Longitudinal Handling Qualities Criteria: An Evaluation

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Compliance with current longitudinal handling qualities criteria is not a guaranteed acceptance of vehicle characteristics. Several criteria for satisfactory characteristics resulting from handling qualities investigations in simulators and variable-stability airplanes are reviewed; in comparison, these criteria reveal significant areas of disagreement. Further, much of the large-airplane data available that reflect satisfactory characteristics in flight would be judged unacceptable to unsatisfactory from these criteria. Consideration of the piloting technique involved in flightpath control indicates the significance of the parameters L_α/ω_n and $n_{z\alpha}/\omega_n$. Mapping the referenced satisfactory regions onto the L_α/ω_n vs ζ plane for those flight conditions exhibiting an $n_{z\alpha} < 15$ g/rad produces good agreement among the several criteria. Flight conditions exhibiting an $n_{z\alpha} > 15$ g/rad also yield good agreement when mapped onto the $n_{z\alpha}/\omega_n$ vs ζ plane. These three parameters—$n_{z\alpha}$, L_α/ω_n, and $n_{z\alpha}/\omega_n$—furnish the framework for complete longitudinal handling qualities criteria. These criteria provide the basis for an over-all correlation of pilot opinion data from four sources: 1) airplane characteristics from fixed-base and inflight simulation of airplanes exhibiting high natural short-period frequency, 2) flight experience of commercial jet transports, 3) fixed-base simulation of the B-52, and 4) inflight simulation of very large transports with low natural short-period frequency on the Boeing 367-80 jet transport prototype.

Nomenclature

$\bar{c}$ = reference chord
C_L = lift coefficient, $L/\frac{1}{2}\rho V^2 S$
C_m = pitching moment coefficient, $M/\frac{1}{2}\rho V^2 S\bar{c}$
$_n$ = short-period undamped natural frequency, cps
g = acceleration due to gravity
I_{yy} = airplane pitch inertia
$K_{\dot{\theta}}$ = steady-state gain, pitch rate-elevator transfer function
L = lift
L_α = $(1/mV)\,\partial L/\partial\alpha$
L_δ = $(1/mV)\,\partial L/\partial\delta_e$
m = airplane mass
M = pitching moment
M_α = $(1/I_{yy})\,\partial M/\partial\alpha$
$M_{\dot{\alpha}}$ = $(1/I_{yy})\,\partial M/\partial\dot{\alpha}$
M_δ = $(1/I_{yy})\,\partial M/\partial\delta_e$
$n_{z\alpha}$ = incremental load factor per unit angle of attack
PR = pilot rating
s = Laplace transform variable
S = reference area
V = true airspeed
α = angle of attack
δ_e = incremental elevator deflection
ζ = short-period damping ratio
$\dot{\theta}$ = time rate of change of airplane pitch attitude
ρ = air density
τ_{θ_2} = numerator time constant, pitch rate-elevator transfer function
ω_n = short-period undamped natural frequency, rad/sec

Subscripts

max = maximum
ss = steady state

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Introduction

ESTABLISHMENT of adequate handling qualities criteria has demanded ever-increasing attention since the beginning of flight. The first formal statement of a general requirement for satisfactory handling qualities was published by Gilruth of NACA.[1] Gilruth specified static and dynamic airplane characteristics that were designed to insure satisfactory handling qualities. Selection of the defining parameters as well as the region of satisfactory longitudinal characteristics is the subject of this paper.

Experimentally derived regions of "satisfactory" and "acceptable" short-period characteristics are compared on the f_n vs ζ plane. This comparison reveals areas of significant disagreement among the data presented. Consideration of airplane flightpath response suggests the significance of the parameter L_α. With this parameter and recognition that the pilot's control mode is not constant for all flight regimes, a set of criteria for satisfactory short-period characteristics is developed which correlates well with current airplane experience and with simulation experiments.

General Considerations

A discussion of the longitudinal mode of control must include at least four airplane characteristics that are intimately involved in the pilot's satisfaction with the airplane: speed stability, phugoid dynamics, short-period dynamics, and flight path response.

Airplane speed stability is most significant during precise low-speed operation such as landing approach. The pilot's control technique during low-speed flight is affected by the degree of speed stability or instability exhibited by the airplane.[2,3] However, the effect on pilot opinion cannot be clearly assessed from available literature (e.g., Refs. 4 and 5) because of wide disagreement in experimental results. Airplane speed stability as related to the data and criteria presented in the balance of this paper is assumed to be satisfactory.

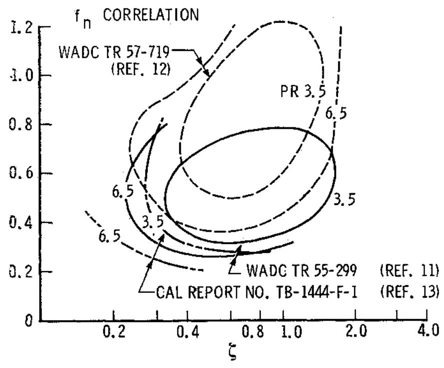

Fig. 1 Iso-opinion boundaries, f_n vs ζ plane.

Phugoid characteristics must be considered independently and in relation to the short period. Throughout this paper, the phugoid is assumed to exhibit positive damping and adequate separation with respect to the short period. This does not imply that the absence of these characteristics is catastrophic; yet the pilot workload is higher, and any ratings established on the basis of the criteria to be presented later would be optimistic.

Control characteristics are also assumed to be satisfactory since the pilot opinion rating of a particular set of airplane dynamic characteristics will deteriorate directly with deterioration of control. Finally, quality of the lateral-directional characteristics of any airplane considered must produce satisfactory pilot opinion to allow application of the criteria to be presented. These restrictions are necessary to allow consideration of longitudinal characteristics singly, since any of these conditions would affect indirectly the rating of the longitudinal mode by lowering the pilot opinion of the complete airplane.

Most airplanes satisfy these assumptions for a majority of flight conditions. Therefore, a second-order description of the short period can be considered in lieu of the complete equations of motion. This simplification permits a more direct consideration of the effect of individual parameters in the equation than would otherwise be possible. These qualifications allow the general subject of longitudinal handling qualities to focus on a discussion of longitudinal short-period characteristics and flightpath response.

Present Criteria

An examination of the development of handling qualities criteria and requirements illustrates the progression from a single qualitative statement to the current practice of requiring certain quantitative airplane characteristics. Westbrook[6] quotes the first statement of handling qualities requirements: "During this trial flight of one hour it (the airplane) must be steered in all directions without difficulty and at all times be under perfect control and equilibrium." The current military requirement for longitudinal short-period characteristics[7] effectively specifies a minimum damping ratio of 0.34 for oscillations with less than 6-sec periods. This is an assumption of negligible short-period frequency effect on pilot acceptance. However, recent research results emphasize the importance of natural frequency on pilot acceptance. A proposed revision to the current military specification[8] employs published variable-stability airplane data to define a region on the ω_n vs ζ plane that is satisfactory for normal operation. This type of criterion describes the quality of the longitudinal short-period oscillation, but fails to account for flightpath response.

Carlson and Sweeney, in Ref. 9, discuss longitudinal short-period characteristics of a representative C-5A configuration in relation to the criteria of Refs. 7 and 8. The simple damping criterion of Ref. 7 is easily met; however, the frequency-damping criteria of Ref. 8 are not satisfied. This illustrates the dilemma facing the designer when frequency-damping criteria are applied to large airplanes. The large airplane usually exhibits a relatively low natural frequency in comparison to the region of acceptance resulting from most variable-stability airplane investigations. The representative C-5A frequency is 0.18 cps, compared to the minimum satisfactory frequency of 0.3 cps from Ref. 9. It could be argued that since the C-5A is not flying, the pilot rating might be less than satisfactory. However, pilot experience with the longitudinal mode of control is generally satisfactory for present airplanes ranging in size from the 727 to the B-52. These similarly exhibit frequencies below 0.3 cps over most of their flight envelopes.

Kehrer concludes[10] that pilot opinion is dependent upon the relationship between $n_{z\alpha}$ and ω_n. This conclusion results from consideration of the piloting task during landing approach. The pilot's goal—control of flight path—is accomplished primarily with longitudinal control, either by elevator or stabilizer. The direct effect of a control movement on the airplane is a disturbance of the longitudinal short-period oscillation. This disturbance results in an attitude change that is, in effect, a change in airplane angle of attack. The airplane load factor response to angle of attack then curves the flight path.

Recent Experimental Results

As pointed out, most of the recent handling qualities research has concentrated on defining regions of acceptable airplane characteristics on the f_n vs ζ plane. Figure 1 illustrates the lack of correlation among three recent investigations that reported regions of satisfactory and acceptable airplane characteristics on the $f_n - \zeta$ plane.[11–13] All three results stem from pilot evaluation of a variable-stability airplane through four specified maneuvers. This set of maneuvers involved trimming the airplane at a specified airspeed, abrupt control steps to specified acceleration levels, slow and rapid turn entries followed by level turns up to 180°, and target acquisition in a 20° dive followed by a constant load factor recovery to level flight.

Pilot ratings shown adjacent to the curves correspond to the scale used in the most recent of the investigations (see Ref. 13). This pilot rating scale, reproduced in Table 1, is a modification of the scale proposed by Cooper.[14] The pilot rating scale used in the two earlier investigations is not currently in use. Therefore, equivalent numerical ratings from Table 1 were determined by comparing the reported pilot interpretations of the rating scales in Refs. 11 and 12 with the descriptions in Table 1. The numerical value of 3.5 represents the maximum rating that is consistent with satis-

Table 1 Pilot opinion rating scale

Category	Adjective description within category	Numerical rating
Acceptable and satisfactory	Excellent	1
	Good	2
	Fair	3
Acceptable but unsatisfactory	Fair	4
	Poor	5
	Bad	6
Unacceptable[a]	Bad	7
	Very bad	8
	Dangerous	9
	Unflyable	10

[a] Additional definitions of unacceptable category: (7) bad—aircraft controllable, but requires major portion of pilot attention, (8) very bad—aircraft controllable, but only with a minimum of cockpit duties, and (9) dangerous—aircraft just controllable with complete attention.

factory airplane characteristics, and similarly, 6.5 corresponds to the limit of acceptable airplane characteristics.

The solid iso-opinion lines of Fig. 1 are reported in Ref. 11. These boundaries are the result of a single pilot evaluation of the variable-stability F-94A, executing the maneuvers just described. The stick force characteristics were approximately constant, with stick force per g varying from 7.7 to 10 lb/g about a mean value of 8.6 lb/g. This slight variation in stick force per g was similarly exhibited in stick deflection per g and resulted from a nonlinearity in the basic F-94A C_m vs α curve.

The dashed lines in Fig. 1 are developed in Ref. 12 from ratings by three pilots flying the F-94A and using the defined maneuver and rating scale discussed previously. Each pilot selected the stick force per g and stick deflection per g characteristics he felt to be most acceptable. The selected control characteristics became the nominal values for the balance of the investigation. Small variations about the nominal value existed, similar to the investigation of Ref. 11, but the author states that this did not bias pilot opinion of short-period dynamics.

The final iso-opinion lines are from Ref. 13, and reflect evaluation by three pilots in the variable-stability B-26 using the same maneuvers described previously, except for the incremental g values, which were lower in this test. The pilots evaluated several frequency-damping combinations using two different evaluation techniques: the "long look" and the "short look." The long look most nearly corresponds to the technique applied in the other two experiments and is the source of data shown in the illustration.

Correlation Parameter Selection

In the opinion of the authors, generally acceptable or satisfactory airplane longitudinal characteristics from experiment and experience will correlate with the proper parameter. Kehrer has suggested that matching of the parameters $n_{z\alpha}$ and ω_n will produce satisfactory airplane characteristics. Consider the simplified airplane pitch rate-elevator (stabilizer) transfer function:

$$\frac{\dot{\theta}(s)}{\delta_e(s)} = \frac{K_{\dot{\theta}}(1 + \tau_{\theta_2}s)}{[1 + (2\zeta/\omega_n)s + (s^2/\omega_n^2)]}$$

The numerator of this transfer function contains the parameter τ_{θ_2}. This time constant relates the maximum pitch rate to the steady-state pitch rate, following a step elevator input, for given values of short-period frequency and damping. In fact, the pitch-rate overshoot $\dot{\theta}_{max}/\dot{\theta}_{ss}$ is uniquely a function of $1/\tau_{\theta_2}\omega_n$ (approximately L_α/ω_n) and ζ. McRuer, Ashkenas, and Guerre[15] point out the significance to the pilot of τ_{θ_2} and other often-ignored parameters. However, these authors state the difference in τ_{θ_2} between Refs. 11 and 12 is insignificant, and charge the lack of agreement to other causes.

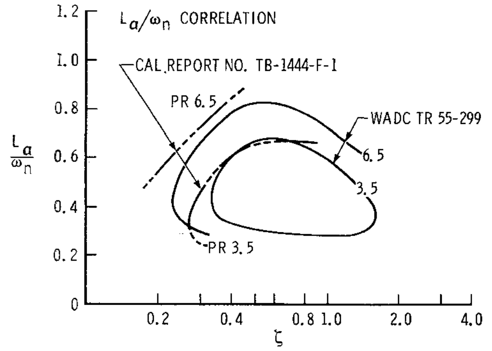

Fig. 2 Iso-opinion boundaries, L_α/ω_n vs ζ plane.

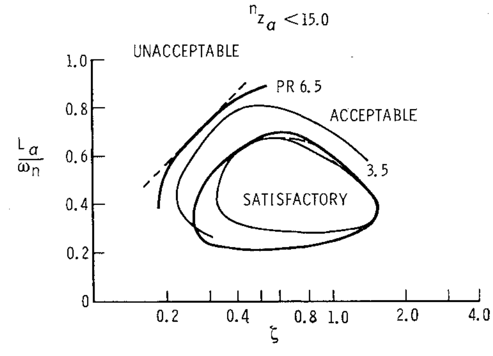

Fig. 3 Proposed longitudinal short-period criterion, $n_{z\alpha} < 15$.

Chalk suggests[16] that the pilot wants precise control of pitch attitude for those combinations of airplane characteristics and flight conditions that produce load factor per unit change in α of less than approximately 10 g/rad. When $n_{z\alpha}$ is greater than 10, the pilot wants to have precise control of normal acceleration. Representative large airplane data (727 and B-52) exhibit values of $n_{z\alpha}$ that group naturally into a low $n_{z\alpha}$ range of approximately 12 g/rad and below, and a high $n_{z\alpha}$ range of 20 and above. In addition, the distinguishing value in Ref. 16 ranges from 8 to 20. Therefore, $n_{z\alpha} = 15$ was selected in lieu of 10 as the distinguishing value.

The parameter L_α/ω_n, approximately $1/\tau_{\theta_2}\omega_n$, appears to relate airplane dynamics to pilot acceptance when the pilot is closing around pitch attitude ($n_{z\alpha} < 15$). Airplanes with the longitudinal control surface located aft of the center of gravity generally exhibit negligible control surface lift. Thus, L_α can usually be employed instead of the complete expression for $1/\tau_{\theta_2}$ shown below:

$$\frac{1}{\tau_{\theta_2}} = \frac{L_\alpha - M_\alpha(L_\delta/M_\delta)}{1 - M_{\dot{\alpha}}(L_\delta/M_\delta)} \approx L_\alpha$$

Throughout this paper, the parameter L_α/ω_n will be used with the understanding that for those cases in which elevator lift cannot be ignored, the complete time constant expression should be used.

Airplane characteristics and flight conditions associated with pilot control of normal acceleration ($n_{z\alpha} > 15$ g/rad) require the use of a new correlating parameter. The selected parameter should reflect airplane normal acceleration characteristics and offer a measure of handling quality that is compatible with that from L_α/ω_n, near the low $n_{z\alpha}$ region. Recourse to $n_{z\alpha}/\omega_n$ ($L\alpha V/g\omega_n$) provides this relationship between high and low $n_{z\alpha}$ criteria and at the same time reflects airplane acceleration characteristics. The three parameters, $n_{z\alpha}$, L_α/ω_n, and $n_{z\alpha}/\omega_n$ furnish the framework for complete longitudinal handling qualities criteria.

Proposed Criteria

The data of Ref. 13 will form the basis of the L_α/ω_n vs ζ criterion. To provide similar criteria near $n_{z\alpha} = 15$ and aid in defining a closed region, the data of Ref. 11 will also be used. Figure 2 shows the iso-opinion boundaries of these references mapped onto the L_α/ω_n vs ζ plane. Comparison of Figs. 1 and 2 illustrates the improved correlation. Judged on the basis of $n_{z\alpha}$, 13 g/rad for Ref. 13 and 29 g/rad for Ref. 11, these data should not agree. However, the similarity in L_α (1.2 and 1.39, respectively) accounts for the correlation. The proposed criterion switches from L_α/ω_n to $n_{z\alpha}/\omega_n$ at $n_{z\alpha} = 15$ and should be compatible at this value. Therefore, Ref. 11 is used as a guide in drawing the proposed boundary shown in Fig. 3. Because the data of Ref. 11 are being used as a guide

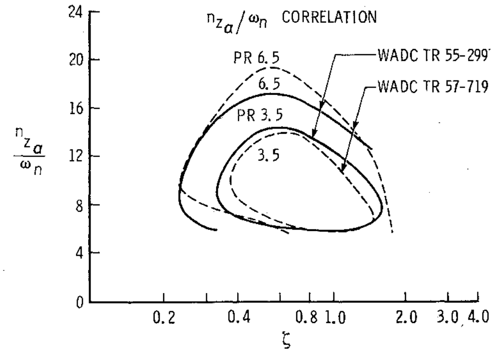

Fig. 4 Iso-opinion boundaries, $n_{z\alpha}/\omega_n$ vs ζ plane.

only, the boundary is drawn only in the area where data existed from Ref. 13. As a result, the pilot rating 6.5 boundary is limited and cannot be extended without further data. Additional Boeing data will be shown in the following sections with respect to this proposed boundary.

Data of Refs. 11 and 12 produce excellent correlation on the $n_{z\alpha}/\omega_n$ vs ζ plane (Fig. 4) while exhibiting little agreement on the $f_n - \zeta$ plane (Fig. 1). The corresponding $n_{z\alpha}$ values are

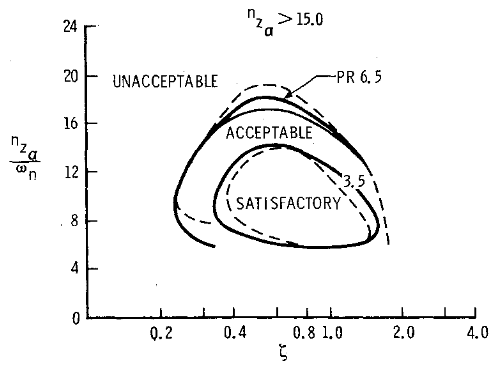

Fig. 5 Proposed longitudinal short-period criterion, $n_{z\alpha} > 15$.

29 (Ref. 11) and 44 (Ref. 12) g/rad. The dashed line, at low values of $n_{z\alpha}/\omega_n$ and damping ratios of 0.3 to 0.6, was derived from limited data[12]; therefore, in drawing boundaries of the proposed criteria this segment of the Ref. 12 boundary was disregarded in favor of the boundary of Ref. 11. The second half of the longitudinal handling qualities criteria is shown in Fig. 5.

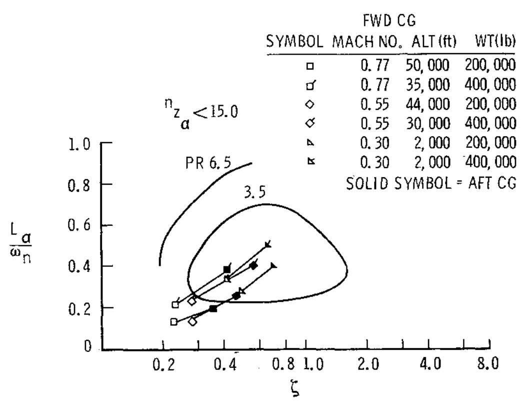

Fig. 6 B-52 longitudinal short-period characteristics, $n_{z\alpha} < 15$.

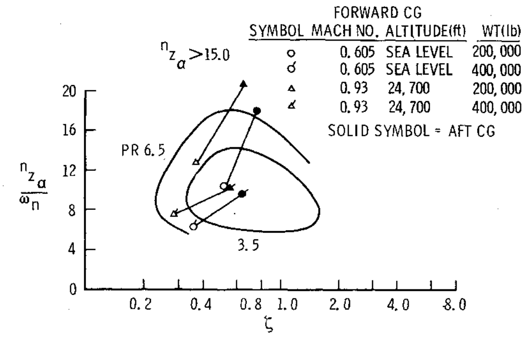

Fig. 7 B-52 longitudinal short-period characteristics, $n_{z\alpha} > 15$.

Present Airplane Experience

A persistent shortcoming exists in previous criteria proposed for longitudinal handling qualities. This fault is evidenced by the disagreement between experience with present large airplanes and these criteria. Figure 6 contains the short-period characteristics of the B-52 at several flight conditions, at 200,000- and 400,000-lb gross weight and fore and aft center-of-gravity positions. These data ($n_{z\alpha} < 15$) exhibit encouraging agreement with the criteria, since pilot experience

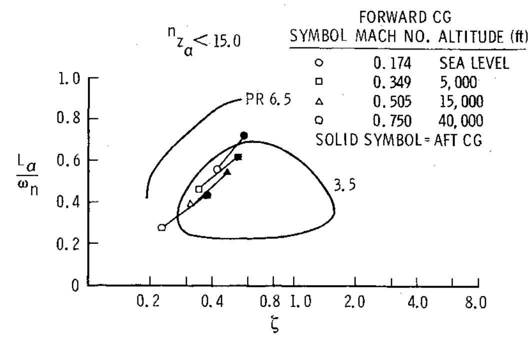

Fig. 8 727 longitudinal short-period characteristics, $n_{z\alpha} < 15$.

with the longitudinal axis of the B-52 reveals characteristics that generally range from acceptable to satisfactory. The natural frequency of all points shown is less than 0.3 cps and as a consequence would be expected to exhibit pilot ratings less than satisfactory, as determined from present criteria. Figure 7 similarly illustrates the general agreement for $n_{z\alpha} > 15$. The two flight conditions shown exhibit pilot acceptance that generally agrees with the criteria. An exception exists: the two aft center-of-gravity points at 200,000 lb are rated acceptable by the pilots, but are indicated unacceptable

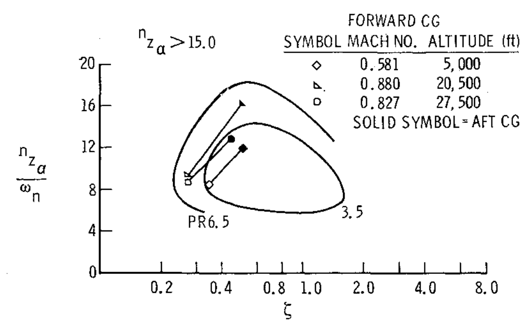

Fig. 9 727 longitudinal short-period characteristics, $n_{z\alpha} > 15$.

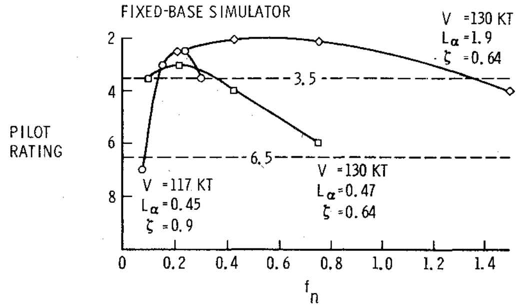

Fig. 10 Effect of short-period natural frequency on pilot opinion.

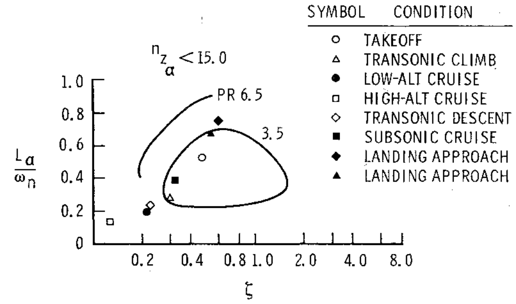

Fig. 12 SST longitudinal short-period characteristics, $n_{z\alpha} < 15$.

in the illustration. This confirms the somewhat tenuous nature of these boundaries, and further study is necessary to refine the proposed criteria.

Figure 8 shows representative 727 characteristics for $n_{z\alpha} < 15$ with fore and aft center-of-gravity limits and a large spread in Mach number. Notable agreement exists between flight experience with the airplane and pilot acceptance predicted from the proposed criteria. Many of the flight conditions shown exhibit f_n of less than 0.3 cps. Figure 9 demonstrates the correlation between flight experience and the criterion for $n_{z\alpha} > 15$, where flight experience indicates the airplane would be rated satisfactory to good. These four illustrations display exceptional agreement between flight experience on two large airplanes and criteria derived from basically small airplane experiments.

Simulation Experience

Significance of the relationship between ω_n and L_α is illustrated in Fig. 10. Pilot ratings of three airplanes in landing approach configuration are shown for various natural frequencies. These data were developed at Boeing on a fixed-base simulator. The pilot ratings display definite peaks, at low frequency for low L_α (0.45, 0.47) configurations, and at a higher frequency for the high L_α (1.9) configuration. Mapping these points onto the proposed criterion, with the pilot ratings tabulated adjacent to the data, results in the excellent correlation of Fig. 11. A single point, the low-frequency point on the $L_\alpha = 1.9$ curve of Fig. 10, falls in the unacceptable region but was rated satisfactory by the pilot.

A representative supersonic transport is shown on Fig. 12 with the criterion for $n_{z\alpha} < 15$. Data shown cover the flight envelope from takeoff to cruise and landing. These data, shown for an unaugmented airplane, agree well with pilot opinion from fixed-base simulator investigation. The high-altitude cruise condition implies a worse rating than simulation predicts. On the other hand, the landing approach condition corresponds to a rating of about 3.5 and is compatible with the criterion.

Boeing has developed a variable-stability airplane capability that allows inflight simulation of very large airplanes. This airplane, the Boeing 367-80 variable-stability jet transport prototype shown in Fig. 13, was used to simulate the C-5A on landing approach. As a parallel effort, many of the same conditions were simulated on a fixed-base simulator in the Boeing facility at Renton, Wash. The results of this study[17] are shown in Fig. 14. The number adjacent to each data point and above the line is the pilot rating assigned during the inflight simulation. Numerical pilot ratings below the line are from the fixed-base simulation. Agreement between both fixed-base and inflight simulation and the proposed criterion is excellent.

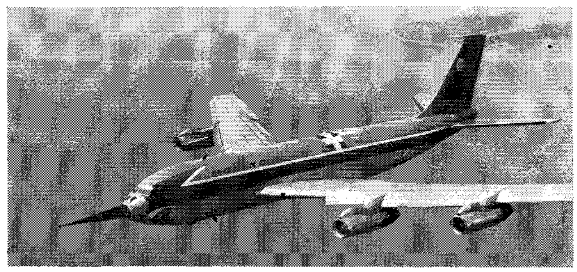

Fig. 13 Boeing 367-80 variable-stability transport prototype.

Conclusions

Regions of satisfactory and acceptable airplane characteristics determined from three separate small airplane experiments were shown to disagree on the conventional f_n vs ζ plane. These data were used to develop unified longitudinal handling qualities criteria, involving regions of pilot acceptance on the L_α/ω_n vs ζ plane for values of $n_{z\alpha} < 15$ g/rad, and on the $n_{z\alpha}/\omega_n$ vs ζ plane for $n_{z\alpha} > 15$ g/rad.

These criteria have been shown to be further substantiated by B-52 and 727 flight experience over a large range of flight conditions. The low $n_{z\alpha}$ portion of the criteria correlates well with available fixed-base and inflight simulation data.

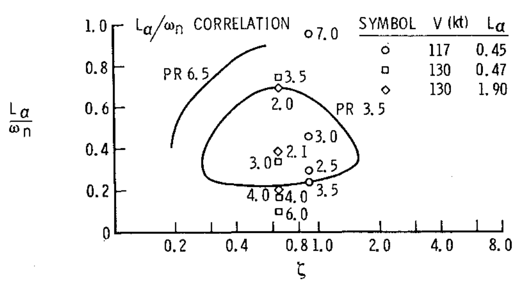

Fig. 11 Fixed-base simulator data, $n_{z\alpha} < 15$.

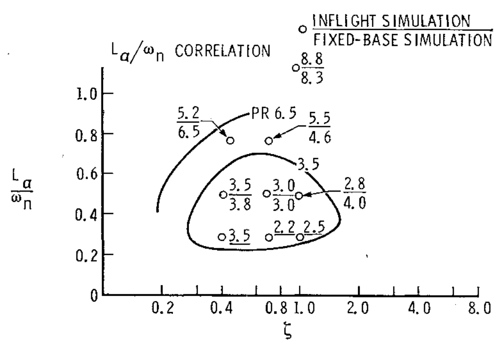

Fig. 14 Inflight simulator data, $n_{z\alpha} < 15$.

Finally, it must be recognized that absolute limits of L_α and ω_n probably exist which will individually produce unsatisfactory pilot opinion even though the proposed criteria are satisfied. However, currently available data are insufficient to determine these limits.

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