given configuration to the time required to halve or double the amplitude. One example is the work reported in reference 11 and presented in figure 15, which shows that the minimum "acceptable" mean time to double was found to be approximately 2.4 sec.

Since pitch attitude was used in this study to track the glide slope when the autospeed was operative, the time to double the amplitude was calculated for various values of C_{m_α} and C_{m_q}, and the results are presented in figure 16. These values of t_2 were then related to the maximum values of C_{m_α} and C_{m_q} which the pilots had designated as being acceptable for the conditions presented in figures 3 and 14. As can be seen, these pilot evaluations agree very well with those of reference 11 in that the minimum acceptable value of t_2 was found to be between 2.0 and 2.5 sec in this study compared with the value of 2.4 sec reported in reference 11.

It must be mentioned, however, that the calculated t_2 values plotted in figure 16 did not include the effects of $C_{m_{C_T}}$, since t_2 was calculated for a constant airspeed and a constant thrust setting. In contrast, the "acceptable" boundaries of figures 3

and 14 were, at least to some extent, affected by the magnitude of $C_{m_{C_T}}$. However, if the maximum values of C_{m_α} and C_{m_q} found to be acceptable when $C_{m_{C_T}} = 0$ (fig. 10) are related to the corresponding values of t_2 of figure 16, it will be seen that the minimum acceptable mean value of t_2 is 2.5 sec. Likewise, the minimum acceptable mean value of t_2 is 2.25 sec when the maximum acceptable values of C_{m_α} and C_{m_q} presented in figure 14 are used. (The parameter $C_{m_{C_T}}$ affected the pilot ratings indicated in fig. 14 only during the glide-slope capture since thrust was held constant during the glide-slope tracking.) Therefore, the "acceptable" boundary having a mean t_2 of 2.3 sec and shown in figure 16 is believed to be valid.

It is concluded, then, that a STOL airplane which has positive values of C_{m_α} (destabilizing) in combination with negative values of C_{m_q} (stabilizing) that result in an oscillation, or divergence that takes more than 2.5 sec to double the amplitude, could be safely controlled (pilot rating of 6.5 or better on an ILS approach). In addition, divergences that required less than 2.5 sec to double the amplitude were either marginal or unacceptable.

Effects of Atmospheric Turbulence

As has been discussed in previous STOL simulation programs (in ref. 1, for example), turbulence level and mean wind speed and direction are important task variables in STOL operations. Although the results discussed thus far were obtained without turbulence, atmospheric turbulent conditions were considered in the present study. The simulated turbulence was described by the pilot as being representative of "light to moderate" turbulence.

After many of the previously discussed stable and unstable conditions were flown in the presence of turbulence, the effects of turbulence were found to be as follows: for the "satisfactory" pilot ratings in calm air, the pilot rating increased about 1/2 rating in turbulence; for the "acceptable" pilot ratings in calm air, the pilot rating increased 1/2 to 1 rating with turbulence; and for the "unacceptable" pilot ratings in calm air, the pilot rating increased 1 or more ratings in turbulence. It is believed, however, that the previously discussed pilot opinion "boundaries" are still valid, even when turbulent conditions are considered, since the "boundaries" were drawn as "bands" wide enough, to encompass pilot rating changes up to 1 rating.

Effect of Aircraft Size

As stated previously, a larger aircraft, which had a gross weight of 578 kN (130 000 lbf) and a wing loading of 3831 N/m^2 (80 lbf/ft^2), was briefly evaluated. The pilot opinion boundaries obtained when various magnitudes of C_{m_α} and C_{m_q} were used as inputs for the larger airplane are presented in figure 17. If the "acceptable"

boundary shown for the larger airplane (fig. 17) is compared with that shown for the smaller airplane (fig. 3), it is apparent that the general shapes of the boundaries were very similar but that the magnitudes of both C_{m_q} and C_{m_α} were very different. Therefore, it was concluded that any pilot opinion boundary that may be drawn from the results of this study should not be presented in coefficient form, since the coefficients are independent of aircraft size. The "acceptable" boundaries of figures 3 and 17 were replotted and are presented in figure 18 in dimensional form. As can be seen from figure 18, the results were in excellent agreement.

CONCLUDING REMARKS

A fixed-base simulator program was conducted to determine the minimum acceptable level of longitudinal stability of a representative turbofan STOL (short take-off and landing) transport airplane during the landing approach. The pilot ratings and opinion boundaries presented in this paper reflect the effects of a combination of the level of apparent pitch damping, the responsiveness of the airplane to a column input, and the amount and direction of pitch-attitude disturbances caused by changes in thrust coefficient.

The pilot opinion data showed that the pilot would accept, for emergency use, a decidedly unstable airplane. Pilot ratings of 6.5 or better were assigned to many conditions having positive values (destabilizing) of C_{m_α} (pitching-moment coefficient due to angle of attack) and negative values (stabilizing) of C_{m_q} (pitching-moment coefficient due to rate of pitch). The degree of tolerable instability was a function of the amount of damping present. The change in pitching moment with thrust coefficient had a stabilizing effect when $C_{m_{C_T}}$ (pitching-moment coefficient due to thrust coefficient) had a negative value.

Pilot opinion was found to be related to divergence time rather than the degree of static instability. It was concluded that, when a STOL airplane was unstable and required 2.5 sec or longer to diverge to double the amplitude in pitch, it could be safely controlled on an ILS (instrument landing system) approach (a pilot rating of 6.5 or better). Divergences that doubled the pitch amplitude in less than 2.5 sec were either marginal or unacceptable.

The results of this study correlate well with some of the most recently published STOL longitudinal handling qualities criteria. Most of the results were obtained in calm air. However, the introduction of "moderate to light" atmospheric turbulence did not appreciably affect the pilot opinion boundaries.

It was concluded that any boundary or boundaries that may be drawn from the results of this study should be presented in dimensional, not coefficient, form since the

coefficients are independent of aircraft size. Aircraft size did not affect the conclusions drawn in this paper.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., June 28, 1974.

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TABLE I.- MASS AND DIMENSIONAL CHARACTERISTICS

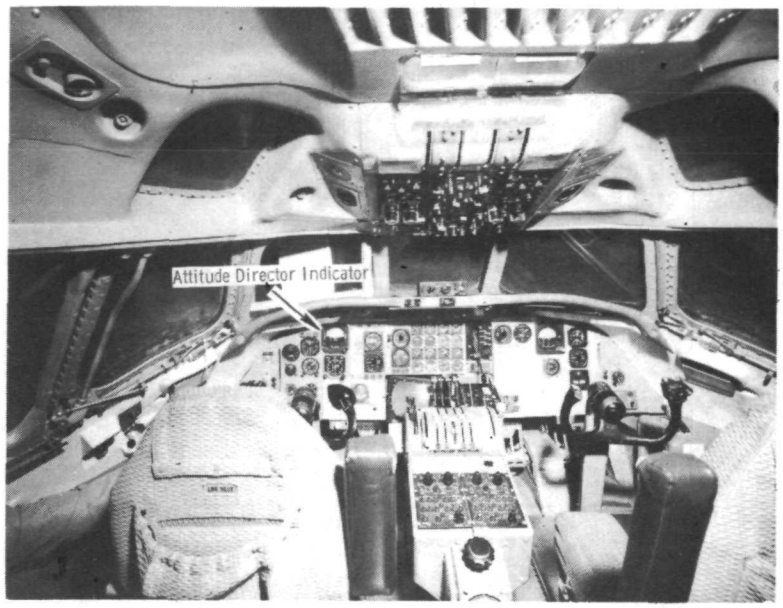
	Basic aircraft		Larger aircraft	
Weight, N (lbf)	245 096	(55 100)	578 266	(130 000)
Wing area, m^2 (ft^2)	78	(843)	151	(1 625)
Wing span, m (ft)	24	(78)	32	(105)
Mean aerodynamic chord, m (ft)	3.58	(11.74)	4	(13)
I_X, kg-m^2 (slug-ft^2)	331 103	(244 212)	1 525 275	(1 125 000)
I_Y, kg-m^2 (slug-ft^2)	334 637	(246 819)	3 558 975	(2 625 000)
I_Z, kg-m^2 (slug-ft^2)	625 677	(461 482)	4 880 880	(3 600 000)
I_{XZ}, kg-m^2 (slug-ft^2)	27 690	(20 423)	0	(0)

TABLE II.- SIMULATOR CONTROL CHARACTERISTICS

Control	Maximum travel in –			Breakout force		Force gradient	
	deg	cm	in.	N	lbf	N/cm	lbf/in.
Column:							
Forward	9.9	13.97	5.50	13.3	3.0	14.0	8.0
Aft	20.5	25.25	9.94				–
Wheel	±130.0	±37.34	±14.70	11.1	2.5	5.3	3.0
Pedal		10.80	4.25	31.1	7.0	28.9	16.5

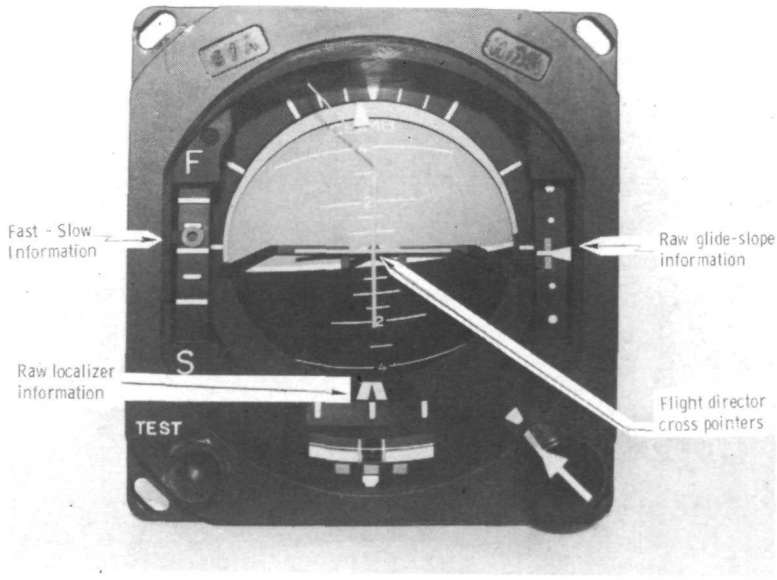
TABLE III.- PILOT RATING SYSTEM

CONTROLLABLE Capable of being controlled or managed in context of mission, with available pilot attention.	ACCEPTABLE May have deficiencies which warrant improvement, but adequate for mission. Pilot compensation, if required to achieve acceptable performance, is feasible.	SATISFACTORY Meets all requirements and expectations; good enough without improvement. Clearly adequate for mission.	Excellent, highly desirable.	1
			Good, pleasant, well behaved.	2
			Fair. Some mildly unpleasant characteristics. Good enough for mission without improvement.	3
		UNSATISFACTORY Reluctantly acceptable. Deficiencies which warrant improvement. Performance adequate for mission with feasible pilot compensation.	Some minor but annoying deficiencies. Improvement is requested. Effect on performance is easily compensated for by pilot.	4
			Moderately objectionable deficiencies. Improvement is needed. Reasonable performance requires considerable pilot compensation.	5
			Very objectionable deficiencies. Major improvements are needed. Requires best available pilot compensation to achieve acceptable performance.	6
	UNACCEPTABLE Deficiencies which require improvement. Inadequate performance for mission even with maximum feasible pilot compensation.		Major deficiencies which require improvement for acceptance. Controllable. Performance inadequate for mission, or pilot compensation required for minimum acceptable performance in mission is too high.	7
			Controllable with difficulty. Requires substantial pilot skill and attention to retain control and continue mission.	8
			Marginally controllable in mission. Requires maximum available pilot skill and attention to retain control.	9
UNCONTROLLABLE Control will be lost during some portion of mission.			Uncontrollable in mission.	10



L-72-3813.2

(a) Simulator cockpit.



L-73-4451.1

(b) Attitude director indicator (ADI).

Figure 1.- Simulator cockpit and instrument display.

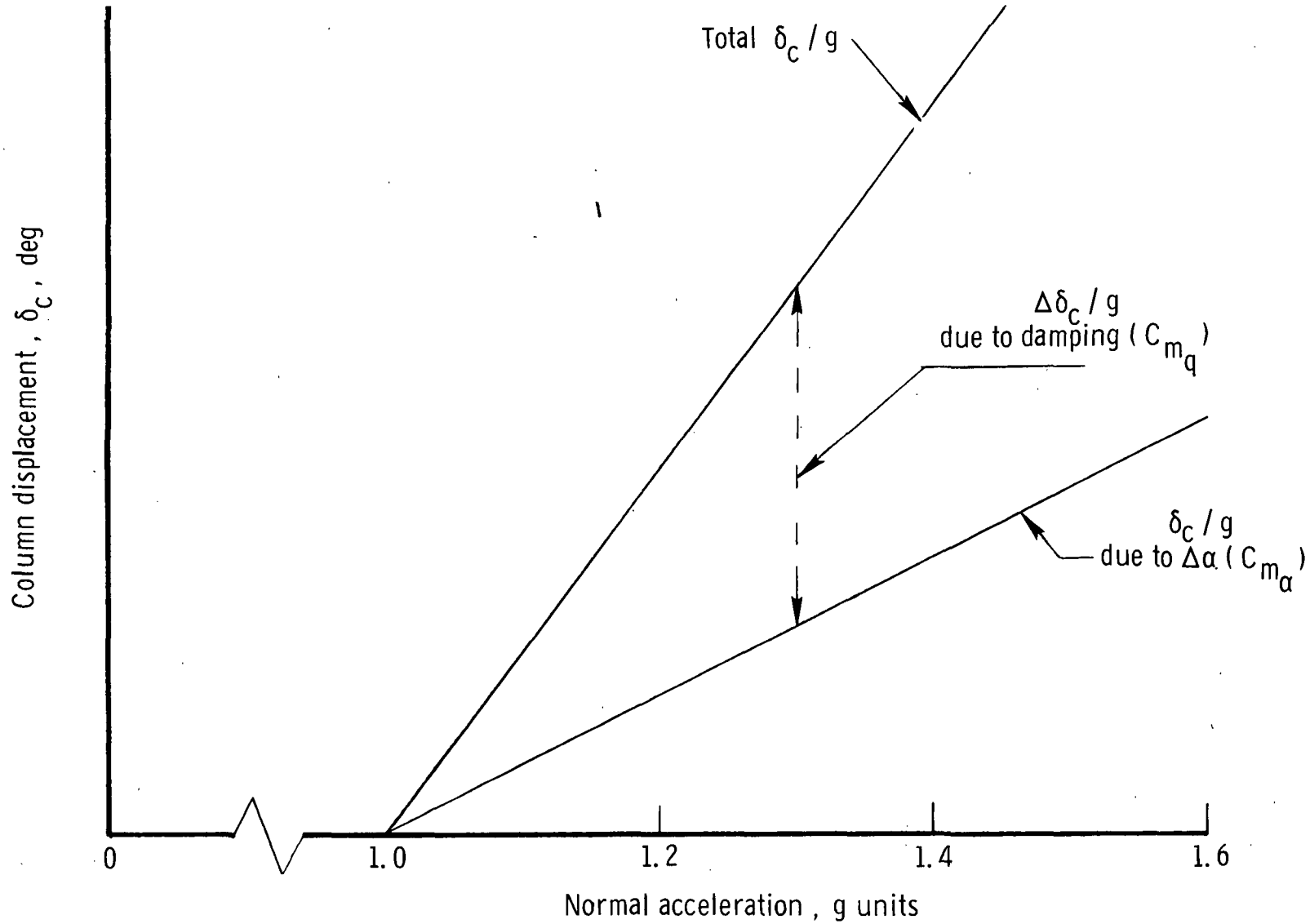


Figure 2.- Indication of the effect of C_{m_q} on the "apparent" static stability.

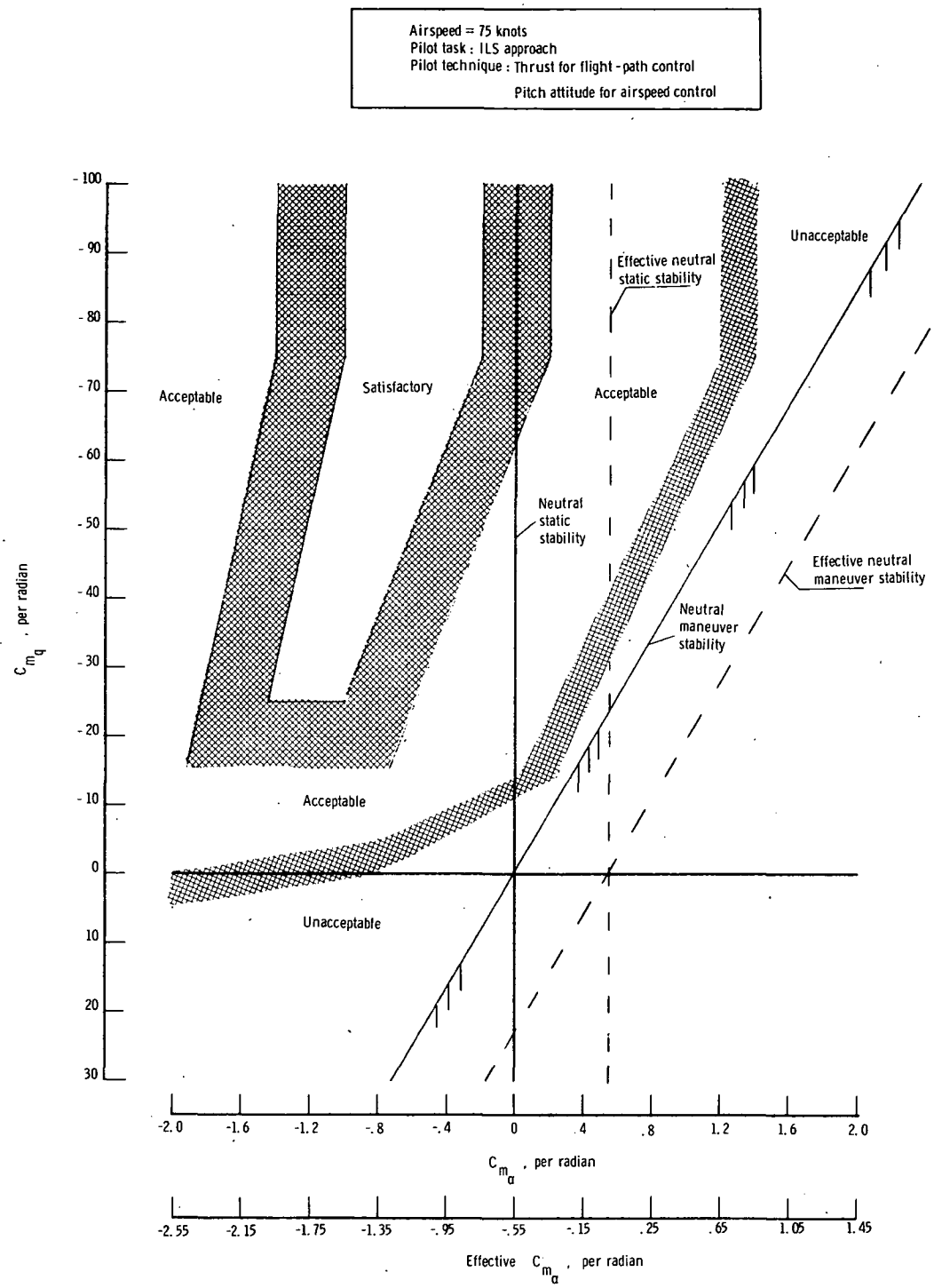


Figure 3. Effect of C_{m_q} and C_{m_α} on pilot opinion for $C_{m_{C_T}} = -0.10$.

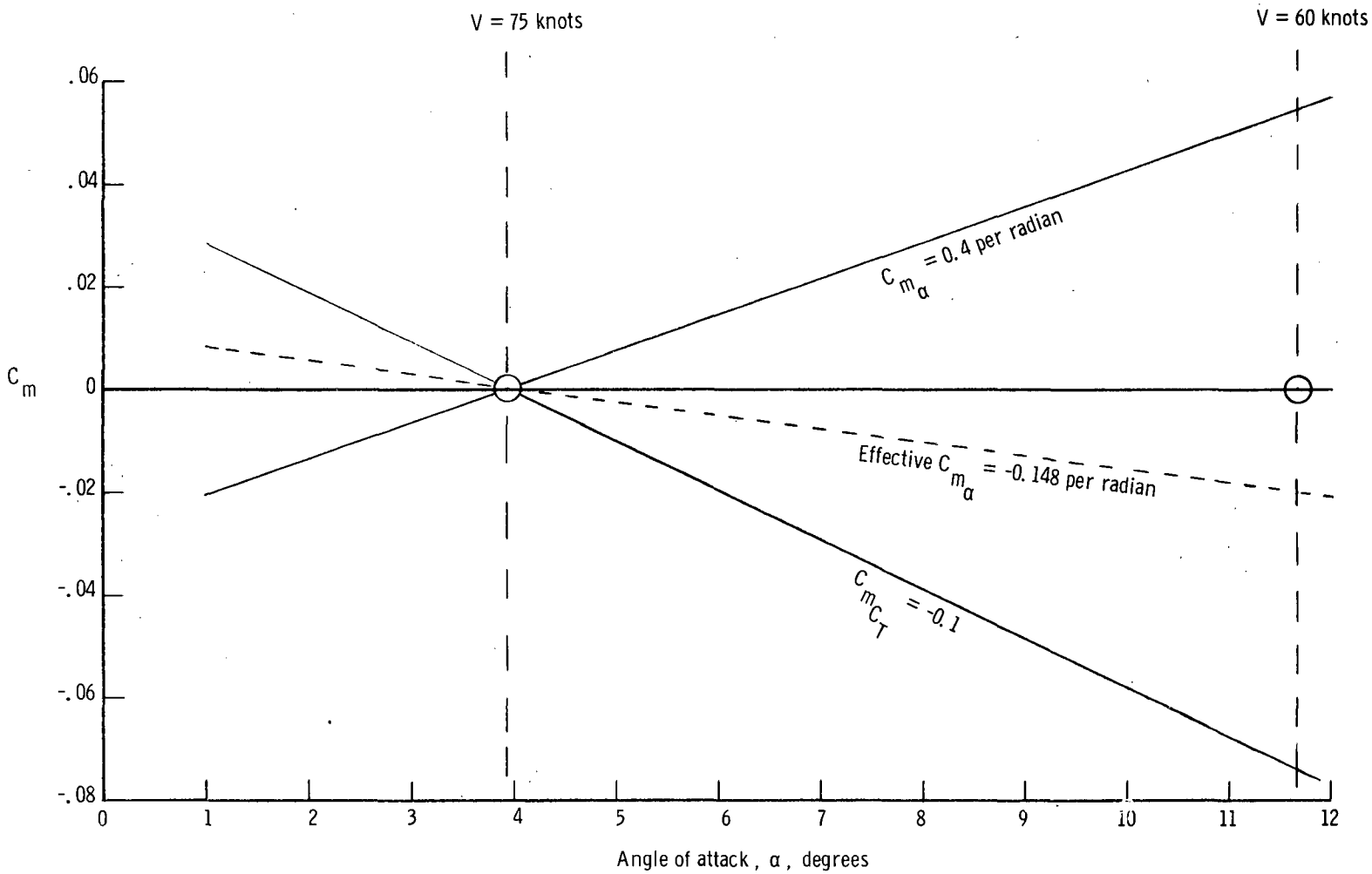
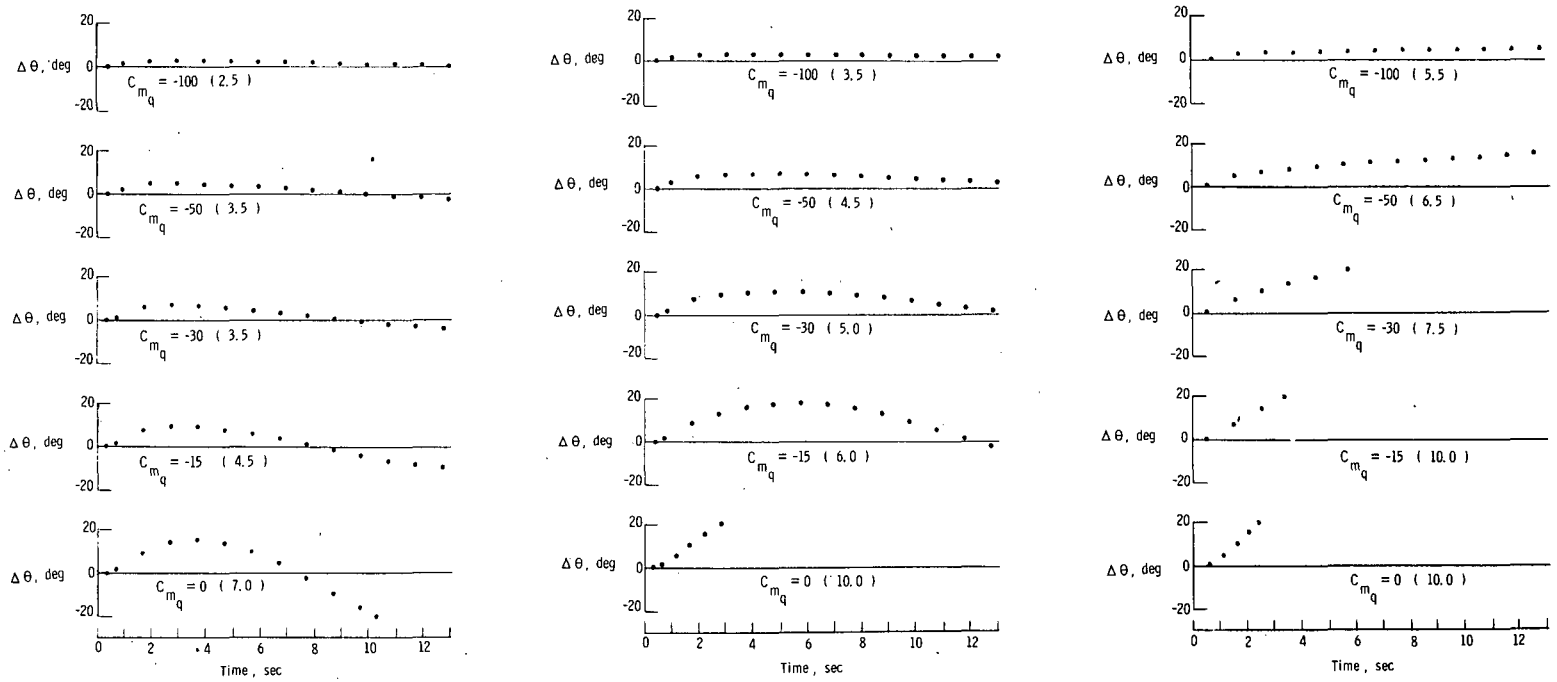


Figure 4.- Indication of the effect of $C_{m_{C_T}}$ on "effective" C_{m_α}.



(a) C_{m_α} = -0.5 per radian. (b) C_{m_α} = 0.2 per radian. (c) C_{m_α} = 0.8 per radian.

Figure 5.- Pitch-attitude response to a pulse of the horizontal tail. The numbers in parentheses indicate pilot rating.

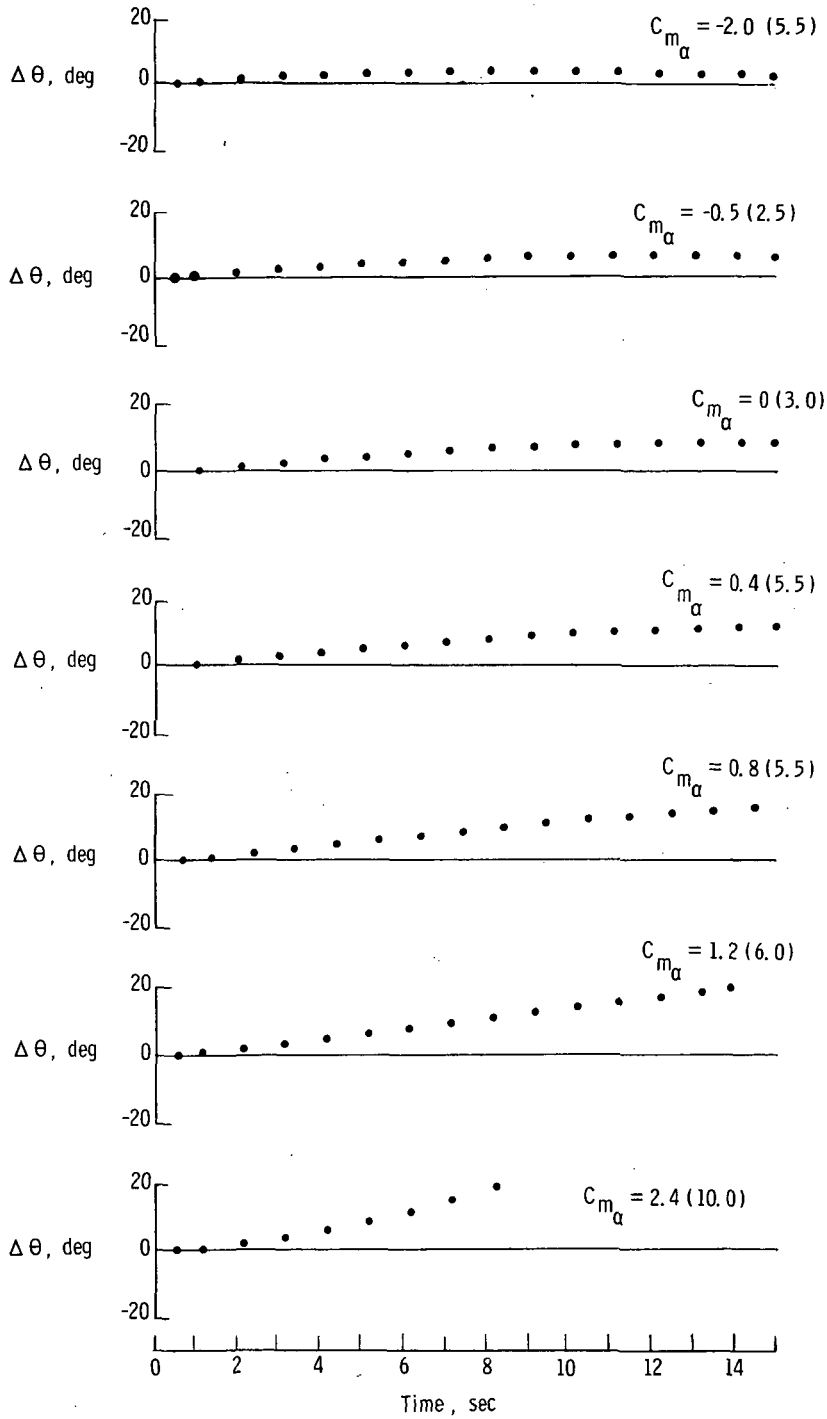


Figure 6.- Pitch attitude response to a step input of the horizontal tail. C_{m_q} = -100 in each instance. The numbers in parentheses indicate pilot rating.

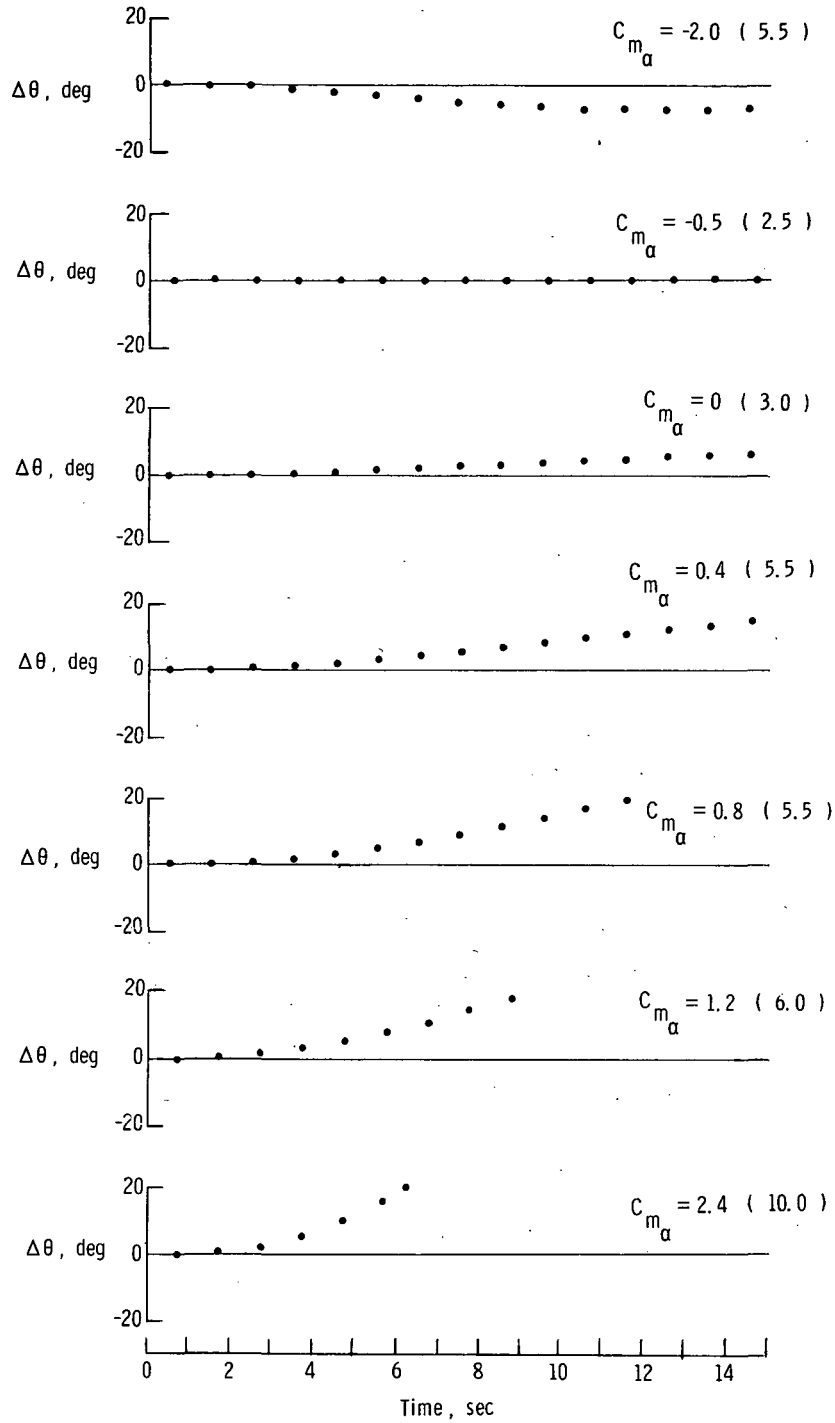
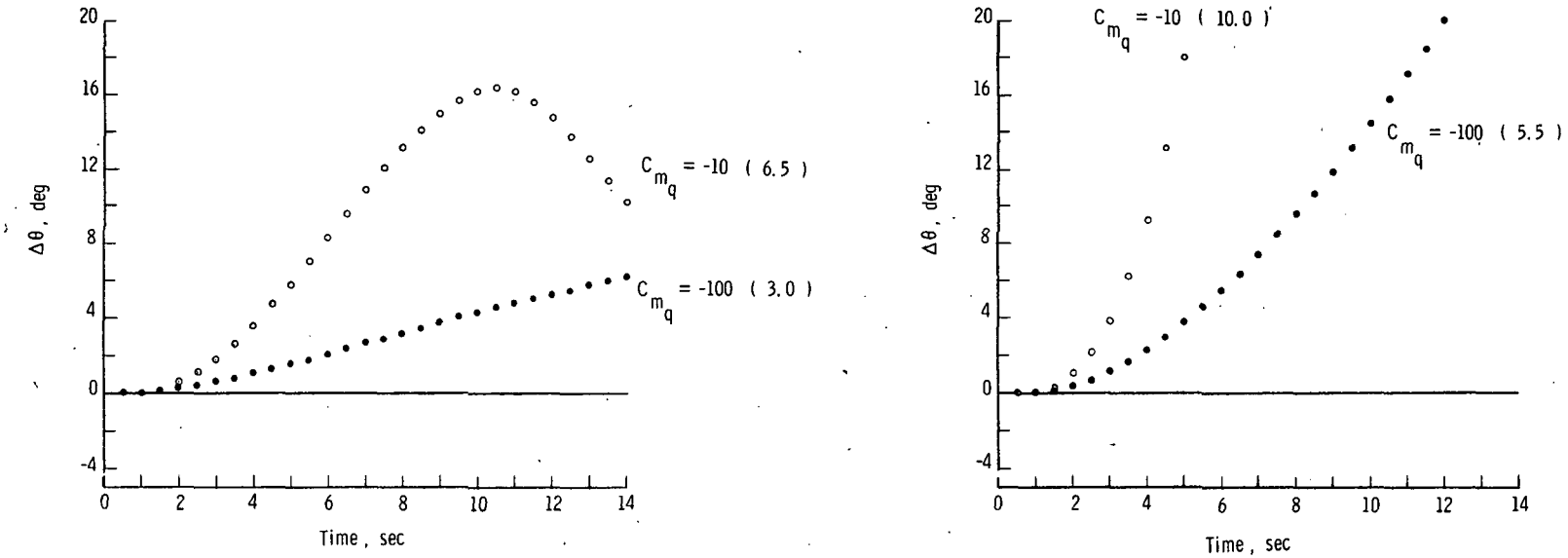


Figure 7.- Pitch-attitude response to a thrust reduction step input. $C_{m_q} = -100$ and $C_{m_{C_T}} = -0.10$ in each instance. The numbers in parentheses indicate pilot rating.



(a) $C_{m_\alpha} = 0.$

(b) $C_{m_\alpha} = 0.8.$

Figure 8.- Effect of C_{m_q} on pitch-attitude response to a reduction in thrust step input. Numbers in parentheses indicate pilot rating.

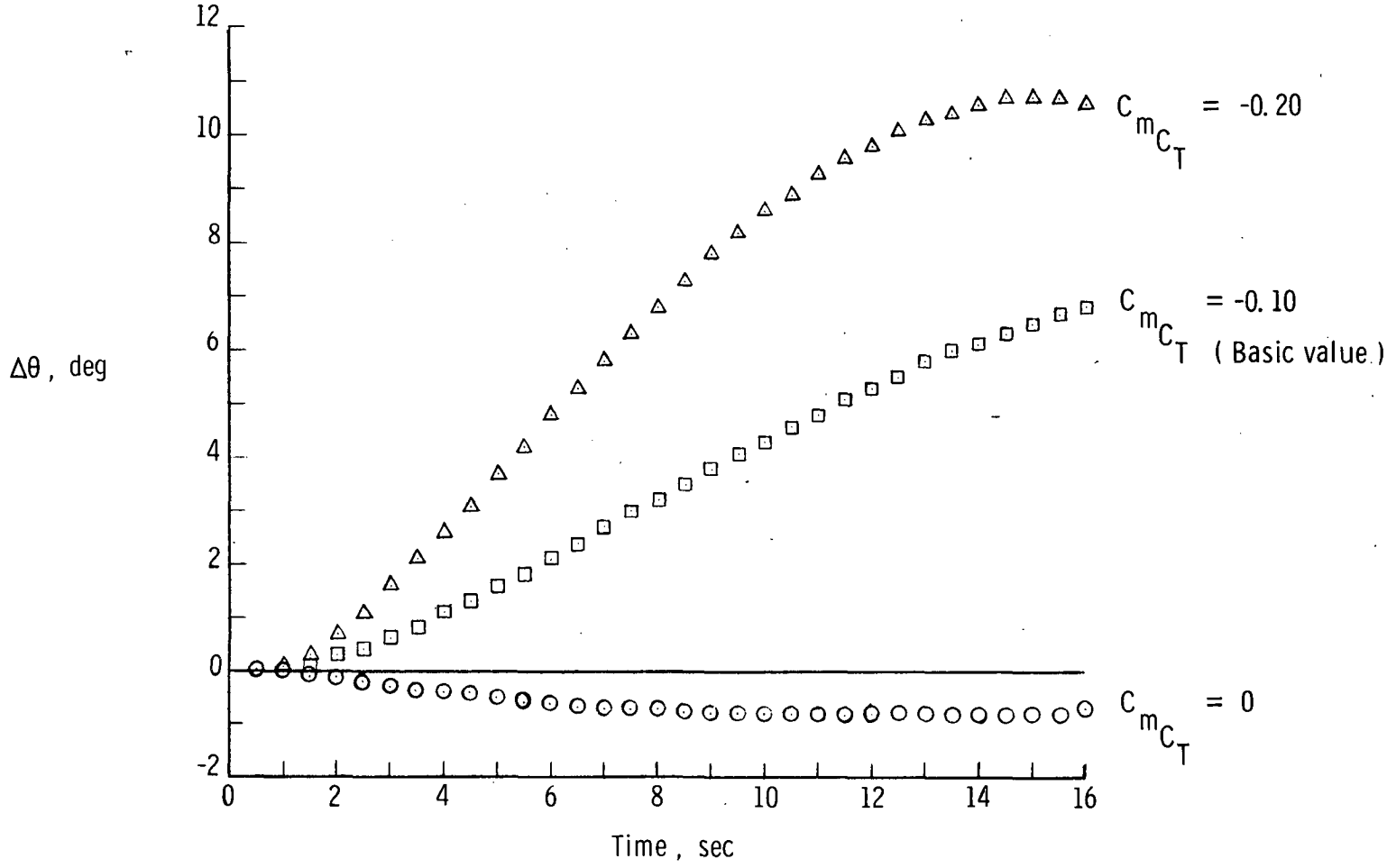


Figure 9.- Effect of $C_{m_{C_T}}$ on pitch-attitude disturbance due to step reduction in thrust. $C_{m_\alpha} = 0$; $C_{m_q} = -100$.

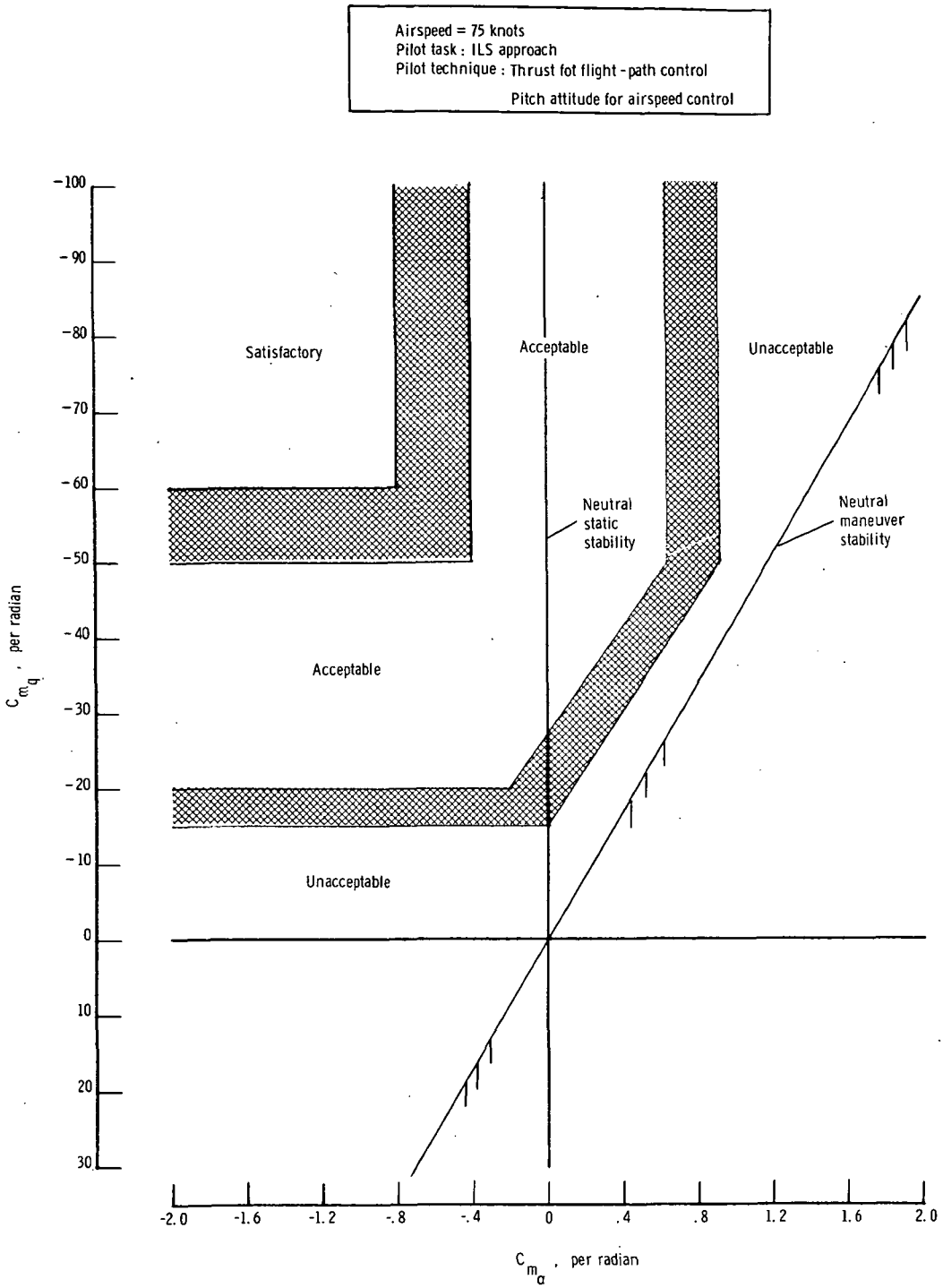


Figure 10.- Effect of C_{m_q} and C_{m_α} on pilot opinion for $C_{m_{C_T}} = 0$.

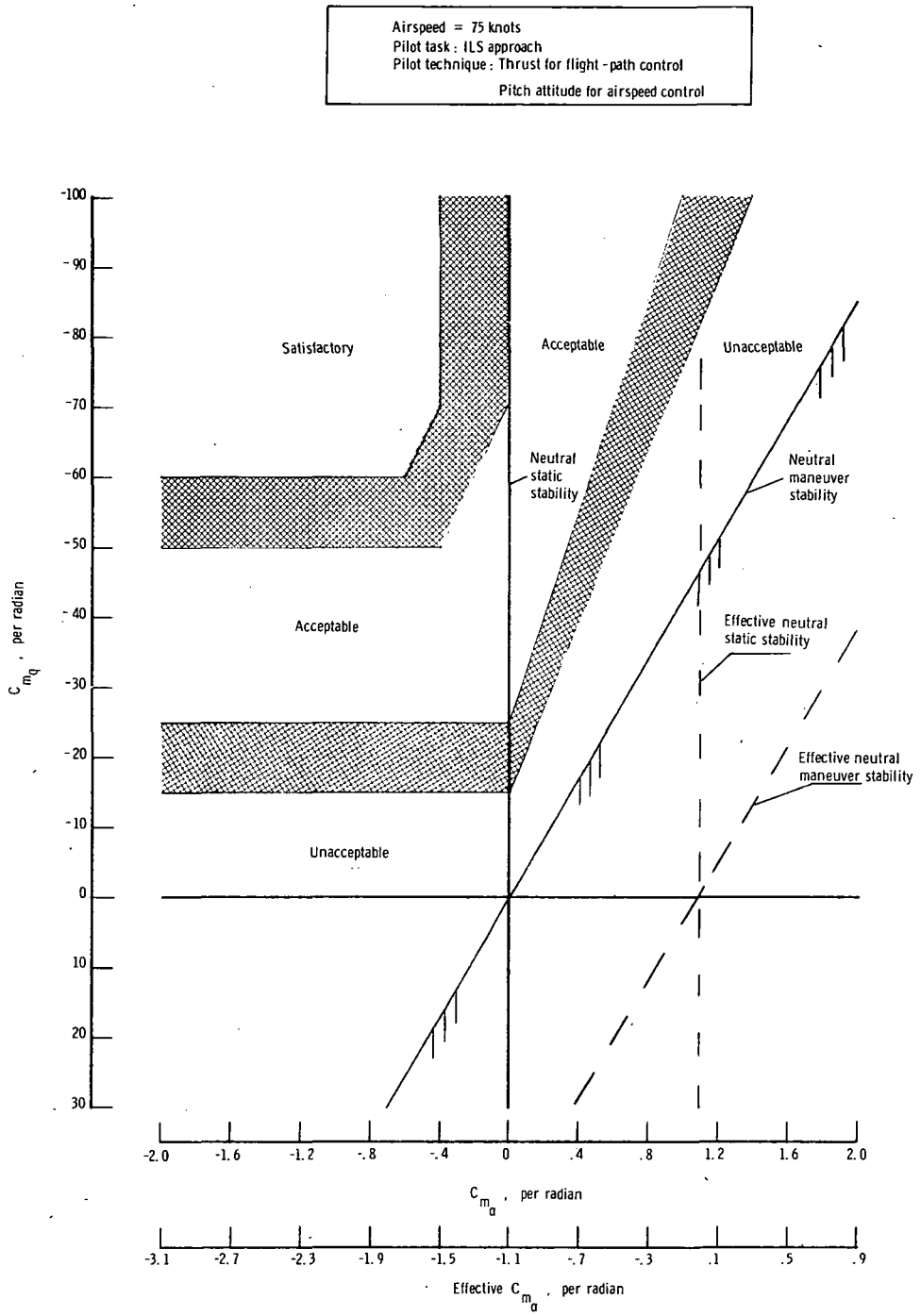
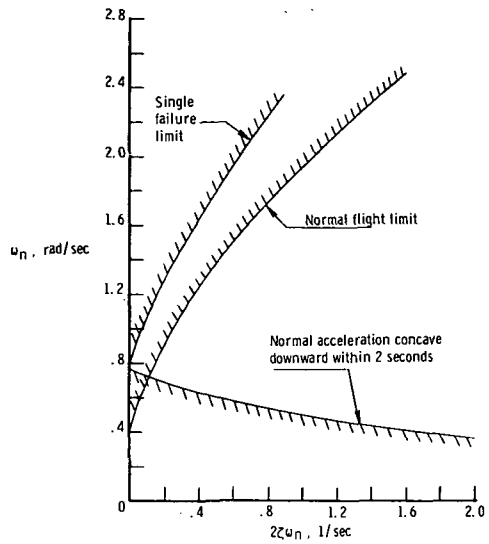
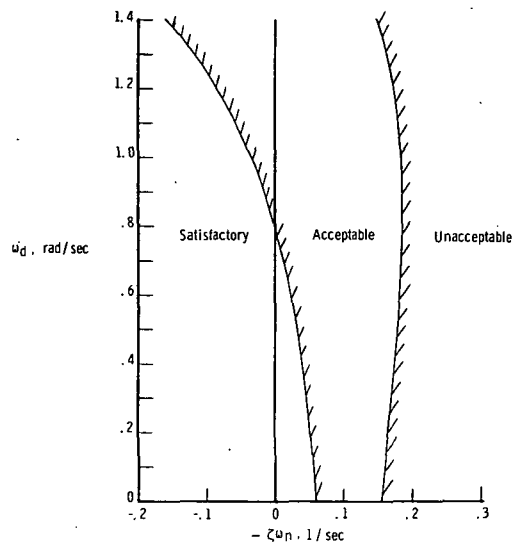


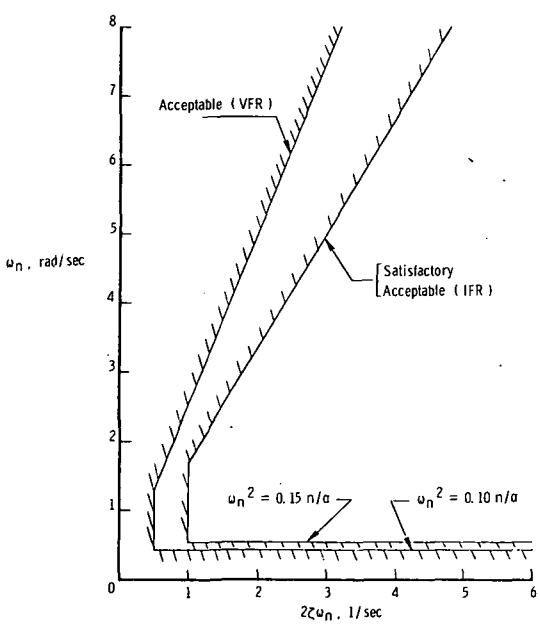
Figure 11.- Effect of C_{m_q} and C_{m_α} on pilot opinion for $C_{m_{C_T}} = -0.20$.



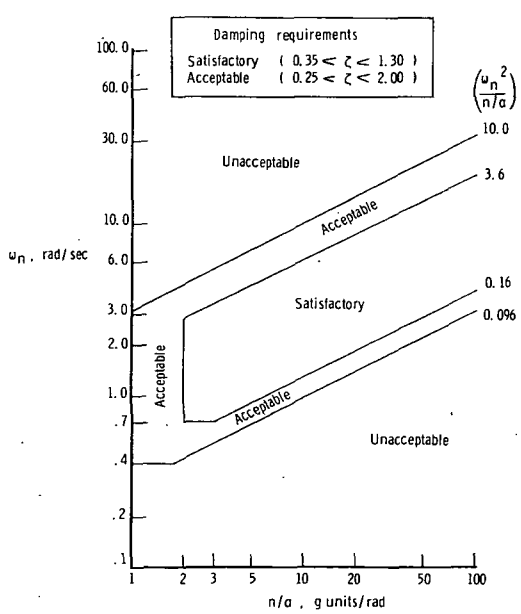
(a) Dynamic requirements of AGARD 408A (ref. 7).



(b) Longitudinal dynamic stability criteria of AGARD 577 (ref. 8).

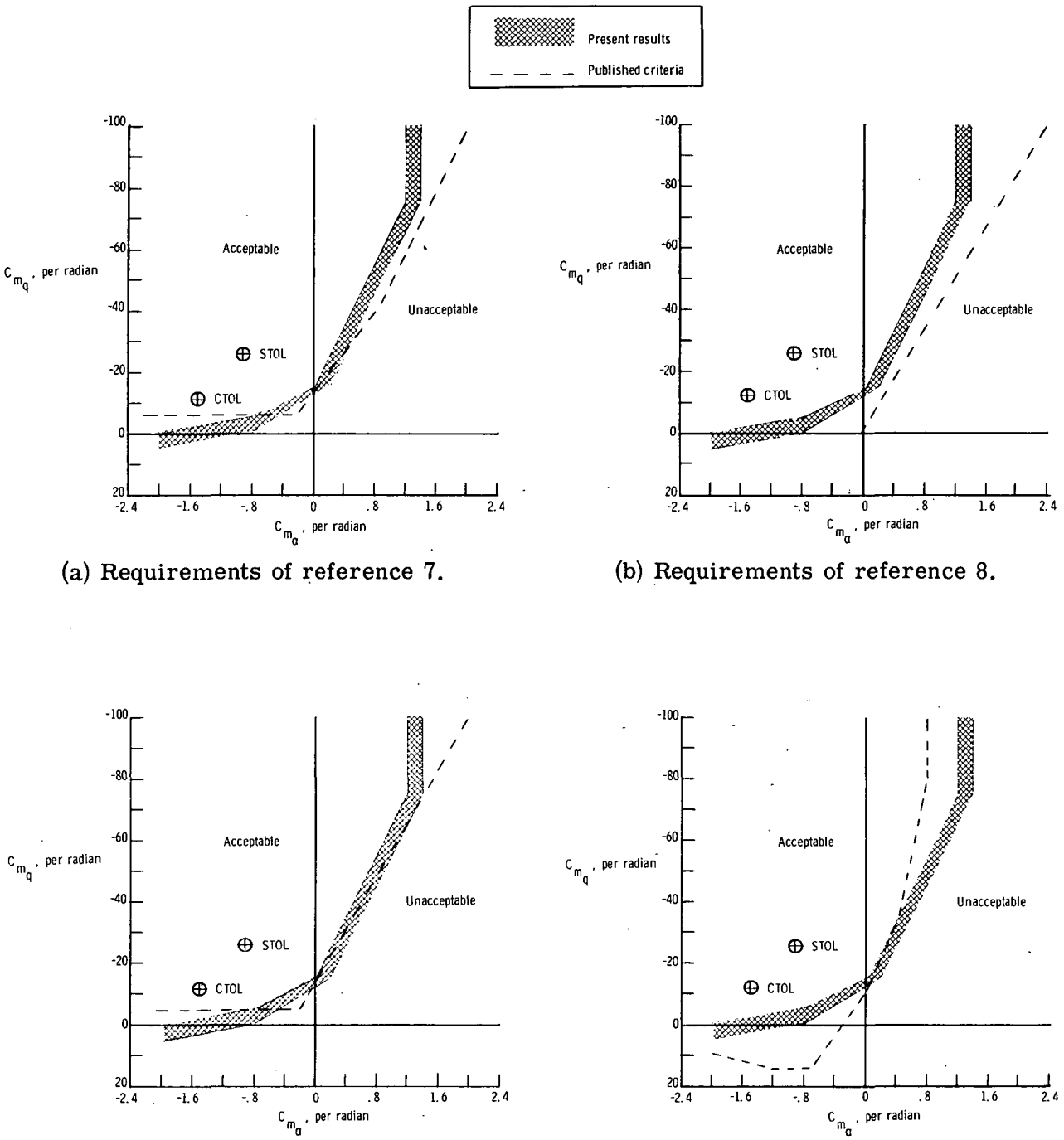


(c) Short term response requirements of MIL-F-83300 (ref. 9).



(d) Short-period frequency and damping requirements of MIL-F-8785B (ref. 10).

Figure 12.- Some published longitudinal handling qualities criteria.



(a) Requirements of reference 7.

(b) Requirements of reference 8.

(c) Requirements of reference 9.

(d) Requirements of reference 10.

Figure 13.- Comparison of results presented in figure 3 with the criteria of figure 12.

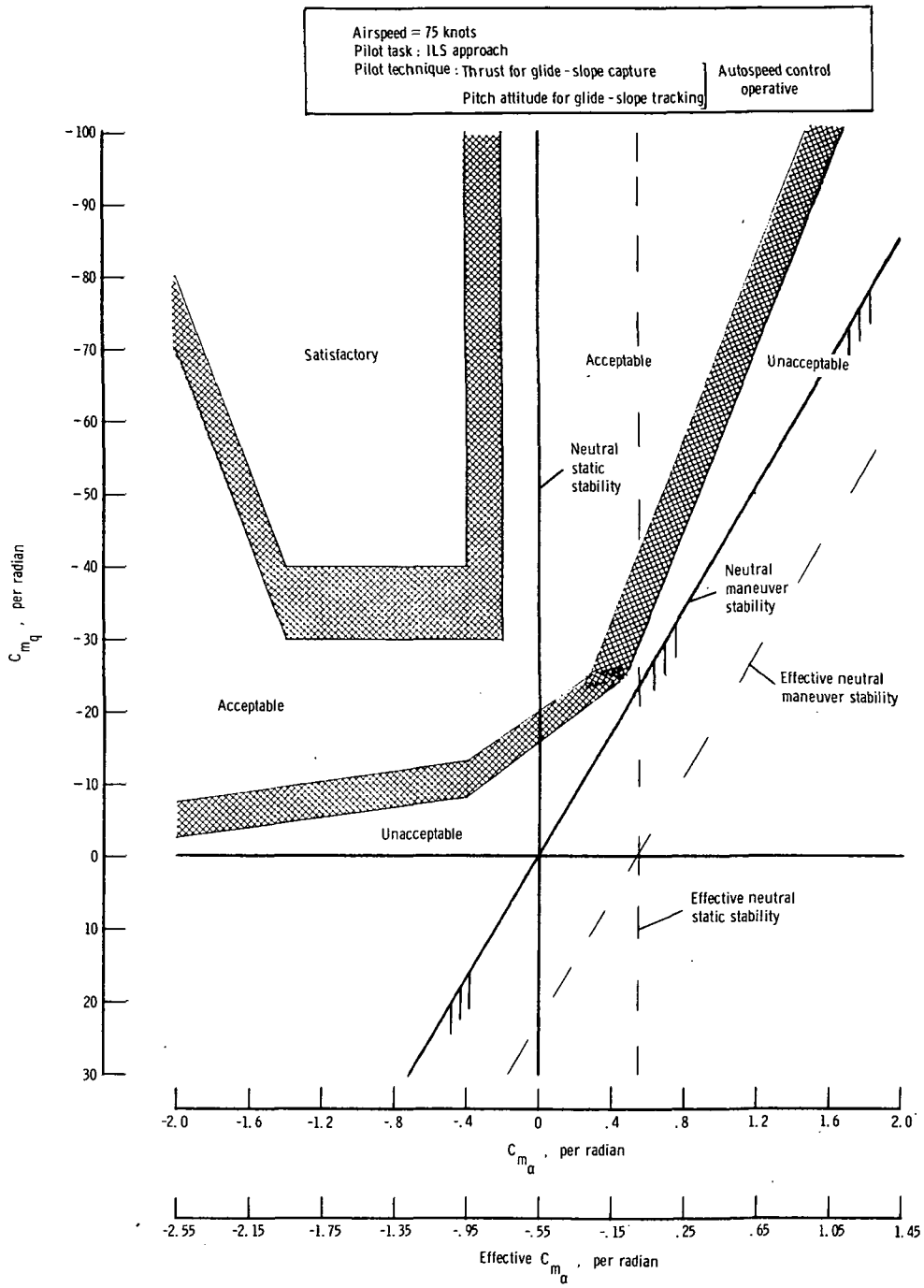


Figure 14.- Effect of C_{m_q} and C_{m_α} on pilot opinion for $C_{m_{C_T}} = -1.10$ and autospeed operative.

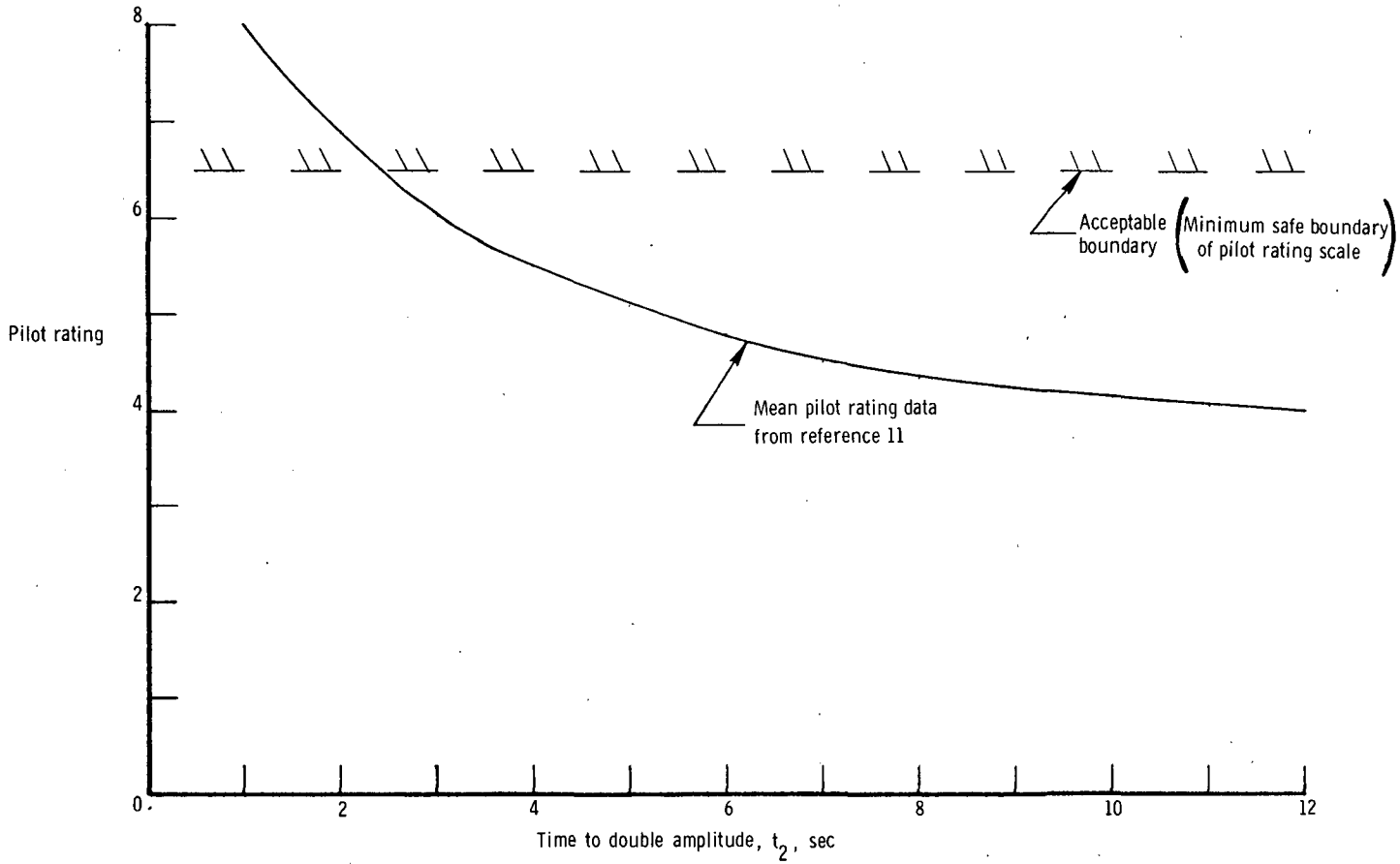


Figure 15.- Variation of mean pilot rating with time to double the amplitude, as taken from reference 8.

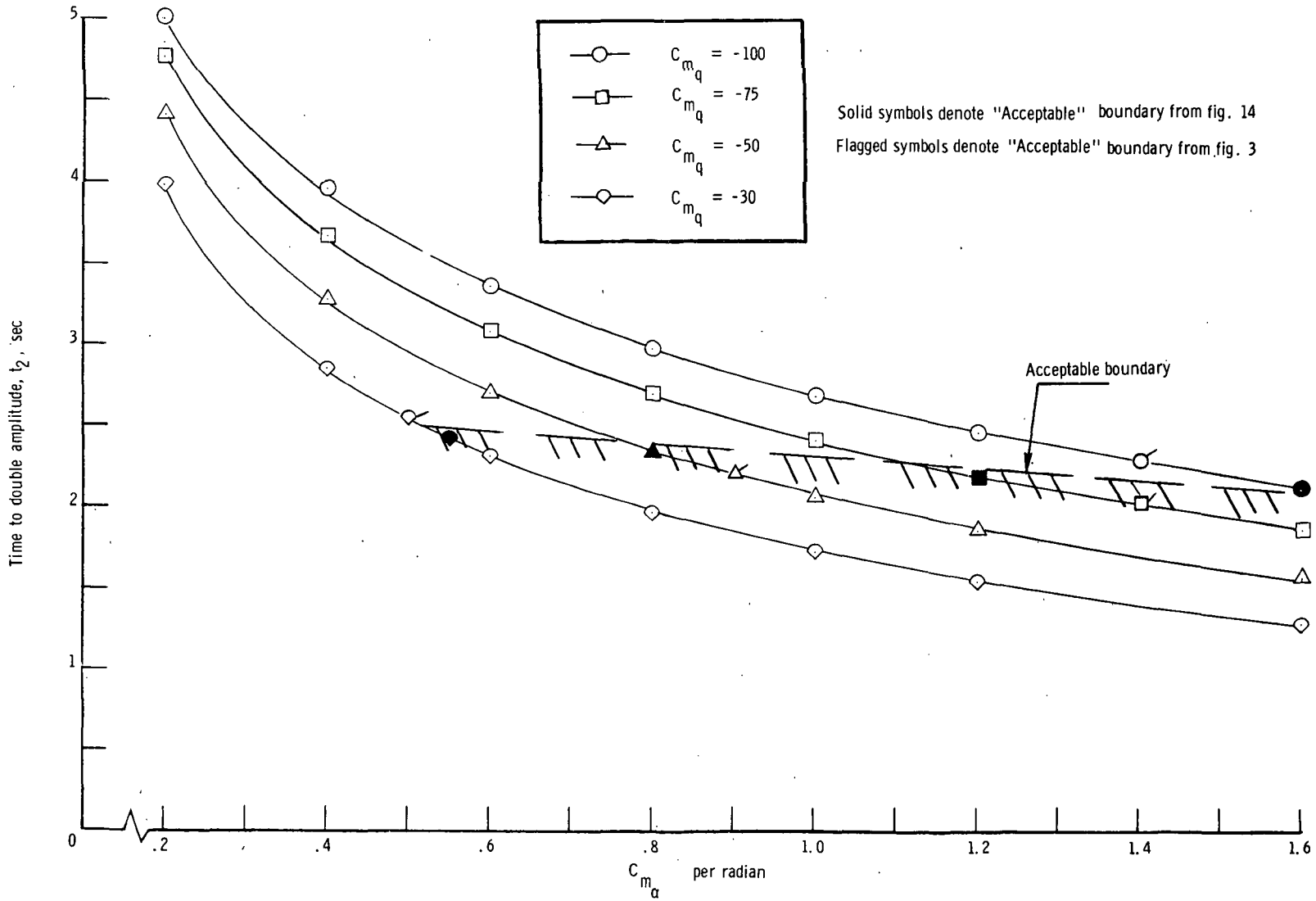


Figure 16.- Indication of the effect of C_{m_q} and C_{m_α} on time to double the amplitude.

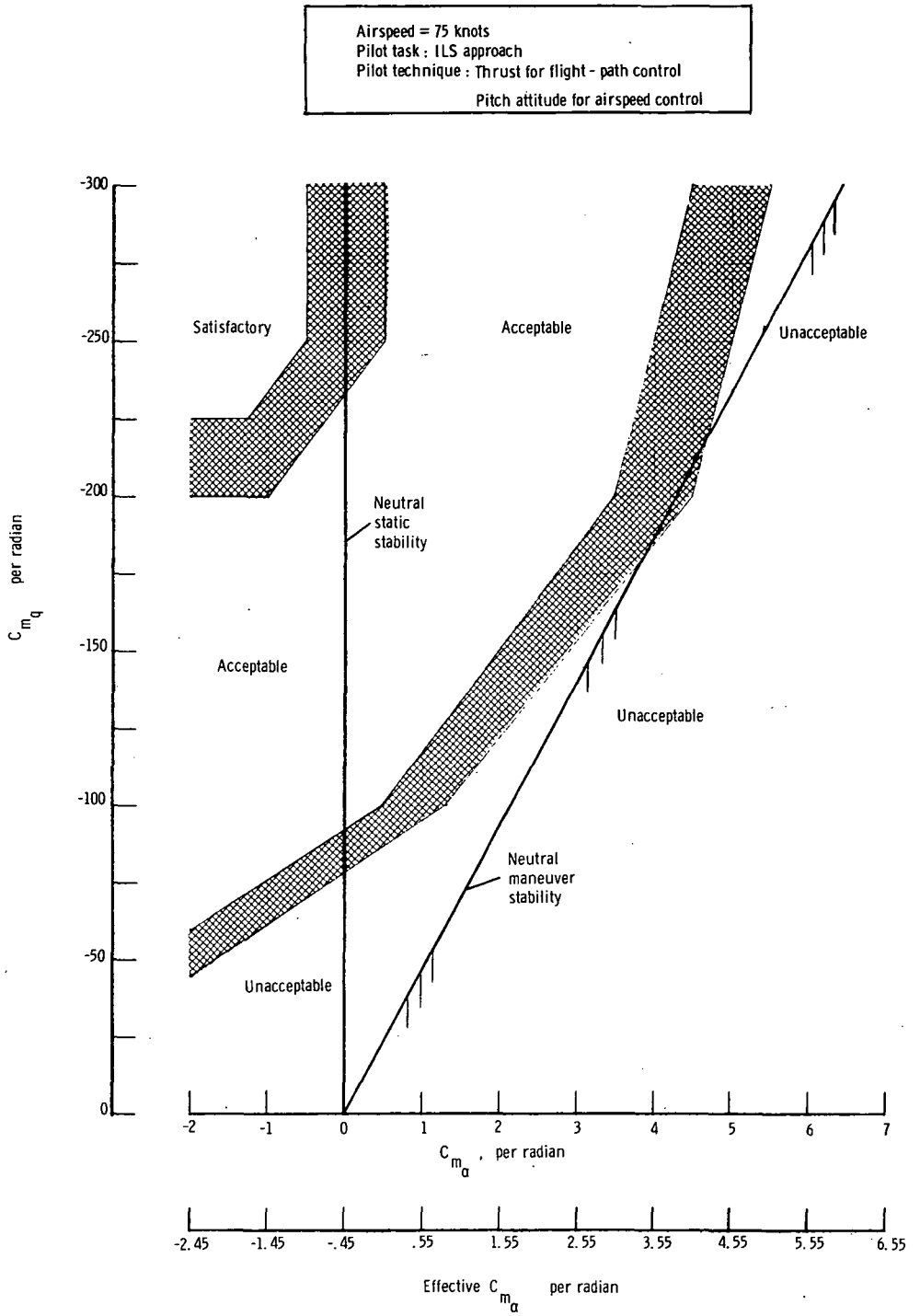


Figure 17.- Effect of C_{m_q} and C_{m_α} on pilot opinion for the "larger" aircraft.

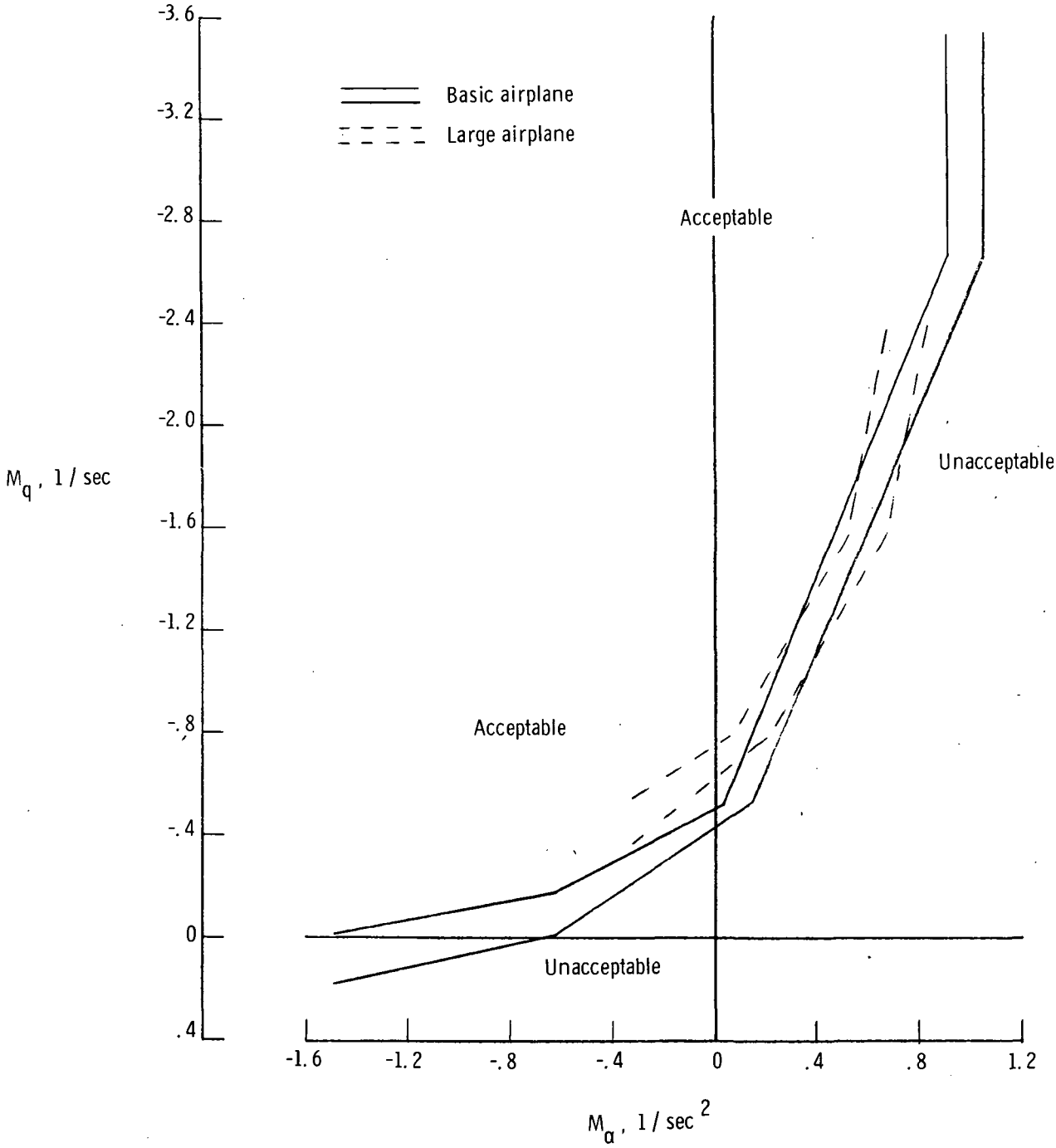


Figure 18.- Comparison of pilot opinion of the "basic" and "large" airplanes.

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