Additional experience is required to insure that the present requirements are optimum. Also, some consideration is needed for other factors that affect height control.

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Navy Variable-Stability Studies of Longitudinal Handling Qualities

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A study of longitudinal handling qualities in the simulated carrier approach was performed at Princeton University in a North American Navion so equipped as to vary its static and dynamic longitudinal stability characteristics. Five Navy pilots flew "meatball" approaches in 24 configurations and gave ratings using the Cooper scale. Short-period dynamics with frequencies greater than 1.4 rad/sec and damping ratios greater than 0.2 were found to be satisfactory. Control sensitivity was variable and was found to be a critical parameter for some configurations. Stick force per g ranged to extremes and was found to be of little consequence in visual landing approach. A comparison is made with several proposed longitudinal handling qualities criteria, with little agreement. Further work in landing approach, as well as high-speed flight, is currently in progress at the Naval Air Test Center, using a variable-stability F-8D. Short-period frequencies ranging from 0.2π to 4π rad/sec are being flown through typical tactical mission profiles. The handling qualities of higher-order dynamics, typical of augmented aircraft, are of prime interest, and data will be compared with numerous criteria that have been proposed for the longitudinal dynamics of aircraft.

Nomenclature

α = angle of attack, rad
δ_{es} = stick deflection, in.
F_s = stick force, lb
g = gravitational acceleration, 32.2 ft/sec^2
M_α = dimensional pitching moment due to $\Delta\alpha$, 1/sec^2
$M_{\dot\alpha}$ = dimensional pitching moment due to $\dot\alpha$, 1/sec
$M_{\delta_{es}}$ = dimensional pitching moment due to δ_{es}, rad/sec^2/in.
$M_{\dot\theta}$ = dimensional pitching moment due to $\dot\theta$, 1/sec
ω_{sp} = short period frequency, rad/sec
s = Laplace operator
ss = steady state
θ = pitch attitude, rad
V = airspeed
Z_α = heave acceleration due to $\Delta\alpha$, 1/sec
$Z_{\delta_{es}}$ = heave acceleration due to δ_{es}, 1/sec
ζ_{sp} = short-period damping ratio
$(\dot{\ })$ = time rate of change, $\partial/\partial t$

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Introduction

In the Fall of 1965, the Naval Air Systems Command contracted Princeton University to conduct an in-flight study of longitudinal handling qualities in a simulated carrier approach task.[1] The objectives of this undertaking were as follows: 1) to determine if, and to what extent, the Princeton variable-stability Navion was suited to studying the longitudinal handling qualities of carrier-type aircraft, and 2) to compare Navion pilot-opinion ratings with a) results obtained in a similar program using a variable-stability jet trainer[2] and b) various proposed criteria on longitudinal flying qualities.

Flight Program

Description of Airplane

The airplane used was a North American Navion (see Fig. 1) modified to provide 3-axis variable stability and control. In the pitch axis, angle of attack (α) and pitch rate ($\dot\theta$) were fed back to the elevator servo to effectively alter the M_α and $M_{\dot\theta}$ derivatives and thereby vary the short-period dynamics.

Evaluation pilots flew from the right seat (see Fig. 2), which was equipped with a center stick in place of the original yoke

Fig. 1 Princeton variable-stability Navion.

control. An extension was affixed to the panel-mounted throttle to approximate the geometry of a lever-type, side-mounted throttle. The stick and rudder pedals on the right side were completely fly-by-wire with feel provided by fixed springs. The fore-and-aft force gradient on the stick was 3 lb/in. No other feel device, such as a bob-weight, was used. Pitch control sensitivity ($M_{\delta_{es}}$) was a test variable along with the short-period characteristics.

The safety pilot rode in the left seat, which retained the original mechanical control system. Servos for the variable-stability system (VSS) were connected in parallel to the mechanical control system, causing the yoke and pedals on the left side to follow the movements of the control surfaces. This motion of the safety pilot's controls served to indicate proper functioning of the system in flight.

Flight Pattern

A racetrack pattern was flown around the airfield at Princeton's Forrestal campus, as shown in Fig. 3. The evaluation pilot flew each configuration through the latter portion of the downwind leg, around the 180, and onto final approach. Airspeed was maintained at 105 knots at all times, with wheels and flaps up, simulating the closure between an airplane flying at 140 knots on approach to a carrier with 35 knots of wind over the deck.

Final approach was started approximately 1 mile out. A light bar landing aid was set up beside the runway to give a $3\frac{1}{2}°$ glide slope reference similar to the mirror optical landing aid used aboard carriers. Waveoffs were initiated at an altitude of 20–30 ft, after which the evaluation pilot radioed his comments and rating (Cooper scale) to the ground.

Five Naval aviators served as evaluation pilots. Two were graduates of the U.S. Naval Test Pilot School, and each of the five had at least a minimum of carrier landing experience.

Longitudinal Dynamics

Figure 4 shows the effect on the Navion short-period poles (□) as M_α and $M_{\dot\theta}$ are varied. Test configurations are indicated by circled numbers. It should be noted that for most

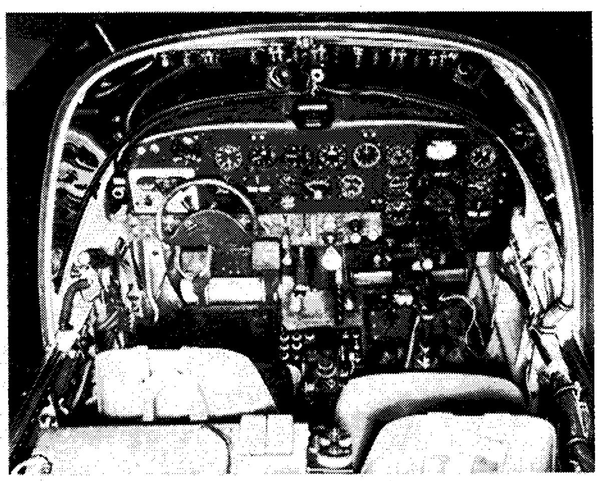

Fig. 2 Cockpit arrangement.

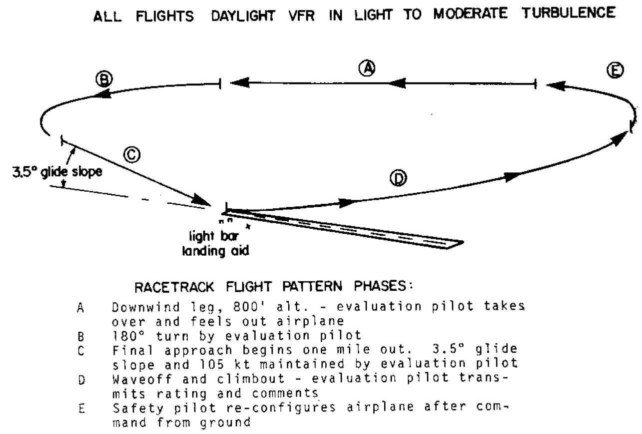

Fig. 3 Flight pattern.

configurations $M_{\dot\theta}$ was an aerodynamically unrealistic positive value. The necessity for going to such values of pitch damping can be shown with the equations for the short-period approximation,

$$\begin{bmatrix} (s - Z_\alpha) & -1 \\ (-sM_{\dot\alpha} - M_\alpha) & (s - M_{\dot\theta}) \end{bmatrix} \begin{bmatrix} \Delta\alpha \\ \Delta\dot\theta \end{bmatrix} = \begin{bmatrix} Z_{\delta_{es}} \\ M_{\delta_{es}} \end{bmatrix} \delta_{es} \quad (1)$$

The resulting characteristic equation is

$$s^2 + 2\zeta_{sp}\omega_{sp}S + \omega_{sp}{}^2 = s^2 + (-Z_\alpha - M_{\dot\theta} - M_{\dot\alpha})s + (Z_\alpha M_{\dot\theta} - M_\alpha) \quad (2)$$

Both frequency and damping of the short-period mode are seen to be a function of the Z_α derivative. On a typical Navy carrier airplane with a low-aspect-ratio swept wing and relatively high wing loading, Z_α is approximately -0.5 in the power approach (PA) configuration. For the Navion at 105 knots, Z_α was -2.0. To achieve the low-frequency dynamics typical of jet fighter aircraft in PA it was therefore necessary to overcome the high Z_α term with positive $M_{\dot\theta}$.

Assuming for simplicity that $Z_{\delta_{es}} = 0$, the steady-state values of α, $\dot\theta$, and normal acceleration (n_z) resulting from a step input of control stick (δ_{es}) are

$$\alpha_{ss} = M_{\delta_{es}}/\omega_{sp}{}^2 \qquad \text{rad/in.} \quad (3)$$

$$\dot\theta_{ss} = -Z_\alpha M_{\delta_{es}}/\omega_{sp}{}^2 \qquad \text{rad/sec/in.} \quad (4)$$

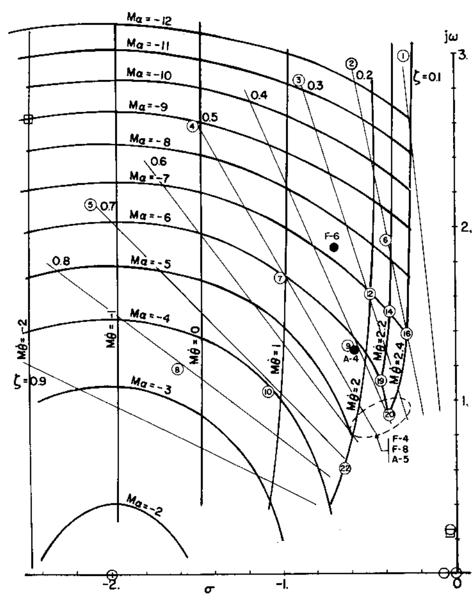

Fig. 4 Root locus net for Navion showing configurations and short-period pole locations of current carrier-based aircraft in power approach.

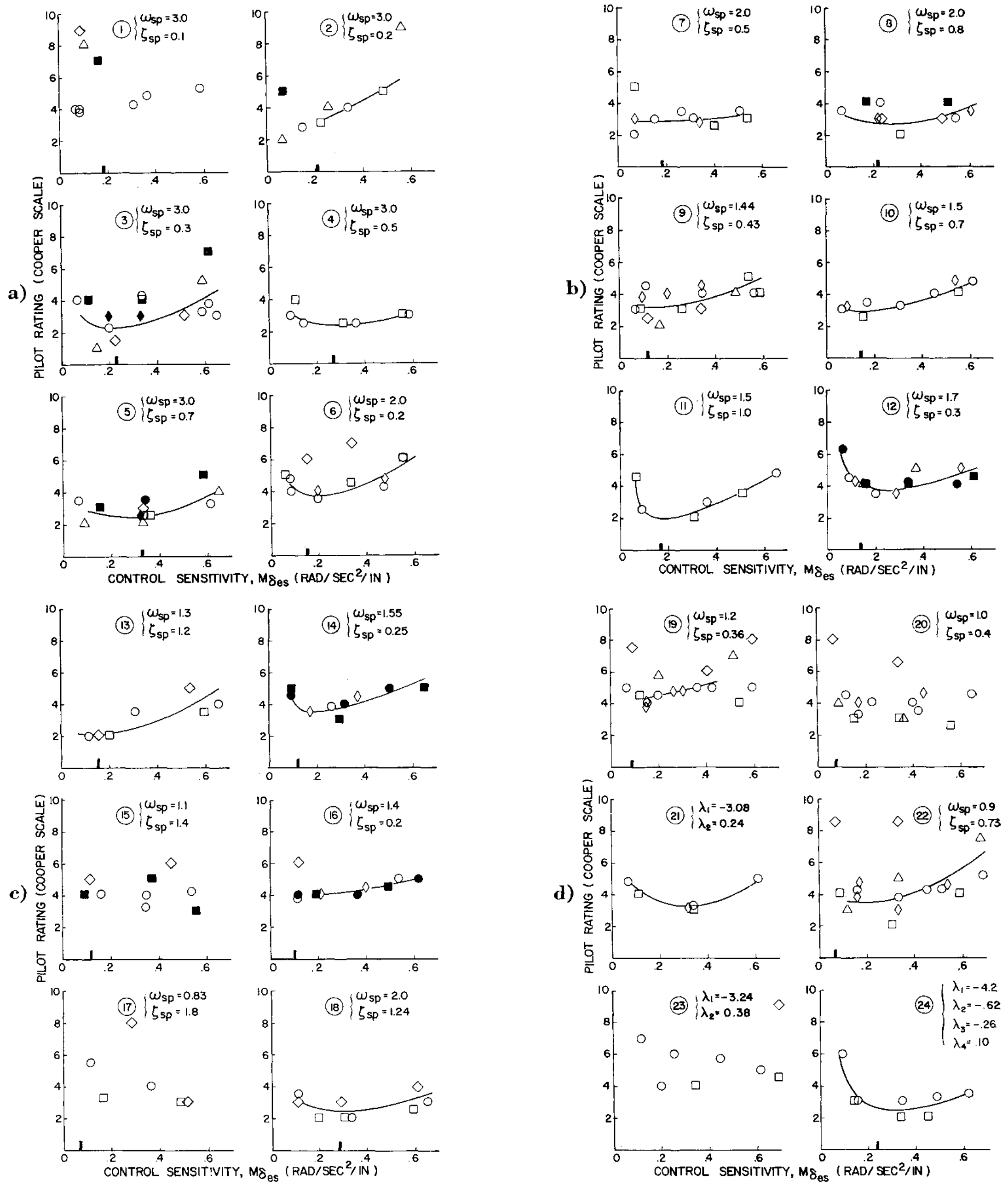

Fig. 5 Pilot rating vs control sensitivity. Open points denote light turbulence; dark points, moderate turbulence. (▮) denotes CAL selected optimum.

$$n_{z_{ss}} = -Z_\alpha V M_{\delta_{es}}/g\omega_{sp}^2 \qquad \Delta g/\text{in.} \tag{5}$$

The Z_α derivative is seen to determine the gain on $\dot{\theta}$ and n_z in an explicit fashion.

Previous Cornell Tests

A similar landing approach program was conducted by Cornell Aeronautical Laboratory (CAL) in 1964 using a variable-stability T-33 jet trainer.[2] That program tested various short-period dynamics for operation at different points along the thrust-required curve. The Princeton Navion study was analogous to that portion of the CAL program performed on the front side of the thrust-required curve.

Dynamically, the CAL T-33 in *PA* differed in several respects from the Navion configured for low short-period frequencies. Z_α on the T-33 was approximately -1.0 (half the Navion value). Phugoid motions were controlled by variable drag, whereas the Navion phugoid was coupled, in extreme cases, with the short period. Thirdly, a strong contrast existed in terms of stick force per g. A simplified expression for stick force per g follows from Eq. (5),

$$F_s/n_{z_{ss}} = (F_s/\delta_{es})(g\omega_{sp}^2/-Z_\alpha V M_{\delta_{es}}) = K\omega_{sp}^2/M_{\delta_{es}} \tag{6}$$

where $K = (F_s/\delta_{es})/(-Z_\alpha V/g)$. The stick force gradient in the CAL study was on the order of 8 lb/in., and both programs were flown at similar airspeeds. The values of K are then about 1.8 for the T-33 and 0.27 for the Navion. Therefore, given the same short-period frequency and damping, and the same stick sensitivity, stick force per g in the T-33 was six times the stick force per g in the Navion.

The Cornell tests had the evaluation pilot choose an optimum sensitivity at altitude before making his approach. It was found that the trend was to increase sensitivity for increasing ω_{sp}. The CAL experimenters interpreted this as being an attempt to keep α_{ss} per inch of stick at a constant value by Eq. (3). Princeton assigned various values of $M_{\delta_{es}}$ on each

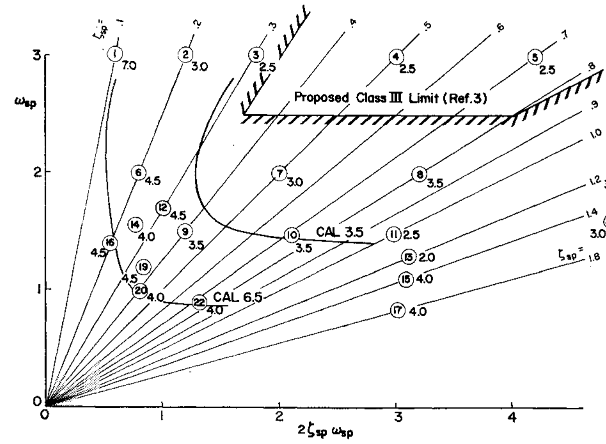

Fig. 6 Navion configurations and ratings (with optimum $M_{\delta_{es}}$) superimposed on CAL boundaries for front side operation.

run to determine the relative effect on handling qualities. The results are shown in Figs. 5a–5d. Note that the CAL pilot-selected optimum sensitivity is indexed along the abscissa in each case. Five different data point figures refer to the five evaluation pilots. The Cooper rating scale has been plotted increasing upward, making optima appear as low points in the curves. The scatter in the data is believed to be typical of handling qualities studies. Curve fairing was based on a thorough familiarity with the pilots' commentary that went with each numerical rating. In areas of wide scatter, the curves were biased toward data believed to be the more firm, based on pilots' experience, perceptiveness, and skill in performing the task. For many configurations, the scatter is as large as the total variation in pilots' rating, making the determination of an optimum sensitivity rather arbitrary. Only on the lightly damped configurations, with $\omega_{sp} > 1.4$, is the optimum clearly defined.

Fairly good agreement is seen to exist between the CAL selected optima and the optima of the Navion curves. Strong disagreement arises in the area of static instability. The pilots' commentary here tended to show that control power available ($M_{\delta_{es}} \times \delta_{es_{\max}}$) became the critical parameter in this case. The pilots did express a preference for the lower sensitivities, in keeping with the loose response dynamics, but complained of hitting the forward stick stop and "almost losing it, once it go upset."

The pilot rating with optimum $M_{\delta_{es}}$ for each of the Navion configurations is shown in Fig. 6 superimposed on the boundaries for front-side operation taken from the CAL report.[2] In a point-for-point rating comparison, there is good agreement between the two sets of data. Reference 2 shows no actual rated configurations on or near the curve for the 6.5 rating boundary, which was determined by a least squares computation. This 6.5 boundary therefore represents an extrapolation. Strictly speaking, there is no justification for assuming that rating degradation continues at a constant rate beyond experimental data. The CAL 6.5 boundary for front-side *PA* operation therefore is considered questionable.

Proposed Criteria

The current military specification for aircraft handling qualities (MIL-F-8785) only restricts the damping of the short-period mode. Several criteria for longitudinal dynamics have been proposed which do take the importance of ω_{sp} into account.

Reference 3 is a formal proposal for a revision of -8785 and suggests the short-period requirements shown in Fig. 7. The boundary is based on the results of early CAL work. No qualifications were put forth regarding flight condition, implying that the limit applies in the *PA* configuration as well as in cruising flight. The data taken in the Princeton landing approach study show ratings of 3–4 well outside the suggested limit, in the area in which most current carrier aircraft in *PA* are found. The lower portion of the normal operation boundary in Fig. 7 has been plotted in Fig. 6 for an additional comparison. The CAL work on which this boundary is based was a tracking study done at high speed and high altitude. The landing approach studies described here indicate that a separate specification for *PA* might be in order.

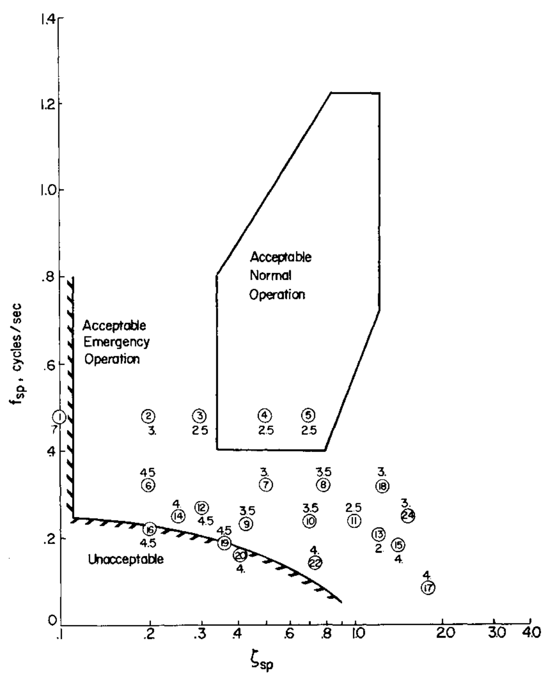

Fig. 7 Comparison with proposed short-period requirements for fighter aircraft, taken from Ref. 3.

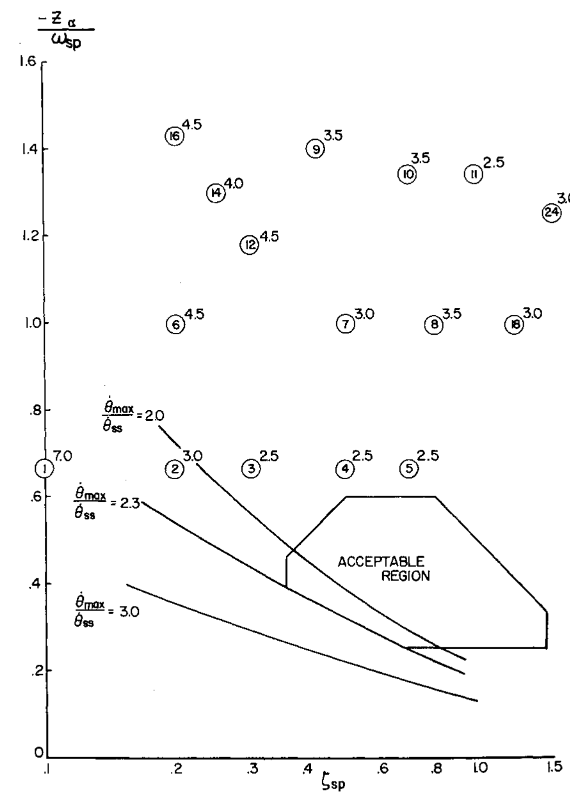

Fig. 8 Comparison with proposed short-period criterion of Ref. 4.

Figure 8 (taken from Ref. 4) shows a similar boundary which also includes the parameter Z_α. Here again, the results of early Cornell tracking studies form the basis for the proposed boundary. All of the Navion data fall outside this proposed limit, however; this includes the best-tested configurations rated 2.5. The ratio of $-Z_\alpha/\omega_{sp}$ used as the ordinate in Fig. 8 was, of course, taken to extreme values in that the Navion had a high Z_α and the simulation forced ω_{sp} to low values. The extreme appears to have made a point, however.

It is stated in Ref. 5 that all discussion of longitudinal dynamics in terms of frequency and damping of the short-period poles implies an unnecessary limitation to second-order sys-systems. The response of an aeroelastic, stability-augmented aircraft is not readily and completely definable in terms of ω_{sp} and ζ_{sp} only. Instead, a more general step response time history envelope is proposed.

In proposing criteria for optimum (not "acceptable") response of a stability-augmented fighter aircraft, Ref. 5 suggests various envelopes for the step response in pitch rate, normal acceleration, and angle of attack. Separate envelopes are given for each flight regime. For *PA*, only an α envelope is drawn.

All envelopes are normalized about a steady-state value that is not defined. For a 1-in. step stick input, the steady-state motion variables are a function of the control sensitivity $M_{\delta_{es}}$. In order to make a comparison, the steady-state values for well-rated configuration 5 were adopted as a standard and the α envelope from Ref. 5 was scaled about a $2.2°\,\alpha_{ss}$.

Figure 9 shows the response of five configurations rated 2.5, and two others rated 4.5. In each case, the 1-in. stick input was scaled according to the optimum sensitivity for that configuration. Two of the five well-rated configurations conform to the α envelope. Configuration 3 failed in having too low an α_{ss}, and therefore too low a sensitivity. Configurations 11 and 13, rated 2.5, had dynamics markedly different from configurations 3–5, and violated the α envelope criterion quite strongly. The two configurations rated 4.5 stand out, having no apparent steady-state value of any motion variable.

A further refinement of the time history approach is made in Ref. 6. A parameter designated C^*/δ_e or C^*/F_s is de-

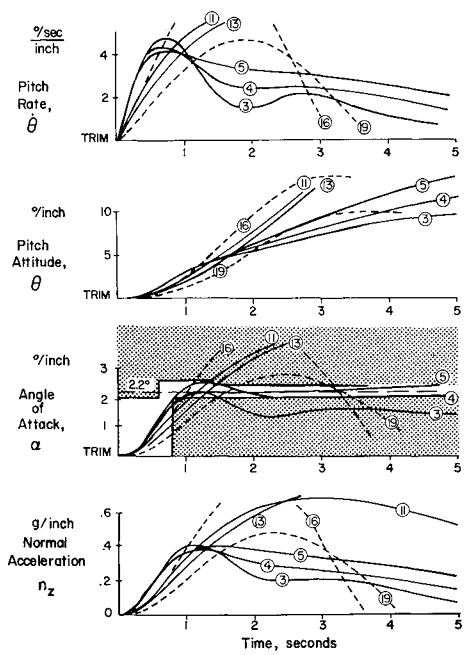

Fig. 9 Step input response time histories of selected configurations; ——2.5 rating; - - - - 4.5 rating. Envelope for α taken from Ref. 5.

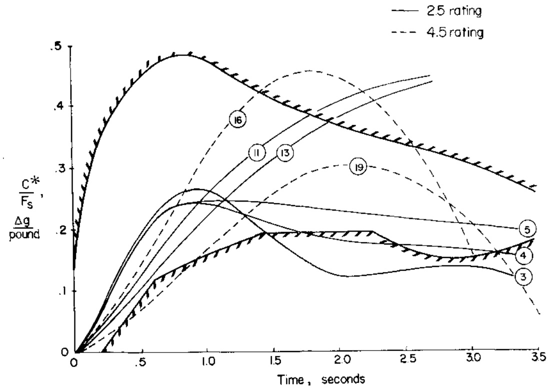

Fig. 10 Proposed time history boundary for hybrid motion variable "C*" (Ref. 6); ——2.5 rating; - - - 4.5 rating.

veloped through a weighted combination of normal acceleration, pitch rate, and pitch acceleration ($\ddot\theta$). The latter arises in situations where the pilot is displaced from the center of gravity (c.g.) of the airplane. In computing C^* for the Navion, the pitch acceleration factor is 0 since the pilot seat is essentially coincident with the c.g.

C^*/F_s time histories were computed for the same seven configurations shown in Fig. 9. For the Navion, C^* is the sum of normal acceleration and pitch rate, the latter weighted by the flight speed. Again, Ref. 6 normalizes about an undefined steady-state value; so again, configuration 5 was used to scale the C^*/F_s envelope. C^* has the units of normal acceleration (g's) and, as computed, is the response to a unit stick force (1 lb), which is equivalent to one-third of an inch of δ_{es} on the Navion.

The resulting comparison shown in Fig. 10 is directly analogous to the previous figure. Here, configuration 4 as well as 3 seems shy on control sensitivity (low C_{ss}*). Again, configurations 11 and 13 (rating 2.5) exceed the boundary. The character of the 4.5 rated configurations has also remained unchanged.

The only point that can be made regarding these time history comparisons is to say that configurations satisfying the boundaries were indeed well-rated. However, some which exceeded the boundaries were equally well-rated.

Another entry in the proposed criteria field is the "control anticipation parameter" (CAP) put forth by Bihrle.[7] This approach, involving no curves or boundaries, specifies a minimum numerical value of the ratio $\ddot\theta_0/\Delta n_{z_{ss}}$, where $\ddot\theta_0$ is the instantaneous acceleration in pitch caused by the step elevator deflection required to give a certain $\Delta n_{z_{ss}}$. This ratio is approximated[7] as

$$\text{CAP} = \ddot\theta_0/\Delta n_{z_{ss}} \approx \omega_{sp}^2/n_\alpha \qquad (7)$$

where $n_\alpha = -Z_\alpha V/57.3g$ (Δg/deg). For the Navion, $n_\alpha = 0.19\ \Delta g$/deg. The unusual longitudinal dynamics of the Navion configured for the *PA* simulation makes the application of this criterion difficult. The approximation in Eq. (7) overlooks the damping ratio ζ_{sp}, and implies that, for example, Navion configuration 1 ($\zeta_{sp} = 0.1$, rating 7.0) is equivalent to configuration 5 ($\zeta_{sp} = 0.7$, rating 2.5), since both have a

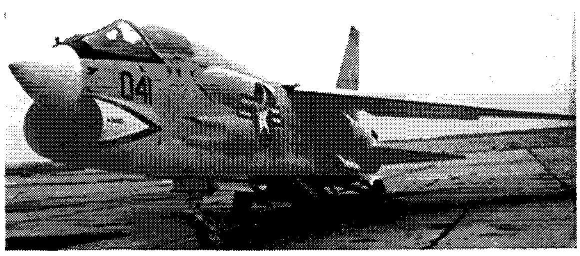

Fig. 11 Variable-stability F-8D.

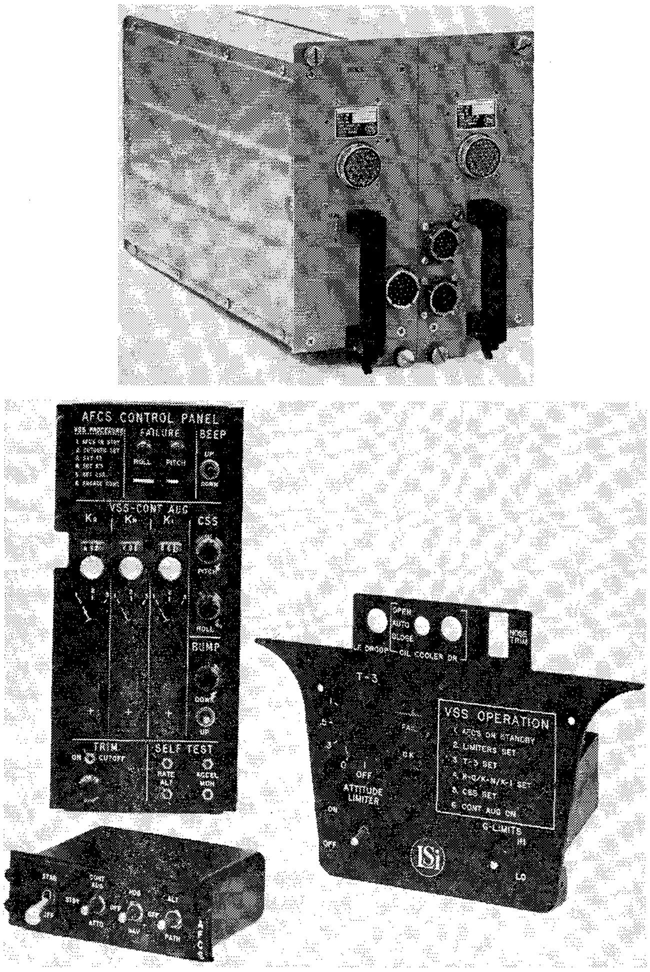

Fig. 12 Lear Siegler variable-stability system components.

CAP equal to 47.3. The literal definition of CAP is inapplicable because of the relatively high-frequency phugoid washing out the n_{zss} (see Fig. 9).

All of the currently proposed criteria imply, in one way or another, that the aircraft's response in pitch is predominantly, if not entirely, second order. Their lack of sufficient generality is made evident when applied to the fourth-order response of the Princeton Navion.

In summary, none of the proposed criteria for longitudinal handling qualities was found to be compatible with the data obtained in the Navion program. There still exists a need for further variable stability flight data and, perhaps, a more astute analysis and synthesis of this data.

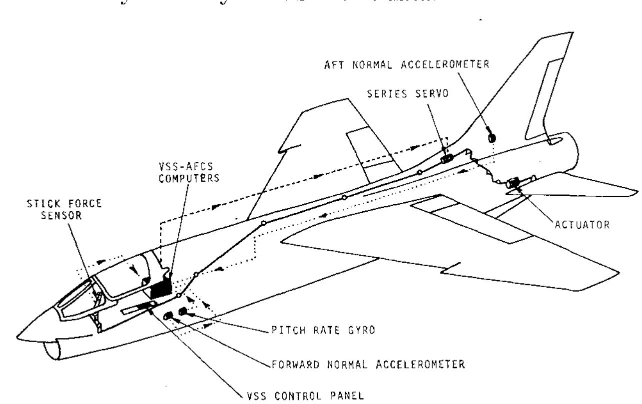

Fig. 13 Variable-stability system installation in F-8D.

Table 1 VSS/F-8D flight conditions

	Power approach	Low altitude, high speed	High altitude, high speed
V	140 knots	0.9M	1.2M
h	sea level	5000	40,000
Z_α	-0.55	-1.9	-0.94
ω_{sp}	0.2π–0.5π	2π–4π	2π–4π
ζ_{sp}	0.1–0.9	0.1–0.9	0.1–0.9

Variable-Stability F-8D

The Navy is currently undertaking variable stability handling qualities research in an F-8D (Fig. 11) at the Naval Air Test Center, Patuxent River, Md. This airplane is equipped with a Lear Siegler A-7A automatic flight control system, which has been modified to include variable longitudinal stability in the augmentation mode, shown in Fig. 12. The VSS designed at the Naval Air Development Center, Johnsville, Pa., consists of three variable feedbacks to the horizontal tail, pitch rate, pitch acceleration ($\ddot{\theta}$), and normal acceleration. Fore and aft normal accelerometers shown in Fig. 13 are used to sense n_z and $\ddot{\theta}$. In addition, a four-value variable lag is included in the n_z loop.

In the current F-8 program, three distinct flight conditions are being studied (Table 1) to allow an extreme variation in Z_α as well as in the short-period dynamics. Tasks for the high-speed conditions will be typical mission profiles including formation flying, tail-chase tracking, and loft-bombing maneuvers.

While the conventional frequency and damping terminology is still being used to describe the configurations on the F-8, the higher-order nature of the airframe dynamics is very much recognized. Phugoid mode coupling is quite pronounced on some PA configurations with $\omega_{sp} = 0.2\pi$. At the other extreme, actuator and linkage dynamics become significant in the 4π high-speed case. All of the proposed criteria mentioned herein, and any now forthcoming, will be tested further by the results of this more widely ranged flight program.

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