Design of a Small Supersonic Oblique-Wing Transport Aircraft

Alexander J. M. van der Velden*
Stanford University, Stanford, California
and
Egbert Torenbeek†
Delft University of Technology, Delft, the Netherlands

Previous work in the early 1970's has shown the merits of a (large) transonic oblique-wing transport. In this paper, the suitability of the oblique-wing planform for a small supersonic transport aircraft will be shown. The aircraft is designed to transport 24 passengers with first-class accommodations at a cruising speed of 1500 km/h over a distance of 5800 km. It complies to the JAR 25 and FAR 25 airworthiness requirements and the FAR 36 stage 3 noise regulations and is powered by two medium bypass turbofan engines. The proposed aircraft offers a typical increase in blockspeed of 53% at ranges of 4000–7000 km compared with similar small transport aircraft, with comparable fuel efficiency, range, and field performances.

Nomenclature

C_D	= drag coefficient
C_L	= lift coefficient
D	= drag
L	= lift
M	= flight Mach number
q	= dynamic pressure
S	= gross area (no index: wing)
T_{to}	= total engine thrust at SLS, ISA
t/c	= wing thickness-to-chord ratio
W_p	= design payload weight
W_{to}	= aircraft takeoff weight
$(W/S)_{to}$	= takeoff wing loading
$(W/T)_{to}$	= takeoff thrust loading
Λ	= sweepback angle at 25% chord of wing
ϵ	= ellipse ratio of wing
η	= overall engine efficiency

Subscripts

n	= normal to wing leading edge
h	= horizontal tail plane
to	= takeoff
v	= vertical tail plane

Introduction

TEN years after the introduction of the Concorde into commercial service, it is generally concluded that, despite its relatively high maintenance costs, its technology generally satisfies or exceeds the expectations at the start of the project. However, economically it does not fit into the current structure of air traffic due to its high fuel costs, and the high research and development costs cannot be negotiated by the small number of aircraft in operation. And though Concorde's high cruise speed reduces the time to travel drastically, the sonic boom it produces makes overland flights impossible at supersonic speeds.

Nevertheless, the Concorde's high load factors have shown that a market exists for faster and more comfortable passenger transport than is currently available. Present-day first-class, long-range, high-subsonic transportation does offer good spatial comfort and catering service, but the high-priced tickets do not result in reduced traveling times due to the moderate cruise speed and the long boarding times of large, wide-body aircraft.

A new type of aircraft with a maximum cruise speed of about 1500 km/h (Mach 1.4) and a maximum capacity of 24 passengers could have some advantages over both high-subsonic transports and the Concorde:

1) The cost of developing a low-supersonic aircraft is considerably less than that for a Mach 2 aircraft, especially when the aircraft has a limited passenger capacity.

2) A low-supersonic aircraft can be designed in such a way that supersonic overland flights become acceptable from an environmental point of view.

3) The low-speed performance of such an aircraft can be comparable to the low-speed performance of high-subsonic aircraft, in particular when the configuration is selected, which is proposed in the present article.

4) Such an aircraft could more easily be fitted into the present-day structure of holding patterns, approach speeds, and noise regulations.

Choice of the Configuration

Mascitti[1] showed some of the problems associated with the application of a symmetrical fixed wing to small supersonic transports:

1) Applying area ruling to the symmetrical wing/body configuration results in severely waisted fuselage contours at the fuselage center sections.

2) In view of the low lift-to-drag (L/D) ratios over the entire speed range, very low payload fractions could be achieved, resulting in high takeoff, empty weights and costly aircraft.

3) The poor low-speed aerodynamics do not allow the aircraft to operate from small airfields, thus significantly reducing operational flexibility and increasing the passenger's overall traveling time.

The oblique-wing configuration proposed by Jones[5] has the advantage that a near-cylindrical passenger cabin can be used, since the equivalent area distribution of the wing is better spread out longitudinally. The resulting higher L/D ratios increase the payload fraction significantly. The low-speed aerodynamic qualities of the aircraft can be made comparable to efficient subsonic transports, provided the wing is unswept at subsonic speeds.

Received April 5, 1987; revision received Feb. 15, 1988.

*Ph.D. Student, Department of Aero-Astro.

†Professor of Aircraft Design.

A disadvantage of such a concept is the need for a pivot structure and the limited data base available on oblique-wing designs. One of the main objections to the large oblique-wing transport designs of the early seventies[2]—that its cruise speed does not allow it to fit into the current transatlantic operations of the major airlines—may not apply to a low-supersonic transport operating at altitudes above 15,000 m.

The medium bypass ratios that will be required to fulfill the FAR 36 stage 3 noise requirements pose serious problems to a successful airframe-propulsion integration. For transonic aircraft, the wave drag of podded engines may be the single largest contribution to the total zero-lift drag due to the low engine mass-flow ratios in the transonic regime. Burying the engines in the rear fuselage section allows area ruling of the fuselage in such a way that there is virtually no extra spillage drag due to engine installation in subsonic cruise[2] and low extra wave drag in transonic flight.

The horizontal tail must be designed and located in such a way that good control over the aircraft and minimum trim drag are realized in all flight conditions. It is, therefore, objectionable to locate the tail close to the engine exhaust flow. For this reason, it was decided to select a T-tail configuration. The complexity of the T-tail structure is clearly a disadvantage, but its low drag and good control qualities make it superior to other positions. A long-coupled canard configuration was rejected because of the expected unfavorable aerodynamic interference with the flow over the high-mounted wing and through the engine inlet.

Baseline Design

A layout drawing of the proposed Small Supersonic Oblique-Wing Transport Aircraft (SSOTA) is shown in Fig. 1. During the design process, this configuration adapted many of the features of the earlier Boeing 5-3a design.[2] The oblique wing planform is mounted to the top of the fuselage by means of a pivot. It has an elliptic planform with an elliptic spanwise distribution of the thickness-to-chord ratio, resulting in minimum wave drag for a given volume.[3] For high-aspect-ratio oblique wings, the chordwise thickness distribution appears to have only a secondary effect on the equivalent body shape.

The provisionally selected NLR supercritical airfoil sections[4] achieve a high cruise C_L with very limited drag rise, allowing a buffet-free cruise L/D ratio near the unconstrained maximum value. The wing is designed for a normal lift coefficient of 0.9 and a normal Mach number of 0.7, allowing for a 1.3-*g* pull-up maneuver. The high t/c ratio of the supercritical wing (the root section has a t/c ratio of 15%) reduces wing weight and creates a sufficiently large fuel tank to contain all the fuel in the wing.

To obtain an elliptic spanwise lift distribution, the elliptic wing planform must obtain a uniform distribution of lifting pressures, even at large angles of yaw. This can be realized by giving the wing an upward curvature along the span. For the oblique wing with an ellipse ratio of 10, the optimum wing warp is described in Ref. 5.

The wing is swept during acceleration and cruise, maintaining a constant M_n of 0.7, resulting in a 60-deg sweep at a cruise Mach number of 1.4.

The minimum cruise altitude of 14,500 m at Mach 1.4 sets a maximum structural design equivalent airspeed of 170 m/s. The wing beam structure is based on graphite-epoxy honeycomb panels. This material is plied in such a way that the wing possesses enough stiffness to accommodate static and dynamic bending moments that result from aeroelastic deformation.

The wing is located on top of the center fuselage frame with load-bearing rings in between. These rings are integrated into the wing and the body without interrupting their carry-through structures. Vertical loads and rolling and pitching moments are transferred via the bearings at the circumference of the pivot. Shear forces are carried through the bearings and the pivot joint. Hydraulic and flight-control systems, running from the body to the wing, are routed through the center of the pivot. A gear drive attached to the fuselage and a rim fastened to the wing ribs actuate the sweep mechanism. It remains to be investigated whether such a configuration would be acceptable from a safety point of view.

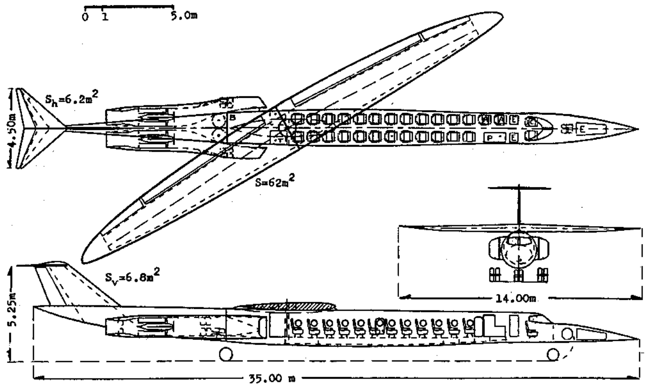


Fig. 1 Small, supersonic, oblique-wing tranport aircraft layout.

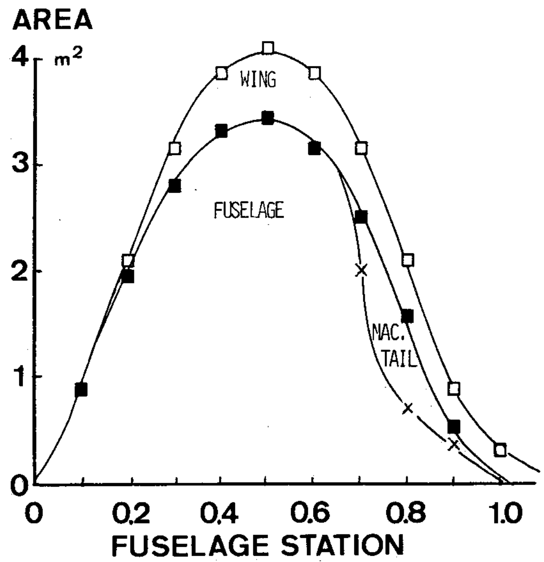


Fig. 2 Equivalent area distribution for the SSOTA configuration at Mach 1.4.

The external shape of the fuselage is to a great extent determined by the area distribution of the other aircraft components. However, the components locations have been chosen carefully in order to create a near-cylindrical cabin for maximum cabin-layout flexibility. The equivalent area distribution at Mach 1.4 is depicted in Fig. 2, which clearly illustrates that insertion of any substantially cylindrical fuselage section will seriously impair the area distribution.

Compared with small supersonic aircraft with fixed wings, and using a considerable waisting of the cabin, the resulting fuselage structural design problem is quite moderate in the proposed oblique pivoting wing configuration. It is now possible to design a near-cylindrical cabin with a minimal internal cross-sectional diameter of 1.70 m for the front row and up to 1.90 m for the center rows. There is very limited double curvature.

The cockpit layout is essentially similar to the one in the Gates-Learjet 35. Though not very spacious, this cockpit will accommodate two pilots with dual controls side by side. In combination with a suitable nose section it has a low-drag geometry.

The pressurized cabin, to be constructed of aramid reinforced aluminum laminate (ARALL) material, stretches from the rear of the baggagehold to the front bulkhead of the cockpit. Preliminary investigations have shown a typical 20%

weight reduction when ARALL is used in comparison to conventional materials.[6] Added to this comes the shielding effect of the fuselage to the wiring and avionics from electromagnetic interference.

To provide the aircraft undercarriage with adequate wheel track, the main gear hinge is mounted to an extension frame at about 75 cm distance from the rear bulkhead frame. The upper part of the gear leg is located in the nacelle structure aft of the inlet scoop. The wheels are retracted into the fuselage behind the rear pressure bulkhead. The nose gear hinge is mounted to the front pressure bulkhead.

Power-Plant Installation

The design goals for the engines were high cruise and climb efficiency, minimal power-plant weight, and acceptable development costs in case of selection of a new or modified engine. To comply to the FAR 36 stage 3 noise regulations, medium bypass ratio turbofan engines are required to reduce the exhaust jet velocity. To satisfy the thrust requirements during cruise, a turbine entry temperature (TET) in excess of 1600 K will have to be used.

To minimize wave drag, the engines are buried in the rear fuselage section. The utilization of this space for the power-plant installation is not penalized by any decrease in passenger cabin volume. The fixed-intake geometry is of the two-dimensional shock type. The air is compressed by one oblique and one normal shock. This will provide a good intake shock efficiency at the design Mach number 1.4 without the necessity of a variable geometry inlet. The intake is S shaped and separated from the sides of the fuselage to capture the undisturbed free air. Behind the straight diffusor section the inlet ducts are bent toward the aircraft centerline, and the duct area gradually diffuses, decelerating the air to an intake Mach number of about 0.50.

There are auxiliary air intake doors in the diffusor section. These doors guarantee sufficient inlet airflow and minimal compressor face distortion at takeoff. In addition, there are outlet doors to cope with excessive intake air in low power conditions. The rear nacelle structure houses the convergent-divergent nozzles. To avoid the complexity of a variable nozzle geometry, the SAAB-VIGGEN exhaust concept was used. During takeoff, an extra air inlet just behind the nozzle throat sucks the air into the divergent nozzle section, thereby avoiding overexpansion of the flow. At Mach 1.4 the exhaust gases can expand fully inside the condi-nozzle, thus providing maximum thrust and fuel efficiency.

Optimization of the Design

While complying with the specifications and additional geometric, airworthiness, and technological constraints, the wing ellipse ratio, thrust-to-weight ratio T/W, wing loading W/S, engine cycle, and bypass ratio have been optimized for maximum payload fraction (W_p/W_{to}). Reference 10 shows that this parameter will yield an optimum configuration that is sufficiently close to the configuration for minimum direct operating costs (DOC).

The optimization was carried out by means of the program AVSAD, developed by the first author. Based on the methodology of Refs. 7 and 10, this program uses parametric input and available technological information to generate realistic aerodynamic, weight, and performance data for supersonic aircraft. The AVSAD program was tested for seven supersonic designs by NASA, Boeing, and MDD, as well as Concorde, with cruise Mach numbers ranging from 1.2–2.7 and W_{to} ranging from 360–3400 kN. It was found that the major aerodynamic weight and performance data were typically within a 15% error margin from the data generated by the various design teams.

A typical plot used to select T/W, W/S, and the ellipse ratio is shown in Fig. 3. After comparing plots for different ellipse ratios, it was concluded that $\epsilon = 10$ represents the optimum value. Reducing ϵ decreases the payload fraction, whereas increasing it results in violation of the various design constraints indicated in Fig. 3:

1) The initial cruise altitude of at least 14,500 m.

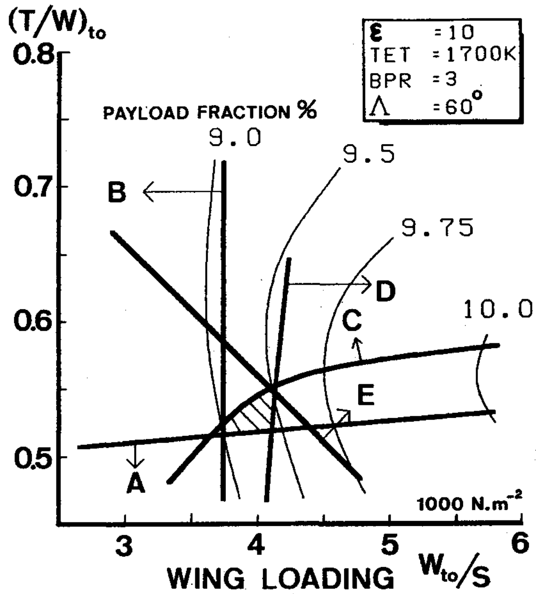
2) The bow shock wave from the fuselage nose must not hit the forward wing tip at $M = 1.5$ to avoid flutter problems.

3) Excessive additional engine nacelle wave drag should be avoided by restricting the engine mass flow to 50 kg/s.

4) The wing must have enough volume to contain all the fuel for the transatlantic flight.

5) A buffet-limited cruise lift coefficient of 0.23 has been assumed.

From Fig. 3, it can also be derived that it is not useful to increase the C_L constraint, unless the t/c limit would also be



CONSTRAINTS:

A: 14,500 M INITIAL CRUISE ALTITUDE
B: BOW SHOCKWAVE HITS WING TIP
C: EXCESSIVE ENGINE WAVE DRAG
D: WING FUEL CAPACITY INSUFFICIENT
E: C_L > 0.23, BUFFETTING

Fig. 3 Wing- and thrust-loading optimization.

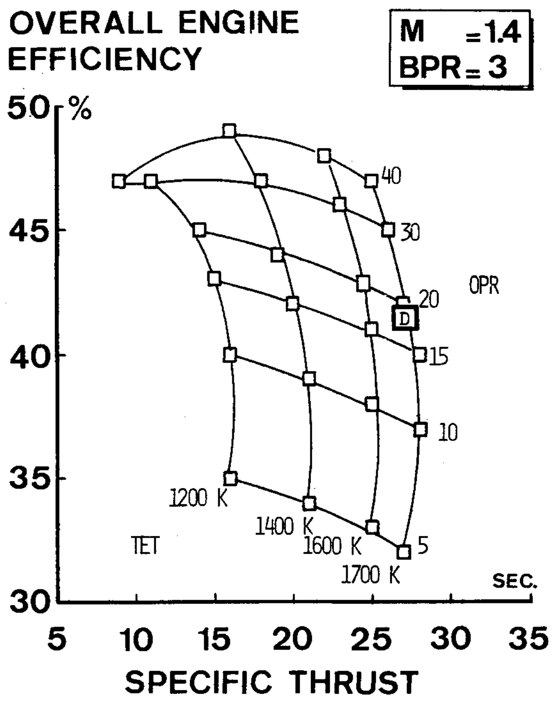


Fig. 4 Engine cycle optimization.

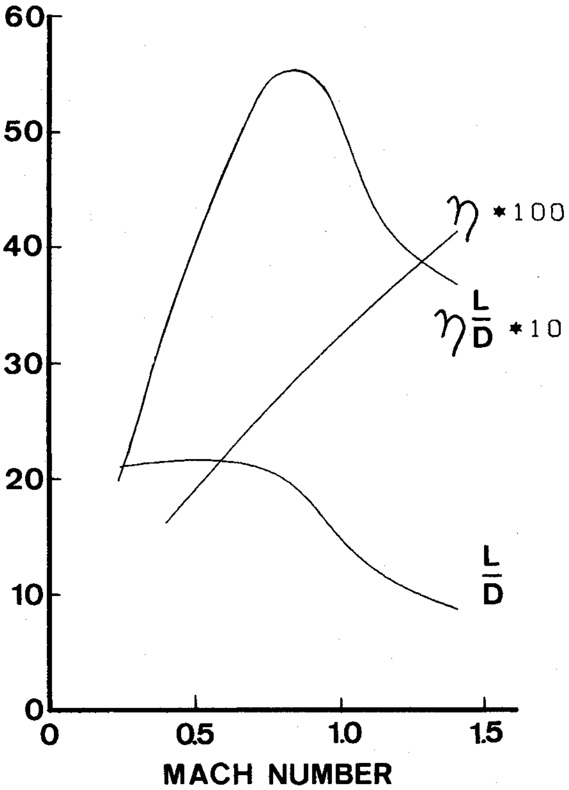


Fig. 5 Variation of L/D and overall engine efficiency with Mach number.

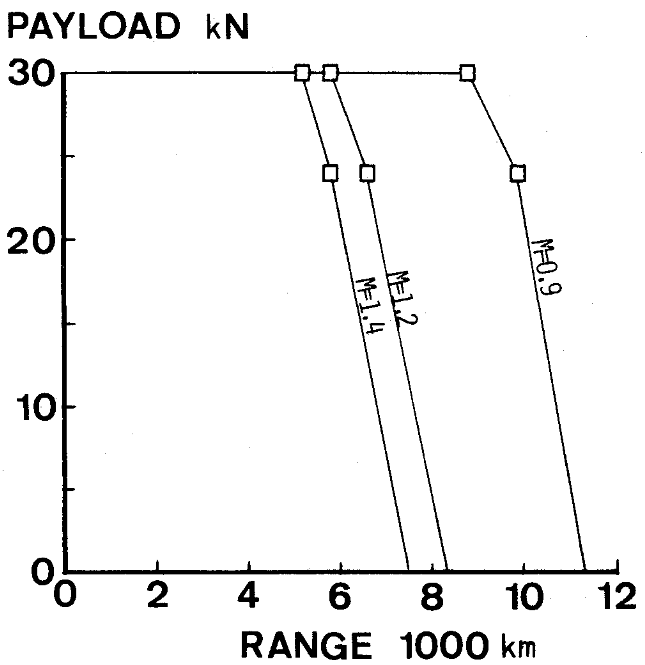


Fig. 6 Payload-range diagram.

relaxed. Inside the feasible region the best design is obtained for a T/W of 0.55 and a wing loading of 4.1 kN/m^2.

The engine optimization is concentrated on the design condition (cruise). The TET and overall pressure ratio (OPR) were optimized for maximum overall efficiency at sufficient thrust. In Fig. 4, it is shown that, for a bypass ratio (BPR) of 3, a TET of 1400 K, and an OPR of 40, an overall engine efficiency of 48% can be achieved. However, at this TET only 50% of the 27-s initial specific thrust requirement at cruise is met. Maximum specific thrusts are typically reached at OPR

Table 1 Drag breakdown at $M=1.4$, $C_L=0.23$, $h=15{,}200$ m

Drag Component	Drag coefficient
Friction	
Wing	0.0052
Fuselage	0.0038
Tail/nacelle	0.0019
Wave	
Wing	0.0011
Fuselage	0.0028
Tail/nacelle	0.0028
Roughness	0.0015
Lift	
Induced	0.0062
Wave	0.0011
Total	
Drag coefficient	0.0264

Table 2 Weight breakdown for the harmonic range (5800 km/3130 nm)

Weight component	Weight, kN
Structure	
Wing	21.4
Fuselage	30.6
Tail	4.8
Undercarriage	10.0
Nacelles	9.8
Power plant	23.9
Systems and equipment	32.3
Operational/miscellaneous items	8.5
Payload	
18 Passengers	18.0
Baggage	6.0
Fuel	
Trip	78.0
Reserve	11.0
Maximum takeoff weight	254.3 kN (57,150 lb)

values of 15. A good design compromise appears to be point D, with an OPR of 18 and a TET of 1700 K.

To keep the engine development costs as low as possible, the core of the RB 199 with a BPR of 3 fan was selected. The RB 199 is used in the Tornado fighter and is still being improved further. With a BPR of 3, only limited acoustical lining will be necessary, while a high overall efficiency and sufficient thrust can be obtained.

Design Characteristics

In Fig. 5, the effects of Mach number variation on maximum L/D and engine efficiency are shown; in Table 1, the drag breakdown for Mach 1.4 cruise is given. The maximum aerodynamic efficiency at cruise is not more than 8.7, whereas at Mach 0.7 a value in excess of 20 can be reached. The reason for this lies primarily in the high value of the sweep angle during cruise, compared with the high-aspect-ratio subsonic configuration.

The weight breakdown for the transatlantic range and design payload is given in Table 2. This shows the relatively low fuel weight fraction, which is obtained because the relatively low L/D ratio is compensated by a high engine efficiency. In addition to this, the oblique-wing configuration significantly reduces the reserve fuel fractions necessary for holding and flight to an alternate airport. The high cruising speed will enable the aircraft to operate under ETOPS regulations over the North Atlantic routes.

The takeoff and climb performance is such that the aircraft is able to take off from almost all international airports. At W_{to}, the aircraft requires a balanced field length of only 1100 m and reaches the initial cruise altitude of 15,000 m in less than 15 min. The SSOTA is able to fly at blockspeeds that are on average 53% higher compared to existing aircraft, at ranges between 4000 and 7000 km. Figure 6 gives the payload vs range diagram.

Though the sonic boom overpressures (47 N/m^2 at initial cruise) are significantly lower than those for the Concorde, it is very doubtful whether this value will be acceptable to the public, so the overland cruise Mach number may have to be limited to a value near Mach 1.2, allowing boomless supersonic flight in a standard atmosphere.

Aeroelastic Aspects and Stability and Control

The SSOTA has a sufficient tail volume to maneuver and control the aircraft in all conditions. For the entire speed and center of gravity (c.g.) envelope, adequate static stability can be shown to exist.

After significant simplification of the problem, a method was derived to determine the stability derivatives and the motion matrix of all medium- and high-ellipse-ratio oblique wing/body configurations in subsonic flow. It was found that the natural frequencies of both the short-period longitudinal oscillation and the dutch roll were typically 1 rad/s for all sweep angles. According to MIL requirements,[8] the aircraft can be controlled for $C_L > 0.3 \cos\Lambda$ without stability augmentation.

A lateral stability augmentation system will have to be designed for normal flight. In the asymmetric configuration, all oscillations will involve simultaneous pitching, rolling, and yawing motions, making it very difficult for the pilot to control the aircraft. In view of the cross-coupling effects involved, design of such an augmentation system will be more difficult than that for a symmetrical aircraft.

If the automatic unsweeping mechanism fails during approach, the aircraft cannot be landed on small airfields. To cope with this problem, a manual backup system is installed to unsweep the wing.

The oblique wing of the SSOTA does not show aeroelastic divergence up to values of 4 q at cruise, i.e., twice the Federal Aviation Administration (FAA) limit. Stabilized bank angles will originate after excitation of the leading or trailing wing. It will therefore be necessary to install an active stability augmentation system to correct the bank angle continuously. This system may use the outboard placed ailerons as a control surface, since they do not increase the aeroelastic instability once they are used both to the same deflection. The fact that aileron effectiveness is not influenced by aeroelastic effects renders high-speed inboard ailerons unnecessary.[9]

Conclusions

1) The oblique-wing configuration is very suitable for small transport and executive aircraft flying at transonic and low-supersonic speeds.

2) The performance of the present aircraft design in terms of fuel efficiency, range, and comfort is comparable to existing subsonic aircraft, whereas the maximum cruise speed is increased by 75%. The block speed increment is in excess of 50%.

3) The technology to manufacture this aircraft exists today, and it can therefore be expected that the costs of developing, manufacturing, and operating such an aircraft will be acceptable.

References

[1]Mascitti, V. R., "A Preliminary Study of the Performance and Characteristics of a Supersonic Executive Aircraft," NASA TM-74055, Vols. 1 and 2, 1977.

[2]Kulfan, R., McBarron, J. P., Mulally, A. R., Neumann, F. D., Gimmestad, D. W., Murakami, J. K., Nisbet, J. W., Noble, E. C., Stalten, J. L., and Sussman, M. B., "High Transonic Speed Transport Aircraft Study," NASA CR-114658, Sept. 1973.

[3]Smith, J. H. B., "Lift/Drag Ratios of Optimized Slewed Wings at Supersonic Speeds," *Aeronautical Quarterly*, Vol. 12, Aug. 1961, pp. 201–218.

[4]Sloof, J. W. and Voogt, N., "Aeronautical Design of Thick Supercritical Wings Through the Concept of Equivalent Subsonic Pressure Distribution," NLR MP 78001U, 1978.

[5]Graham, L. A., Jones, R. T., and Boltz, F. W., "An Experimental Investigation of Three Oblique Wing and Body Combinations at Mach Numbers Between 0, 60, and 1.40.," NASA TM-X-62256, April 1973.

[6]Vogelesang, L. B. and Gunnink, J. W., "ARALL, a Material for the Next Generation of Aircraft, a State of the Art," Delft Univ. of Technology, Rept. LR-400, Aug. 1983.

[7]Torenbeek, E., *Synthesis of Subsonic Airplane Design*, student ed., Delft Univ. Press/Nijhoff, Delft, The Netherlands, 1982.

[8]Anonymous, "Flying Qualities of Piloted Airplanes," MIL-F-8785B (ASG), Aug. 1969.

[9]Jones, R. T. and Nisbet, J., "Aeroelastic Stability and Control of an Oblique Wing," *Aeronautical Journal*, Vol. 20, Aug. 1976, pp. 365–369.

[10]Torenbeek, E., "Fundamentals of Conceptual Design Optimization of Subsonic Transport Aircraft," Delft Univ. of Technology, Dept. of Aerospace Engineering, Rept. LR-292, 1980.