Low-Speed Aerodynamic Characteristics of the Double-Delta Supersonic Transport

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Extensive tests of the double-delta supersonic transport (SST) show that unique low-speed aerodynamic characteristics are inherent using this concept, and the double-delta transport will offer low-speed handling qualities and safety of operation that will surpass the levels of current jet transports. Flow visualization studies show coiled vortex sheets that increase in strength with increasing angle of attack and provide steady unseparated flow well beyond the range of practical flight attitudes. The double-delta wing does not experience lift stall, pitch-up, or increase in drag due to stall. Lateral control power is retained and directional stability increases with increase in attitude. These favorable aerodynamic characteristics lead to a simple, conventional control system and an airplane that is simple to operate, displaying excellent stability, control, and safety margin characteristics. Abused takeoff procedures are less critical than for current jets because of greater lift and rate of climb margins. Lateral control power provides favorable aileron response during approach and landing. Ground effect simplifies the flare maneuver prior to touchdown. Directional and lateral control characteristics combine to provide excellent cross-wind landing characteristics. Achievement of these characteristics using a simple fixed geometry wing is one of the attractive features of the double-delta SST.

Introduction

THE development of the supersonic commercial transport must focus serious recognition not only on the problems of high-speed operation during acceleration and cruise, but also on low-speed operation during takeoff, hold, approach, and landing. The extremes in speed and altitude introduced when considering all these flight regimes impose many varied requirements calling for design and aerodynamic ingenuity to provide a practical and economic aircraft. The successful supersonic transport will be the design that offers the simplest solution and least compromise. Studies to date indicate that the most promising configuration incorporates a light wing loading, fixed geometry, double-delta wing of tailless design (Fig. 1). A more complete discussion of the design philosophy and airplane development is given in Ref. 1.

This airplane employs a fixed geometry wing area of over 8000 ft^2, with conventional ailerons and elevators mounted along the trailing edge. Wing span is 116 ft, which is similar to the spans of the current jet transports. However, unlike the current jet aircraft, no spoilers, trailing edge high lift flaps, leading edge devices, or adjustable stabilizers are required. The design purposely emphasizes simplicity of design, operation, and maintenance, to insure achievement of maximum safety with best economics.

Two considerations relating to the low-speed characteristics of this double-delta transport proved to be key factors that led to the adoption of this approach for the SST. One of these factors was related to a serious examination of low-speed vortex flow. Studies and wind-tunnel tests showed that by proper airplane configuration selection, uniform vortex flow could be exploited to provide improved low-speed aerodynamic characteristics. The second factor was the decision to utilize a large wing-low lift coefficient philosophy, so that resulting airplane attitudes, drag levels, and lift margins at low speed would offer low-speed handling qualities that were better than those for current jet aircraft.

Vortex Flow Characteristics

At one time or another we have all seen the vortex shed from the wing tip of a conventional high aspect ratio wing; its presence is often made known by visible vapor trails in the sky. The cause of the vortex on the wing tip can be simply explained as a flow of positive pressure air from beneath the wing around the tip to the negative pressure region on the upper surface. On a delta planform wing, the swept leading edge can be thought of as the wing tip, and the same flow from positive to negative pressure exists. Since the leading edge of the delta wing extends over a far greater length than a conventional wing tip, the strength of the wing vortex is magnified.

The occurrence of these vortices on any lifting body or finite surface is unavoidable. Even the lift on a fuselage forebody produces a series of small vortices. Lockheed wind-tunnel tests of canard-delta SST models indicated that these forebody vortices, in combination with those generated by a canard and wing, can produce unfavorable and nonuniform flow characteristics. During these wind-tunnel evaluations, which included many different shapes of delta wings, canards, forebody strakes, and fuselage shapes, flow visualization tech-

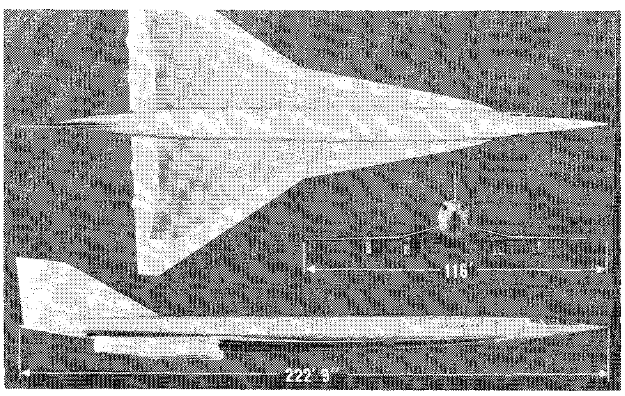

Fig. 1 General arrangement.

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*TAKE-OFF GROSS WT (LBS)	325,000	450,000
*WING AREA (SQ FT)	2,760	8,370
*T.O. WING LOADING (PSF)	118	54
*T.O. SPEED (KTS)	165	168
*LDG. WING LOADING (PSF)	87	32
*APPROACH SPEED (KTS)	144	138

Fig. 2 Minimum operating speeds.

niques were employed to obtain an understanding of these flow characteristics. From these studies came the disclosure that a design employing a tailless double-delta wing properly positioned on the forebody could produce a uniform vortex flow field, with the body and forward delta wing vortices smoothly blending and merging with the aft delta vortex. Smoke studies revealed that the core of vorticity remained along the leading edge of the wing and was displaced laterally away from the vertical tail. The uniformity of the flow field remained intact for airplane attitudes beyond 30° and to sideslip angles of over 20°.

Observation of the boundary-layer behavior on the wing under the influence of this vortex flow revealed that a powerful spanwise pumping action prevented boundary-layer thickening and permitted achievement of high lift values without flow separation, wing stall, or creation of stall drag. The pumping action was first suspected when these beneficial aerodynamic effects were noted in the wind-tunnel test results. A verification of the vortex flow behavior was obtained by using a simple boundary-layer visualization technique. A mixture of oil and kerosene, mixed with a coloring dye, was coated on the model. The movement of the boundary layer caused by the vortex influence caused the oil film to form streaks and reveal the boundary-layer behavior. These tests clearly indicated that unstalled flow could be maintained to high angles of attack and yaw angles. The reasons for realizing high control effectiveness at these extreme angles became apparent; the trailing edge control surfaces were operating in a region of the wing where the boundary layer was not allowed to thicken.

Wing Design Philosophy

The second key design consideration of the double-delta planform is related to the fact that this wing provides a low aspect ratio planform shape that is ideal for high-speed flight and provides good structural efficiency. The low unit weight of this type of wing allows the incorporation of a large area. This large wing provides not only a high cruise lift drag ratio and reduced sonic boom characteristics, but because of its area will provide low takeoff, approach and landing speeds, and attitudes without reliance on mechanical high lift devices (Fig. 2). With a wing loading of 54 psf for takeoff and 32 psf for landing, speeds of 168 and 135 knots, respectively, are achieved using operating lift coefficients of approximately 0.60. Needed lift is achieved by using a large wing area in combination with moderate lift coefficients, not by using moderate wing areas and high lift coefficients as has been the practice with the current jets. This large wing area approach proves to have significant advantages in both low- and high-speed operation and provides a simple, straightforward solution to many of the diverse requirements of the SST. It also eliminates the need for leading and trailing edge high lift devices and lift-destroying spoilers, as employed by the current jets.

Wind-Tunnel Pitch Characteristics

Wind-tunnel tests of the double-delta wing show that no loss of lift occurs up to angles of attack of 30°; no wing stall

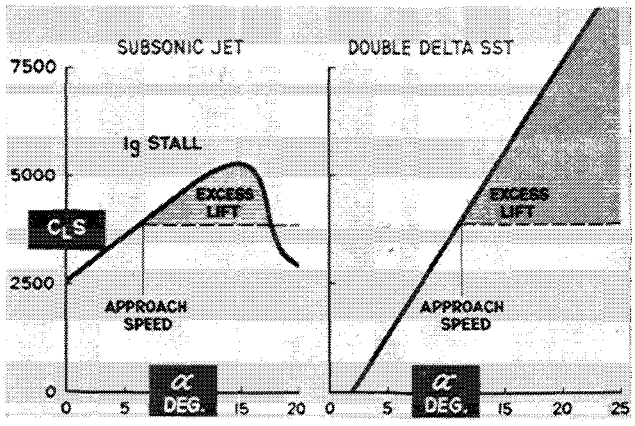

Fig. 3 Lift margins.

occurs because of vortex action. A comparison of these wind-tunnel data with the current jet transports, plotted as $C_L S$ to more properly indicate lift rather than lift coefficient, shows the large lift margins gained by the double-delta concept. The large wing - low lift coefficient philosophy and the unstalled flow, due to vortex boundary-layer control, provide substantially greater lift margins than for the subsonic jets, as indicated by the shaded areas (Fig. 3). This shaded area is a lift margin that improves maneuvering and gust penetration.

To operate safely in this excess lift margin area, handling characteristics must remain satisfactory (Fig. 4). Wind-tunnel tests indicate that pitch characteristics are favorable up to angles of attack beyond 30° and do not exhibit any erratic changes whatsoever. Note in this figure that elevator control power retains its effectiveness throughout the angle-of-attack range. Vortex flow provides for 100% control power, even when gust encounters or emergency maneuvers place the SST in this lift margin region. An obvious question with regard to elevator effectiveness of a tailless configuration is whether sufficient control is available for maneuvering. A direct measure of the pitching moment control power is given by the expression

$$M_{\delta_e}/I = [(C_{m\delta_e}/I) \quad S\bar{c}]q \qquad \text{(per degree of elevator)}$$

Values of this parameter for the double-delta SST are slightly greater than those achieved with current jet transports at approach speeds of 138 knots, for example (Fig. 5). The value of $C_{m\delta_e}$, which is multiplied by q, S, and $\bar{c}$ to obtain actual foot-pounds of moment per degree of elevator angle, compensates for the increase in pitch inertia of the heavier SST, and provides more than adequate pitch control power. Instantaneous pitch accelerations of 13°/sec² are attainable even at takeoff weight. This means that small rapid attitude changes are available to the pilot in the low-speed regime.

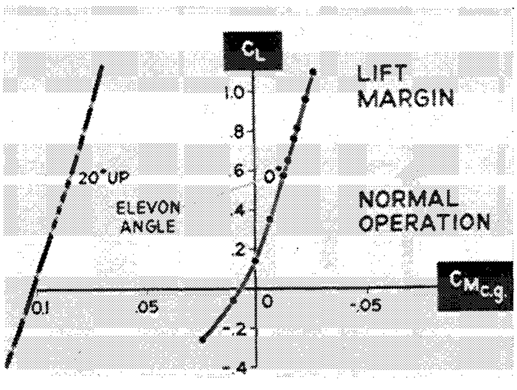

Fig. 4 Longitudinal characteristics.

		CURRENT JETS	DOUBLE DELTA SST
$C_{M_{\delta e}}$	PER DEGREE	-.0125	-.0044
$S\bar{c}$	FT^3	65,000	521,000
PITCH INERTIA	$SLUG\text{-}FT^2$	6.7×10^6	17.4×10^6
$M_{\delta e}/I$		.0078	.0085
PITCH ACCEL.	DEG. PER SEC^2	12	13

Fig. 5 Longitudinal control power; $M\delta_e/I = [(C_{M\delta_e}S\bar{c})/I] \times q$.

The uniform vortex flow field produced by the double-delta planform shape and combined with the large wing, low lift coefficient design philosophy, eliminates another low-speed handling quality problem, operation near or at attitudes where stall drag is encountered. This can be seen by comparing the drag polars of a current jet and the SST airplane (Fig. 6). The shaded areas indicate the region where operation at speeds below approach speed still provide thrust greater than drag for the landing configuration, gear down. For the current jet example, the shaded area is smaller because of stall drag and lower available thrust. The double-delta SST can operate at a lift coefficient twice that required during normal approach, and still maintain a positive rate of climb. Zero rate of climb speed for the SST is 55 knots below normal approach speed at normal landing weights with three engines operative.

Wind-Tunnel Lateral Control Characteristics

Wind-tunnel tests to measure the effectiveness of trailing edge control surfaces on the double-delta transport revealed that full-span ailerons, cut out to allow for engine nacelles, gave unfavorable lateral control characteristics. Because of adverse sidewash effects produced on the vertical tail by the inboard flap segment, large proverse yawing moments were produced. However, by utilizing only the midspan and outer control surfaces for lateral control, aileron-induced yawing moments were appreciably reduced, and for the normal low-speed operating region, no problem due to yawing moments caused by aileron deflection are experienced.

Attainable roll performance using this outboard aileron arrangement is equal to or better than achieved with current jet aircraft. To make such a comparison, the criterion is roll power, not rolling moment coefficient, since both wing area and span influence the foot-pounds of rolling moment (Fig. 7). During approach at 138 knots, the roll power of the double-delta SST is 37% greater than for the current jet shown.

Inspection of roll power vs angle of attack reveals that the urrent jets experience a serious loss at attitude approaching all. For the double-delta wing, vortex flow provides lateral

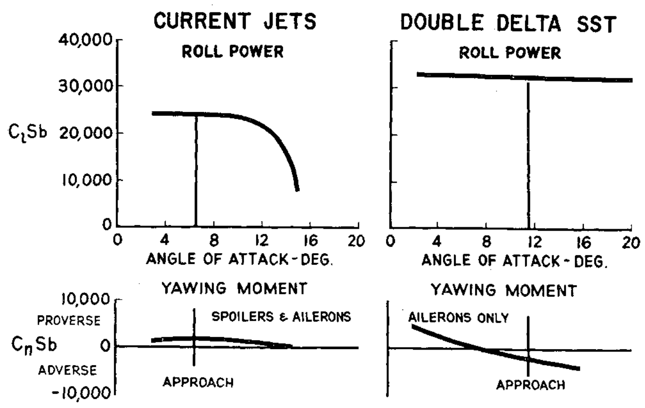

Fig. 7 Lateral control.

control effectiveness to attitudes twice that to be experienced in normal operation. Even at speeds 20 knots below normal approach speed, roll rates of 20°/sec can be realized.

Wind-Tunnel Lateral-Directional Characteristics

Wind-tunnel data related to lateral-directional characteristics of the double-delta wing are compared with the current jets in Fig. 8. An increase in directional stability occurs for the double-delta airplane as attitude increases. The uniform vortex flow field provides this desirable characteristic. For the current jet aircraft, directional stability degenerates as stall is approached.

Dihedral effect, or rolling moment coefficient due to yaw angle, is small for the double-delta wing as compared to the subsonic jets. There are two reasons for this. The subsonic jets employ geometric wing dihedral to remedy nacelle pod ground clearance problems. The double-delta SST, with nacelles snugged against the wing lower surface, requires no geometric dihedral. High aerodynamic dihedral with the swept double-delta planform is avoided by employing low lift coefficients for all normal operations. The double-delta planform has a higher C_{n_β}–C_{l_β} ratio than for the subsonic jet. This means that dynamic characteristics, such as dutch roll, will be improved over the current jet aircraft.

Operational Characteristics

The early portions of this paper have described the double-delta transport in terms of design philosophy and wind-tunnel analysis. In the following section, these engineering facts will be expressed in conventional operational terms and compared with the characteristics of current subsonic jet transports. From these comparisons it will be clear that the double-delta SST has a level of flight safety at least equal to,

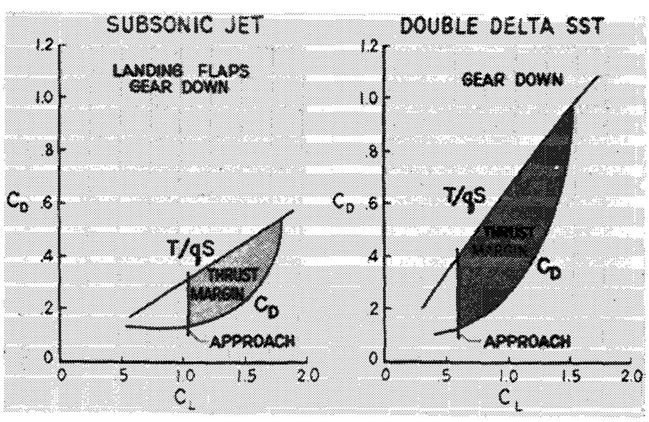

Fig. 6 Landing drag polar.

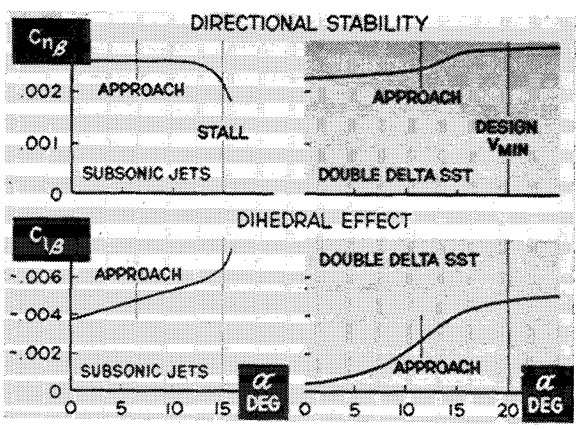

Fig. 8 Lateral-directional characteristics.

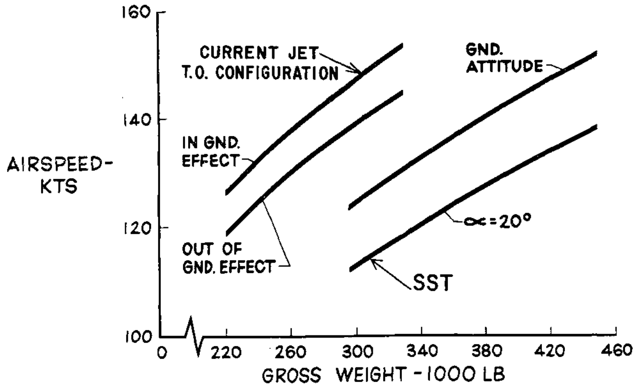

Fig. 9 Stall and minimum speed summary.

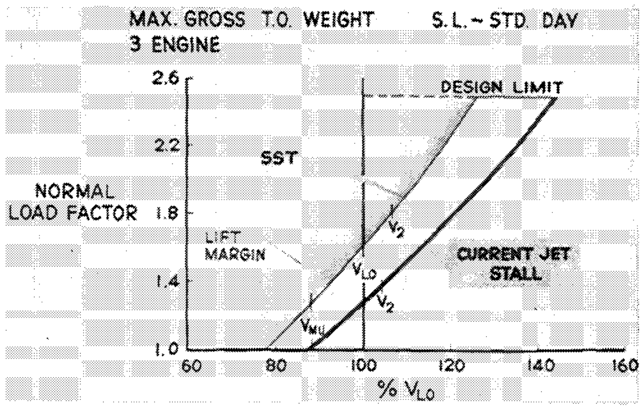

Fig. 11 Takeoff maneuver capability.

and in many cases superior to, current operational transport aircraft. Much of the inherent safety of the SST is the direct result of its simplicity of operation and design. Wing trailing edge and leading edge flaps, slots, spoilers, and trimmable stabilizers have all been deleted from the double-delta configuration. Coupled with this design simplicity is a performance capability that by any standard must be termed outstanding. Operationally, these factors will combine to provide the highest level of safety and handling ease of any commercial transport.

Stall

Civil transport aircraft for almost their entire history have been depending upon a single, universally-accepted criterion for establishing safety margins for performance and handling qualities, the stall. Margins of safety above the stall have been established based largely upon experience, and this method has served the industry well even into the jet transport fleet. Wind-tunnel data and flight experience have shown that (in or out of ground effect) the double-delta wing will continue to lift at near maximum lifting capability to angles as high as 30°; or in the case of ground operations, even with the tail in contact with the ground. Figure 9 offers a comparison of these effects for the double-delta SST and for a current jet transport. What this means from an operational standpoint is that flight safety will be markedly improved, particularly during the takeoff and landing phases where slow flight is a requirement.

Takeoff Considerations

Since we no longer have a well-defined point such as the *1-g* stall, where the lifting capability of the wing suddenly can no longer sustain the weight of the airplane, it might be well to examine instead the performance of the airplane in terms of its climb capability. Specifically, we can determine the "zero rate of climb speed." It is at this speed that the excess performance of the airplane is reduced so that it can just sustain constant-speed *1-g* level flight. Examination of the three-engine data (Fig. 10) shows that the SST has a zero rate of climb speed margin of over 25 knots and that the excess climb gradient has increased by nearly 300%. The SST excess climb performance is a bonus resulting from the engine size selection being based upon the transonic acceleration requirement and not the takeoff field length, which was the case for the jet fleet.

Excess Lift Capability

The excess lift capability of any civil transport is most critical during the takeoff, when excess performance and margins above the stall are lowest and the airplane is closest to the ground. Jet transport certification rules require the normal liftoff speed to be at least 1.1 times the minimum-safe liftoff speed (V_{MU} or "minimum unstick speed"). A small allowance is made for the normal rotation vs a fast rotation, so that the in-service takeoff speed will be about 1.11 times the in-ground-effect stall speed. The gust or maneuver capability in terms of excess lift or normal load factor corresponding to this margin is 1.23 *g*. Aircraft that feature a ventral fin, and can demonstrate dragging the fin during takeoff, have been certified for a normal liftoff speed of 1.08 times the minimum-safe liftoff speed. This can provide a normal load factor capability, or excess lift capability, of 1.16 *g*, hardly an impressive margin for safety. Deflection of spoiler lateral control, a gust of wind, or a pilot pullup can all decrease such margins drastically and without warning.

An examination of Fig. 11 shows that the double-delta planform can sustain 2.5 *g* at the normal liftoff speed at maximum gross weight without fear of a stall condition. In fact, at the minimum liftoff speed the airplane can sustain 1.3 *g* and still have positive performance (zero climb) at sea level on a standard day, as compared with a 1.0 *g* capability for the current jet transport. This enormous increase in extra lift

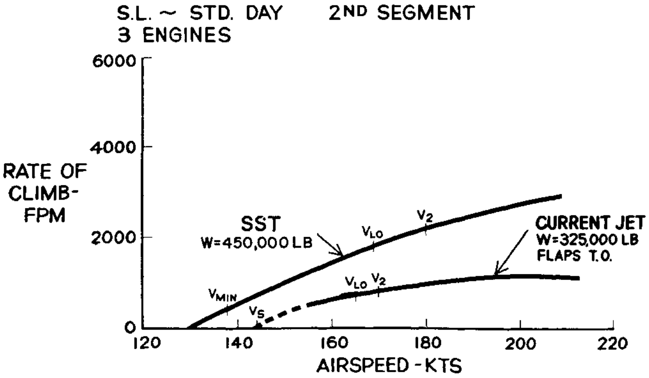

Fig. 10 Takeoff climb performance comparison.

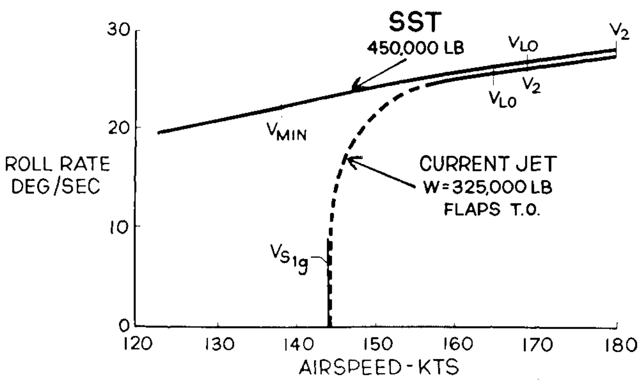

Fig. 12 Roll rates takeoff; rudder pedals neutral.

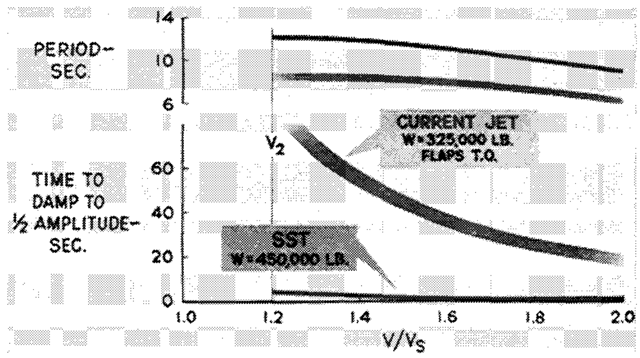

Fig. 13 Lateral-directional damping; takeoff configuration dampers off.

capability close to the ground is one of the inherent safety features of the double-delta planform.

Takeoff Handling Characteristics

We have seen that the unique combination of effects from the lift and drag characteristics of the double-delta planform and the high-thrust engines offer performance and lift margins of safety greater than ever before enjoyed by civil transports. The next logical question, therefore, is whether the handling qualities are commensurate with this performance.

The lateral control has been shown in Fig. 7 in coefficient form. In terms of roll rates we see in Fig. 12 that at the normal V_2 speed during takeoff the roll performance is about the same as for current jet transports. The current jets roll control power however is about zero at the 1-g stall (rudder manipulation is necessary to keep the wings level during stalls), whereas the SST has excellent roll response even at the minimum airspeed. The adverse yaw generated during rudder-fixed aileron rolls with dampers off is similar to the present-day jet transports, so that very little rudder will be required to accomplish coordinated maneuvers.

The lateral-directional (dutch roll) damping of the double-delta configuration is enhanced by the low dihedral effect (Fig. 8), the excellent directional stability that actually improves with an increase in angle of attack, and by the lack of a spoiler lateral-control system. The damping of the lateral-directional mode in terms of the time required to damp to $\frac{1}{2}$ amplitude is shown in Fig. 13. This figure indicates that there is real encouragement that the dutch roll problem, so prevalent in subsonic jets, will not be carried over to the SST.

The in-flight minimum control speed using 5° of bank to assist the rudder is shown in Fig. 14. For their respective maximum thrust values, this figure indicates that the SST and current jets have comparable minimum-control speeds. The effects of V_{MC} upon field length requirements are shown on Fig. 15. These data indicate that the minimum control speeds of the SST do not have a significant effect on the operational economics of the airplane.

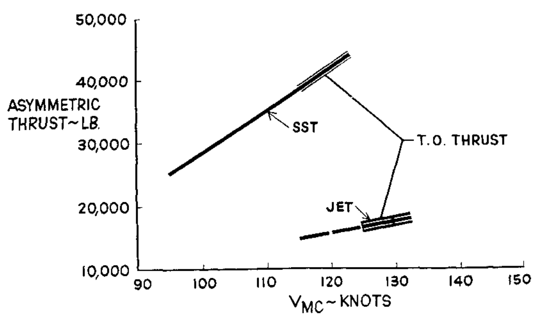

Fig. 14 Air minimum control speed; 5° bank to assist rudder.

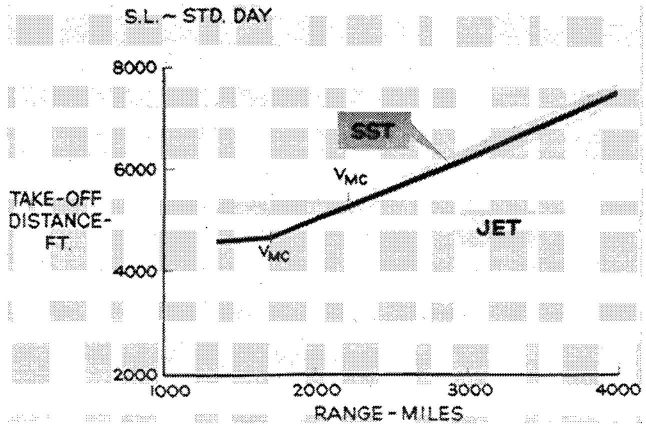

Fig. 15 Takeoff performance.

The SST fully-powered control system will produce all required attitudes, regardless of trim setting, without any performance penalty. The pilot will sense a 15-lb control wheel force change from normal as a warning, but airplane safety margins and performance are unchanged.

Approach and Landing Considerations

The discussions concerning the lack of a classic stall for the double-delta wing for the takeoff case apply equally well to the landing approach. The reason for this is that the configuration of the SST remains the same for both flight conditions. This is made possible by the large wing area that is characteristic of this design. With this large area, any need for high-lift devices has been eliminated. Moreover, since the normal landing weight is 265,000 lb or about 60% of the takeoff weight, and because the approach speed is normally accomplished at a greater percentage of the minimum speed than the conventional V_2 speed (i.e., 1.3 vs 1.2), the performance and maneuver margins are even greater than the margins quoted for takeoff. Figures 16 and 17 compare these approach characteristics with those of the present jets. Particularly significant is the fact that the performance margin of the SST is three and one-half times that of the jet, whereas the speed margin is improved by nearly 50%.

Landing Flare Characteristics

The performance and lift margins discussed previously are further enhanced when the airplane is operated in close proximity to the ground. A number of theoretical investigations and wind-tunnel studies have been conducted to determine how much landing flare cushion results from ground effect on the SST. All of the current delta wing fighters and bombers have experienced this beneficial effect to a significant degree, whereas the swept-wing configurations have little or no such effect apparent. Shown in Fig. 18 is a typical landing sink rate comparison for a subsonic jet transport and a delta

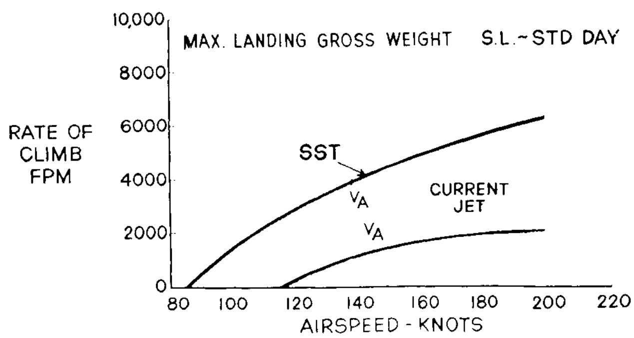

Fig. 16 Three-engine approach climb.

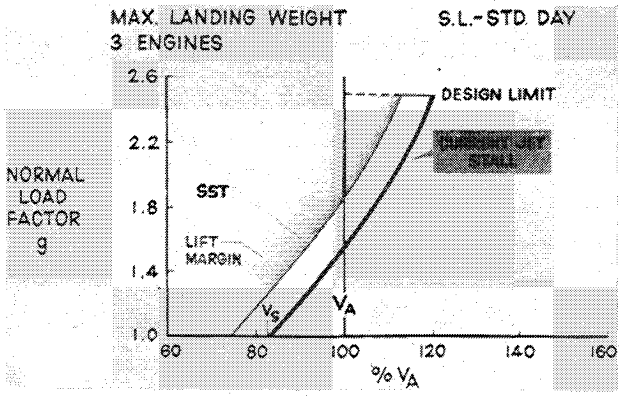

Fig. 17 Approach maneuver capability.

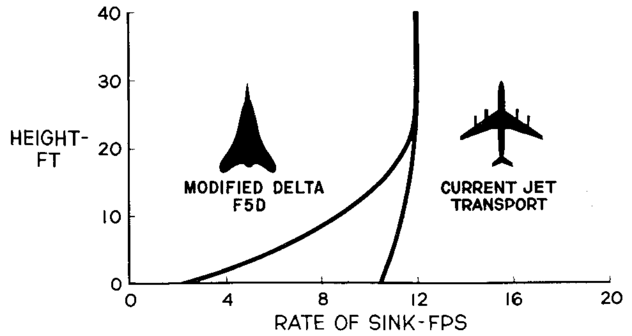

Fig. 18 Landing sink rate in ground effect; constant pitch altitude.

wing fighter, which has been modified to reflect an SST planform. The data shown for this fighter are based on wind-tunnel test results conducted by Lockheed¶ recently for comparison with actual flight results. It is interesting to note that these results compare quite favorably with the results of full-scale flight tests that are being conducted at the present time. Similar landing flare analyses are currently being conducted on the double-delta SST configuration. Preliminary results have indicated that a strong ground cushion exists, which is quite similar to the F5D characteristics. For the studies shown in Figure 18, a constant pitch attitude was assumed so that direct comparisons could readily be made. Besides acting as a safety factor for the pilot, this characteristic will considerably ease the burden of the autopilot designer for the all-weather landing design effort.

Landing Approach Handling Characteristics

The landing approach handling qualities are identical to those described in the takeoff discussion except for changes in weight and airspeed. This is because the external configuration remains the same since no high-lift devices are employed.

The roll capabilities at the minimum speed are nearly as high as those available on today's jets at their normal approach speeds. Indeed, this roll capability is about the same as our jet fighter aircraft of the 1950's. Such control power indicates that small control deflections will be required during critical instrument approaches and cross-wind landings. The low dihedral effects combine with the excellent directional stability, as shown in Fig. 8, to produce lateral-directional damping so that the dutch roll problem of the subsonic jets will not exist for the SST.

Until recently, there was some concern that the fuselage contribution to side force during wings-level sideslips would produce turn effects opposite to the direction of yaw because of fuselage length. Data indicating that this is not the case are contained in the wind-tunnel results, but appear more obviously in the simulator that shows a very slight turning rate in the direction of yaw, as would be desired.

Visibility Considerations

The delta wing configuration is not unfamiliar to the military services. Many fighter and bomber aircraft placed into service since 1950 are using this planform. Civil transport operators however have consistently commented that the nose-high attitudes exhibited by a number of such designs would be worrisome in commercial service. The answer to this concern is straightforward; first of all, the military mission by its very nature stresses performance. Such aircraft therefore are flown to speeds and minimum performance levels that are unacceptable by commercial transport standards. With this as their design criterion, high attitudes for takeoff and landing are to be expected and are entirely acceptable. The SST however is designed to operate with somewhat larger margins in the areas of performance, control, sonic boom, airport noise abatement, etc. These considerations will result in flight attitudes that are entirely conventional when compared with existing transport category aircraft. A comparison of attitudes during flight is offered in Fig. 19. An interesting historical note in regard to this is that the passenger and flight deck angle of the DC-3 in the taxi condition is 11° airplane nose up. None of the attitudes listed in this table are undesirable either in terms of passenger comfort or flight safety. It should be emphasized, however, that in the latter respect the flight crew must be assured adequate visibility under all conditions. The visibility criterion for the SST is inherent in the following two demands: 1) to reliably and safely accomplish visual landings with 1300 ft runway visual range (100-ft ceiling and $\frac{1}{4}$-mile visibility), and 2) to maintain a nose shape that offers minimum drag and at the same time provides a fuselage diameter giving good passenger accommodations and a flight deck design equivalent to the jet transport facilities, i.e., side-by-side pilots and a three-man crew.

Meeting these aerodynamic criteria produces a fuselage width of at least 125 in. and a nose length almost 25 ft forward of the pilot's eye. These requirements, which dictate the nose length forward of the pilot, greatly influence the visibility capabilities. How then do we properly examine what visual requirements exist? Considerable work has been done in this area recently and has resulted in the establishment of certain criteria that must be met. Examples of the type of criteria that current thinking has produced follow:

1) How many of the 1300 ft must be seen by the pilot at the most critical decision point to assure that safe approaches and landings can be accomplished consistently?

2) The critical condition must include the most shallow practicable glide path. This is because the fuselage attitude is equal to the difference between the angle of attack and the glide slope angle. Since the angle of attack remains fixed for a given weight and speed, the fuselage attitude is reduced in direct proportion to any change in glide slope. For visibility considerations, a minimum glide slope angle of 2.5° must be

Condition	CURRENT JET	SST
* TAKE-OFF	10°	11°
* V_2 CLIMB	14°	15°
* ENROUTE CLIMB	7°	12°
* CRUISE	2°	4°
* DESCENT	0°	0°
* APPROACH	3°	9°
* TOUCHDOWN	6°	10°

Fig. 19 Body attitude comparisons.

¶ In cooperation with the Douglas Aircraft Company.

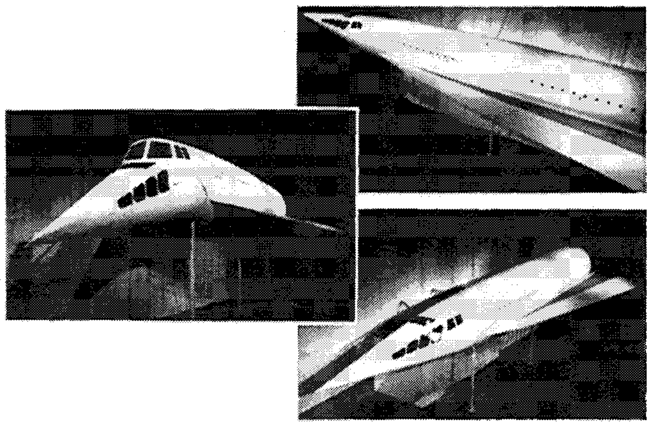

Fig. 20 Weather vision nose.

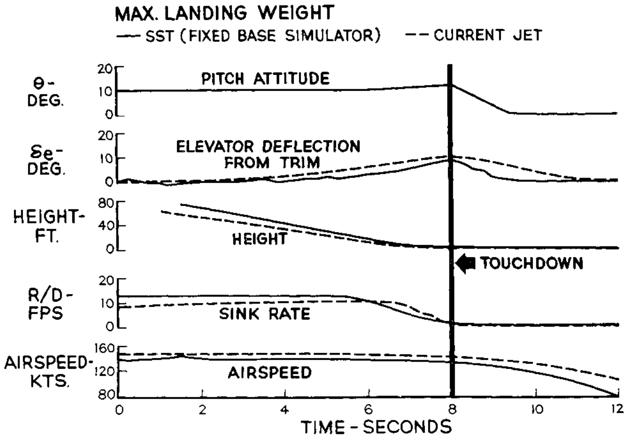

Fig. 22 Typical landing time history.

used to be certain that the maximum nose-up angle is evaluated.

3) The critical conditions must consider the lowest point on the airplane at the moment of decision.

In answering the first criterion, the airline pilots have decreed that 3 sec at the approach speed (about 750 ft) is the minimum acceptable value. Another criterion would be "at least three approach lights for localizer alignment, and two sets of touchdown and landing lights for roll alignment." This also is about 750 ft. It would also be wise to require the same visibility requirements to exist for the certified cross-wind component. The only practical method of assuring that all of these conditions are met is to design a nose section that moves down and out of the field of view. This would be true even if the approach attitudes were equal to the jet transports. When the nose is moved down to accommodate the forementioned criteria, additional beneficial effects are realized, which more than compensate for the small weight increase: cruise drag is markedly decreased, amounting to 12 passengers from New York to Paris per trip; the nose shape will offer the ideal shape for flight deck noise at supersonic and transonic speeds; and the windshield is protected from the hot air and heat rise caused by any shock waves that might impinge upon the windshield. The Lockheed design that considers each of these effects is shown in Fig. 20 and offers excellent visibility.

A subject related to visibility is the height of the pilot's eye above the ground during the landing maneuver. Experience is the best teacher in showing that the SST heights are acceptable. Figure 21, for example, shows that the United States Air Force (USAF) C-124 places the pilot's eye 4 ft higher above the ground than the SST during taxi, and about the same amount lower for the touchdown situation. The important point here is not the absolute magnitude, but simply that existing aircraft are operating with no difficulty under conditions closely approximating those of the SST. Adequate visibility at all times, however, is mandatory.

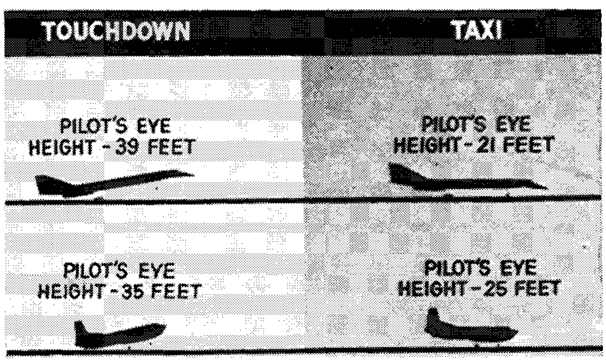

Fig. 21 SST/C-124 pilot height comparison.

Speed Stability

An area of operation which will be new to some of the civil transport operators concerns flight at speeds during takeoff and landing, which are "on the backside" of the thrust-required curve. This simply means that as the airplane slows down, the pilot must add thrust to maintain steady flight. The amount of thrust required to balance the speed loss is indicated by the term $(\partial\ T/S)/\partial V$. Previous investigations of these effects have tended to indicate that at some combination of values of $(\partial T/W)/\partial V$ and static stability margin, the workload for the pilot may increase significantly. In evaluating these effects for the double-delta SST it is not enough to consider only the static stability margin and the speed stability, but in addition, the following factors must also be kept in mind:

1) There is no stall, and the maneuvering and gust margins at the minimum takeoff and approach speeds are equal to the design strength of the aircraft, far exceeding those of any previous transport aircraft.

2) For all takeoff and approach conditions, a performance margin of at least 40 knots from the zero rate of climb condition exists.

3) The effect of the ground upon lift, shown in Fig. 18, is sufficiently great so that a pronounced reduction in rate of sink from a normal 3° glide slope upon entering ground effect will occur. This provides an added safety margin, especially for the all-weather landing condition.

4) The handling qualities that are unique to the double-delta configuration result in more than adequate lateral control capabilities even at approach speeds below what amounts to the stall speed. Dutch roll damping is almost four times as good as the jets. Directional stability actually improves with an increase in angle of attack, and engine-out controllability is assured down to what used to be the stall speed.

5) A weather vision nose is incorporated which provides far better visibility and better pilot references for vertical and horizontal than on any previous transport.

The capabilities that ease the pilot landing workload on the SST combine to produce the landing time history shown in Fig. 22. These data are based on tests conducted on the NASA 5-degree-of-freedom simulator at the Ames Laboratories. Notice that the pilot effort was not noticeably different for the current jet transport based upon the time history of control parameters. The simulator studies are further substantiated by the considerable military experience in the delta wing fighter and bomber aircraft, which confirms the ease with which landings are accomplished.

The use of automatic throttles for speed control therefore will not be a requirement, only an added device to be used if desired just as it is today in the jet fleet. The emphasis upon blind landing capabilities for the SST and the result of the excellent Federal Aviation Agency U. S. Air Force

SST Pilot Factors Program at Randolph Air Force Base indicate that such a device may well be required for any airplane attempting blind landing performance in order to ease the pilot workload. For these reasons alone, provisions will be made to incorporate the automatic throttles as future all-weather landing studies dictate.

Summary

In summary, the Lockheed studies to date show that the low-speed handling qualities of the double-delta SST are considerably better than those of the current subsonic jet transports. Considering the impressive safety record of the jet fleet and the increased margins that the SST will bring, we can anticipate that the transition to the SST will be accomplished with unprecedented ease and operational safety.

Reference

[1] Heppe, R. R. and Hong, J., "The double-delta supersonic transport," AIAA Paper 64-602 (August 1964).

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Development of a BLC High-Lift System for High-Speed Airplanes

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This paper presents the significant steps in the development of a boundary-layer control (BLC) high-lift system for the 367-80 (707 prototype) airplane. The design is based on an advanced boundary-layer control concept using an ejector for momentum augmentation of BLC air and primary air bleed from the propulsion system. A modulated thrust reverser for flight-path control has been integrated into the over-all design. Considerations leading to the selection of the design concept are discussed, and the importance of a well integrated program of aerodynamic and mechanical system development is shown. Pertinent results of research involving two-dimensional and complete configuration tests in the wind tunnel and full-scale ejector tests in the laboratory are given. A recently completed, joint flight research program by Boeing and NASA shows that large gains in low-speed performance can be made with blowing boundary-layer control. Landing speeds less than 85 knots at 140,000 lb airplane gross weight have been consistently achieved. Careful flight evaluation shows that conventional aerodynamic controls with stability augmentation can provide satisfactory handling characteristics for large jet airplanes throughout the extended low-speed flight envelope.

Introduction

THE problem of achieving high-lift coefficients for safe airplane operation at low speeds which is a crucial factor in modern airplane design has existed since the early days of aviation. As the art of airplane design progressed, the disparity between the requirements for efficient cruise flight and low landing and takeoff speeds became increasingly apparent. It was not long before compromises in wing and airfoil design were being made to favor the low-speed operation and soon thereafter high lift devices of varied types made their appearance. The identification of flow separation as the central problem in achieving high lift, focused attention on the mechanism of this phenomenon. The concept of the boundary layer and the influence of viscosity in leading to flow separation in adverse pressure gradients was advanced by Prandtl as early as 1904. He also showed how the application of suction to critical areas on the surface of a body could eliminate or delay the onset of flow separation. This idea, and that of rotating or moving part of the surface at the local fluid velocity, was explored by early workers in aerodynamics.

The first application of BLC using tangential blowing at the leading edge of an airfoil, was proposed by Baumann[1] in 1921. The application of this principle has long been recognized as providing, potentially, a powerful method of obtaining high lift coefficients. Various concepts, using both suction and blowing BLC have been studied intensively and a large amount of research both in the United States and in Europe has been carried on, particularly following World War II.[2] Impetus for this activity was provided by the availability of the jet engine as a potential source of air for BLC. However, practical difficulties have permitted only limited applications of the BLC technique to production airplanes up to this time and these have been exclusively on military airplanes where safety and economic considerations are somewhat less important than for commercial transport airplanes.

The subsonic jet transport, now well accepted in airline service, introduces several new factors, which interact unfavorably with those relating to good low-speed performance. The increase in airplane speeds, achieved largely by means of wing sweep, and the increase in wing loading have greatly complicated the problem of maintaining or improving low-speed performance to stay within acceptable takeoff and landing field-length limits. The prospect of the supersonic transport development which requires further design compromises in favor of efficient cruise performance extends existing design trends and further heightens the problems of achieving acceptable low-speed performance. The potential applications and extensions of high-lift technology to the military field have received a great deal of attention in the past. Current interest in a new configuration spectrum of

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