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Effect of Variable Sweep on Supersonic Transport Handling Qualities

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The supersonic transport (SST) requirements challenge the ability of the designer to assemble an economic airplane that will be safe and pleasant to fly. Extreme values of Mach number, true airspeed, and dynamic pressure aggravate some of the classical causes of poor handling qualities such as large flexible structures and low aerodynamic damping. Variable sweep compensates in many ways for the difficult environment and provides new solutions to stability and control problems; the landing configuration (wings forward) approximates that of a moderately swept "conventional" airplane. High span in the low-speed configuration is compatible with good roll control. Low roll inertia in the high-speed configuration allows high roll acceleration. At high speeds, the low $C_{L\alpha}$ of the flexible arrow wing compensates for high dynamic pressure thereby reducing pitch sensitivity. The landing configuration has a stable thrust-speed relationship. Motions of the aerodynamic center caused by wing sweep, Mach number, and aeroelastic distortion can be played against each other to minimize trim drag and to maintain good maneuverability throughout the flight envelope.

Introduction

FIGURE 1 shows that the cruise speed of the SST will be dramatically higher than today's subsonic transport, although the new airplane must be operated from the same runways that are in use today. It follows that the ratio of maximum to minimum speed in the SST must be much greater than previously experienced. The large speed ratio, the large dynamic pressure ratio, and the wide range of operating Mach numbers are the source of major problems confronting the SST designer. Much has been said about the contribution of the variable sweep wing to the solution of the performance problems of the SST; however, in this paper, emphasis will be placed on the effect of the variable sweep wing on the stability and control of the SST. It will be shown that good design, using the variable sweep concept, can produce an airplane quite similar in important characteristics to current large subsonic transports. Several examples will be given in which the requirement for stability augmentation is avoided by the use of variable sweep.

Figure 2 shows the planforms of the variable sweep SST with a subsonic transport superimposed. The SST is somewhat larger, but its landing configuration wing aspect ratio is similar to the smaller airplane. The tail of the SST is proportionately larger, and the high-speed configuration of the wing is radically different.

Figure 3 compares the planforms of the variable sweep wing SST with a representative delta wing SST. The latter has a larger wing and lighter wing loading than the variable sweep airplane. The wings-forward span of the variable sweep airplane is greater than the span of the delta, whereas the high-speed, wings-back span of the variable sweep airplane is less than the span of the delta.

Low-Speed Roll Control

Good lateral control is essential for accurate instrument approaches. Three primary characteristics govern the quality of response to roll commands: 1) roll acceleration, 2) roll time constant, and 3) roll-yaw coupling.

If any of the three primary characteristics are weak, right

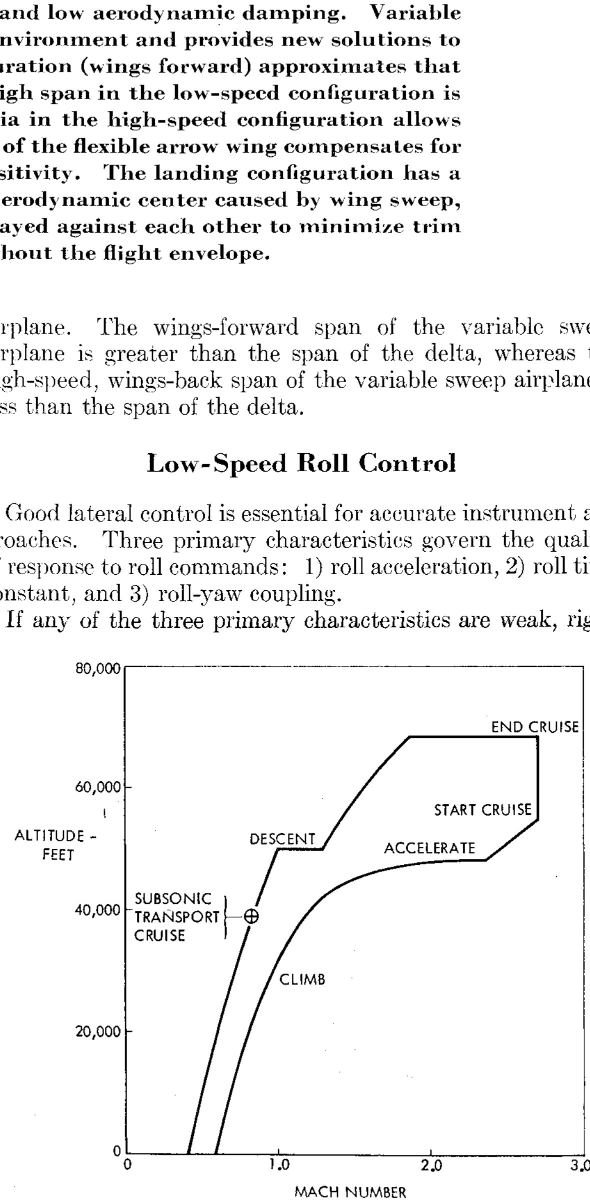

Fig. 1 Variable sweep SST flight profile.

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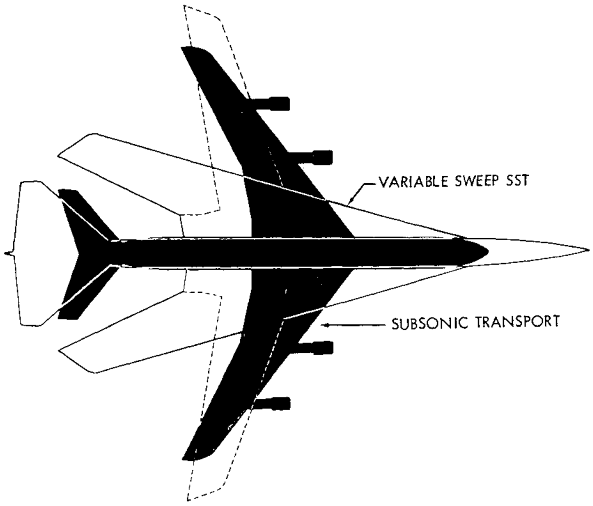

Fig. 2 Planform comparison.

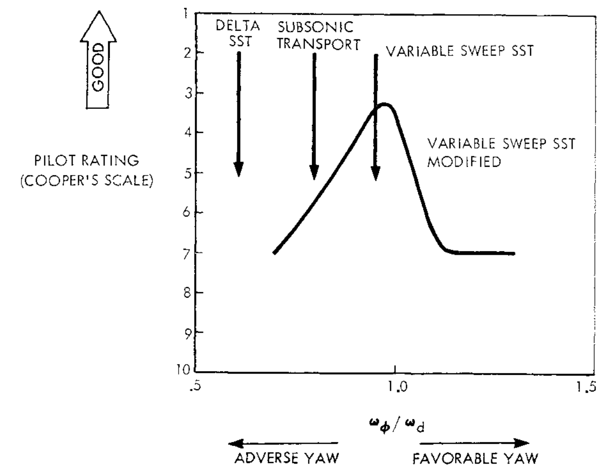

Fig. 4 Roll-yaw coupling, landing approach.

and left steering will be indefinite and the pilot's task will be increased in difficulty, especially during the critical landing approach. Wing span has a first order effect on each of the three characteristics. Table 1 compares the landing approach lateral control characteristics of the variable sweep SST, a typical subsonic transport, and a delta SST.

The initial roll acceleration of the variable sweep SST is very high because of the powerful lateral control system and the low roll inertia of this configuration. Lateral control is provided by ailerons and essentially full-span spoilers, and roll inertia is low because the engines are located inboard. The subsonic transport has outboard engines and a high roll inertia resulting in fairly low roll acceleration. The delta SST uses ailerons of less span than the variable sweep SST spoilers. Therefore the roll acceleration is less than that of the variable sweep SST, although the delta roll inertia is smaller.

The roll time constant shown in Table 1 is the time in seconds required to get to 63% of steady-state roll rate following a step control input. Large roll time constants result from low damping in roll and high roll inertia and are undesirable. A maximum limit on the roll time constant has been proposed between 1.0 to 1.5 sec by Creer, Stewart, Merrick, and Drinkwater.[1] The large span and low roll inertia of the variable sweep SST produces the desirable low time constant shown in the table. The relatively high roll inertia of the subsonic jet has an adverse effect on roll time constant, and the low damping associated with the short span of the delta SST produces the same end result. It is obvious that low-speed roll damping augmentation will not be required on the variable sweep SST.

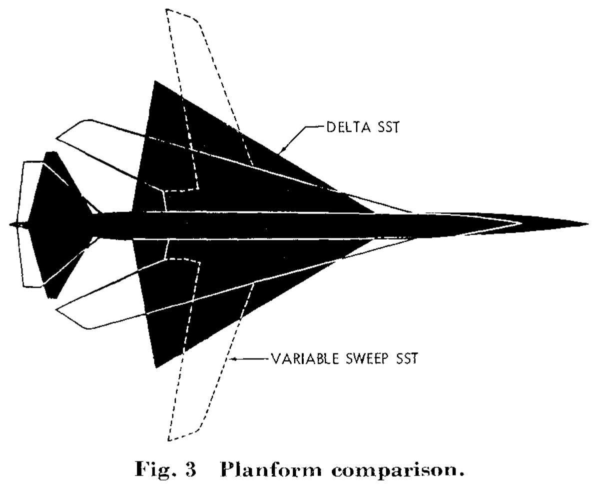

Fig. 3 Planform comparison.

Adverse yaw induces rolling and yawing oscillations during a turning maneuver. Several aerodynamic and inertial characteristics affect the quality of the complex Dutch roll motion that results; e.g., directional stability, yawing moment due to spoiler and aileron deflection, roll and yaw inertia, dihedral, yaw damping, and yawing moment due to roll rate.

The ratio ω_ϕ/ω_d was proposed as a measure of the ability of an airplane to produce pure roll without yaw coupling by Ashkenas and McRuer[2] (see also Refs. 3 and 8). A value of ω_ϕ/ω_d less than unity is associated with adverse yaw, and a value greater than unity indicates favorable yaw. Uncoupled motion and good handling qualities are expected when the value is near 1.0.

The results of a flight simulator test of the variable sweep SST with the control characteristics altered to give a variation of ω_ϕ/ω_d are shown in Fig. 4. The pilot rating was best when the value was near unity and fell off quite steeply on each side. Values of ω_ϕ/ω_d for the example subsonic transport and example delta SST are shown in Fig. 4 and also in Table 1. It is not correct to use the value of pilot rating measured on the variable sweep configuration for the other two airplanes, because Dutch roll damping and roll-yaw ratio, characteristics not included in ω_ϕ/ω_d, have a large effect on pilot rating. However, the data show in broad terms a tendency toward superior low-speed turn performance for airplanes having large span and low roll inertia as is the case with the variable sweep SST.

The low-speed configuration of the variable sweep SST also has a high level of Dutch roll damping and a low roll-to-yaw ratio. As a matter of interest, the configuration studied will not require the use of a yaw damper on the landing approach.

High-Speed Roll Control

The two principal features of the cruise Mach number turning maneuver of the SST are poor roll damping and slow turn rates. Both of these characteristics are caused by very high

Table 1 Lateral control characteristics landing approach unaugmented

	Variable sweep (SST)	Subsonic transport	Delta (SST)
Initial roll acceleration, deg/sec^2	76.7	11.8	28.8
Roll time constant, sec	0.38	1.40	1.39
Roll-yaw coupling parameter, $\omega\phi/\omega d$	0.95	0.80	0.61

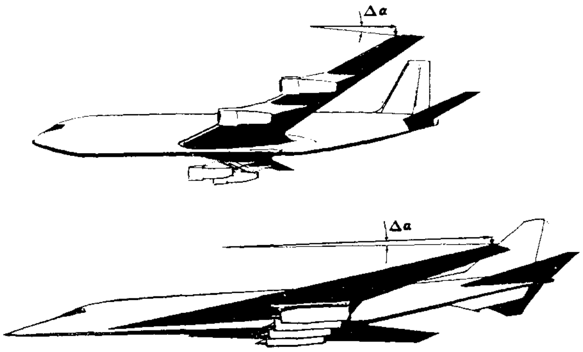

Fig. 5 **Roll-damping, cruise-steady roll.**

true air-speed. Configuration effects are small and all designs would be expected to have inherently high roll rates and low yaw coupling. The short span of the variable sweep airplane does result in considerably lower damping than the more lightly loaded, higher span delta. However, both configurations will probably require artificial roll damping in order to attain roll time constants in the range of 1.0 sec.

Figure 5 illustrates the effect of very high true airspeed on roll damping. When the lateral control of an airplane is deflected, the airplane will accelerate in roll until the damping moment equals the control moment. The damping moment is proportional to the change in angle of attack caused by the rolling velocity. The figure compares the wing tip $\Delta\alpha$ of a subsonic transport and an SST when both are at the same roll rate. The vertical velocity at the wing tip resulting from roll rate is large for the subsonic transport because of its large span. The true speed of the SST is extremely large. These two factors define $\Delta\alpha$ and combine to produce low roll damping for the SST.

Turning rate is indicated in Fig. 6, which compares the time to turn through a 10° heading change in a 30° bank for the three comparison airplanes. At the relatively low speed of the subsonic jet, a navigational correction of 10° could be made in about 7 sec. At SST speeds this modest heading change will occupy the attention of the crew for some 25 sec. With this rate of turn there is little reason to use the roll rates of 60° or more per second, which are potentially available. The large rolling moments available from the lateral control system can be used with better effect to augment the naturally low roll damping.

Figure 7 shows the characteristics of the variable sweep SST with the roll damper on and off. It can be seen that the improvement in time constant is accompanied by a reduction of maximum steady-state roll rate, but the bank angle in the first second after control deflection is essentially unaltered.

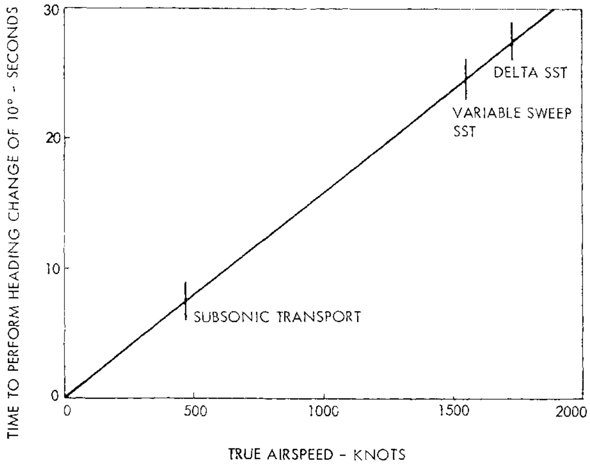

Fig. 6 **Turn performance, cruise 30° bank angle.**

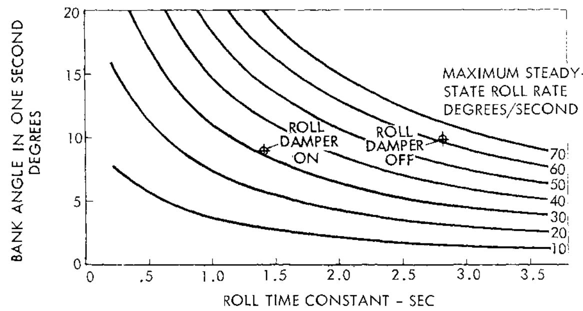

Fig. 7 **Roll performance, variable sweep SST cruise.**

Landing Approach Speed Stability

Flight on the "backside" of the drag curve (drag increasing with decreasing speed) is more difficult than flight on the "frontside" for conditions where the pilot is accurately controlling the flight path as during an instrument landing system (ILS) approach. Any difficulty is avoided by the use of autothrottle, but the unaugmented characteristics should be understood because of the possibility of autothrottle malfunction. Aircraft with large span tend to approach on the "frontside" or speed stable portion of the drag curve, whereas airplanes with small span and large induced drag tend to operate on the "backside" or speed unstable branch.

Figure 8 shows the landing approach drag of the three comparison airplanes. The delta SST has a minimum drag occurring at high speed and approaches in the speed unstable regime. The variable sweep SST and the subsonic transport have low values of induced drag, and their minimum drags are at a speed slower than their approach speeds.

Figure 9 presents speed stability criteria. The parameter used is the reciprocal of the time to halve or double the amplitude of an airspeed disturbance during a flight-path controlled maneuver. The parameter is a minor variation of the one used by Spence and Lean.[5] According to Ref. 5, the maximum tolerable instability is $1/T_2 = 0.073$ sec^{-1} and should be reserved for cases where slow flight is very advantageous, such as during a carrier approach. The minimum level of stability for instrument approaches was set at $1/T_{1/2} = 0.024$ sec^{-1}. Attention is drawn to the strong effect of turbulence on the interaction of speed stability and handling qualities.

The effect of speed stability on pilot rating of control characteristics has purposely been omitted from Fig. 9. Results shown in Refs. 4 and 6 indicate the wide disagreement existing in the literature between flight simulator results and flight test results. Factors other than the change of drag with speed also affect the pilot's judgment of handling qualities. Engine response and pitch damping are examples of characteristics interacting with speed stability.

Regardless of the SST configuration, autothrottles will probably be used on the airplane for operation with automatic landing systems. As noted previously, speed stability

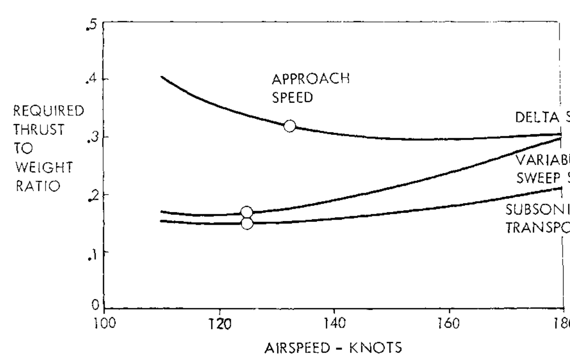

Fig. 8 **Speed stability, landing approach.**

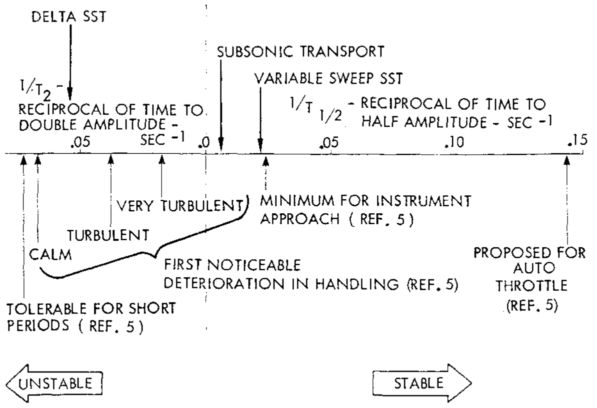

Fig. 9 Speed stability, landing approach.

is insured by the use of an autothrottle; however, the speed stability of the unaugmented airplane is important in the determination of the change in pilot work load accompanying an autothrottle failure. It is reasonable to assume that the autothrottle, if installed, will be used for routine landings. Therefore, a failure of the autothrottle will confront the pilot with a relatively unfamiliar control situation. It follows that speed stability would be desirable in this unusual event even though it is recognized that several successful types of current airplanes make routine landing approaches on the "backside" of the drag curve. The landing approach speed stability of the three transports is shown in Fig. 9. The subsonic transport is successfully flying today without benefit of an autothrottle. This fact indicates that the Ref. 5 instrument approach criterion is somewhat conservative. Since the variable sweep SST is more stable than the subsonic transport, pilot work load should not be adversely affected by autothrottle failure. The delta SST, on the other hand, is strongly unstable and will undoubtedly rely on an autothrottle to reduce the pilot's work load during landing approach and to allow use of an automatic landing system.

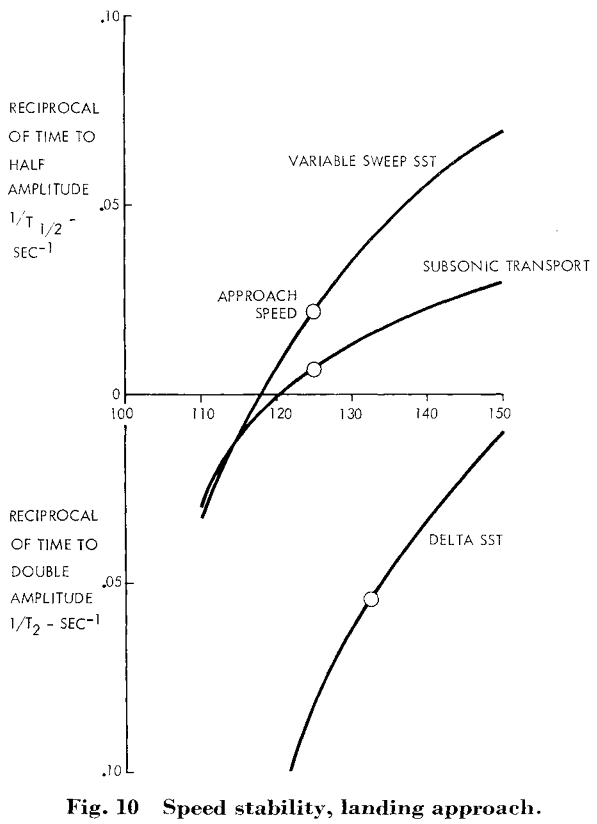

Fig. 10 Speed stability, landing approach.

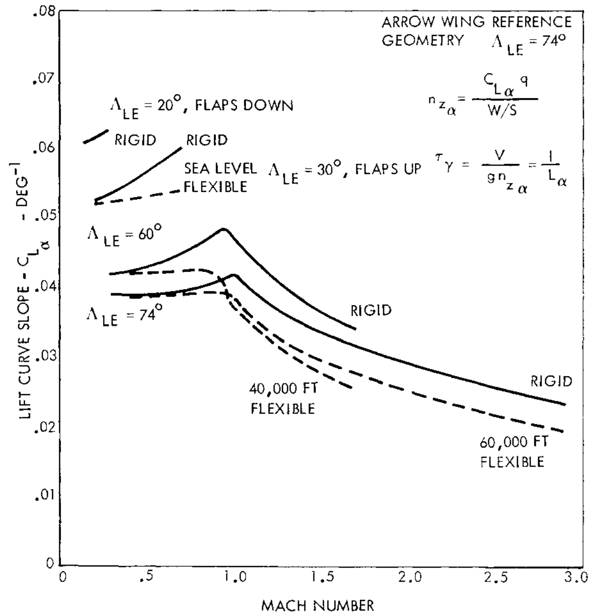

Fig. 11 Lift curve slope.

The variation of speed stability with airspeed is shown in Fig. 10 for three comparison airplanes. The speed stability of each of the three airplanes deteriorates with decreasing speed. The variable sweep airplane and the subsonic transport, flying in their useful speed range (down to 1.1 V_S), never become as unstable as the delta at approach speed.

Longitudinal Response

The rate of change of vertical acceleration with angle of attack n_{z_α} is a useful parameter for examining the characteristics of longitudinal control. The two equations in Fig. 11 illustrate the physical significance of the lift response parameter n_{z_α}. In the first, lift response is seen to vary with lift curve slope, dynamic pressure, and wing loading. In the second, flight-path time constant τ_γ (the time lag of flight path behind attitude change) is proportional to the ratio of true speed to n_{z_α}. If C_{L_α} were constant, as would be the case with a rigid airplane of fixed geometry flying in an incompressible medium,

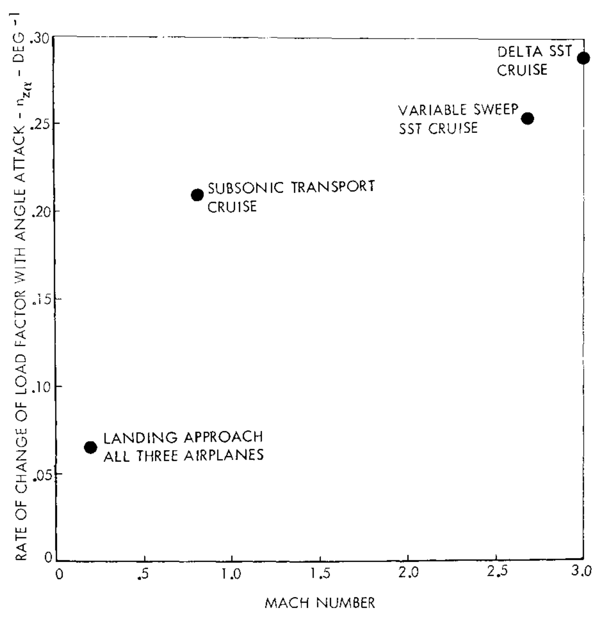

Fig. 12 Load factor sensitivity.

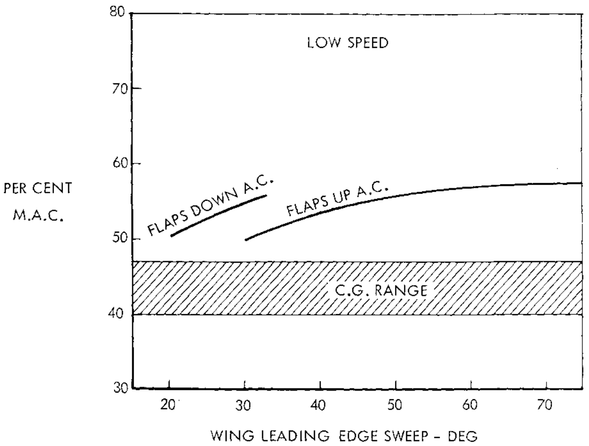

Fig. 13 Static stability variable sweep SST.

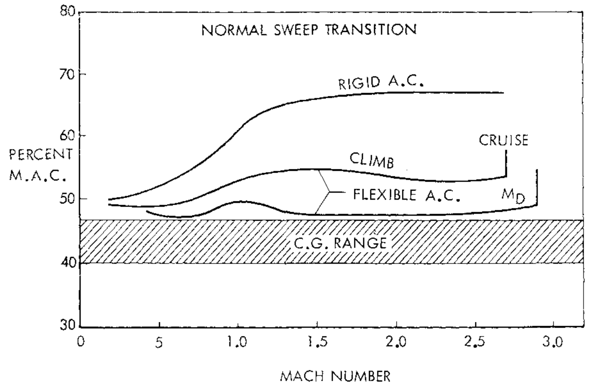

Fig. 14 Static stability variable sweep SST.

n_{z_α} would go up with q, and time constant would be proportional to the reciprocal of velocity; low-speed flight would be sluggish with a large angle-of-attack change required to produce a small vertical acceleration occurring long after the control input; at high speed, the opposite effects would create extremely sensitive response. The undesirability of extreme values of n_{z_α} has been shown in the Cornell Aeronautical Laboratory handling quality research reported in Ref. 7.

Figure 11 shows that C_{L_α} is not constant. It changes with Mach number for aerodynamic reasons and it decreases with dynamic pressure because of structural flexibility. C_{L_α} also changes as geometry is altered. The retraction of flaps having Fowler action has a large effect, and variation of wing sweep causes a similar reduction of C_{L_α}.

The relative values of n_{z_α} for the variable sweep SST, the subsonic transport, and the delta SST are shown in Fig. 12. The SST's have only a slightly greater variation of n_{z_α} than the subsonic transport in spite of their much greater dynamic pressure range, because of the compensating effects of Mach number, flexibility, and variable wing sweep in the case of the variable sweep SST, and because of Mach number and very high altitude in the case of the more rigid delta. Without the use of variable sweep, an SST with a high wing loading would not only have an undesirably large variation of flight-path time constant but might well require a change of stick-to-elevator gearing to avoid extreme pitch control sensitivity at high speed.

Variable Sweep Longitudinal Static Stability

It might be assumed that a variable sweep airplane would become undesirably stable as the wing sweeps aft, especially during transonic acceleration. In fact, the stability can be maintained approximately constant at a desirably low level by careful design using the variable sweep principle.

Figure 13 shows the variation of the aerodynamic center accompanying flap retraction and wing sweep, all done at low speed, where compressibility effects are absent and flexibility effects are minimum. It is seen that the aerodynamic center shift due to wing sweep is slightly more than that resulting from flap retraction.

Figure 14 shows the variation of the aerodynamic center throughout the Mach number range for a hypothetical rigid airplane and a flexible airplane. On this chart, the wing is assumed to move through its normal sweep angle schedule as the airplane maneuvers throughout the flight envelope. The rigid curve shows the large increase of stability accompanying acceleration through Mach 1.0. If the airplane were rigid, the maneuverability would be severely reduced in supersonic flight. As it is, the large structural aspect ratio wing is very flexible. The forward movement of the wing aerodynamic center due to flexibility compensates for the combined aft shift due to wing sweep and Mach number in supersonic flight. This effect of wing flexure allows the selection of an essentially constant center of gravity range (shown as the shaded band in Figs. 13 and 14), with both sweep angle and Mach number. The variable sweep SST has an essentially constant minimum static margin throughout the flight envelope, without any requirement for fuel pumping or restrictive wing sweep schedule.

Conclusions

The use of the variable sweep wing in the design of an SST can result in a configuration having excellent unaugmented handling qualities. The landing approach configurations will require neither a roll damper, a yaw damper, nor an autothrottle. Although the physical environment of high-speed flight imposes a requirement for artificial damping, control response will be rapid and precise. A single value of elevator gearing can be used throughout the flight envelope, and an optimum level of static margin can be maintained without fuel transfer.

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