Approach Flying Qualities—Another Chapter

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Two parameters, each purported to be fundamental to good flight path control, but with significantly different implications on setting the wing size and geometry, are pilot-evaluated in a carrier approach flight simulation program. The parameters $1/\tau_{\theta_2}$ and η_{z_α} were independently varied over an exaggerated range of values in order to accentuate variations in pilot rating and assure applicability of results to future vehicles. The results of this investigation conclusively indicate $1/\tau_{\theta_2}$ to be the parameter of merit, rather than η_{z_α}. Thus, there is a preference for the approach used in the July 1968 draft of the Revised Flying Qualities Specification (MIL-F-8785) rather than the final approach of the October 1968 issue. This conclusion results in a significant reduction on the wing size required for specification compliance at low-approach speeds.

Nomenclature

CAP = control anticipation parameter $(\ddot{\theta}_0/\Delta n_{z_{ss}})$, rad/sec²/$g$
$C_{L\alpha}$ = slope of aircraft lift curve vs angle of attack, 1/rad
g = acceleration due to gravity, 32.2, ft/sec²
$\dot{h}$ = Rate of change of altitude (+ for increasing altitude),
K_α = static gain of angle of attack control equation, rad/in.
K_{n_z} = static gain of load factor control equation, g's/in.
K_q = static gain of pitch rate control equation, rad/sec/in.
l_p = distance from pilot to c.g., ft
$M_\delta{}^F$ = fuselage pitch attitude control sensitivity, (rad/sec²)/in.
$M_\delta{}^W$ = wing angle of attack control sensitivity, (rad/sec²)/in.
n_z = vertical load factor, g
$n_{z\alpha}$ = steady state normal acceleration change per unit change in angle of attack, g/rad
S = wing area, ft²
s = Laplace operator, l/sec
V = airspeed, fps
W = aircraft weight, lb
α = angle of attack, deg
θ = pitch angle, deg
$\ddot{\theta}_0$ = initial pitch acceleration caused by a step input, rad/sec²
ω_n = short period natural frequency, rad/sec
ζ = short period damping ratio
τ_{θ_2} = numerator time constant in attitude control equation, sec

Superscript
F = fuselage
W = wing

Introduction

REVISING the Flying Qualities Specification for Military Aircraft (MIL-F-8785) has stimulated vigorous discussion as to the validity and practicality of many of the proposed modifications. In evolving the revised specification, the criticisms and comments of industry were heeded as much as possible consistent with assuring a meaningful improvement over the 15 year old predecessor. However, some items remain with unresolved differences between the various factions of industry and government. Had the revised specification awaited the resolution of these controversial items, the date of issuance would surely never have arrived. However, by expeditiously adopting a somewhat controversial (progressive) specification, the burden of documenting exceptions and justifying subsequent revisions has been adroitly placed squarely on industries' shoulders.

The purpose of this paper is to address one of these controversial items. The specific question pertains to the truncation of the Level 1 region for longitudinal stability ($\omega_n{}^2$)—load factor sensitivity ($n_{z\alpha}$) as shown in Fig. 1 at the low-stability low-sensitivity end. Those of you who have closely followed the various drafts of the revised specification will recall that the minimum allowable $n_{z\alpha}$ was dependent on the approach speed in the July 1968 draft (Ref. 1, Paragraph 3.2.2.1a), but was subsequently revised to simply specifying a minimum $n_{z\alpha}$ in the October 1968 revision (Ref. 2, Fig. 3). This difference might appear trivial at first glance. However, a comparison of the influence of the two requirements on the minimum lift curve slope-maximum wing loading combinations as indi-

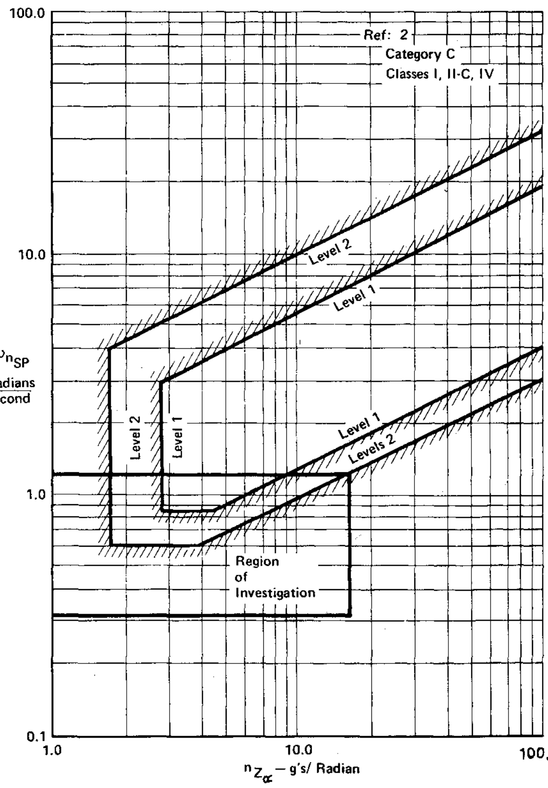

Fig. 1 Short period frequency requirement.

Presented as Paper 69-895 at the AIAA Guidance, Control, and Flight Mechanics Conference, Princeton, N. J., August 18–20, 1969; submitted August 1, 1969; revision received March 4, 1970.

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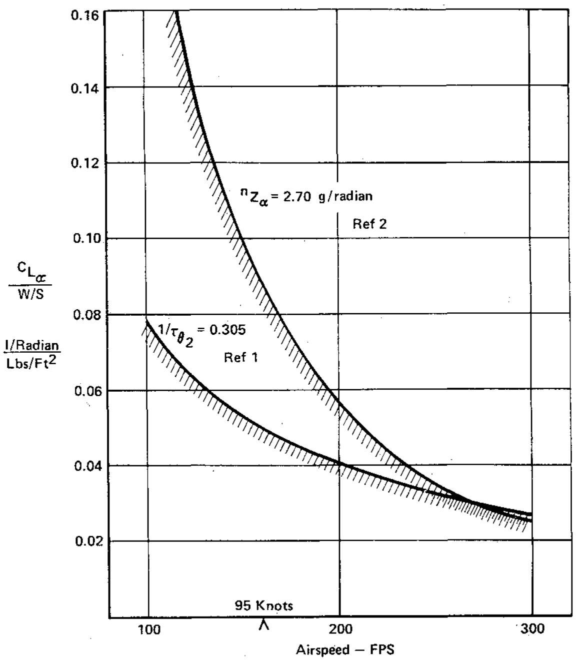

Fig. 2 Effect of requirements on wing sizing.

cated in Fig. 2, quickly dispels any doubts as to the nontrivial nature of the topic. For example, the wing size for similar geometry wings on a vehicle with an approach speed of 95 knots is 70% larger to meet the pure $n_{z\alpha}$ requirement than for the $n_{z\alpha}f(V)$.

As for the origin of the requirements, the $n_{z\alpha}f(V)$ or more commonly $1/\tau_{\theta_2}$ ($\approx n_{z\alpha}g/V$) has been suggested by Jex, Stapelford, Ashkenas et al., Refs. 5 and 10, as being the fundamental parameters limiting flight path control. Alternately, the carrier approach flight simulation results of Shooter (Ref. 11) and Bihrle (Ref. 13) reported limits on $n_{z\alpha}$. Therefore, the intent of the simulation program discussed herein is to conclusively establish which of two parameters is the more valid index of flight path control acceptability.

Simulation Description

The Dynamic Flight Simulator utilized in this investigation consists of a moving base cockpit with functional control system and flight instruments, a closed-circuit television network to provide a real world view of the carrier, landing aid system, and seascape. A combination of digital and analog computers were used for solving the required equations. Figures 3 and 4 present the major components of the flight simulation.

Table 1 Moving base simulator performance limits

Axis	Position	Velocity	Acceleration
Vertical	+10 ft	±14 fps	±5 g
Side	±2 ft	±10 fps	±0.7 g
Pitch	±15°	±50°/sec	1030°/sec^2
Roll	±40°	±200°/sec	1735°/sec^2

The full-scale replica of a typical cockpit is mounted on a four-degree-of-freedom moving base simulator having performance limits as given by Table 1.

The simulator motion provides kinesthetic cues of aircraft transient response in the frequency range from 0.1 to 10.0 cps. Lower frequency motion is attenuated by a low-frequency washout used to maintain the cockpit at a nominal mid-position. While the combination of the subtle acceleration cues characteristic of the carrier approach and the simulator washout circuit resulted in relatively low-amplitude motion, the pilots unanimously indicated a preference for the moving base rather than fixed base simulation. Also the simulation of the impact at touchdown resulted in more realistic piloting control techniques just prior to touchdown. For example, the tendency to "dive for the deck" or perform a "high dip" which was prevalent during previous fixed base investigations, was not evident during the moving base work.

The computer mechanization consisted of the 6-degree-of-freedom equations of motion for the aircraft, a parallel transfer function mechanization for pitch and heave from conventional elevator control, and appropriate modeling of the carrier-generated turbulence and wake. The longitudinal equations are given by Table 2.

The control system consists of the conventional stick and rudder pedals. Feel bungees provided control force gradients of 7.5 lb/in. for longitudinal control and 1.5 lb/in. for lateral control. Throttle controls were operational but used only for wave-off power applications since speed was held nominally constant with automatic power compensation. The control inputs were transformed into aircraft motion via the hybrid computing equipment. The resulting signals drove the camera transport assembly, the g seat, and the cockpit instruments.

A realistic visual presentation was provided by a closed-circuit television system incorporating a high-resolution camera viewing on Enterprise class carrier and seascape model, and an Eidopher projector transmitting the scene to a 24-ft wide, 30-ft high screen. The camera transport and gimble system provided six-degree-of-freedom motion for the visual system. The carrier model was servo-driven in pitch and heave to provide a realistic sea-state simulation. A line stabilized Fresnel lens optical landing system of the type cur-

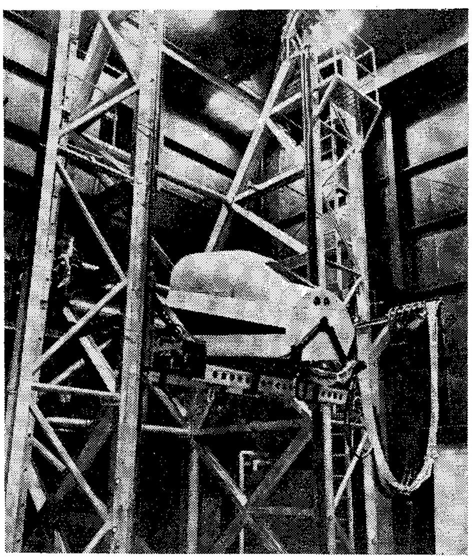

Fig. 3 Four-degree-of-freedom g seat.

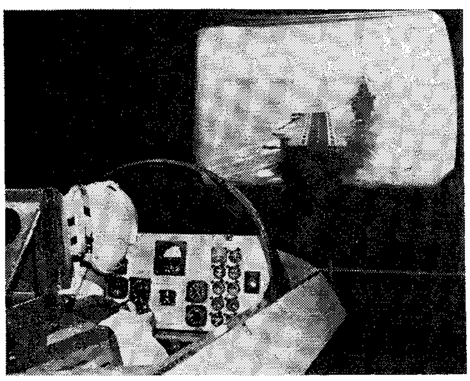

Fig. 4 Cockpit, instrumentation and seascape.

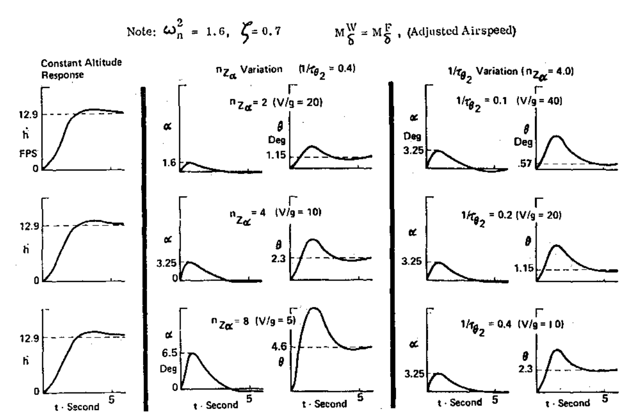

Fig. 5 Response to impulse—fixed wing.

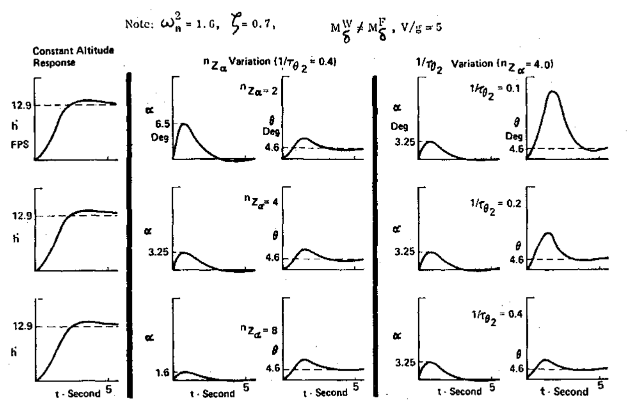

Fig. 6 Response to impulse—controlled incidence wing.

rently operational in the fleet, provided the flight path guidance for a 4° approach.

Experimental Procedure

The one pilot participating in the evaluation was a former carrier qualified Navy pilot with considerable evaluation experience. He was chosen because of his demonstrated ability to consistently discriminate configuration characteristics.

Approximately five approaches were flown with each configuration before a rating was assigned. The revised Cooper-Harper rating scale was utilized in the evaluation. The information collected included pilot rating data and recorder charts showing control inputs and the associated vehicle responses. Wind-over-deck was adjusted to maintain a constant closure speed of 95 knots with the carrier. The approach started 7000 ft aft of the carrier at an altitude of 350 ft and with the aircraft trimmed for level flight. The optical glide slope was first acquired as a "low ball" at which time the pilot initiated the descent. The simulation terminated at hook engagement.

Table 2 Longitudinal equations

Equations:

$$\frac{\alpha(s)}{\delta(s)} = K_\alpha \left[\frac{1}{\Delta_{sp}}\right]$$

$$\frac{\eta_{z_{c.g}}(s)}{\delta(s)} = K_{n_z} \left[\frac{1}{\Delta_{sp}}\right]$$

$$\frac{q(s)}{\delta(s)} = K_q \left[\frac{\tau_{\theta_2}\, s + 1}{\Delta_{sp}}\right]$$

$$\frac{\eta_{z_{pilot}}(s)}{\delta(s)} = \frac{\eta_{z_{c.g.}}(s)}{\delta(s)} + \frac{l_p}{g}\left(\frac{\dot{q}(s)}{\delta(s)}\right)$$

Where:

$$\Delta_{sp} = l_p{}^2/\omega_n{}^2 + 2\zeta l_p/\omega_n + 1$$

$$K_\alpha = M_\delta{}^W/\omega_n{}^2$$

$$Kq = (M_\delta{}^F/\omega_n{}^2)(1/\tau_{\theta_2})$$

$$K_{n_z} = \eta_{z\alpha}\,(M_\delta{}^W/\omega_n{}^2)$$

$$\eta_{z\alpha} = \frac{V}{g}\left(\frac{M_\delta{}^F}{M_\delta{}^W}\right)\frac{1}{\tau_{\theta_2}}$$

Fixed parameters:

$$\zeta = 0.7$$

$$l_p = 20.0 \text{ ft}$$

$$\text{Closure speed} = 95 \text{ kts.}$$

Discussion

The crux of conclusively establishing the proper index of pilot acceptance when the exhaustive flight and simulation data had thus far failed, was to independently vary the parameters in question without violating other constraints placed on the approach task. For example, the conventional approximation relating $n_{z\alpha}$ to $1/\tau_{\theta_2}$ is $n_{z\alpha} \approx V/g\ (1/\tau_{\theta_2})$. Independent variation of $n_{z\alpha}$ and $1/\tau_{\theta_2}$ thus requires a change in airspeed, which under normal circumstances implies a change in piloting task during the approach. That is, as approach speed increases the associated piloting task becomes more difficult as a result of the diminished interval for flight path corrections.

Constant Closure Speed

In order to hold a constant closure-speed-dependent task level, wind-over-the deck compensation was utilized to main-

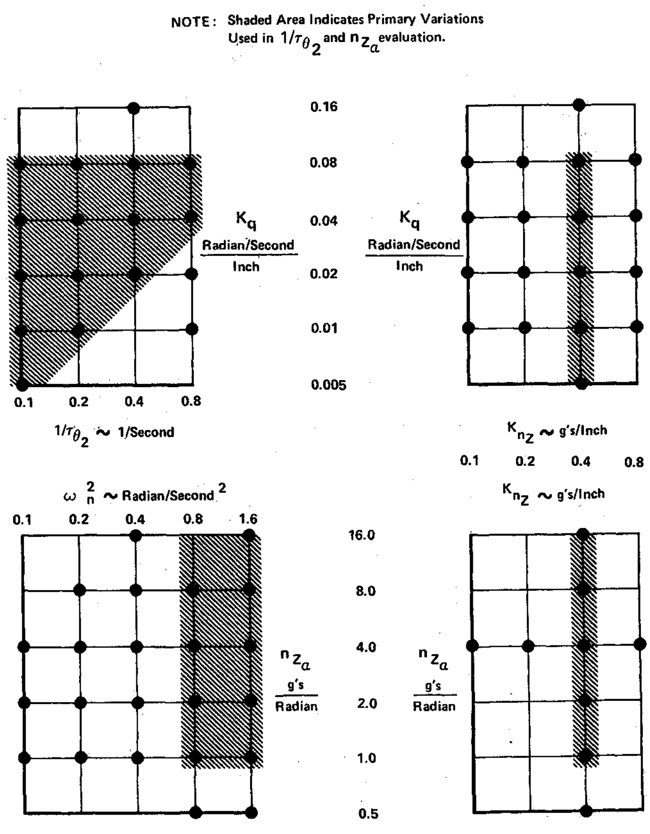

Fig. 7 Range of parameters investigated.

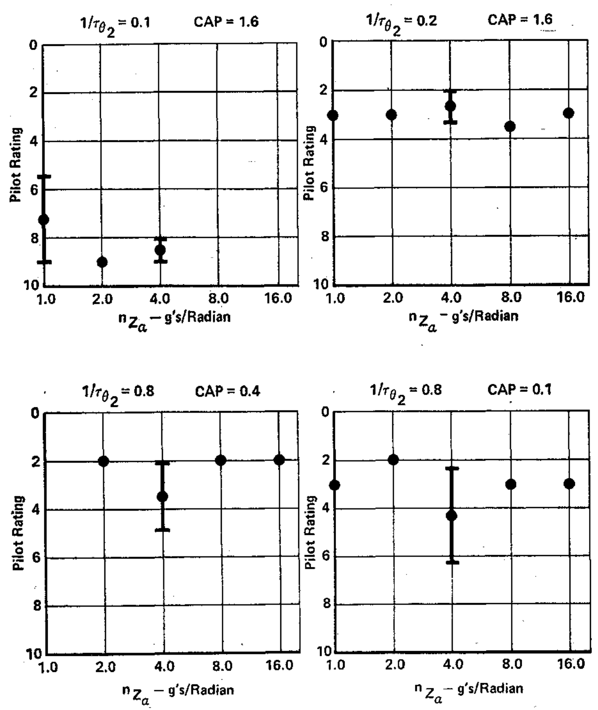

Fig. 8 Typical variations in pilot rating with $n_{z\alpha}$.

tain the closure speed at 95 knots while airspeed ranged from 47 to 760 knots. Such an approach provides great flexibility in the independent selection of $1/\tau_{\theta_2}$ and $n_{z\alpha}$.

The influence of $1/\tau_{\theta_2}$ and $n_{z\alpha}$ on the vehicle response can be seen by examining the pertinent equations of motion, or the typical time histories shown in Figs. 5 and 6. Note that the rate of climb response is constant throughout the parameter variations of Figs. 5 and 6, and that $n_{z\alpha}$ and $1/\tau_{\theta_2}$ only influence the angle of attack and pitch excursions, respectively.

Controlled Incidence

The independent variation of Bihrle's control anticipation parameter CAP (defined as the ratio of initial pitch acceleration to steady state load factor $\ddot{\theta}_0/\sigma_{z_{ss}}$) and $n_{z\alpha}$ dictated the introduction of the controlled incidence wing. Controlled incidence introduces a new degree of freedom in selecting the initial pitch acceleration response of the fuselage ($\ddot{\theta}_0 = M_\delta{}^F\delta$) and the load factor response from the wing ($n_{z_{ss}} = M_\delta{}^W\delta n_{z\alpha}/\omega_n{}^2$). Thus, $\ddot{\theta}_0/n_{z_{ss}}$ can be varied for constant $n_{z\alpha}$ (and $\omega_n{}^2$) by varying $M_\delta{}^F/M_\delta{}^W$. Conversely, $\ddot{\theta}_0/n_{z_{ss}}$ can be held constant for variations in $n_{z\alpha}$ (again constant $\omega_n{}^2$) by appropriate compensation of $M_\delta{}^F/M_\delta{}^W$. For example, the CAP values for the $n_{z\alpha}$ variation on Fig. 6 are constant.

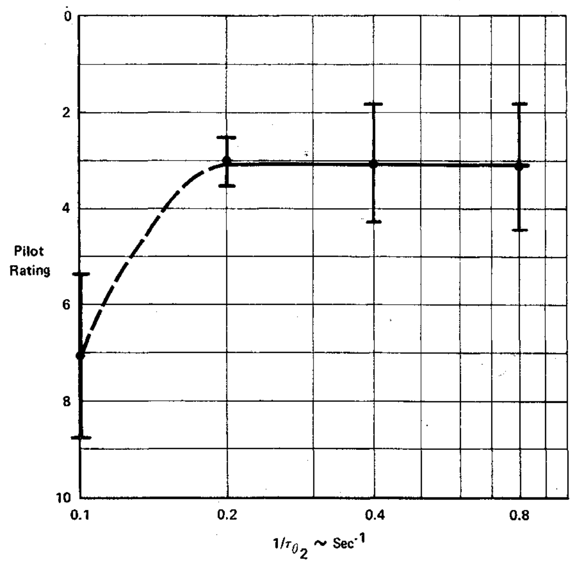

Fig. 9 Typical variation in pilot rating with $1/\tau_{\theta_2}$.

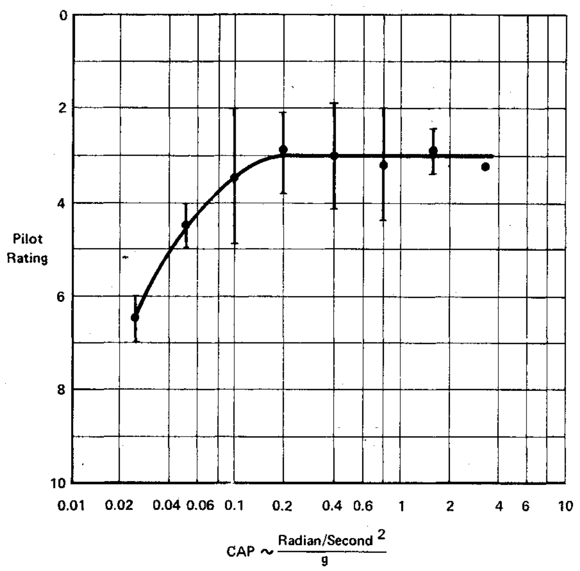

Fig. 10 Typical variation in pilot rating with CAP.

Independent variation of CAP and $1/\tau_{\theta_2}$ is realized with the variable airspeed, fixed wing approach. A typical example of a $1/\tau_{\theta_2}$ variation with a fixed CAP is shown in Fig. 5.

The range of parameters evaluated during the investigation as portrayed in Fig. 7, appears exaggerated when compared with the corresponding aircraft characteristics during approach conditions. For example, a sampling of eight representative Navy aircraft gave $1/\tau_{\theta_2}$ values from 0.35 to 0.56 while this investigation covered 0.1–0.8. However, the exaggerated variations were considered necessary to assure significant differences in pilot rating for the limited sample size.

Influence of $n_{z\alpha}$

The variation of pilot rating with $n_{z\alpha}$ for four combinations of $1/\tau_{\theta_2}$ and CAP is presented on Fig. 8. This data show no significant dependency of pilot rating with the gross (i.e., by a factor of 16) changes in $n_{z\alpha}$. The fact that the pilot rating is essentially constant with $n_{z\alpha}$ even though the configurations vary from satisfactory to unacceptable, conclusively shows that $n_{z\alpha}$ is not a fundamental acceptance parameter.

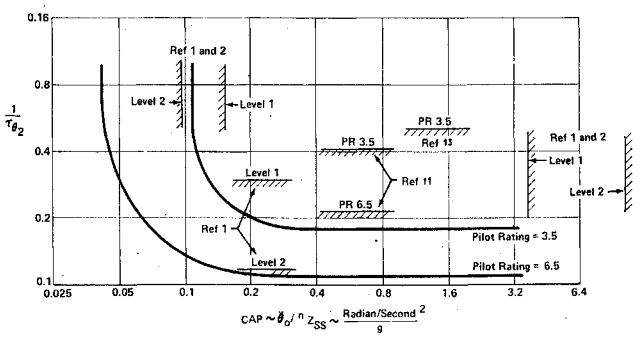

Fig. 11 Acceptance boundaries for longitudinal short period characteristics.

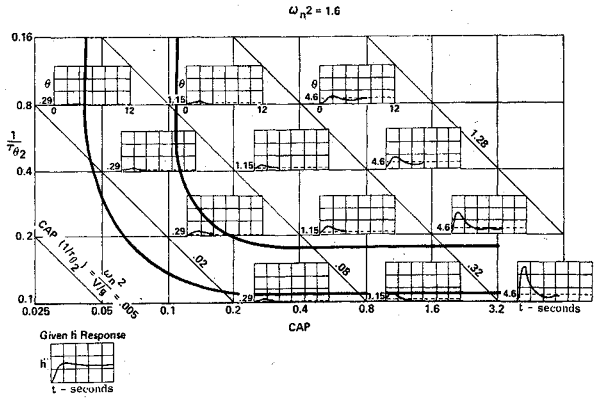

Fig. 12 Typical attitude responses in acceptance region—constant short period stability.

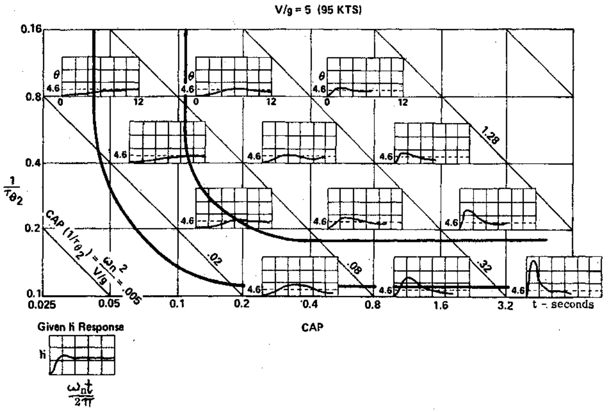

Fig. 13 Typical attitude responses in acceptance region—speed constant.

Influence of $1/\tau_{\theta_2}$

The influence of $1/\tau_{\theta_2}$ on the pilot ratings is indicated in Fig. 9, for CAP values between 0.1 and 3.2 (rad/sec^2)/g (pilot rating better than 3.5 from CAP considerations). The data clearly indicate a rapid deterioration of pilot acceptance somewhere between $1/\tau_{\theta_2}$ values of 0.2 and 0.1. While the precise variation of pilot rating with $1/\tau_{\theta_2}$ between the values of 0.1 to 0.2 remains ill-defined, this in no way detracts from the conclusion that $1/\tau_{\theta_2}$ is an important pilot acceptance parameter.

Influence of CAP

The variation of pilot rating with the control anticipation parameter is shown in Fig. 10. This data show a well defined degradation of pilot acceptance for CAP values less than 0.1, and indicates CAP to be a significant pilot acceptance parameter. Note that the data shown are for $1/\tau_{\theta_2}$ values considered satisfactory by the pilot (i.e., $1/\tau_{\theta_2} > 0.2$).

Comparison with Other Results

The results of this study are presented on Fig. 11, in terms of acceptance boundaries for the parameters $1/\tau_{\theta_2}$ and CAP. Superimposed on the figure are the boundaries recommended in Refs. 1, 2, 11, and 13. Note that the results of Refs. 11 and 13 have been translated from the original $n_{z\alpha}$ data to $1/\tau_{\theta_2}$. Since both the referenced studies were done at fixed speed, the specification of $n_{z\alpha}$ limits (as opposed to $1/\tau_{\theta_2}$ limits) was arbitrary.

The results of this investigation are shown in Fig. 11 to be most closely aligned with Ref. 1, which is an interesting observation but not particularly significant because of the study limitations (e.g., single evaluator, limited sample).

The point of significance is that for the greatly exaggerated parameter range investigated, the recommended requirements of Ref. 1 would have properly established the acceptance level, indicating the fundamental soundness of the specification approach.

To provide the reader with an indication of the response variations within the acceptance boundaries of Fig. 11, typical time histories of pitch attitude response for a given flight path correction have been superimposed on the acceptance region in Figs. 12 and 13. The response variation of Fig. 12 are for a range of airspeeds (increasing airspeed from right to left) with the short period frequency held constant. Alternately, the response variation of Fig. 13 are for a range of short period frequencies (increasing from left to right) with airspeed held constant.

Conclusions

Based on a moving base flight simulation investigation of an exaggerated range of longitudinal characteristics evaluated during the final approach to a carrier, the following conclusions are made: 1) The parameter $1/\tau_{\theta_2}$ rather than $n_{z\alpha}$ is the more valid index of pilot acceptability; 2) The minimum short period frequency requirements specified in terms of $\omega_n^2/n_{z\alpha}$ of the proposed revision to MIL-F-8785A (dated Oct. 1968) are fundmentally sound; and 3) The minimum value of $n_{z\alpha}$ should be specified in the manner of the July draft (i.e., a minimum value of $1/\tau_{\theta_2}$) rather than the subsequently recommended limitation on $n_{z\alpha}$.

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