LONGITUDINAL STABILITY AND CONTROL OF LARGE SUPERSONIC AIRCRAFT AT LOW SPEEDS

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ABSTRACT

Studies of many different types of supersonic transport configurations have shown that the complex task of landing a large supersonic aircraft under adverse weather conditions poses formidable design problems in the area of stability and control. This paper confines itself to the discussion of longitudinal handling qualities under these conditions, and more specifically to the short-period flight path response characteristics of these aircraft.

In recent years the analyses of these flight-path response characteristics have been mostly confined to the study of short-period pitch attitude dynamics. The plane of undamped natural frequency ($\omega_{n_{sp}}$) versus damping ratio (ζ_{sp}) has been employed to delineate areas of acceptability for aircraft short-period dynamic stability characteristics. However, analyses of this type are incomplete and often misleading in their results when they neglect the important L_α or n_{z_α} parameters. The handling qualities analyses and flight simulator investigations discussed herein have demonstrated the importance of matching carefully the $\omega_{n_{sp}}$ with the L_α or n_{z_α} characteristics. Aircraft possessing characteristically low n_{z_α} capability, for example, provide the best handling qualities when $\omega_{n_{sp}}$ is maintained at relatively low values.

The attainment of acceptable low-speed handling qualities will be difficult for some types of large supersonic aircraft. Aerodynamic and mass-distribution characteristics commonly tend to produce airplanes that are extremely sluggish about the pitch axis. Configurations with conventional aft tails have been found to provide good handling qualities without stability augmentation if good matching is obtained between $\omega_{n_{sp}}$ and n_{z_α} characteristics. These configurations are also amenable to the adoption of systems to augment $\omega_{n_{sp}}$ to the small degree necessary for the best match with n_{z_α}. However, tailless aircraft that are short-coupled (elevons-to-center of gravity) and

characterized by higher pitch inertias will be excessively sluggish and difficult to handle without some form of augmentation to improve the flight-path dynamic-response characteristics. Development of the required augmentation for these aircraft will prove extremely difficult, and in some cases may not be possible within practical design limitations.

INTRODUCTION

The generation of large supersonic aircraft now being developed will differ greatly from current jet transport and large bomber designs in size, aerodynamic configuration, and mass distribution. Range and payload requirements dictate that the airplanes will be massive by today's standards, and efficient supersonic operation demands long, slender configurations, with highly swept, low-aspect-ratio wing planforms. The resulting aerodynamic and mass-distribution characteristics present the designer with new and unique problems in the field of stability and control.

It is generally recognized that commercial supersonic transports must provide handling qualities that are equal or superior to those of current transports. The attainment of these characteristics will, of course, require some form of stability augmentation throughout much of the flight envelope. However, it is obvious that for commercial operation the basic airplane should be sufficiently tractable to ensure safe flight with the stability augmentation system inoperative. Good handling characteristics are especially important for low-speed operation, where the pilot is faced with the demanding tasks imposed by the performance of instrument landing approaches under adverse weather conditions.

It is difficult to overemphasize the importance and immediacy of the need for establishing stability and control requirements. Accurate boundaries of minimum acceptable handling qualities must be determined for operation without stability augmentation, and areas of desirable characteristics need to be established to guide the tailoring of stability-augmentation systems. Unfortunately, there is little information in existence today to provide accurate guidance to the designers of this new breed of aircraft. Current military and civil flying qualities specifications, for example, are greatly in need of revision and expansion before they can be considered applicable. It is true, of course, that interest in development of the supersonic transport has spurred some excellent research work in this area in recent years. However, none of the investigations to date have been successful in formulating accurate handling qualities criteria. A great deal of additional, well-directed research must be accomplished before guidelines and requirements can be established.

In recent years the author has been associated with stability and control analyses of many different types of supersonic transport configurations. These have included flight-simulator and analytical studies of such configurations as canard deltas, tailless deltas, tailed deltas, and fixed-arrow-wings, as well as widely differing concepts of variable-sweep airplanes. Some of the handling qualities found typical of various types of supersonic aircraft will be described herein, and comparisons will be drawn with the characteristics of current jet transports. It is the intent of this paper to single out tentative areas of desirable characteristics and to suggest regions of further exploration to establish stability and control requirements for large supersonic aircraft. The discussions are confined to the critical low-speed portion of the flight envelope, where the handling tasks are most demanding of the pilot.

THE APPROACH AND LANDING TASK

The most demanding task faced by the pilots of large transport or bomber aircraft is that of performing the approach and landing on instruments under severe weather conditions. Analysis of the stability and control characteristics of a new aircraft design must therefore include a thorough study of the handling qualities exhibited during these phases of operation. The pilot's task consists of acquiring and maintaining the desired approach path rate-of-sink and direction and the proper airspeed during the approach phase, followed by a rapid transition to what is often marginally visual flight for performance of the flare and touchdown. The overall amount of pilot effort required and the difficulty of properly directing the airplane are increased greatly when rough air and crosswinds are introduced into the problem. Consideration of the total piloting task involved during these operations leads to the obvious conclusion that the severity of the piloting problems should not be compounded further by deficiencies in the basic handling qualities of the airplane.

Much experience has been gained with operation of current large jet transports. These aircraft provide longitudinal handling qualities in the approach and landing that can be assessed as "satisfactory with some mildly unpleasant characteristics," or a NASA scale pilot rating of about 3.0 (see Table 1). The "mildly unpleasant" rating results primarily from the tendency toward slow responsiveness in pitch inherent for these large, heavy aircraft. Landing studies have indicated that, as a result of these characteristics, sinking rates at touchdown are greater than consistently experienced by previous propeller aircraft [1-4]. On the basis of this experience, it is generally agreed that the longitudinal handling qualities of

TABLE 1. NASA OPINION RATING SYSTEM

	Adjective rating	Numerical rating	Description	Primary mission accomplished	Can be landed
Normal Operation	Satisfactory	1	Excellent, includes optimum	Yes	Yes
		2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
Emergency Operation	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes	Yes
		5	Unacceptable for normal operation	Doubtful	Yes
		6	Acceptable for emergency condition only*	Doubtful	Yes
No Operation	Unacceptable	7	Unacceptable, even for emergency condition[1]	No	Doubtful
		8	Unacceptable—dangerous	No	No
		9	Unacceptable—uncontrollable	No	No

* Failure of a stability augmenter.

current jet transports probably approach the lower limits of acceptability for satisfactory operation of commercial airplanes.

Attainment of good low-speed stability and control characteristics may pose a formidable design problem for large supersonic aircraft because of their size, aerodynamic configuration, and mass-distribution characteristics. Some appreciation for the magnitude of the difference existing between current jet transports and future supersonic transports can be gained from the information presented in Fig. 1. Here a comparison is made between a current large jet transport and two different supersonic transport (SST) configurations: a variable-sweep-wing (VSW) airplane and a delta-wing airplane. In addition to the obvious dissimilarities in size and aerodynamic configuration between the SST's and the subsonic transport, the differences in mass distribution are strikingly apparent. The concentration of mass along the bodies of the supersonic airplanes results in extremely large moments of inertia about the pitch and yaw axes (particularly for the delta, with its aft engines) and relatively low inertia about the roll axes. At typical

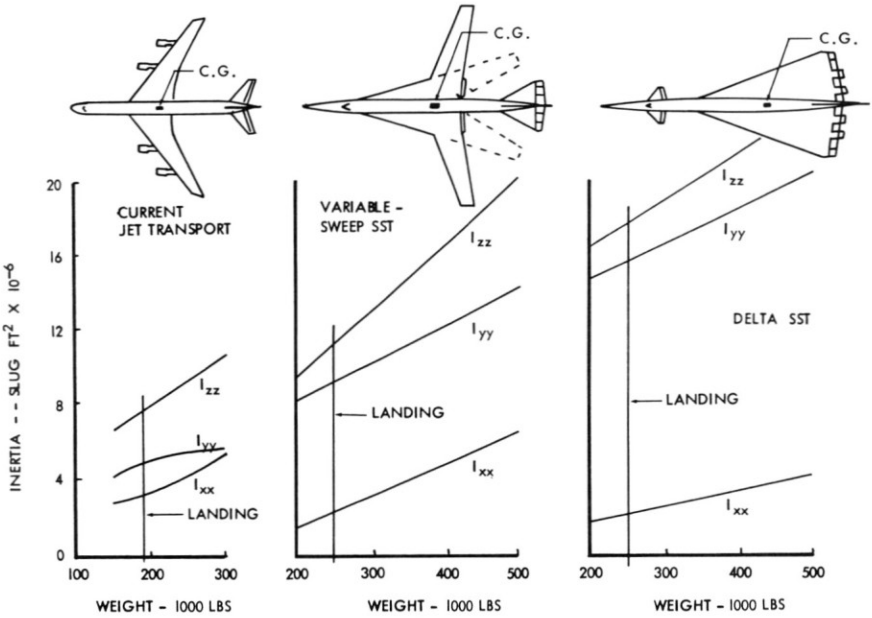

Figure 1. Comparison of geometrical and mass distribution characteristics of a current jet transport and two supersonic transport configurations.

landing weights, for example, the pitch inertia of the delta SST is three times that of the subsonic jet transport, while the roll inertia of the delta is only ⅔ that of the subsonic. These large differences in aircraft configuration are reflected primarily in differences in dynamic handling qualities, with the effects of mass distribution becoming extremely important during low speed operation.

LONGITUDINAL HANDLING CONSIDERATIONS

There are two areas of stability and control in the longitudinal mode which are of particular significance during low-speed operation. In order of importance, these are:

1. Flight-path short-period dynamic response
2. Speed-thrust stability

Item (1) involves the airplane short-period pitch-attitude dynamic characteristics, combined with the capability of the airplane to develop normal acceleration with attitude change. Closely interrelated with this are the

M_δ/L_δ characteristics of the pitch control system, and the control system force and gearing characteristics. Item (2) is the variation of thrust-required-for-steady-flight with airspeed, and involves the thrust-loading and lift-to-drag characteristics of the airplane and their relation to the desired approach trim speed.

It must be realized, of course, that the complex piloting task inevitably results in many interactions between the above parameters and also that the long-period, or phugoid, mode of dynamic motion, since it involves pitch angle, airspeed, and altitude, will also inter act to influence the total piloting task. Caution must be exercised, therefore, when an attempt is made to isolate either of these areas for examination to establish tentative requirements for handling qualities. For example, aircraft which must fly on the "back side" of the drag curve during landing approach (thus subject to speed-thrust instability) require different control techniques in which the pilot controls attitude with elevator and rate-of-descent with throttle [5,6]. The technique of altitude control with throttle, being characteristically low in frequency, approaches the phugoid motions of the aircraft. Thus, the phugoid mode of motion may become of equal or even greater importance than the short period, or maneuvering, mode of motion.

Aircraft that approach on the "front side" of the drag curve are much more easily controlled, because the pilot uses the elevator alone to make flight-path corrections, with very little throttle manipulation required following the initial trim power setting. In the latter case, the flight-path short-period dynamic-response characteristics may be isolated for handling qualities studies.

It is beyond the scope of this paper to discuss in detail all of the important low-speed stability and control areas. The subject of flight-path short-period dynamic response has been selected for discussion with the assumption that supersonic transport aircraft either will possess speed-thrust stability, or, if not, will incorporate automatic throttle-control devices to ease piloting tasks. In either case, the pilot's primary control of both airplane attitude and flight path will be through use of the pitch-control surface.

FLIGHT-PATH SHORT-PERIOD DYNAMIC RESPONSE

The dynamic response of the airplane to deflection of the longitudinal control is of particular importance during approach and landing. Through the elevator control, the pilot controls the pitch attitude to adjust the flight path. His ability to alter the flight path is therefore a function of the airplane attitude response to a control input, combined with the charac-

teristic airplane normal acceleration response to attitude change. The airplane responds in pitch attitude as a function of its short-period natural frequency ($\omega_{n_{sp}}$). Thus, the plane of $\omega_{n_{sp}}$ versus ζ_{sp} (damping ratio) expresses the quality of the airplane pitch-attitude response. However, it is flight-path response that the pilot seeks when he commands an attitude change, and to evaluate this, we must consider the important parameter, L_α, which appears in the transfer functions relating airplane responses to control inputs. L_α is a measure of the amount of which n_z, and $\dot{\gamma}$ lag θ. It is expressed by the equation: $L_\alpha = (\rho SV/2m)\, C_{L_\alpha}$. The relation between flight-path angle and pitch angle may be seen from the following simplified equation:

$$\frac{\gamma}{\theta} = \frac{1}{\frac{1}{L_\alpha} s + 1}$$

In the above equation, $1/L_\alpha$ is the time constant by which flight-path angle lags pitch attitude. Aircraft with low L_α will thus be slow to respond in flight-path angle following an attitude change.

A parameter that more clearly expresses the flight-path response characteristics of an airplane is the quantity $n_{z_\alpha} = L_\alpha(V/g)$. This parameter is simply the ratio of the incremental normal acceleration attainable per incremental angle of attack. It may be expressed as g per radian, or more appropriately as g per degree α; it is a direct measure of the ability of the airplane to change flight path when the attitude is changed.

Frequency and damping ratio have long been accepted as the basis for analyzing the short-period dynamic qualities of aircraft, and many attempts have been made to delineate boundaries of acceptability in the $\omega_{n_{sp}}$ versus ζ_{sp} plane that are applicable to general classes of aircraft. However, none of these efforts have been successful because they have confined themselves to analyses of dynamic response in attitude only, neglecting the flight-path response characteristics as expressed by the L_α or n_{z_α} parameters. Within a given class of aircraft, such as Class II (large transport or bomber aircraft) specified in Ref. 7, for example, the n_{z_α} characteristics can vary over a wide range, as a function of airspeed, altitude, and aerodynamic configuration. This variation will greatly influence the desired pitch attitude frequency and damping characteristics.

Supersonic transport studies conducted at Boeing flight-simulator facilities, which are discussed in subsequent paragraphs, have shown that it is important to obtain a good match of $\omega_{n_{sp}}$ and n_{z_α}. Airplanes with inherently low n_{z_α} provide the best handling characteristics when the short-period natural frequency is maintained at relatively low values. Thus, the location of the boundaries delineating areas of acceptability on the $\omega_{n_{sp}}$

versus ζ_{sp} diagram are a definite function of the L_α, n_{z_α} parameters. The significance of these parameters has been demonstrated to some extent in the flight-simulator studies conducted by Chalk [8], and the flight-control analyses reported by Ball and Rynaski [9]. Notess and Gregory have also discussed the significance of L_α with regard to supersonic transport flying qualities [10]. However, considerably more research work must be done in this area before the desired relationships between $\omega_{n_{sp}}$ versus ζ_{sp}, and L_α or n_{z_α} are understood well enough to permit an accurate definition of requirements for short-period dynamic characteristics.

PITCH-ATTITUDE DYNAMICS OF LARGE SUPERSONIC AIRCRAFT

Considerable concern has been expressed over the probability that large supersonic aircraft, because of their mass distribution and aerodynamic characteristics, will be extremely sluggish about the pitch axis and thus difficult to control during low-speed operation. This concern results because analyses of many different types of supersonic transports have shown that the short-period longitudinal dynamics are often characterized by unusually low natural frequencies and high damping, indicating that the airplane pitch-attitude response to control inputs will be extremely slow. Various investigators, upon examining these configurations without considering carefully the n_{z_α} characteristics, have concluded that a solution to the problem could be found in a stability-augmentation system that would increase the pitch responsiveness by increasing $\omega_{n_{sp}}$. A more rigorous analysis shows, however, that this approach may actually lead to a pronounced deterioration in handling qualities. This deterioration is caused by the mismatch produced between attitude response and flight-path response, by pitch-overshoot problems, and by the undesirable negative n_z response characteristics inherent when elevon surfaces on short-coupled aircraft are used to augment attitude response. These problems are examined in the following discussions of supersonic transport short-period and n_{z_α} characteristics.

The pitch-attitude short-period dynamic characteristics of several different supersonic transport configurations are shown in Fig. 2 at landing approach conditions (V_e = 130 knots). These include an arrow-wing-plus-aft-tail configuration, a delta-wing-plus-aft-tail airplane, a delta-wing-plus-canard airplane, and a variable-sweep-wing (VSW) airplane (shown in Fig. 1) with its movable wing at the normal landing sweep angle, 20 degrees, and also with the wing fixed at its maximum sweep angle, 74 degrees (V_e = 172 knots for the maximum-sweep condition). A shaded, bounded area of frequency and damping ratio representative of current

Boeing jet transports (for a wide range of wing-loading and center-of-gravity conditions) is shown for comparison. In addition, an iso-opinion diagram developed during Cornell research employing a variable-stability B-26 airplane [11] is included in Fig. 2 to illustrate the areas of good and bad handling qualities determined for that specific type of airplane. The B-26 data is an example of some of the excellent research conducted by Cornell for the purpose of delineating areas of desirability for the short period dynamics of various aircraft during inflight maneuvering. These investigations have been confined to relatively small aircraft operating at relatively high n_{z_α} (see also Refs. 12–16).

Unusually low natural frequency and heavy damping characterize most of the supersonic aircraft configurations examined. As would be anticipated, the VSW configuration most closely approximates the short-period characteristics of current jet transports. This results primarily from the reduced pitch inertia of the more conventional wing-plus-tail arrangement. The tailless delta airplanes, with their inherently higher pitch inertias, are characterized by lowest frequencies and heaviest damping.

A comparison with the B-26 iso-opinion diagram of Fig. 2 implies that, in any case, the supersonic airplanes will lie in a highly unsatisfactory area on the $\omega_{n_{sp}}$ versus ζ_{sp} chart. However, examination of several factors will reveal that this is not necessarily true. For example, the bounded area of frequency and damping shown for current jet transports, although it lies well below the "poor" boundary of the iso-opinion diagram, nevertheless does define an area of acceptable handling qualities for these aircraft.

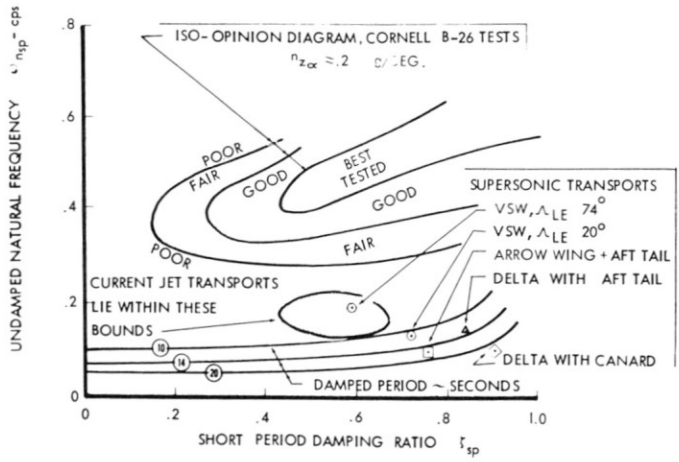

Figure 2. Longitudinal short period dynamic characteristics of current jet transports and several supersonic transport configurations, landing approach condition.

A consensus of pilot opinions shows that, while these transports handle like "big, heavy airplanes" they are nevertheless quite tractable, and merit a pilot rating of about 3 (by the NASA scale, Table 1).

This apparent contradiction occurs because the B-26 frequency-versus-damping-ratio boundaries cannot be employed to delineate regions of good and bad handling qualities for either the current jet transports or the supersonic aircraft. The reasons for this are twofold. First, large differences exist in n_{z_α} between the tested B-26 and the transports. The n_{z_α} of the transports is approximately 0.07 g/degree during the landing approach, as contrasted to the much larger n_{z_α} of approximately 0.20 g/degree characteristic of the B-26 during the tests conducted to develop the iso-opinion diagram. Second, rapid maneuvering and simulated gunnery runs were employed to obtain the data of the B-26 tests. Thus, the piloting tasks differed greatly from those involved in performing the transport landing approach.

PILOT RATING VERSUS SHORT-PERIOD FREQUENCY FOR LOW n_{z_α}

Experiments conducted at Boeing flight simulator facilities have provided ample evidence that aircraft operating at low values of L_α and n_{z_α} provide the best handling qualities when the short-period natural frequency is relatively low. The results of one such study are presented in Fig. 3. Here we see how the pilot rating varies with short-period natural frequency when the damping ratio is held constant and the n_{z_α} is maintained at a low value typical of large transport aircraft in the landing approach. These experiments were conducted by performing landing approaches in a supersonic transport configuration with widely varying $\omega_{n_{sp}}$, but with n_{z_α} and ζ_{sp} held constant at 0.064 g/degree and 0.72, respectively. One basic VSW airplane was actually evaluated as far as the geometrical, mass, and aerodynamic parameters were concerned, except for the following: C_{m_α} was varied to produce different $\omega_{n_{sp}}$, and $C_{m_{\delta_e}}$ was adjusted to provide constant δ_e-per-g as C_{m_α} changed. $C_{L_{\delta_e}}$ was held constant, and C_{m_α} was adjusted to hold the damping ratio at 0.72. Control column deflection-per-g, and force-per-g were held constant. This, then, roughly approximated one airplane with several tail lengths to provide variation in $\omega_{n_{sp}}$. The n_{z_α} and ζ_{sp} tested were typical for VSW supersonic transport configurations at landing approach conditions. It should be emphasized that the airplane evaluated possessed good speed-thrust stability; consequently, the piloting task involved control of flight path with the elevators, with very little throttle adjustment required during the approach. This experiment was conducted on a fixed-base flight simulator; thus the results in terms of pilot rating are somewhat pessimistic. Experience has shown that the

pilot rating obtained on the fixed-base simulator is generally about 1.0 worse qualitatively than that obtained when the same configuration is actually flight tested.

These tests showed that the best handling qualities were attained with the short-period frequency near 0.2 cps. It is evident from Fig. 3 that as the $\omega_{n_{sp}}$ was increased above this value, handling characteristics deteriorated rapidly. The pilots commented that at the higher frequencies the airplane became too responsive in pitch attitude relative to its slow flight-path response. This mismatching of attitude response to flight-path response led to pilot-induced oscillations and pitch over shoots, with attendant difficulty in acquiring and holding a selected flight-path angle. An interpretation of the Cornell B-26 data from Fig. 2 is presented on the pilot rating versus $\omega_{n_{sp}}$ plot of Fig. 3 for comparison with the supersonic transport flight simulator tests. The B-26, with its higher n_{z_α}, handled best at frequencies near 0.55 cps; and, in contrast to the transport results, would be considered virtually unflyable at near the 0.2 cps value found optimum for the supersonic transport. This type of comparison clearly illustrates the danger of applying short period dynamics criteria established for one specific type of airplane to other aircraft without consideration of n_{z_α} characteristics.

Some additional insight into the desirability of closely matching $\omega_{n_{sp}}$ with n_{z_α} or L_α characteristics may be gained from observation of the

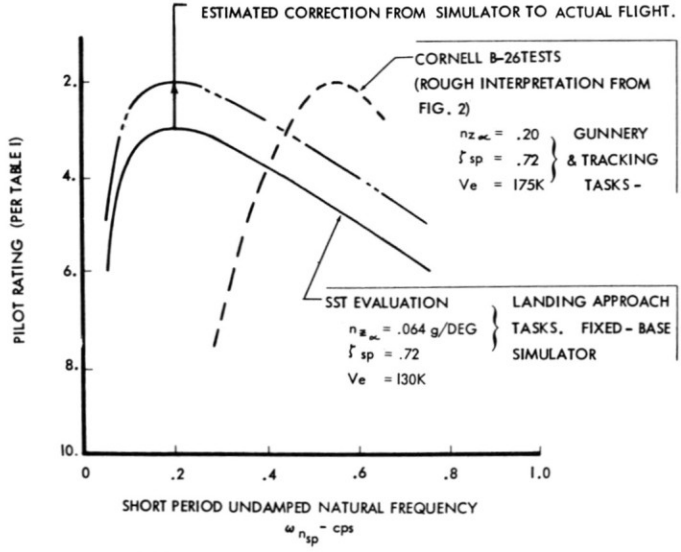

Figure 3. Effect of short period natural frequency on pilot rating, VSW—SST configuration.

effects of the $L_\alpha/\omega_{n_{sp}}$ relationship on the overshoot in pitch following an elevator input. When the natural frequency becomes too high relative to the L_α characteristic inherent in a given configuration, the overshoot in pitch following a control input becomes excessive. This results in attitude control difficulties and tendencies toward pilot-induced oscillations. The effect of the $L_\alpha/\omega_{n_{sp}}$ ratio on pitch-rate overshoot may be seen from examination of the elevator transfer function relating pitch response to elevator input:

$$\frac{\dot{\theta}(s)}{\delta_e(s)} = \frac{L_\alpha + s}{s^2 + 2\zeta_{sp}\omega_{n_{sp}}s + \omega_{n_{sp}}^2}$$

The ratio of the maximum pitch rate attained to the final steady state value ($\dot{\theta}_{max}/\dot{\theta}_{ss}$) for a step input of elevator has been calculated using this equation, and plotted (Fig. 4) versus the $L_\alpha/\omega_{n_{sp}}$ ratio. This was done for a damping ratio of 0.72 so that the results of the pilot rating versus $\omega_{n_{sp}}$ tests (shown in Fig. 3) for the supersonic transport could be superimposed on the $\dot{\theta}_{max}/\dot{\theta}_{ss}$ versus $L_\alpha/\omega_{n_{sp}}$ plot. It is evident from Fig. 4 that when the $L_\alpha/\omega_{n_{sp}}$ ratio decreases below about 0.3, the pitch-rate overshoot rapidly increases to excessive values. The flight simulator evalua-

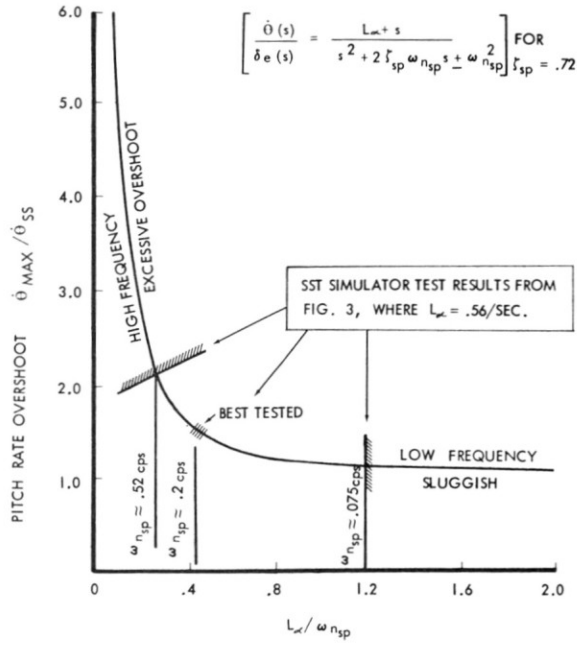

Figure 4. Effect of short period frequency on pitch rate overshoot.

tion of the VSW supersonic airplane ($L_\alpha = 0.56$/sec) demonstrated the best handling characteristics when $\omega_{n_{sp}}$ was approximately 0.2 cps, yielding a $\dot{\theta}_{max}/\dot{\theta}_{ss}$ ratio of about 1.5. When the short-period frequency was increased above this value (reducing the $L_\alpha/\omega_{n_{sp}}$ ratio), the pitch-rate overshoot became excessive. At frequencies below that considered optimum by the pilot, pitch-rate overshoot was not a problem; instead, the problem became one of sluggish response.

BOUNDARIES FOR ACCEPTABLE SHORT-PERIOD DYNAMIC CHARACTERISTICS

An estimate of the type of boundaries that might be drawn to delineate an area of acceptable short-period pitch-attitude dynamics for low-speed operation of large supersonic aircraft is presented in Fig. 5. Scales have been deliberately omitted from this graph because the knowledge required to establish definite boundaries does not exist at this time. The type of boundary implied for Class II aircraft by the published handling qualities research data available today (e.g., Refs. 11–16) is also shown for comparison. The actual shaping of the proper boundaries is in doubt, but it is significant to note that upper limits of $\omega_{n_{sp}}$ will exist as well as lower limits, and that the bounded area of acceptability is low in frequency when compared

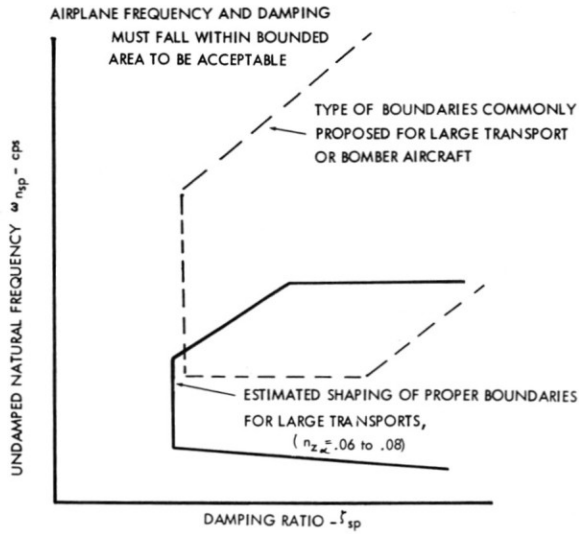

Figure 5. Boundaries of acceptability for short period longitudinal dynamic characteristics of large transport aircraft, approach and landing task only.

to standards implied by currently available research data. Some sloping of the upper boundary is shown to indicate that the pilot will tolerate lower damping ratios only when the frequency is reduced. At extremely low frequencies, it is possible that the pilot will tolerate longer periods if the damping is increased; thus, the lower boundary may be sloped opposite to the upper boundary. The boundaries are left open on the right-hand side of the diagram to indicate that not enough is known of this area to indicate the extent of the limits. Extensive research will be required before areas of good and bad handling qualities can be accurately delineated for short-period pitch-attitude dynamics. However, it is proposed that the boundaries finally established will be functions of n_{z_α} and the specific piloting task to be accomplished.

STABILITY AUGMENTATION TO IMPROVE DYNAMIC RESPONSE

Some of the large supersonic configurations will be characterized by short-period frequencies that will lie below the lower boundary of acceptability. This is true of airplanes that have extremely large moments of inertia about the pitch axis and that operate with low static-stability margins. Flight simulator studies have shown that when the period of oscillation gets to be too long, control of the aircraft becomes difficult. One problem is that the airplane pitch response becomes so slow that the pilot cannot distinguish between the effects of his control inputs and the effects of wind gusts. This difficulty is encountered in rough-air operation when the damped period becomes longer than 16 or 17 seconds. Another problem encountered as a result of the sluggish response characteristics is the excessive amount of altitude required to perform the landing flare. Attempts to resolve these problems with augmentation which speeds up attitude response may meet with little or no success for some configurations because of the problem of $\omega_{n_{sp}}$ and n_{z_α} matching, and because of the low ratio of M_δ/L_δ characteristic of closely coupled airplanes employing elevon surfaces for control and augmentation. Figure 6 illustrates the characteristics of a system that is designed to speed up the flight-path response by initially pulsing the control surface to a value greater than that required for the desired steady state Δ_{n_z}, followed by a programmed washing out of the deflection to the steady-state value to damp the response as necessary. The airplane response characteristics shown are representative of closely coupled, high-pitch-inertia, tailless-delta configurations employing large elevons for pitch control. Contrary to the desired results, the effect of the speed-up and overshoot in elevon deflection is delayed flight-path response. The delay results from the effect of the large decremental elevon

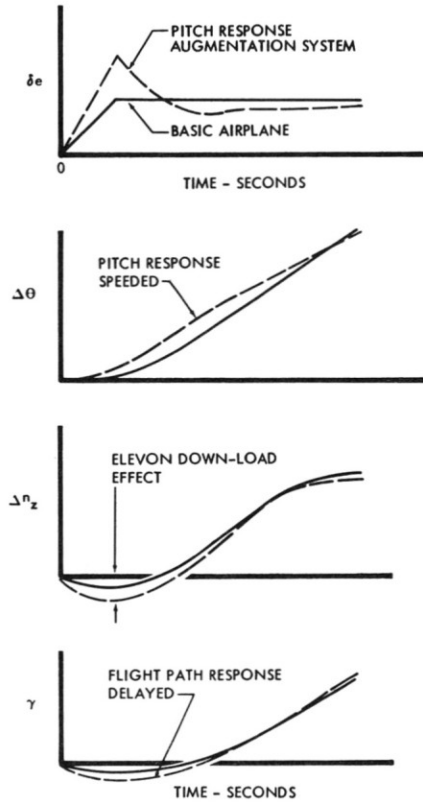

Figure 6. Effect of pitch response augmentation on flight path response.

lift required to pitch the airplane, combined with the low L_α, n_{z_α} characteristics. The loss of lift is felt immediately with elevon deflection as a pronounced initial sinking effect. The sinking is then prolonged abnormally by the low g-per-degree angle-of-attack capability of the airplane. The net effect, therefore, is that flight-path response characteristics deteriorate even though the airplane pitch-attitude response is speeded up. The shorter coupled the airplane (elevon-to-center-of-gravity), and the lower the $\omega_{n_{sp}}$ and n_{z_α}, the more severe this problem becomes.

One way to augment the flight-path response of airplanes with these characteristics is through the use of a forward pitch-control surface. A small canard, for example, could be employed as a pitch augmenter rather than using elevons. In this case, the canard lift is positive, and thus will provide a net increase, both in pitch-attitude response and flight-path response. Employment of the canard surface, however, does introduce

airplane stability and balance problems, and canard stall problems. The additive effects of canard deflection, airplane angle of attack, and body upwash combine to stall the canard rather easily. For example, during landing approach, an airplane α of 11 degrees, plus 2 or 3 degrees of body upwash, place the canard α at 13 or 14 degrees, leaving very little canard deflection available to pitch the airplane without stalling the canard. At higher airplane attitudes, the canard effectiveness may deteriorate completely unless some device such as bounary-layer control is employed on the canard surface. These problems may prevent cons|deration of the canard either as a primary flight control or as an augmentation surface.

The need to improve the flight-path dynamic-response characteristics of aircraft with these extremely long short periods (more than 17 sec) cannot be argued. It is doubtful whether any amount of pilot training or modification of control techniques will provide safe handling when an airplane becomes this sluggish. In some instances there may be nothing the designer can do to alter the basic aerodynamic and mass-distribution characteristics to improve the situation, and the development of a feasible augmentation system to speed up flight-path response may not be practical. The apparent conclusion is that the designer may find that the conflguration is unacceptable without control-response augmentation, and, at the same time, does not lend itself to the adoption of any workable augmentation scheme.

LONGITUDINAL CONTROL POWER

There are many requirements that the designer must satisfy when he configures the longitudinal control system of a new design. The control surface size, rates, and deflection capabilities must provide sufficient control power to meet the following demands:

1. Control to stall or maximum design C_L
2. Control for takeoff rotation capability, which in no way restricts takeoff performance
3. Adequate maneuver capabilities at all flight conditions with the operational envelope
4. Control to handle all airplane trim changes
5. Control for normal landing flare and abrupt flare maneuvers close to the ground

All of these requirements are obvious, perhaps, with the exception of the abrupt flare maneuver. This requirement stresses the importance of providing sufficient elevator control power to enable the pilot to reduce

the rate of descent quickly during the final phase of the landing maneuver. This capability is needed for rapid recovery from gust upsets or errors in pilot judgment that place the airplane in danger of contracting the runway at excessive nose-down attitudes or sinking rates. In earlier designs, the quick-flare capability came as a natural result of providing enough elevator control to stall the airplane at the most forward permissible center-of-gravity loading. However, this will not be the case for large supersonic configurations, which possess two to three times the pitch inertia of current jet transports. The extreme mass-distribution characteristics of supersonic aircraft demand powerful longitudinal control surfaces to develop any reasonable amount of airplane pitching acceleration at low speeds.

In the quick-flare maneuver, the pilot attempts, by pulsing the control at near-maximum rate, to pull the nose up as quickly as possible. It is important that the control be capable of developing substantial pitching acceleration, and that the airplane respond quickly in developing positive load factor to curve the flight path upward. Figure 7 compares the abrupt flare maneuver characteristics of a current jet transport with those of a

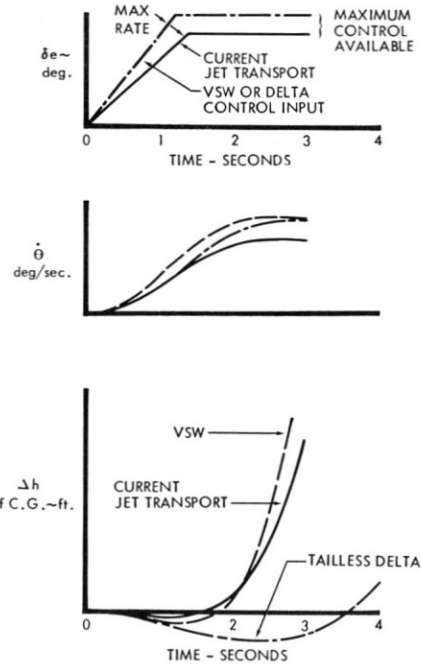

Figure 7. Comparison of airplane response during abrupt flare maneuver, current jet transport, VSW SST, and Delta SST.

VSW supersonic transport and a tailless-delta SST. The powerful control surfaces incorporated for both supersonic airplanes provide pitching accelerations slightly better than those of the subsonic transport for a ramp input of maximum available control deflection at maximum rate. However, this increased control-moment capability is not, in both cases, reflected in good airplane flight-path response. The response of the VSW airplane, with its conventional aft tail arrangement, is similar to that of the current jet transport, except for an increase in the initial dip in altitude following control initiation. Both the subsonic jet and the VSW configuration are capable of developing altitude gain in less than 2 sec following the initiation of control movement. The tailless-delta airplane, however, because of its inefficient tail arm (low ratio of M_δ/L_δ), is seen to experience a prolonged sinking effect following control application. Consequently, the attempt to perform an abrupt flare produces an altitude loss rather than a gain, with nearly 4 sec elapsing before the airplane starts to gain altitude.

Various investigators (such as Pinsker, Ref. 16) upon examining these slow response characteristics, have expressed concern over the ability to safely arrest sinking rates during a normal landing flare. It has been proposed that the solution to the problem lies in correct pilot anticipation of the sinking effect, and that with training and experience, good landings will be attainable fairly consistently for the normal, gradual flare maneuver. However, it is apparent that the quick flare will either not be possible for these short-coupled, high-inertia aircraft, or will be achieved only through adoption of some unique new control, or control techniques.

CONCLUSIONS

The analysis of aircraft flight-path dynamic-response characteristics must include not only short-period pitch dynamics (frequency and damping ratio) but also the L_α or n_{z_α} characteristics inherent in a given configuration. Flight-simulator and analytical studies have shown that good handling qualities depend upon careful matching of the short-period frequency with n_{z_α}. Aircraft with characteristically low n_{z_α} provide the best handling when $\omega_{n_{sp}}$ is relatively low in value. Before accurate guidelines to short-period dynamic handling qualities requirements can be established, much additional research must be accomplished in this area.

The attainment of good low-speed longitudinal handling qualities will prove difficult for some large supersonic aircraft configurations because of their size, aerodynamic configuration, and mass-distribution characteristics. The short-period dynamic or maneuver mode of longitudinal motion

will be characterized by unusually low frequencies and heavy damping, resulting in sluggish pitch response. Attempts to solve this problem with stability augmentation that speeds up the short-period frequency may in some cases deteriorate handling qualities for the following reasons:

1. The mismatch created between pitch-attitude response ($\omega_{n_{sp}}$) and flight-path response (n_{z_α}) presents confusing airplane response signals to the pilot, making flight-path adjustments extremely difficult.
2. The provision of high $\omega_{n_{sp}}$ relative to an inherently low L_α characteristic produces severe pitch-overshoot response to control inputs.
3. The negative L_δ characteristic of an aft control surface employed to augment pitch response produces a sinking effect that may result in delaying the flight-path response rather than speeding it (for short-coupled airplanes).

Some small amount of short-period frequency augmentation will be feasible and beneficial for configurations with substantial tail lengths. However, short-coupled aircraft (elevon-to-center-of-gravity) possessing higher pitch inertias may not be amenable to any workable forms of augmentation to speed flight-path-response characteristics. It seems essential, therefore, that longitudinal stability and control problems be weighed carefully in the early stages of design development, and that handling qualities considerations be permitted to influence the airplane configuration to a significant extent.

REFERENCES

1. Bray, Richard S., "Piloted Simulator Studies Pertaining to the Low-Speed Longitudinal Handling Qualities of a Supersonic Transport Airplane," AIAA Paper presented at AIAA National Meeting (Aug. 26–28, 1963).
2. Staff of Langley Airworthiness Branch, "Operational Experiences of Turbine-Powered Commercial Transport Airplanes," NASA TN D-1392 (1962).
3. Stickle, J. W., "An Investigation of Landing Contact Conditions for Several Turbo-Jet Transports during Routine Daylight Operations at New York International Airport," NASA TN D-1483 (1962).
4. Geoffrion, D. R., and V. M. Kibardin, "Statistical Presentation of Operational Landing Parameters for Transport Jet Airplanes," Federal Aviation Agency, Flight Standards Service, Release No. 470 (1962).
5. Cromwell, C. H., and I. L. Ashkenas, "A System Analysis of Longitudinal Piloted Control in Carrier Approach," Systems Technology, Inc. Report TR-124-1 (June 1962).
6. Ashkenas, I. L., and T. S. Durand, "Simulator and Analytical Studies of Fundamental Longitudinal Control Problems in Carrier Approach" AIAA Simulation for Aerospace Flight Conference (August 1963).

7. Military Specification, Flying Qualities of Piloted Aircraft, MIL-F-8785 (ASG) dated Sept. 1, 1954 with Amendment 4, dated Apr. 17, 1959.
8. Chalk, C. R., "Fixed-Base Simulator Investigation of the Effects of $L\alpha$ and True Speed on Pilot Opinion of Longitudinal Flying Qualities," ASD-TDR-63-399 (November 1963).
9. Ball, J. N., and E. G. Rynaski, "Longitudinal Flight Control for Military Aircraft—A Study of Requirements and Design Concepts," CAL Report No. ID-1757-F-1 (October 1963).
10. Notess, C. B., and P. Gregory, "Requirements for the Flight Control System of a Supersonic Transport," SAE Paper No. 679C, presented at SAE National Aeronautical Meeting, Washington, D. C. (April 1963).
11. Newell, F., and G. Campbell, "Flight Evaluation of Variable Short Period and Phugoid Characteristics in a B-26," Cornell Aero Lab, WADC Technical Report 54–594 (December 1954).
12. Chalk, C. R., "Additional Flight Evaluations of Various Longitudinal Handling Qualities in a Variable-Stability Jet Fighter," WADC TR 57-719, Part (CAL Report No. TB-1141-F-2).
13. Kidd, E. A., and G. Bull, "Handling Qualities Requirements as Influenced by Pilot Evaluation Time and Sample Size," CAL Report No. TB-1444-F-1 (February 1963).
14. Bull, G., "Minimum Flyable Longitudinal Handling Qualities of Airplanes," CAL Report No. TB-1313-F-1 (December 1959).
15. Kidd, E. A., and R. P. Harper, Jr., "Fixed Base and In-Flight Simulations of Longitudinal and Lateral-Directional Handling Qualities for Piloted Re-entry Vehicles," ASD-TDR-61-362 (CAL Report No. TB-757-F-12, July 1955).
16. Pinsker, W. J. G., "Features of Large Transport Aircraft Affecting Control during Approach and Landing," AGARD (January 1963).

SYMBOLS

I_{xx}, I_{yy}, I_{zz}	moments of inertia about the airplane x, y, and z axes respectively
W	airplane gross weight
m	airplane mass
S	wing area
W/S	wing loading, weight/wing area
$\bar{c}$	wing mean aerodynamic chord
c.g.	airplane center of gravity
V	true airspeed
V_e	equivalent airspeed $= V\sqrt{\sigma}$
h	altitude
s	Laplace operator
q	dynamic pressure $= \frac{1}{2}\rho V^2$
n_z	normal acceleration (g units)
PR	pilot rating

t	time
g	acceleration due to gravity (32.2 ft/sec^2)
C_L	lift coefficient, lift/qS
C_m	pitching moment coefficient, moment/$qS\bar{c}$
C_{L_α}	Lift curve slope, $\partial C_L/\partial\alpha$
C_{m_α}	Static longitudinal stability derivative, $\partial C_m/\partial\alpha$
$C_{m_{\dot{\alpha}}}$	pitching moment coefficient due to angle of attack rate, $\partial C_m/\partial(\dot{\alpha}\bar{c}/2V)$
$C_{L_{\delta_e}}$	lift coefficient due to elevator (or elevon) surface deflection
$C_{m_{\delta_e}}$	pitch-control power derivative, $\partial C_m/\partial_{\delta_e}$
M_{δ_e}	pitching moment due to elevator (or elevon)
L_{δ_e}	lift due to elevator (or elevon)
L_α	lift curve slope per unit momentum $L_\alpha = C_{L_\alpha}(\rho SV/2m) = C_{L_\alpha}(qs/mV)$
n_{z_α}	change in load factor per degree angle of attack, $n_{z_\alpha} = C_{L_{\alpha q}}/(W/S) = L_\alpha(V/g)$
$W_{n_{sp}}$	longitudinal short-period undamped natural frequency
ζ_{sp}	longitudinal short-period damping ratio
α	angle of attack
$\dot{\alpha}$	angle of attack rate, $\partial\alpha/\partial t$
γ	flight-path angle
$\dot{\gamma}$	flight-path rate, $\partial\gamma/\partial t$
θ	pitch attitude
$\dot{\theta}$	pitching velocity
$\dot{\theta}_{ss}$	steady-state pitching velocity
$\dot{\theta}_{max}$	maximum pitching velocity
θ	pitch acceleration
δ	surface deflection
δ_e	elevator or elevon deflection
ρ	air density
σ	relative air density, with respect to sea-level standard density
Λ_{LE}	wing leading-edge sweep angle