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UNCONVENTIONAL CONFIGURATIONS FOR EFFICIENT SUPERSONIC FLIGHT

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1. Summary

Alternative configurations for more efficient supersonic aircraft are suggested by consideration of the sources of drag at high speeds. Results of studies described in this paper indicate that supersonic aircraft with much higher efficiencies than previously achieved are possible with reduced Mach number. The paper focuses on two promising candidate solutions: oblique wings and configurations with supersonic laminar flow. In this paper we review some of the fundamental issues for potential efficient supersonic aircraft and describe recent work by researchers at NASA, Stanford University, and industry on unconventional configurations that may provide significant improvements in high speed efficiency.

2. Introduction: Supersonic Fundamentals

Efficient supersonic flight is sometimes considered an oxymoron. Although the savings in time, reduced crew costs, and potential higher utilization are obvious incentives for high speed flight, the penalties in fuel consumption (and corresponding environmental impact) are dramatic. As shown in figure 1, the lift-to-drag ratio of a supersonic airplane is typically half that of subsonic aircraft and continues to drop as the Mach number is increased. The Concorde consumed almost three times the fuel required for subsonic travel over the same distance. This precipitous drop in performance between Mach 0.9 and Mach 1.2 or so is not simply caused by an increase in dynamic pressure but rather a fundamental change in the character of the fluid flow, which leads to dramatic differences in configuration design and aerodynamic efficiency.

This paper addresses the question of how these changes in flow character affect the optimal configuration and how they might be might be used to advantage in an unconventional supersonic design, ameliorating what is generally perceived to be a true barrier to flight efficiency at Mach 1.0.

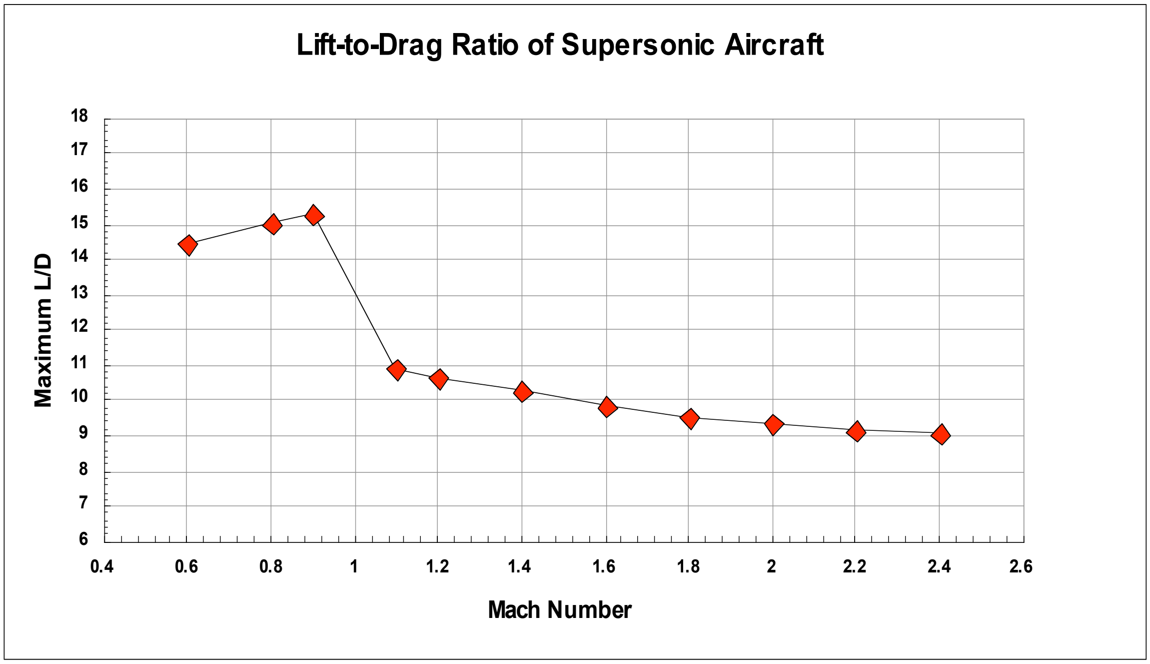

Figure 1. Maximum lift-to-drag ratio of a conventional supersonic aircraft designed for flight at Mach 2.4.

The emphasis of this discussion on aerodynamic performance stems from the great importance of aerodynamics on the performance of supersonic aircraft. This is due to several factors:

- The typical L/D of supersonic aircraft is less than 50% of subsonic aircraft
- Supersonic aircraft missions include significant off-design operation
- Fuel, emissions, and engine size are directly affected by drag
- Indirect effects on performance due to aircraft weight increases from all of the above multiply these effects.

To begin the investigation of supersonic aerodynamic efficiency, we consider a simplified expression for minimum supersonic drag developed by R.T. Jones in the 1950's [1]:

$$D_{min} = qSC_{D_0} + \frac{W^2}{q\pi b^2} + \frac{(M^2-1)W^2}{q\pi \ell^2} + qk_0\frac{Vol^2}{\ell^4}$$

This expression holds at low supersonic speeds when the wing sweep is much greater than the sweep of the Mach lines and includes the familiar viscous drag and vortex drag terms along with the lift-dependent and volume-dependent wave drag.

In this expression: q is the dynamic pressure
W is the weight (assumed equal to the lift)
M is Mach number
b is the span
Vol is the overall volume
S is the reference wing area
l is a measure of the effective length of the aircraft

A few basic configuration-related features are apparent from this expression. First, the two wave drag terms vary inversely with the length of the vehicle, leading to longer supersonic aircraft. Since two of the terms are proportional to q and two are proportional to 1/q, we expect that the minimum drag at fixed lift will occur at an altitude that makes the viscous plus volume wave drag terms equal to the lift-dependent terms. Of course, aircraft usually fly lower than this altitude due to Reynolds number effects on C_{D0}, propulsion system performance, and structural implications (pressurization loads on the fuselage, for example). Figure 2 shows a typical distribution of drag among these components for a large Mach 2.4 supersonic transport. Friction and volume-dependent wave drag together account for about 60% of the total drag. As the Mach number is reduced, the relative contribution of lift-dependent wave drag to vortex drag decreases (due to the explicit M^2-1 dependence of lift-dependent wave drag).

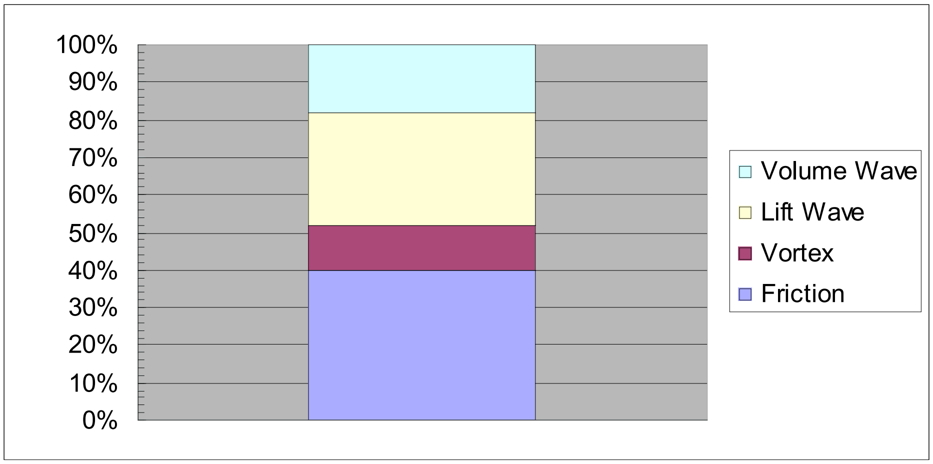

Figure 2. Typical distribution of drag components. Baseline double delta wing, Mach 2.4, L/D = 9, $C_L = 0.1$.

As the Mach number is increased, the optimal altitude increases, with significant implications for environmental impact, cabin safety, and structure. Some of these effects are shown in figure 3, which indicates that even relatively small changes in design cruise altitude can have important effects. More recent analyses also suggest that the influence of emissions such as NO_x and water vapor are very sensitive to deposition altitude. Flight at 45,000 – 50,000 ft is very different from flight at 60,000 – 70,000 ft largely due to reduced mixing in the stratosphere [2].

This, and other considerations, make Mach number perhaps the most significant parameter in supersonic aircraft design affecting the configuration, drag, materials (heating), utilization, propulsion, and operating altitude.

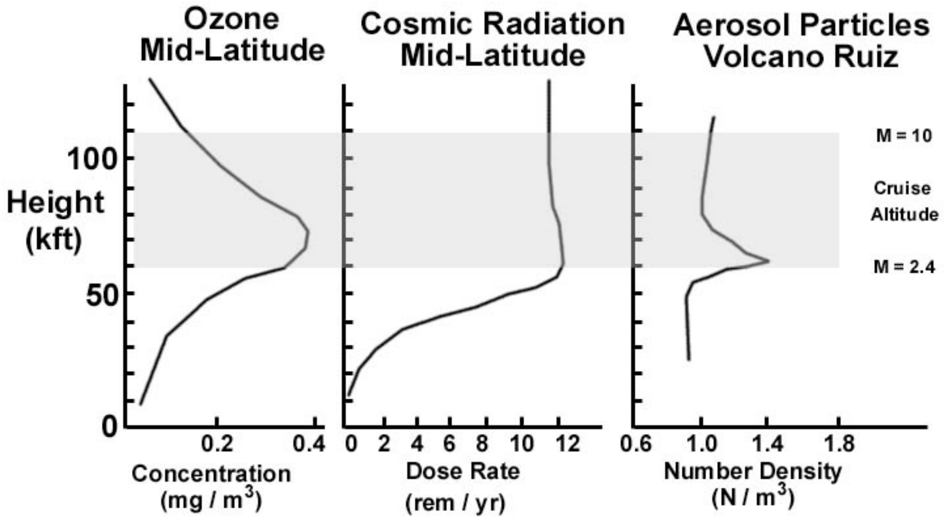

Figure 3. Effect of altitude on cruise environment. (from [3]).

In addition to the direct effect of Mach number on lift-dependent wave drag, the choice of this parameter affects:

- Stagnation temperature (airframe materials, engine life)
- Optimal engine bypass ratio (affects TO noise, subsonic range)
- Optimal cruise altitude (emissions effects, radiation, ozone)
- Optimal sweep and aspect ratio (trades with subsonic performance)

Historically, economic and environmental concerns have plagued supersonic development more than simple technical feasibility. High development and manufacturing costs lead to high acquisition costs and introduce market and development investment risks. Higher Mach numbers also introduce penalties associated with engine and airframe temperature cycles, while higher fuel consumption drives market acceptance through potentially higher fares. Environmental concerns include airport and community noise, sonic boom, and increasingly, en-route emissions.

Despite these difficulties the development of a new supersonic aircraft is of current interest due to three principal factors. First, the concept of a small supersonic aircraft (a business jet, followed perhaps by a 24-48 passenger transport) side-steps many concerns (environmental, technical, investment risks). Second, new analysis and optimization tools make such a complex system design more possible than in the past. And third, new configuration concepts, especially those optimized for lower cruise Mach number lead to higher efficiencies and improved environmental compatibility.

Figure 4. A variety of unconventional designs proposed for efficient supersonic flight.

3. Configuration Concepts

In this section, we examine some aspects of configuration design of importance for supersonic aircraft, focusing on two unconventional design concepts that are especially promising for small aircraft in the Mach number range of 1.4-1.6.

3.1 Conventional and Canard Designs:

In a sense, even conventional configurations for supersonic aircraft are unconventional in many respects. The need for optimal area distributions, high fineness ratios, and a practical minimum cross-section for the cabin leads to aircraft with substantial fuselage volume aft of the cabin. Engine nacelles must be carefully integrated into the wing/body/tail configuration to maintain reasonable area distributions, while the ideal wing sweep and aspect ratio are quite different from familiar values for subsonic aircraft. This has fundamental effects on aerodynamics, structures, and stability. Note for example that as the wing aspect ratio is reduced, the wing downwash approaches the angle of attack at the tail (at least in the limit of slender body theory). Thus increasing the size or aspect ratio of an aft tail does not increase stability when the wing aspect ratio is low enough.

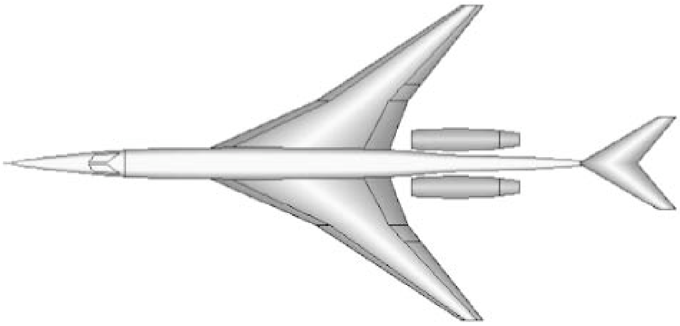

Figure 5. A generic, “conventional” small supersonic aircraft concept.

Canards designs (figure 6), while problematic for many subsonic designs, must be viewed quite differently for supersonic aircraft. A low aspect ratio highly swept canard is much less destabilizing than a higher aspect ratio surface that might be considered on a subsonic counterpart. An ideal longitudinal distribution of lift and area is often more easily accommodated by moving the wing aft, reducing control authority of a conventional tail. The aft location of the large wing also reduces cabin intrusion. In some cases, when the maximum usable C_L is limited by ground angle or approach attitude and when the use of high lift devices on the wing is limited (as may be the case for low aspect ratio, highly swept wings), the canard design can provide an increase in usable take-off or landing C_L.

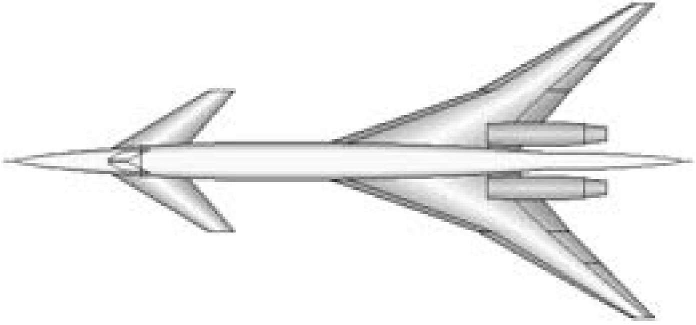

Figure 6. Generic supersonic design with canard control surface.

Careful design of aft-tail or canard configurations at Mach numbers of 1.4-1.6 can lead to relatively conventional designs with efficiencies much higher than previous Mach 2+ designs. The lower Mach number leads to wing sweeps better suited to low speed operation, higher bypass ratio engines that reduce take-off noise, and cruise altitudes that reduce the global impact of emissions. Such concepts may offer practical near term possibilities for flight at speeds of about twice those of conventional civil aircraft.

Further efficiency improvements may require more radical changes in the configuration and subsequent sections deal with two ideas that offer the potential for much better performance, albeit with certain risks inherent in new and unconventional approaches.

3.2 Oblique Wings

Figure 7. Oblique wing design (AD-1) tested by NASA in the early 1980's.

3.2.1 Basic Concepts

In the early development of supersonic flow theory, R.T. Jones noted that for minimum drag at low supersonic speeds, the lift of a wing of a certain length and span should be distributed elliptically in both the spanwise and streamwise directions [4]. If the loading is distributed uniformly over the area this means that wing planform should have an elliptic distribution of area in both directions. This is simply achieved by a yawed ellipse. Other topologically distinct solutions are possible as shown in figure 8, but the asymmetric oblique wing design has certain other advantages that were recognized over the many years of development of the concept at NASA, universities, industry, and other national laboratories.

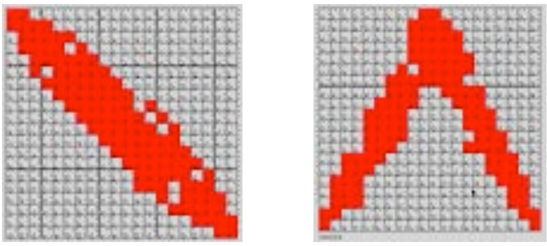

Figure 8. Possible solutions for elliptically loaded wings in spanwise and streamwise directions (from wing design game of Ref. 5). What other geometries achieve this?

The oblique wing arrangement distributes lift over about twice the wing length as a conventional swept wing of the same span and sweep, which provides a reduction in lift-dependent wave drag by a factor of 4. At low supersonic speeds (for which these simple scaling laws apply), the volume wave drag of the wing is only 1/16th that of the symmetrically-swept wing of the same span, sweep, and volume. In addition oblique sweep avoids the unsweeping of isobars at the centerline, maintaining the effect of sweep in the critical center section of the wing as shown in figure 9.

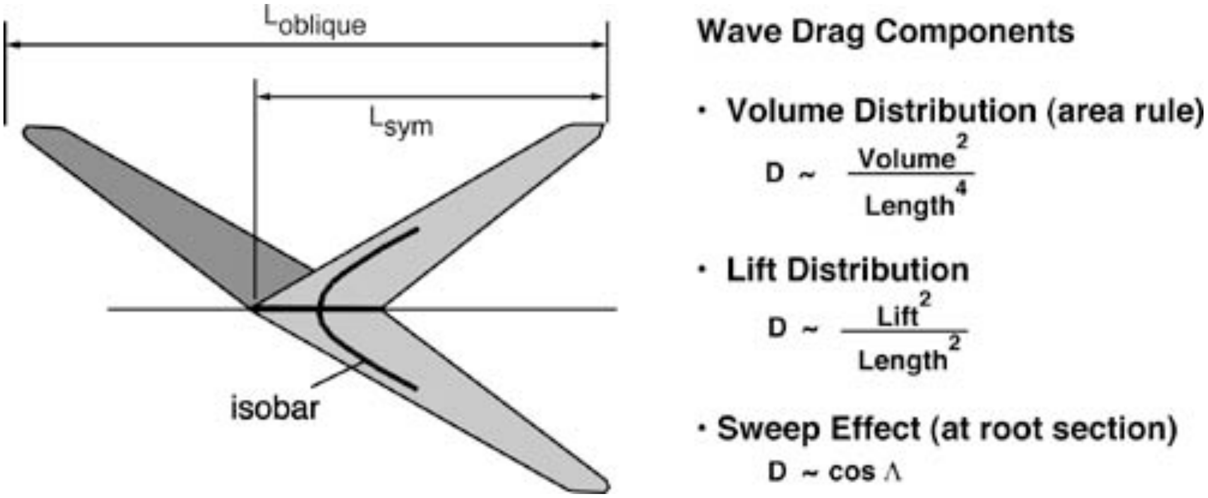

Figure 9. Oblique wing drag reduction features.

Although these aerodynamic features of oblique wings sparked initial interest in the concept, structural characteristics and suitability for a variable geometry design have made the idea the subject of continuing investigations since that time.

The straight carry-through structure of the oblique wing geometry avoids torques that are sometimes reacted by fuselage structure and makes for a simpler structure to manufacture. If variable sweep is incorporated in the design, the oblique wing's single pivot in tension provides structural advantages when compared with two pivots that must carry large bending loads in a conventional variable-sweep design.

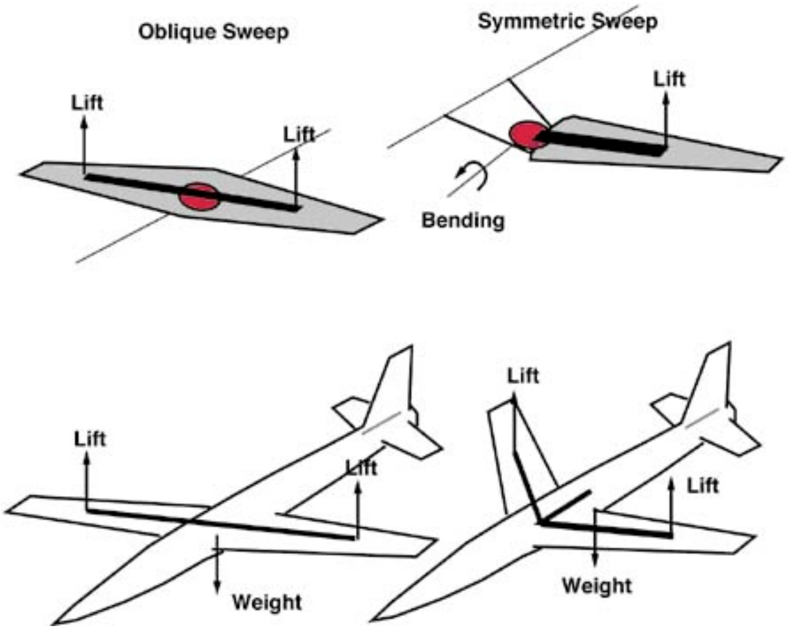

Figure 10. Structural advantages of oblique wings.

Perhaps the most significant advantage of oblique wings for variable sweep aircraft was recognized in a 1940's design by Blohm and Voss, which used oblique variable sweep to avoid the undesirable aerodynamic center shift common with symmetric variable sweep.

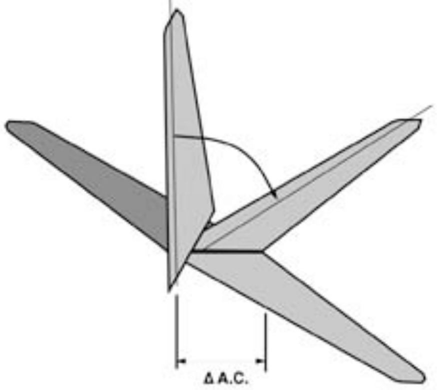

Figure 11. Oblique variable sweep reduces some of the aerodynamic, structural, and control difficulties associated with changes in symmetric sweep.

The desirable features of oblique wings for variable geometry aircraft permit these designs to maximize aerodynamic performance over a wide range of Mach numbers without the penalties usually associated with variable geometry concepts.

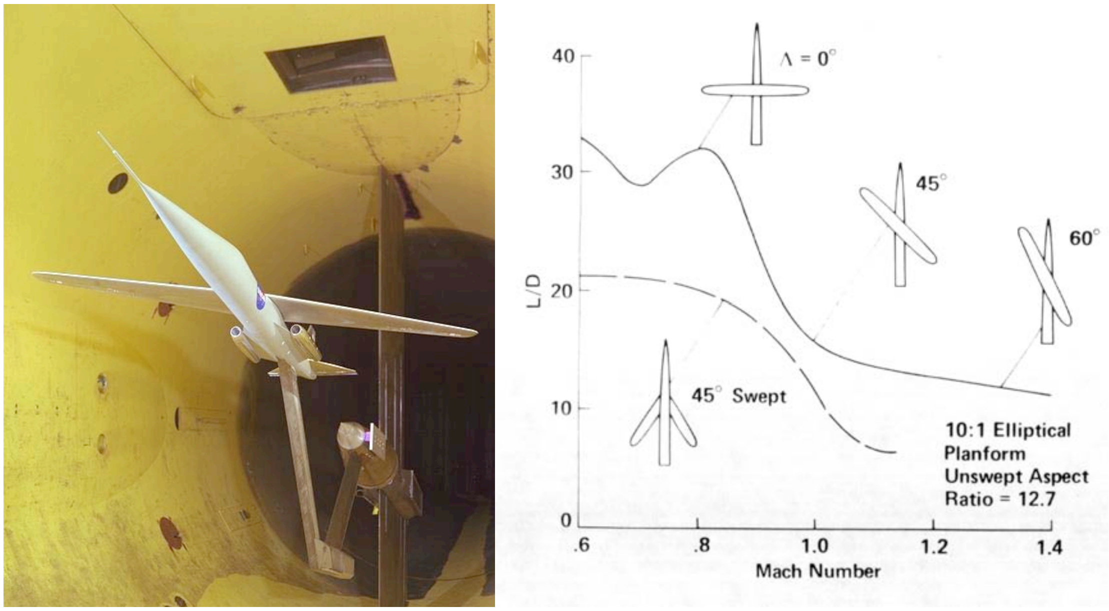

Figure 12. NASA wind tunnel tests illustrate the variation of L/D with Mach number for an oblique wing with optimized sweep compared with fixed geometry symmetric design.

Other features unique to oblique wing designs may make them well-suited for particular missions. Examples of this include efficient storage and/or deck spotting that may be appealing to Navy aircraft [6,7]

3.2.2 Oblique Wing-Body Configuration

The oblique wing concept was developed initially by R.T. Jones and colleagues at NASA Langley and Ames Research Centers. The first wind tunnel test to assess the stability and control of this unusual asymmetric concept was undertaken in 1945 [8], while the most recent NASA test report appeared in 2000 [9]. Designs for Mach 1.2 to 2.0 transports, fighters, business jets, and UAV's have been studied over this time [10-19].

Figure 13. R.T. Jones with a variety of oblique wing designs.

Considerable design experience and wind tunnel data on oblique wings was accumulated over the years, predominantly by NASA, starting with R.T. Jones and continuing with a long list of other researchers. Tests of oblique wings have included:

- High speed and low speed wind tunnel tests of rigid and flexible models, including free-to-roll aeroelastic tests.
- Several UAV's
- A piloted demonstrator (AD-1, Figure 7.)
- Piloted simulations in NASA's vertical motion simulator
- Wind tunnel tests of supersonic business jets and supersonic transport concepts

Results have been reported in numerous publications (see Refs. 20-27). These generally confirmed the aerodynamic predictions and the basic conceptual advantages of the oblique wing/body concept. One of the primary concerns for this asymmetric geometry is related to the coupling between longitudinal and lateral flight dynamics modes. That these could be controlled by a pilot was demonstrated in the AD-1 program in which numerous subsonic test flights were conducted with sweeps up to 60 degrees (figure 7). The aircraft was unaugmented with simple mechanical links from the stick to control surfaces.

Of course, a production design would use an active flight control system to decouple these modes and make the aircraft respond in a manner similar to conventional aircraft. A program to investigate oblique wing flight control at subsonic and supersonic speeds was undertaken by NASA in the mid 1980's [28-30]. The oblique wing research aircraft program was to combine a composite oblique wing with an existing F-8 aircraft, which features a wing that could be removed rather simply.

Figure 13. The oblique wing research aircraft concept was to utilize the digital flight control system of NASA's F-8 aircraft.

The program led to a variety of useful tools for oblique wing aerodynamic design and control system synthesis, a large database of high speed wind tunnel results, and piloted simulations, but funding was not sustained to complete wing fabrication and flight tests.

In addition to modal coupling, control system design for oblique wings is complicated by nonlinear stability characteristics, particularly at high angles of attack, and wing flexibility, which can interact with the vehicle dynamic modes in ways that are either helpful or problematic.

Concern with aeroelastic divergence initially led to suggestions of even more unconventional designs such as that shown in figure 14.

Figure 14. Twin fuselage oblique wing concept intended to reduce wing bending effects on structural loads and control.

More detailed unrestrained flexible vehicle dynamic simulations reduced initial concerns over forward wing divergence [31]. The asymmetric loading produced rolling motions that reduced the loading and avoided divergence. Aeroelastic instabilities could still be encountered, but these generally occurred at speeds much higher than the clamped divergence speed. Wing bending also provides favorable changes in rolling moment that can compensate for the rolling moment due to asymmetric loading changes with angle of attack. Nonetheless, complex dynamic aeroelastic behavior makes the design of control systems for oblique wing aircraft a continuing challenge [32].

3.2.2 Oblique Flying Wing

The research on oblique wing-body aircraft illustrated the importance of fuselage interactions in many aspects of oblique wing aircraft. Aerodynamic interactions lead to significant nonlinear stability characteristics, especially at higher angles of attack; aeroelastic behavior is strongly influenced by the concentration of mass near the wing center; pivot design, although simpler than symmetric variable sweep designs, is still challenging; and many of the wave drag advantages of the oblique concept are overwhelmed by the dominant volume wave drag of the fuselage. These observations led to a subsequent focus on oblique flying wings (often termed oblique all-wings to emphasize the configuration concept rather than the desired operational mode).

Although the oblique flying wing concept was described by Jones in the 1950’s [33,34] and a drawing by G. H. Lee was published in 1962 [35], the concept received little attention until recently when active digital flight control systems have became more capable and widespread.

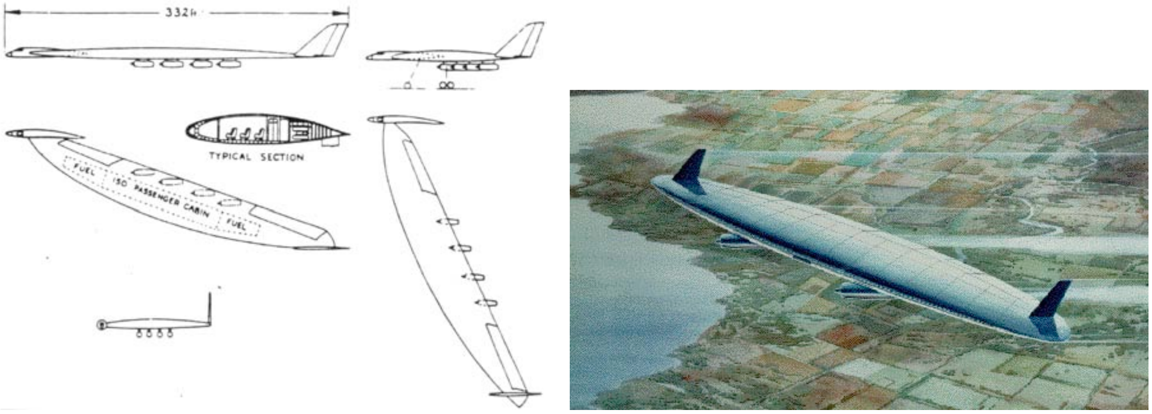

Figure 15. Oblique flying wing concepts circa 1962 (left) and 1992 (right).

In the early 1990's a design study of the oblique all-wing concept for a supersonic commercial passenger transport was conducted by NASA Ames, Boeing Commercial Airplane Company, Douglas Aircraft Corporation, and Stanford University [32,35,36]. The team at Stanford built and flew a 20-foot span oblique all-wing UAV, demonstrating flight with 3% negative static stability. High speed tests of two oblique flying wing designs were conducted in the Ames 9' x 7' supersonic wind tunnel, and included an evaluation of control surfaces and engine nacelles.

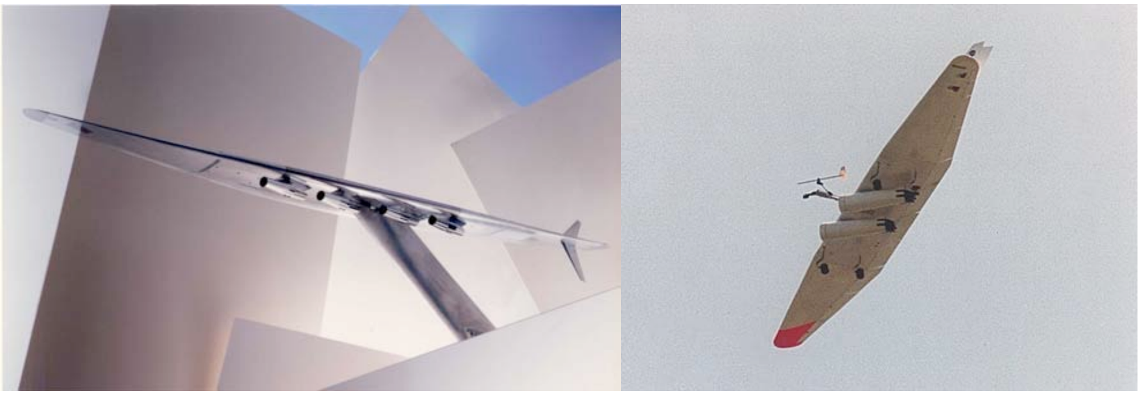

Figure 16. Oblique all-wing model for NASA high speed wind tunnel tests (left) and low speed flight tests of stability and control testbed (right).

In parallel with the aerodynamic and stability and control research, mission studies included assessing airport compatibility, landing gear design, emergency egress, structural design concepts and many other practical aspects of a civil oblique flying wing [37-39]. The conclusions of these studies suggested that such a configuration might provide large improvements in efficiency, but the large size required for passenger accommodation and the large number of new technologies involved, made the design unrealistic for near-term civil applications.

3.3 Supersonic Laminar Flow

Although the desirability of laminar flow for improved aircraft performance has been recognized for decades, the difficulty in achieving extensive laminar flow at subsonic speeds has limited its use for most aircraft. Supersonic aircraft might seem even less well-suited to natural laminar flow because high sweep and high Reynolds numbers make transition more likely.

Supersonic design, therefore, generally starts with a configuration consistent with low inviscid drag and accepts the turbulent skin friction associated with this geometry. When this approach is reversed, and one considers wings with low sweep, designed to achieve pressure distributions consistent with extensive natural laminar flow, but at the expense of some inviscid drag, some interesting design options are created. This is the approach suggested by Tracy [40,41]. Related work on supersonic natural laminar flow (SLF) has been described by Gerhardt [42], and at NAL [43]. Results suggest that significant range improvements are possible by exploiting the favorable pressure gradients associated with supersonic leading edges to achieve extensive natural laminar flow. Low wing sweep produces chordwise pressure gradients that suppress Tollmein-Schlichting instabilities while reducing the spanwise gradients that lead to cross-flow instabilities.

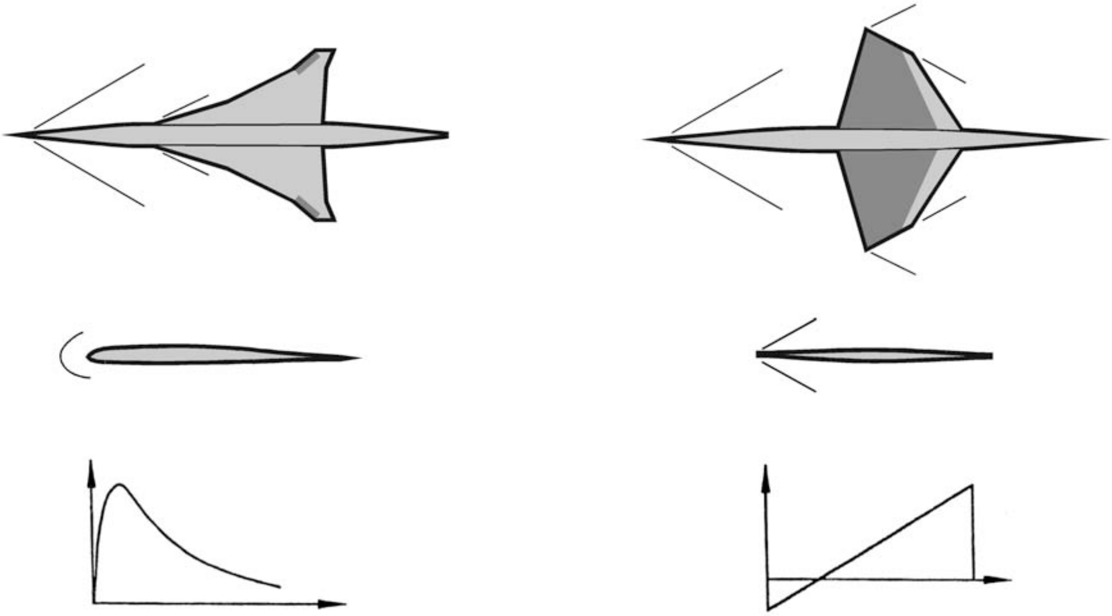

Figure 17. Conventional swept wing supersonic design (left) employs subsonic leading edge airfoils with low inviscid drag, but with adverse pressure gradients, large cross-flows and correspondingly little natural laminar flow. The low-sweep laminar design (right) uses thin supersonic sections that support a favorable gradient from leading edge to trailing edge, maintain small cross-flow, and are compatible with extensive NLF.

Several application studies have suggested that such a concept has significant performance advantages for configurations such as supersonic business aircraft or unmanned reconnaissance vehicles [44]. Figure 18 shows how such a wing configuration might be integrated with a supersonic business aircraft.

Figure 18. Artist concept of supersonic business aircraft with natural laminar flow wing. (Aerion Corporation)

The relative importance of viscous and inviscid drag components for a conventional design and the low-sweep laminar design is shown in figure 19 (from Aerion Corp., adapted from Ref. 45) and the resulting impact on the required take-off gross weight for an aircraft with a 5000 n. mi. range is illustrated in figure 20. The results suggest that if one could achieve extensive laminar flow, the required take-off weight (and fuel consumption) could be reduced dramatically.

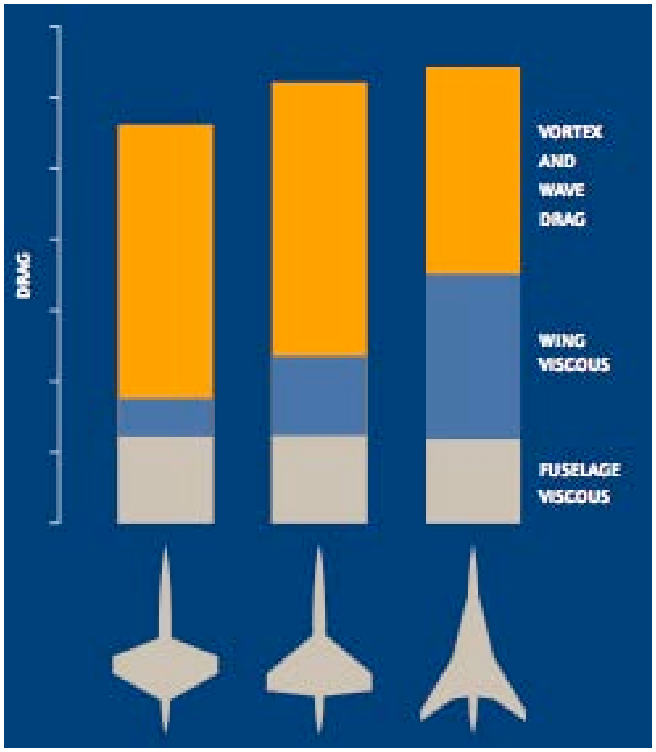

Figure 19. Viscous and inviscid drag distribution for conventional and low-sweep laminar wing concepts.

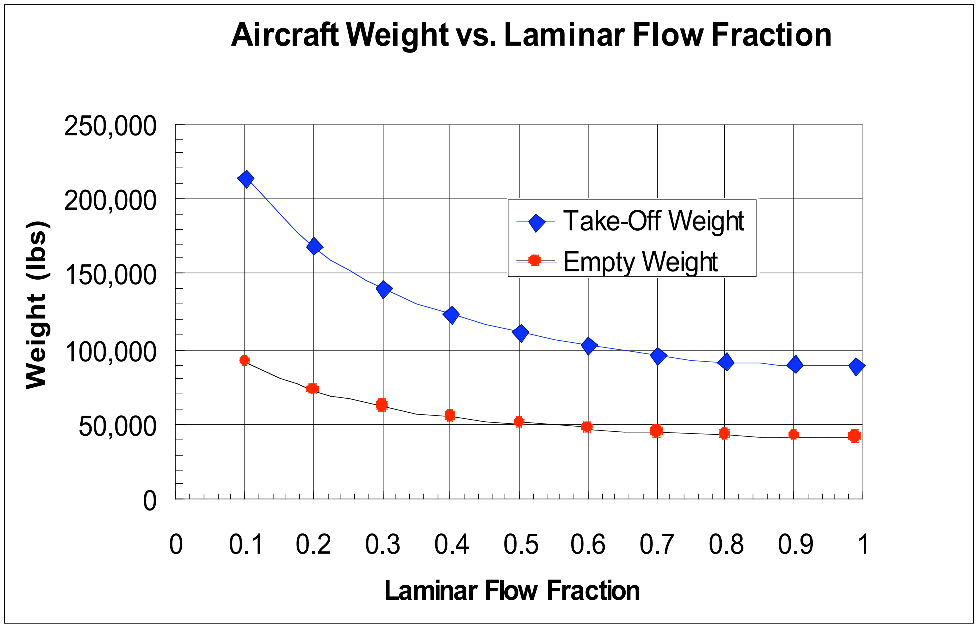

Figure 20. Large reductions in take-off weight might be possible for a small aircraft with 5,000 n mi. range if extensive laminar flow were achieved.

The reduction in sweep that might make supersonic laminar flow realizable increases the wing lift and volume-dependent wave drag. The latter may be reduced by using thin sections, but this increases structural weight. However, the low sweep has a favorable effect on low speed performance and affects the fuselage design for acceptable area distribution. All of these interacting issues require multidisciplinary optimization to arrive at a good design that meets the mission constraints while balancing the advantages of laminar flow and low sweep with the difficulties that thin wings and higher lift-dependent drag impose. Such studies have been conducted by Aerion Corporation and by researchers at Stanford, including application of a high fidelity, distributed design framework illustrated in figure 21 and described by Manning in Ref . 46.

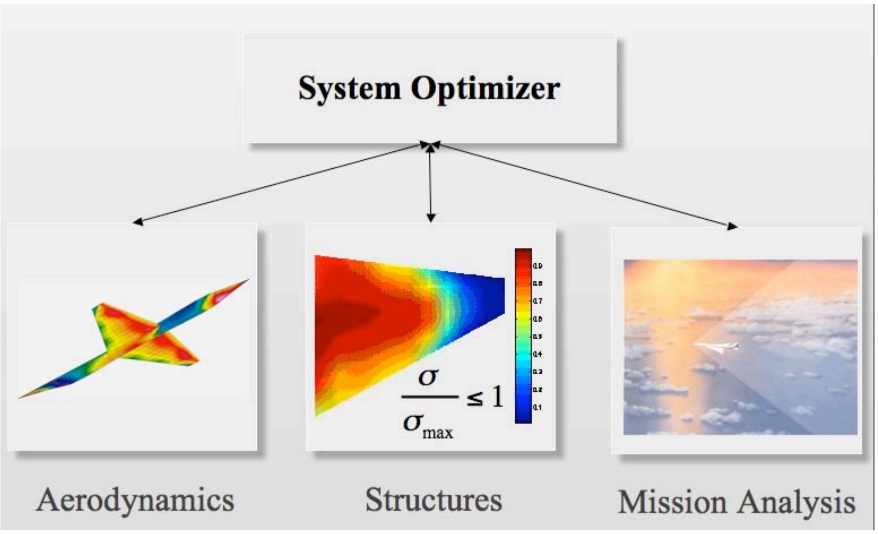

Figure 21. Distributed design framework applied to laminar supersonic aircraft design.

Multidisciplinary optimization studies for supersonic laminar flow aircraft require a method of predicting the effect of various design parameters on the extent of laminar flow, and while several transition prediction tools have been developed, none that could be easily integrated into a design code have been available until recently. The design-oriented boundary layer analysis method developed by Sturdza [47] provides this capability and has been a critical tool in the development of supersonic laminar flow designs.

The method is illustrated in figure 22 and consists of several components. The sweep/taper boundary layer method includes pressure and velocity terms from an inviscid (e.g. Euler) solution. T-S and stationary crossflow 'N' factors for swept and tapered wings are computed using a regression based model that is robust and rapid. The boundary layer and transition methods include sensitivity information via the complex-step method [48].

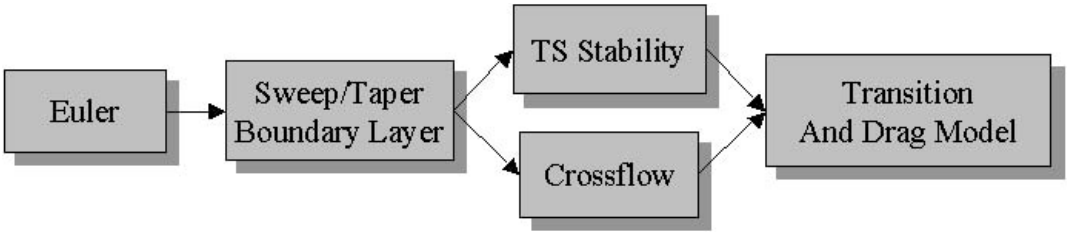

Figure 22. Basic components of design-oriented transition estimation method.

Growth of Tollmein-Schlichting instabilities is computed based on parametric fit of linear stability results. For a range of 2D sections, the LASTRAC code was used to evaluate n-factors for a range of frequencies and wave angles. A parametric fit based on integral properties of the boundary layer, similar to that used in Refs. [49,50] was then developed based on these results.

As in the case of T-S modes, a method was developed for creating parametric fits and/or table lookup approximations of e^N linear stability solutions of the cross-flow instability. The amplification rate is modeled as a function of local mean flow parameters. The three parameters were chosen based on the work of Ref. [51], and appear to work well for compressible flows, although previous work was restricted to incompressible cases. The basic method is compatible with rapid design and the MDO framework.

Figure 23 shows a comparison of cross-flow Reynolds number for a supersonic laminar wing design based on the modified sweep-taper theory and a Reynolds Averaged Navier-Stokes solver.

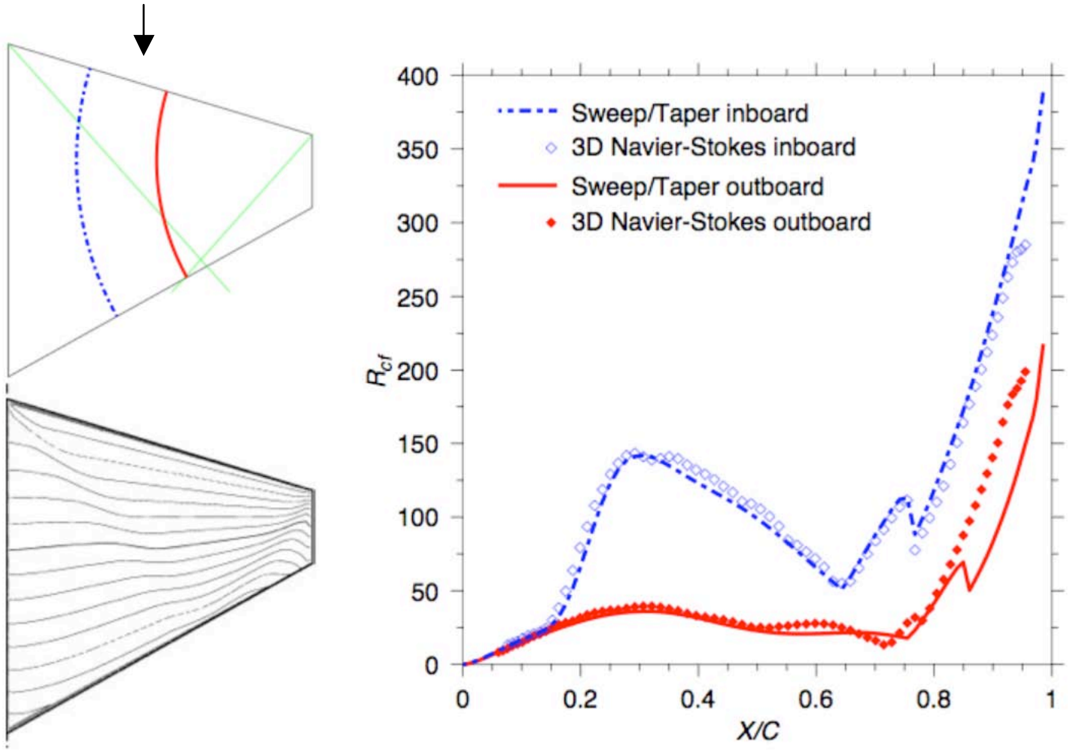

Figure 23. Comparison of cross-flow Reynolds number calculations from design-oriented boundary layer analysis and RANS CFD solution. Solutions at two spanwise stations agree well over most of the chord length. (From [45].)

With support from DARPA, NASA, and internal funding by Directed Technologies, Inc., a flight demonstration of this concept was recently completed [52]. Figure 24 shows the small scale test-blade mounted under the NASA F-15 flight testbed. The figure also shows the mid-wave infrared image taken from an on-board camera, along with the pre-test estimate of transition based on the simplified boundary layer analysis method. A combined T-S and crossflow amplification factor, N*, is shown in figure 24 with interaction effects represented based on previous empirical results (see [45]).

At the flight conditions shown, full chord laminar flow was achieved over much of the wing over a range of operating conditions that included Mach number, Reynolds number, and sideslip (angle of attack on the vertical wing). The sharp supersonic leading edges showed robustness to both contamination (since the potential for insect impact on blunt leading edges is reduced) and angle of attack variation (since the character of the C_p distribution changes little with C_L.

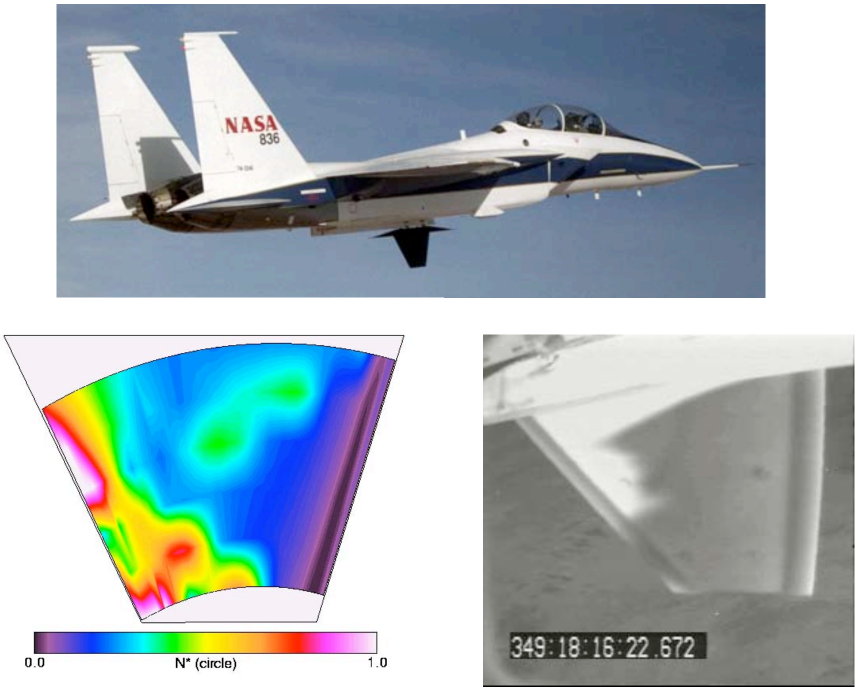

Figure 24. SLF flight test on F-15 with NASA Dryden (top). Predicted transition (left) and infrared image (right) showing extensive natural laminar flow. Mach 1.8, 40,000 ft., Reynolds Number about 10 million.

Although the initial analysis assumed an undisturbed free-steam, the flow characteristics under the F-15 were quite non-uniform and the Euler solution plus boundary layer transition prediction was subsequently used to analyze the test blade with a complete F-15 geometry. This improved comparisons with the experiment, including the influence of shocks from the camera pod that affected transition at lower Mach number. Figure 25 shows the expected transition front on the blade with the complete flowfield simulated. Two roughness elements were added to the blade to intentionally create turbulent wedges and highlight the extent of laminar flow.

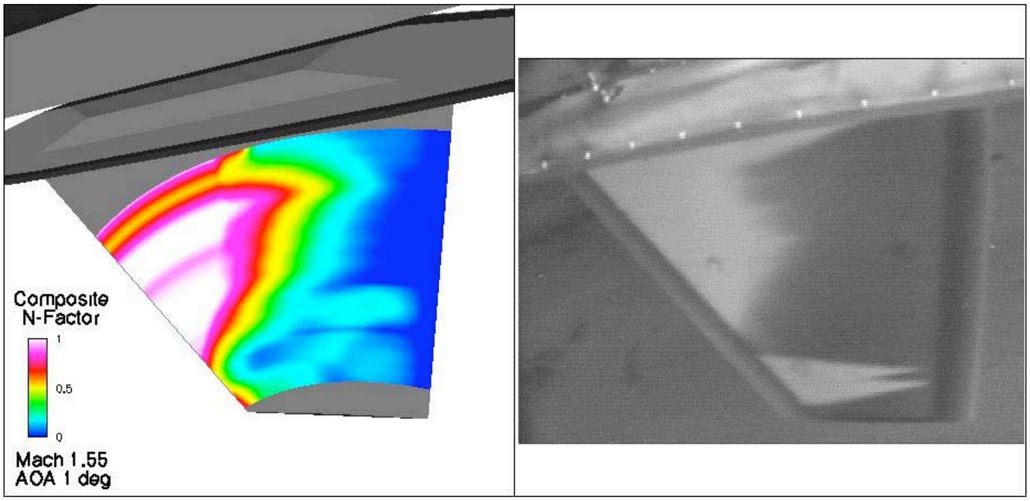

Figure 25. Supersonic Natural Laminar Flow Test Article on NASA F-15B. Simulation and experiment.

More recently the analysis code was integrated into a more complete design optimization method and applied to minimize the total drag of wings, wing/fuselage combinations (figure 26), and finally, complete aircraft designs.

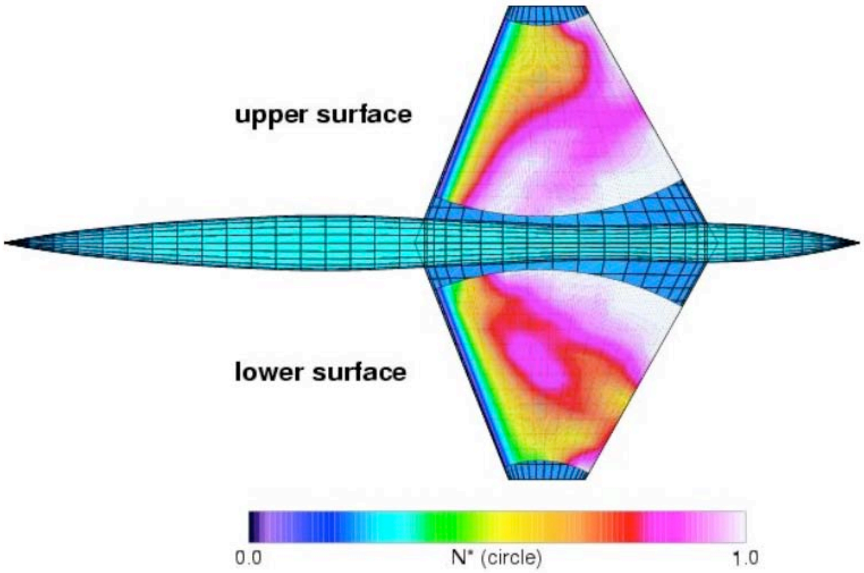

Figure 26. Wing/body optimization for minimum total drag permits tradeoffs between wing/fuselage inviscid drag and the effect of the fuselage pressure field on transition.

The method is being applied to optimize the design of Aerion Corporation's supersonic business jet concept shown in figure 27. This aircraft, designed to fly more than 4000 n. mi. at Mach 1.5 and with a maximum Mach number of 1.6 relies on efficiency gains from extensive laminar flow and good high-lift performance of the unswept wing with flaps to achieve exceptional subsonic and supersonic performance.

Figure 27. Aerion supersonic laminar flow concept.

Current specifications and performance estimates are given in figure 28, based on analysis and recent completion of a low speed wind tunnel test program. See Ref. [53] for additional information.

Maximum cruise speed:	1.6 Mach
Long range cruise (supersonic):	1.5 Mach
No boom cruise (supersonic):	1.1 Mach
High speed cruise (subsonic):	.99 Mach
Long range cruise (subsonic):	.95 Mach
Maximum takeoff weight:	90,000 pounds
Basic operating weight:	45,100 pounds
Maximum fuel:	45,400 pounds
Engines:	Two PW JT8D-219
Thrust:	Flat rated to 18,000-lb class
Wing area:	1,400 sq. ft.
Balanced field length:	< 6,000 feet, ISA, S.L.
Landing distance, wet runway:	< 5,000 feet
Range (NBAA IFR):	> 4,000 nm at 1.5 Mach
Ceiling:	51,000 feet

Figure 28. Basic specifications for Aerion Corporation supersonic laminar flow concept.

The design's high aspect ratio provides good performance at a high transonic Mach number, with a subsonic range that is as great as the supersonic range. This allows the design to cruise efficiently over land at Mach 0.95 or greater without concerns with sonic boom acceptability and to increase speed to Mach 1.6 over water when possible. A trip from Frankfurt to Chicago (3,764 n.mi.) would include subsonic cruise over Europe and the U.S. for a total of 2,154 n.mi. and 1,610 n.mi of Mach 1.6 flight for a total trip time of just over 6 hours even against 85% headwinds (Ref. [53]).

Although the Aerion concept avoids some of the questions surrounding aircraft design for low sonic boom by flying subsonically overland, many interesting configurations have been developed recently to reduce sonic boom overpressure. Designs by most of the major business jet manufacturers include configurations with retractable nose booms, very long aircraft concepts, and joined wings. The short lifting length makes the combination of supersonic laminar flow and very low boom challenging, but still intriguing and work is continuing in this area. Figure 29 (from Ref. [44]) includes a few of the concepts investigated as part of an early study for very low boom laminar flow concepts.

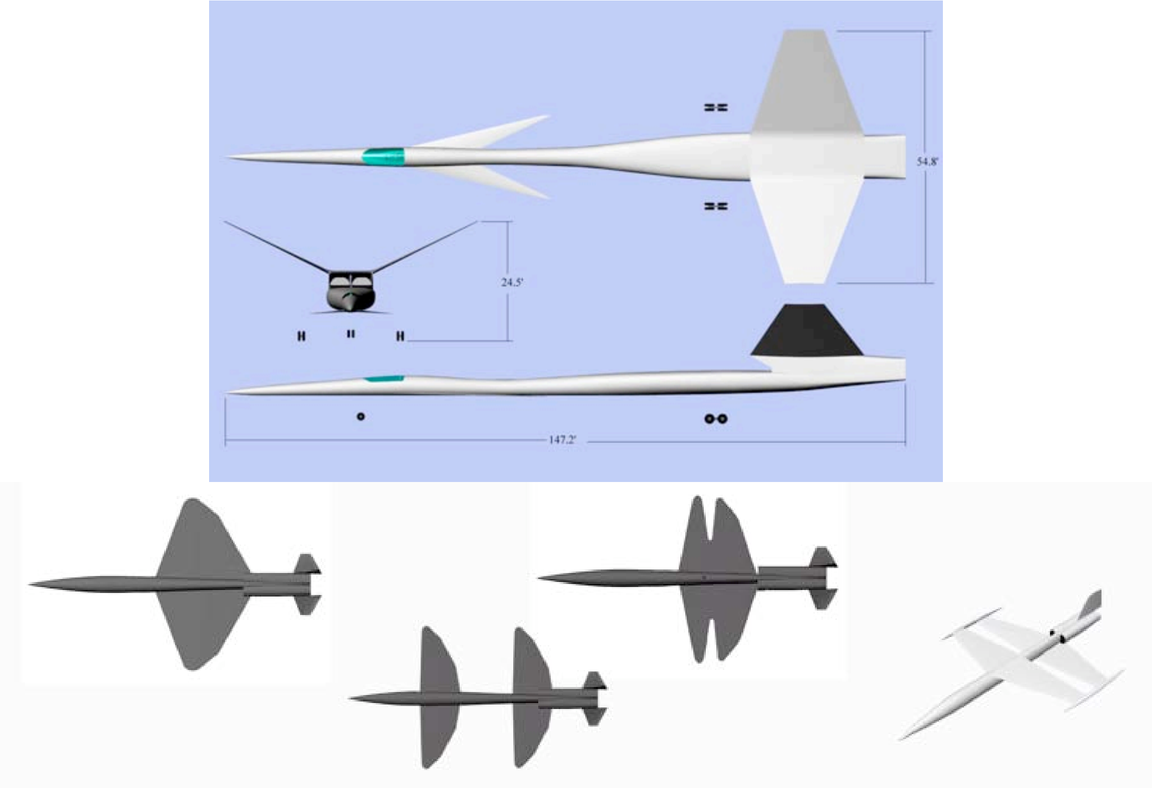

Figure 29. Some very unconventional design concepts considered for low boom supersonic laminar flow aircraft.

4. Conclusions

Supersonic flight represents a domain in aircraft design with many challenges and with many remaining opportunities for unconventional solutions to long-standing problems. One of the most significant design parameters for future supersonic aircraft is the cruise Mach number. Mach numbers of 1.4 – 1.6 are lower than technically possible, but still provide large gains in speed relative to current civil aircraft, while appearing much more feasible in terms of efficiency and environmental impact. Small supersonic aircraft are especially attractive, with reduced community noise and more assured markets.

The oblique wing/body configuration appears promising for these lower cruise Mach numbers in terms of performance and boom, but still represents an engineering challenge, while the oblique flying wing offers the potential for very high efficiency, but likely results in a prohibitively large aircraft.

Supersonic laminar flow also looks very interesting, especially for small aircraft, and although maintenance of laminar flow in a realistic operational environment has yet to be demonstrated, this concept remains very promising. A near term, environmentally acceptable supersonic business aircraft based on this technology with efficient subsonic overland flight appears quite feasible.

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