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THE OBLIQUE FLYING WING AS THE NEW LARGE AIRCRAFT

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Abstract

The Oblique Flying Wing presents the real possibility of large size, as well as transonic and supersonic speeds, at fares not significantly greater than those for subsonic flight. Studies of this aircraft have been few and limited in scope. We review these studies here and provide some new aerodynamic results of our own. We delineate the advantages and disadvantages of an Oblique Flying Wing as the New Large Aircraft and the inadequacies in our current understanding of such aircraft. We conclude that further research could lead to results that justify an experimental aircraft program to better determine the feasibility, and advisability, of an oblique wing transport large enough to accommodate passengers within the wing.

Air Traffic

The current trends in air traffic are well known.(1) Growth has been positive for most of the past twenty-five years. International travel is growing faster than developed countries' domestic travel, leisure travel is growing faster than business travel, and Asia-Pacific traffic has the largest regional growth rate. Air travel has become a commodity in the following sense: 40% of the travel is discount coach travel; the remaining 60% of the travel is 20% full fare coach, 30% business class and 10% first class. Thus, 60% of the passengers are coach passengers and two-thirds of these have discount fares.

On international routes 30% of the traffic is at a premium fare (i. e., business or first class). Two airline systems have now developed. One is the airline system that dominates most markets and provides air service to both the economy and business passengers, subsidizing economy travel by higher fares for the business traveller. The other provides a true commodity service: no seat assignments, no meals, and sometimes no baggage connection to other airlines. The latter airlines have enlarged the market for commodity travel.

For any new aircraft to succeed in these markets, it must compete either in comfort, or in fare, or some combination of the two.

In 1968 nearly eight million international passengers arrived at or departed from Kennedy International Airport with 97 thousand arrivals and departures. In 1982 over eleven million passengers arrived at or departed from Kennedy. Because of the introduction of widebody aircraft, this travel was accommodated with under 55 thousand arrivals and departures. In 1993 fifteen million international passengers used Kennedy, requiring 92 thousand arrivals and departures. Once again aircraft arrivals and departures are close to that airport's capacity.

Expected growth in air traffic cannot be accommodated for long with the world's current airports and aircraft. In developed countries there are but few airports that can be added. Thus, it is presumed that some of the increased traffic will be accommodated by larger aircraft. Larger aircraft pose special problems in that the current airports only accommodate certain size and weight aircraft. What this means for the future is unknown. It was once predicted to mean a transition to Flying Boats,(2) so we must be careful with our predictions.

When the Boeing 747 was introduced many airports

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did not have the required runway length; soon they did. Whether a similar transition is possible for aircraft larger than a stretched version of the Boeing 747, the 747-600x (500 passengers) remains to be determined. This no doubt will be carefully studied by Airbus Industrie's new Large Aircraft Division as they consider the A3XX.

One aircraft geometry, the Oblique Flying Wing (OFW), is remarkably efficient in its packaging of people, baggage and fuel, because all are housed in the lifting surface. It also offers the prospect of increased speeds at little increase in total operating costs. Simultaneously, it presents many technical challenges and may require modest changes in airport runway widths. Unlike current transports, it may distribute its load over the runway, and it could be a space saver on the ground as well.

Adolf Busemann was the first to point out that an infinite swept wing in a supersonic flow was unaffected by the tangential flow.(3) Later he realized the implication of this discovery for wave drag and showed experimentally that wing sweep could be used to fly supersonically without the adverse wave drag of supersonic flight.(4) R. T. Jones made the same discovery in the U.S. in 1944.(5,6) Jones was flying hand-launched oblique wing gliders as early as 1945.

As Busemann and Jones noted, if we could fly wings of infinite extent, we could fly supersonically without the penalty of wave drag, provided the Mach number of the flow normal to the wing is subsonic. But we do not fly wings of infinite extent. The closest we can come is an oblique wing. Jones(6) was the first to point out that for a finite wing, an oblique wing swept behind the Mach cone with an elliptical load distribution minimizes both the wave and induced drag due to lift. Later, Smith(7) considered the optimum volume distribution for such wings. Lee(8) of Handley Page Aircraft proposed a Mach 2 elliptic wing transatlantic transport (see Figure 1) as the aircraft design for what eventually became the Concorde.(9) In his proposal the pilots sat in a small fuselage located on the leading tip of an oblique wing. The vertical tail was located on the trailing tip. He assumed the aircraft would land obliquely.

The Oblique Flying Wing (OFW) Transport

Based on linear aerodynamic theory, the OFW warrants serious study as a large aircraft, both as a subsonic transport and as a supersonic transport. Indeed, because it is efficient at both transonic and supersonic speeds, it can be a near sonic transport over land and a supersonic transport over water, increasing its productivity. Despite being very large, its sonic boom is not much larger than that for a smaller Supersonic Commercial Transport (SCT). [High Speed Civil Transport (HSCT) in the US]

The Oblique Flying Wing, also referred to as the Ob-

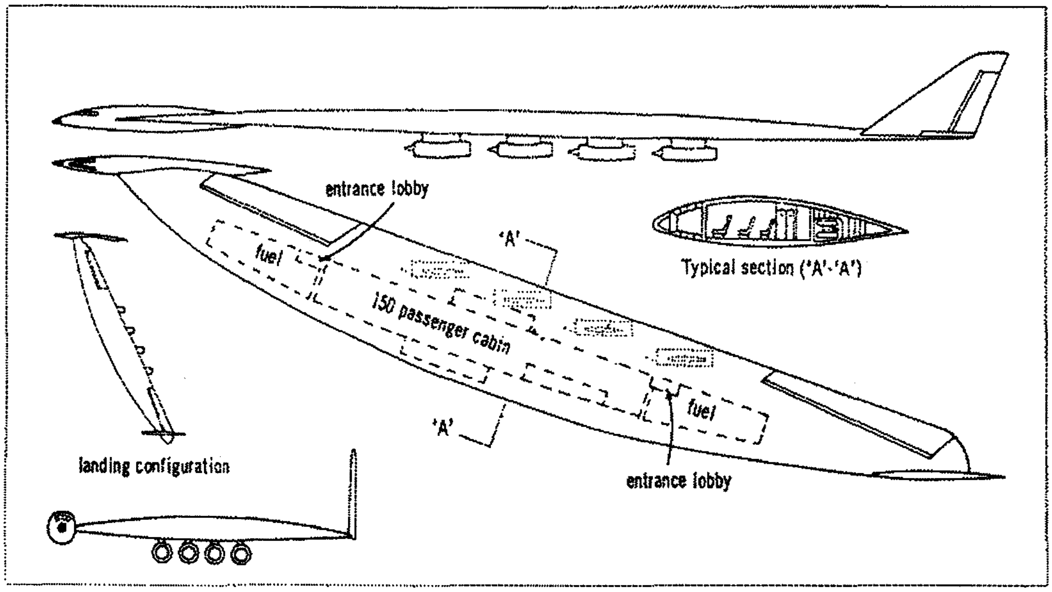

Figure 1. Mach 2 supersonic airliner proposed in 1961 by G.H. Lee of Handley Page, Ltd.

lique All Wing (OAW) to distinguish it from the Oblique Wing Aircraft (OWA), is not just the optimum aerodynamic design, it is also the optimal structural design for carrying loads, as the loads are distributed over the wing. If these loads are passengers, as distinct from cargo (or fuel in a tanker), then the minimum thickness of the wing is set by the need for aisles for the passengers. The chord of the wing is then set by the maximum thickness-to-chord ratio achievable with an airfoil design that results in an efficient wing at the chosen flight Mach. This is, of course, effected by sweep, which is limited by the need for controllability. Induced and wave drag are reduced by higher span and longer lengths, respectively, and thus the wing span (and length) are set by the aerodynamic efficiency required to compete with current subsonic transports. This means that, as a passenger transport, the OFW must be a large aircraft.

The advantage of an oblique wing over a symmetrical configuration with swept back (or forward) wings of comparable lift is clearly evident in the general expression for drag:

$$Drag = qS_f C_f + \frac{L^2}{\pi q b^2} + \frac{128 q V^2}{\pi l_v^4} + \frac{\beta^2 L^2}{2\pi q l_l^2}\ .$$

Here q is the dynamic pressure, S_f the reference area for skin friction, C_f the skin friction coefficient, L the lift, b the wing's span, V the wing's volume, and $\beta^2 = M^2 - 1$. The first two terms represent the drag due to skin friction and that induced by the trailing vortex sheet. The last two terms represent the wave drag due to volume and due to lift. The lengths in these two terms, l_v and l_l, are the average over all azimuthal angles of the effective length for volume and lift for each azimuthal angle, as determined by the supersonic area rule.

An oblique wing simultaneously provides large span and large lifting length. The reduction in the wave drag of an oblique wing of finite span comes from the very considerable average length over which lift and volume are attained. Thus, there is a clear aerodynamic advantage for the oblique wing over the swept wing. It was pointed out, at the time the importance of wing sweep was discovered, that the oblique wing was the perfect compromise between the advocates of forward sweep and those of rearward sweep.

We can see more clearly the advantages of wing sweep. Figures 2 and 3, taken directly from Jones,(10) make the point (for a complete discussion, see Ref.11). The first compares the drag due to lift of an oblique and a swept wing for a given lift; the second compares the wave drag due to volume of an oblique wing and a swept wing of the same volume as a function of the Mach number. A discussion of the theoretical background for the OFW is found in Ref. 12.

Oblique Wing Aircraft (OWA)

Oblique wing aircraft were proposed as early as 1942. Blohm & Voss in Germany proposed a specific design in 1944. They were studied by NASA for more than 40 years.(13-18) A low speed oblique wing research aircraft was built and flown on fifty flights by

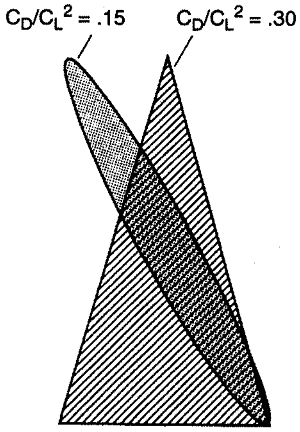

Figure 2. Drag due to lift. Oblique elliptic wing and delta wing, M = 1.4 (Ref. 10).

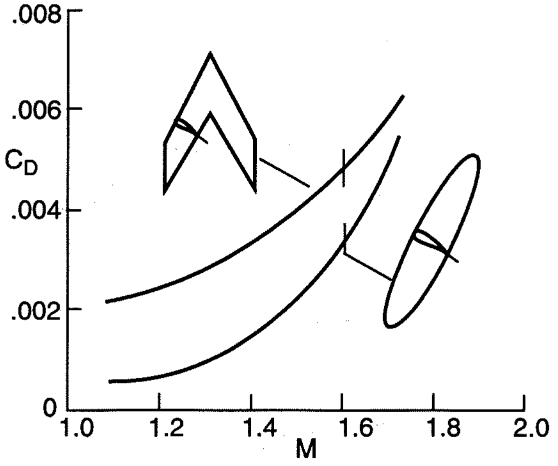

Figure 3. Wave drag due to volume of oblique elliptic and swept wings as a function of Mach number (Ref. 10).

Figure 4. Artist's concept of an Oblique Flying Wing (courtesy of NASA).

17 pilots, including three landings at 45 degrees sweep. Handling qualities were judged acceptable at sweep angles up to 60 degrees. This remains an attractive concept for selected military and commercial applications. But OWA do not lend themselves well to large size and are not considered further here.

Recent Oblique Flying Wing Studies

The recent interest in OFWs derives from studies at Stanford by Jones,(19,20) Van der Velden and his thesis advisor Kroo, and from a proposal from Stanford to NASA to build and fly a small radio controlled model to evaluate the low speed stability and control issues evident for an OFW. The early Stanford studies by Jones led to studies by the Systems Analysis Branch at NASA Ames, a Boeing in-house assessment of the concept, contractual studies funded by NASA at Boeing, McDonnell Douglas, Stanford, and the University of Kansas, over the five year period 1989-1994, and culminated in wind tunnel tests of two candidate OFWs in 1994. An early NASA artist's concept of an OFW is shown in Figure 4.

Our own investigations were prompted by the possible application of methods we developed for supercritical airfoils and wings to supersonic wings in general and to the OFW in particular. The Daimler Benz Aerospace Airbus studies derive from Van der Velden's subsequent employment there.

An excellent synopsis of the NASA supported work is provided by Galloway et al.,(21) who describe these studies and discuss the conclusions NASA drew from their own and the contracted investigations. Some of the discussion that follows derives directly from this report.

Stanford Studies

As his Ph.D. thesis at Stanford, Van der Velden undertook the development of a general evaluation tool for preliminary design of commercial supersonic aircraft including the OFW.(22,23,24) This resulted in the preliminary design of an OFW that provided additional impetus and guidance to the NASA Systems Analysis Branch in their own studies of such aircraft. Since Van der Velden's designs continued to evolve while he was employed at Daimler Benz Aerospace Airbus, we report his studies later.

Morris, in his Stanford Ph.D. thesis, examined the integrated aerodynamic - control system needed for a rigid oblique wing aircraft, showing that by tilting the pivot axis, adverse coupling could be reduced and handling qualities improved.(25) He subsequently extended these studies to the integrated aerodynamic and control system design of an oblique flying wing. The configuration matched that of a NASA design for a 400 passenger OFW.(26)

Morris noted the utility of designing the control law for the principal axes. He then demonstrated this control law with two radio-controlled OFWs. The first was ten feet in span and flew successfully at up to 65 degrees sweep. The second was a twenty foot span OFW powered by two pivoting, 5 horsepower ducted fan engines. Ten 25% chord trailing edge flaps were controlled by a Motorola 68020 CPU and a 68881 math coprocessor. The aircraft was designed to be able to fly at sweep angles from 35 to 65 degrees. Flight sensors were a 3-axis rate gyro, a 2-axis wind vane and an airspeed indicator.

In addition to the 10 trailing edge control surfaces, 2 flying vertical fins, 2 throttles and 4 landing gear struts were driven by commercially available actuators. Actuator bandwidth limited the static stability margin to -1.8%. This aircraft flew in May 1994, successfully completing a four minute flight circling the field twice, changing its sweep from 35 to 50 degrees and back. It circled the field by turning toward the trailing tip, which resulted in sweep angles as low as 20 degrees because of the high damping in yaw.

The predicted time-to-double the pitch amplitude about the wing's long axis was 0.5 seconds. Flight test data verify this negative stability margin. Figure 5 depicts the measured and the commanded angle of attack early in this flight. These and other flight results demonstrate the success of the control law. Ground maneuverability was considerable because of the landing gear strut control.

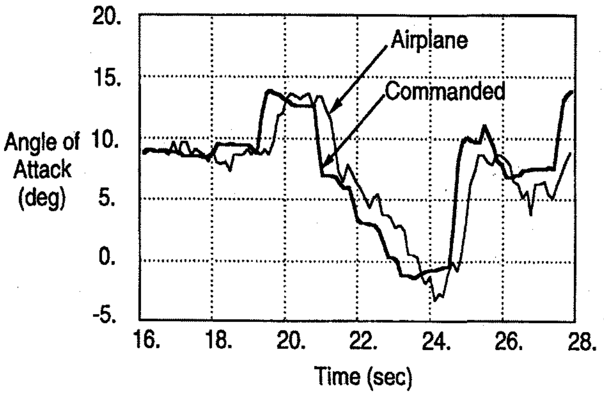

Figure 5. Commanded and actual angle of attack for Morris' radio-controlled OFW as reported in Ref. 26.

Boeing Studies

After their own in-house study of an OFW transport, the Boeing Company, under contract from NASA, developed an OFW design that would fit current airport designs and meet current FAA requirements. To satisfy the FAA requirement that the passengers face no more than 18 degrees away from the flight direction on takeoff and landing (or have head restraints), the aircraft was designed to take off without sweep, which required folding wing tips. The landing gear track was set at 60 feet.

This FAA requirement is, of course met by, and may agree with, the upper deck seat angles on Boeing 747 aircraft. One might argue that if passengers were seated facing rearward in a seat with side head cushions, a much larger angle might be permissible.

Passenger entry and emergency egress, engine and landing gear integration, as well as airport compatibility and terminal utilization were studied.(27) Four engines were used, and they were placed under the passenger compartment. This configuration, because it is designed to take off without sweep, could not become the New Large Aircraft. Nevertheless it could accommodate 440 to 460 passengers and demonstrated an OFW could be designed with existing constraints.

NASA Studies

Waters, et al.(28) studied the design of OFWs. They considered their aerodynamics, structures, and layout. This first comprehensive study highlights several critical issues for OFWs. Principal among them were the design of the structure to carry the pressurization load, and the design of the landing gear to meet FAA taxi bump requirements.

Galloway et al.(29) assessed the economics of 200, 400 and 500 passenger subsonic transports (M = 0.85), 300 passenger OWAs operating at Mach numbers 1.6 and 2.0, a 400 passenger OWA operating at Mach 2, and 291, 440, and 544 passenger OFWs operating at Mach 1.6. They assumed a five year development period, with 500 aircraft produced in the 15-year delivery schedule.

Aircraft prices varied from $114M to $158M for the subsonic transports, from $172M to $239M for the

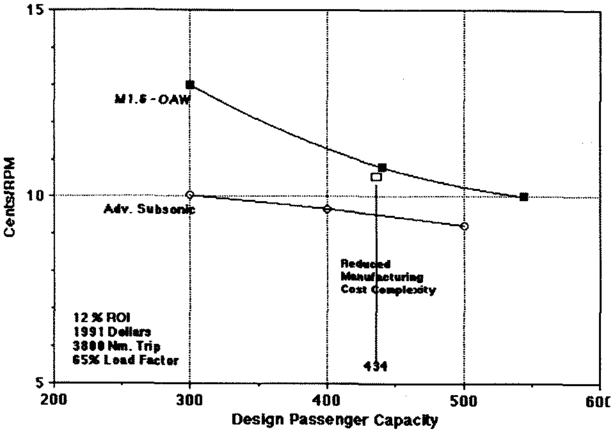

Figure 6. NASA Ames economic assessment of the revenue required per RPM to provide a 12% return on investment (ROI) for advanced subsonic transports, and for a M =1.6 OFW (OAW) aircraft as a function of size (from Ref. 21).

OWAs, and from \$212M to \$260M for the OFWs. For a manufacturer and the operating airlines to achieve a 12% return on their investments required 11 to 10.1 cents per Revenue Passenger Mile (RPM) for the subsonic transports, decreasing with increasing size, 12 to 12.4 cents per RPM for the OWA and 14.2 to 11.1 cents per RPM for the OFWs, again decreasing with increasing size. This trend toward economic equality between OFWs and advanced subsonic transports is depicted in Figure 6.

Cheung used Computational Fluid Dynamics tools to optimize a Mach 1.6 NASA OFW design(30) that was swept to 68 degrees. This optimized design, and that by McDonnell Douglas reported in the following section, were tested in the NASA Ames 9- by 7-foot Supersonic Wind Tunnel at Mach number 1.6.(31) The NASA design was tested at Mach numbers between 1.56 - 1.80 with unit Reynolds numbers of 1.0 to 4.5 million per foot. The angle of attack was varied from 0 to 6 degrees at a single sweep angle of 68 degrees. The 1.8% scale model included four nacelles and two vertical fins, one on the top and the other on the bottom of the trailing tip. The results of these studies are not yet published. Preliminary results indicate that the experiments validate well the numerical studies which resulted in a design that, while not optimum, was realistic in layout.

McDonnell Douglas Studies

Studies by McDonnell Douglas Aerospace West provide guidance on how many passengers a large OFW might carry, how much it might weigh, and at what speeds and altitudes it might fly. They first considered a Mach 1.6 wing swept to 68 degrees.(32) Subsequently, they studied OFW designs for Mach

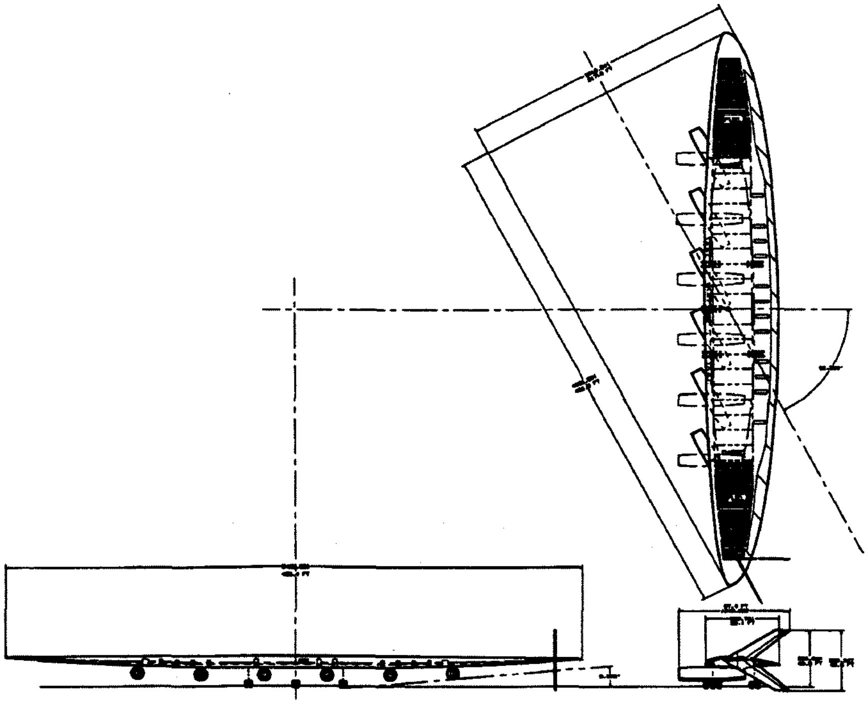

Figure 7. McDonnell Douglas M = 1.3 OFW capable of carrying 800 passengers 5146 nautical miles (Ref. 33).

numbers of 0.85, 0.95, and 1.3 over a large range of sizes. These designs were compared at M = 0.85 to point designs for a conventional subsonic transport and a blended wing body at M = 0.85.

This study(33) concludes that with M = 1.3, a 750-800 passenger OFW with a 5200 nautical mile range would require an unswept aspect ratio of about 10 (see Fig. 7). With a passenger cabin height of 82 inches and a nominal airfoil thickness of 17%, the chord becomes about 55 feet and the span about 455 feet. This results in a wing area of 20,788 square feet and an aircraft with a Takeoff Gross Weight of 1.6 million pounds, with 0.75 million of this weight in fuel. A sweep angle of 62.5 degrees was used; with M = 1.3 this provides a nominal normal Mach number of 0.6.

Daimler Benz Aerospace Airbus

Van der Velden,(34) in a comprehensive extension of his Ph.D. thesis, considered the preliminary design of a 250 passenger, Mach 1.6, OFW with a range of 5000 nautical miles. The passengers may face the leading or trailing tip. The latter may be desirable for safety reasons, as the back rests may serve as head restraints on takeoff and landing. As Van der Velden notes, the passengers would use shoulder straps. He presumed a 19% thick airfoil operating efficiently at a normal Mach number of 0.6, requiring 68 degrees of sweep. With a center airfoil thickness of about 10 feet, the chord at mid-span is about fifty feet. A span of 370 feet is required to carry the 250 passengers. For stability the wing is trimmed at 32% chord, providing an aircraft that is close to neutrally stable. The gear track is 115 feet and the engines are outboard as shown in Figure 8.

The loading needs to be elliptical for minimum drag due to lift. This requires a linear twist, increasing with Mach numbers. This is accomplished, as suggested by R. T. Jones, by wing bending which effectively provides variable linear twist as the wing is swept.

The aircraft would take off at 45 degrees, increase its sweep to 52 degrees to reduce it response to gust loads, climb subsonically to the tropopause, then accelerate to Mach 1.6 as the wing is swept to 68 degrees. The Total Operating Cost reported was 25% larger than that of a 747-400. Van der Velden concludes that OFW with 375 or more passengers will have lower TOCs than current subsonic transports, which is considerably more favorable toward OFWs than the results of Galloway given in Figure 6.

University of Colorado Aerodynamic Studies

We have considered both the aerodynamic design of OFWs and their sonic boom. We report briefly on our aerodynamic design studies here.

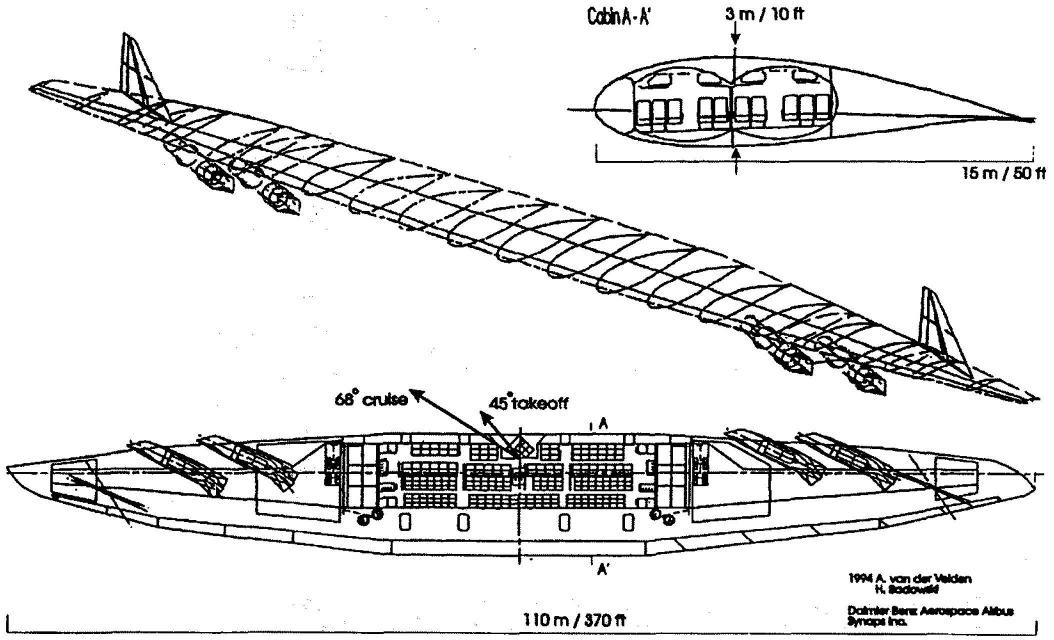

Figure 8. Daimler Benz Aerospace Airbus design for a 250 passenger, Mach 1.6 OFW (Ref. 34).

At cruise conditions, the flow over an OFW is that behind the nearly conical shock wave emanating from the leading tip. The wing is swept so that the component of this flow normal to the wing's leading edge will be sufficiently subsonic that a thick, shock-free airfoil may be found. We have assumed this sweep to be 60 degrees.

Boerstoel$^{(35)}$ provides guidance on how thick a non-lifting airfoil might be if designed to be shock free. His results, and those of others, suggest it should be possible to design an 18% thick shock-free airfoil for a normal Mach number, M_n, of 0.76. This suggests to us that a 17% thick airfoil with a c_l of 0.6 should be possible for a Mach number of 0.7. We presume here that at their design point optimum OFWs will have neighboring lift coefficients for which they are shock free, but not optimum, as is often the case for supercritical airfoils and wings. Conversely, we presume a shock-free design will have a neighboring lift-to-drag ratio (L/D) that is even higher.

The normal component of the flow accelerates over the wing to become locally "supersonic." The return of this component to "subsonic" cross flow is normally through a shock wave, just as it is on supercritical but not shock-free airfoils. This cross-flow shock wave adversely affects the boundary layer and, thereby, the wing's lift and drag, just as it does on subsonic, supercritical airfoils and wings (see, e.g., 36).

We can fix our ideas for supersonic flow by considering supersonic conical flow past a wing with subsonic leading edges and conical camber. Such a wing will, unless designed using special tools, have a cross-flow shock wave like that depicted in Figure 9. While this flow is supersonic, the cross-flow plane equations are mixed, being hyperbolic outside the conical shock wave and inside the local "supersonic" cross-flow region, but subsonic elsewhere.

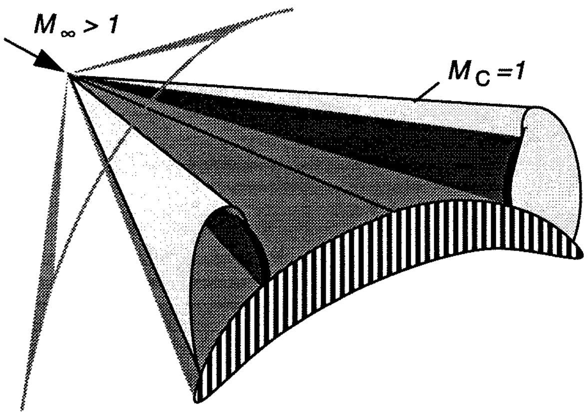

Figure 9. Embedded shock wave in a conical cross-flow.

Thus, the fictitious gas method proposed by Sobieczky$^{(37)}$ for the design of supercritical airfoils, which has been extended to more general gas laws and applied to three-dimensional wings,$^{(38\text{-}41)}$ applies to conical supersonic flows as well. This extension to supersonic flows was first demonstrated by Sritharan.$^{(42)}$ Recently, we have suggested that this method may apply to fully three-dimensional supersonic flows.$^{(43)}$ The studies reported here derive from the work reported in Ref. 43.

Because of the axial component of the flow, which we may estimate to be the flow over a slender body of revolution whose cross-sectional area equals that of the wing, there is first a decrease, and then an increase down the wing, in the Mach number of the normal component, requiring different airfoil designs, or at least thickness, along the wing. We realize, then, that the upper surface curvature and thickness of wing sections should be decreasing toward the wing trailing tip, in order to avoid creating a cross-flow shock or increasing a shock's strength if one has already formed. Our objective was to find out how well we might do in designing an OFW, finding supercritical airfoils that we developed using our methods, and then appropriately blending them to form the wing.

We need to remark here that two goals come immediately into conflict. The OFW design that maximizes inviscid L/D, that is, has the minimum induced and wave drag due to lift, has an elliptic load. The optimum area distribution to minimize the wave drag due to volume, or due to thickness, is the Sears-Haack body for volume, and the Sears body for thickness. Consequently, we have endeavored to minimize the drag due to lift, accepting the resulting wave drag due to volume.

We choose a sweep angle of 60 degrees for ease of control and aeroelastic stability, and a freestream Mach number of $\sqrt{2}$ for simplicity, giving a normal Mach number of $\sqrt{2}/2$. Higher speeds are possible with more sweep, or less thickness (which means a larger wing), but stability and control become increasingly difficult, with 60 degrees being judged acceptable in previous studies on OWAs.

At first we perform a preliminary airfoil design using our fictitious gas method. A 17.4% thick baseline airfoil is generated by Sobieczky's geometry tool$^{(44)}$ for

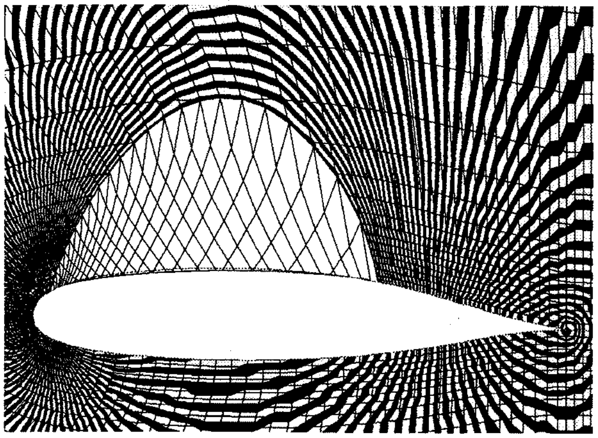

Figure 10. Pressure contours and grid in the subsonic flow, and the characteristics pattern in the supersonic flow for a shock-free airfoil designed for OFW applications: $M_\infty = 0.707$, $c_l = 0.6$.

a flow of $M_\infty = 0.707$ with $c_l = 0.6$, which corresponds to the normal flow component of the supersonic flow over the swept OFW. For choosing the fictitious equations used in the Euler solver, we prescribe a new energy equation(43) to change the equations inside a local supersonic region so that they remain elliptic there. This results in a shock-free flow with a smooth sonic line, but the wrong gas law, inside the supersonic region. The correct mixed type structure of the transonic flow is recovered in the next step: supersonic flow recalculation by means of the characteristic method using the just calculated data on the sonic line for the initial values. This recomputation of the flow with the correct equations of state has a lower density in the supersonic flow and provides a modified, and thinner, airfoil design. The result is a slightly flattened section (see Fig. 10) with a thickness of 17%.

Figure 10 shows the pressure contours in the subsonic flow and the characteristics in the local supersonic region for this new airfoil. In some cases we will find limit lines in the real supersonic flow calculation, indicating a smooth flow does not exist.

For the airfoil considered above we have selected a design lift coefficient appropriate for an OFW transport. The OFW's lift coefficient for its supersonic Mach number will be lower by the square of the ratio of the normal to freestream Mach numbers, or in this case, by a factor of 4. Thus the wing design will have a lift coefficient, C_L, of about 0.15.

We use this shock-free, redesigned airfoil as the center section for our OFW. We calculate the three-dimensional flow using the code CFL3D,(45,46) which was developed at NASA Langley. To determine the blending of wing sections, we have calculated the variation of the normal Mach number along the body caused by the tangential flow component of free stream by using the linear theory for bodies of revolution, as noted earlier.

To achieve the elliptic load distribution, twist variation along the wing span is needed, which is in a linear form near the center, strongly decreases at the trailing tip, and slightly increases at the leading tip. As noted earlier, the elliptic loading can be better realized by bending the wing up at the tips. For simplicity we have used wing twist in our studies.

In Figure 11 we depict the blending of supercritical sections and the variation of twist used to achieve a nearly elliptic loading at the shock-free design point. The twist was varied from -10 to +5.5 degrees, the wing section thickness parameter from 0.3 to 1.5 from the trailing to the leading tip. Between the center section and trailing tip, three support airfoils are

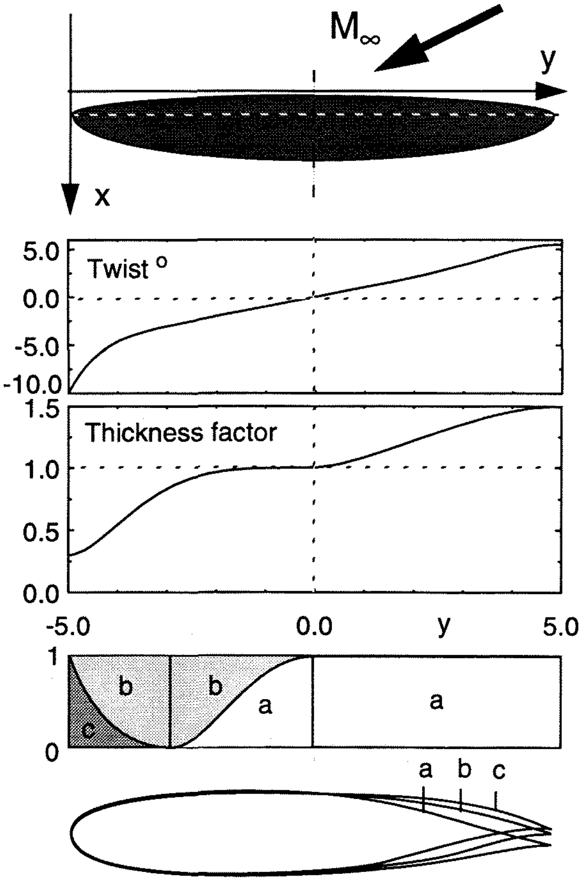

Figure 11. Wing geometry parameters: planform, twist distribution and thickness function along span, support airfoils and their blending weight.

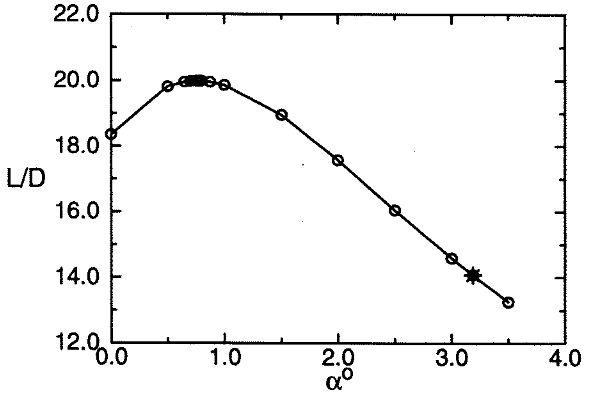

Figure 12. Lift-to-drag ratio as a function of angle of attack, ∗ denotes the shock-free design point.

blended.

The resulting lift-to-drag ratio of this OFW is an unsatisfactory 14.1. This should not be surprising. We have designed a wing that would perform well in a subsonic normal flow of $M_n = 0.707$ and then varied its twist and thickness to achieve an elliptic load at design conditions corresponding to a wing swept at 60 degrees in a Mach $\sqrt{2}$ flow. We are accustomed to the observed fact that highly efficient supercritical wings (and airfoils) frequently have nearby shock-free flows, usually at a lower Mach number and/or C_L.

Consequently, we explored the variation in the L/D with angle of attack for the above wing swept to 60 degrees in the constant Mach $\sqrt{2}$ flow.

Figure 12 shows this variation of the lift-to-drag ratio of the designed wing with the angle of attack. Surprisingly, we find that the nonlinear optimum inviscid L/D of about 20 occurs at a C_L much lower than the design C_L. A lower C_L means a lower flight altitude and thereby lower structural requirements for pressurization.

Then, at this new design condition, we changed the twist distribution from that in Figure 11 to one that varies from -6 to +3.5 degrees between the trailing and leading tip. We also carefully varied the sensitive ordinate of the support airfoil in the trailing portion of the wing to obtain the results shown in Figure 13. By this process we have recovered a nearly elliptic loading and the shock waves on the trailing portion of the wing are relatively weak. The inviscid L/D of this wing is 22.5.

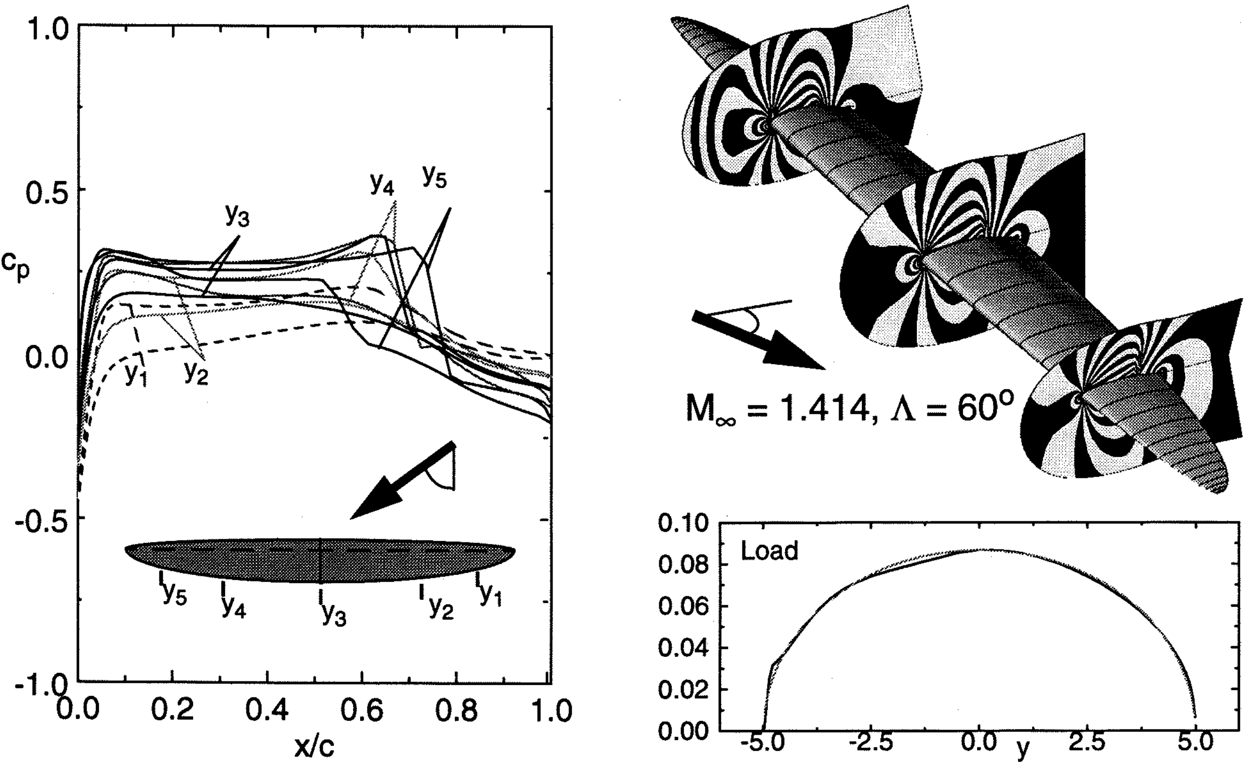

Figure 13: Pressure distributions at five span stations and isotachs on three grid surfaces for OFW with elliptic load distribution obtained with varying wing sections and nonlinear twist distribution, L/D = 22.5.

In a previous study(43) we conjectured that the fictitious gas method may be extended directly to three-dimensional supersonic flows. Such an extension, or robust optimization tools such as that developed by Jameson(47) and implemented by Reuther et al.,(48) should be able to improve considerably on our modest results. Our results, nevertheless, serve to reinforce the optimistic conclusions of Van der Velden regarding OFW aerodynamics.

Market

What might the market be for an OFW? Several market studies have been made for an SCT (HSCT), predicting a market for 500-1000 aircraft.(49,50) Davies, on the other hand, finds it to be between 9 and 36 depending on how optimistic one is.(51) The difference stems from what one projects for the fare required to pay the Total Operating Costs.

Figure 14, with the first four columns taken from Ref. 52, depicts an older Boeing forecast of the percent distribution of Available Seat Miles from Scheduled Airlines as a function of aircraft size classes for 1991, 2010 and 2015, combined with the NASA forecast of the change in this distribution in 2015 by the introduction of an HSCT [SCT] in the fourth column. We have augmented these forecasts by a fifth column showing the size of the market available to an OFW, assuming it captured the large aircraft and supersonic aircraft markets. A successful OFW might quickly capture 25% of the total Revenue Passenger Miles.

Advantages / Disadvantages of the OFW

The advantages of the OFW are its low aerodynamic drag at all speeds and its low structural weight, providing thereby excellent subsonic, transonic and supersonic performance, low airport noise, and less concern about its emissions in supersonic flight because it would fly at lower altitudes than an SCT (HSCT) in supersonic flight.

The OFW's disadvantages are the multiple new technologies that would be introduced, its match to existing certification requirements and runway widths, the non-ideal shape for the structure required to contain cabin pressurization, the need for active control, the limited speed of perhaps Mach 1.6 or less, and the psychological impact of an unsymmetrical configuration.

Conclusions

Adam Brown(53) has pointed out that, "... as the size of an aircraft is increased, economies of scale can be obtained. But at some point, the engineer's dreaded 'square/cube' law takes over and increasing size ac-

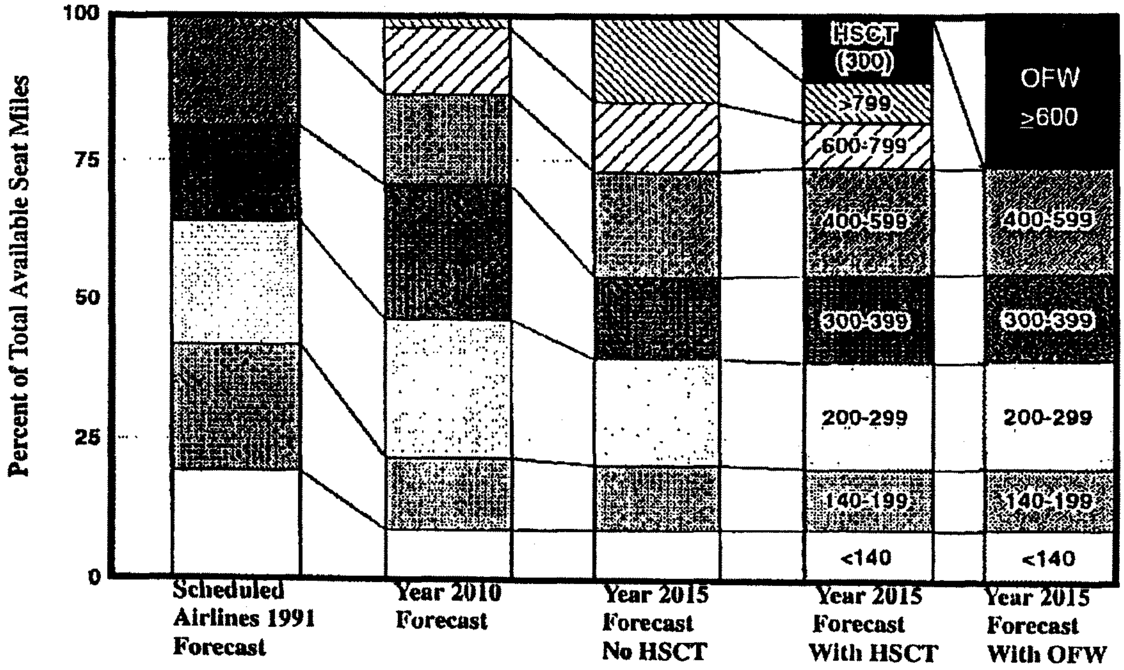

Figure 14. Current and forecast available seat miles for various aircraft class sizes, and the effect of the introduction of an HSCT, or an OFW (first four columns from Ref. 52).

tually results in *worse* structural efficiency. The Very Large Aircraft appears to be close to this cross-over point." This suggests, then, that we must side step this dreaded law by considering new geometries. Among them, the OFW represents the aerodynamic and structural optimum.

As a large aircraft, the OFW has both aerodynamic and structural advantages over conventional configurations. Because of its aerodynamic efficiency at transonic and supersonic speeds, it also offers the prospects of a 50% or more increase in speed on over water routes, and as much as a 25% increase on over land routes. And it may do this at no more than current subsonic transport total operating costs because of its increased productivity. A successful OFW could ultimately capture 25% of the revenue passenger miles.

Much remains to be determined about the OFW's aerodynamics, structures, and control. Today, leading edge computational technologies make it possible to address the aeroservoelasticity of an OFW. If promising results are obtained to the technical challenges of the OFW, then an experimental aircraft program is warranted to verify these findings and explore related issues. The world-wide excess military aircraft production capability could make such a program less expensive than it might otherwise be.

Because of its high efficiency and productivity, as well as the need for active control, this aircraft might first enter service as a cargo aircraft, where it could be smaller, in order to demonstrate the safety of the technology for commercial passenger service.

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