DYNAMICS ANALYSIS of Two Pusher Aircraft

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EAA 135915

Dedication
This article is dedicated to the memory of Professor Edgar Lesher, who died on May 19, 1998.

INTRODUCTION

Previously, the application of Computational Fluid Dynamics to the RV-6, Nemesis® and Shadow was presented. In this installment, we will look at several pusher aircraft. Once again, the goal will be to see what we can learn from the application of computational analysis methods to these aircraft.

Pusher aircraft seem to hold quite an attraction for aircraft designers. Quite a few have been designed. Sometimes, the intent has been to eliminate the drag caused by the wake of the propeller passing over the components behind it. Sometimes, the intent was to eliminate the destabilizing influence of the propeller wake on regions of laminar flow on downstream surfaces. Sometimes, the intent is to place a major noise source behind the passenger cabin. Others have extended a theoretical argument that a pusher aircraft's propulsive efficiency will be superior, as the propeller will be ingesting and reaccelerating much of the air in the aircraft's boundary layer. For various reasons, these expectations have rarely been realized.

One particular category of pusher aircraft are those with long driveshafts, that allow the engine to placed quite far forward of the propeller. There have been many aircraft that fall into this category, such as Molt Taylor's Mini-Imp and the Cirrus VK30. The two representative aircraft of this type that will be discussed here are Professor Ed Lesher's Teal and the Lear Fan.

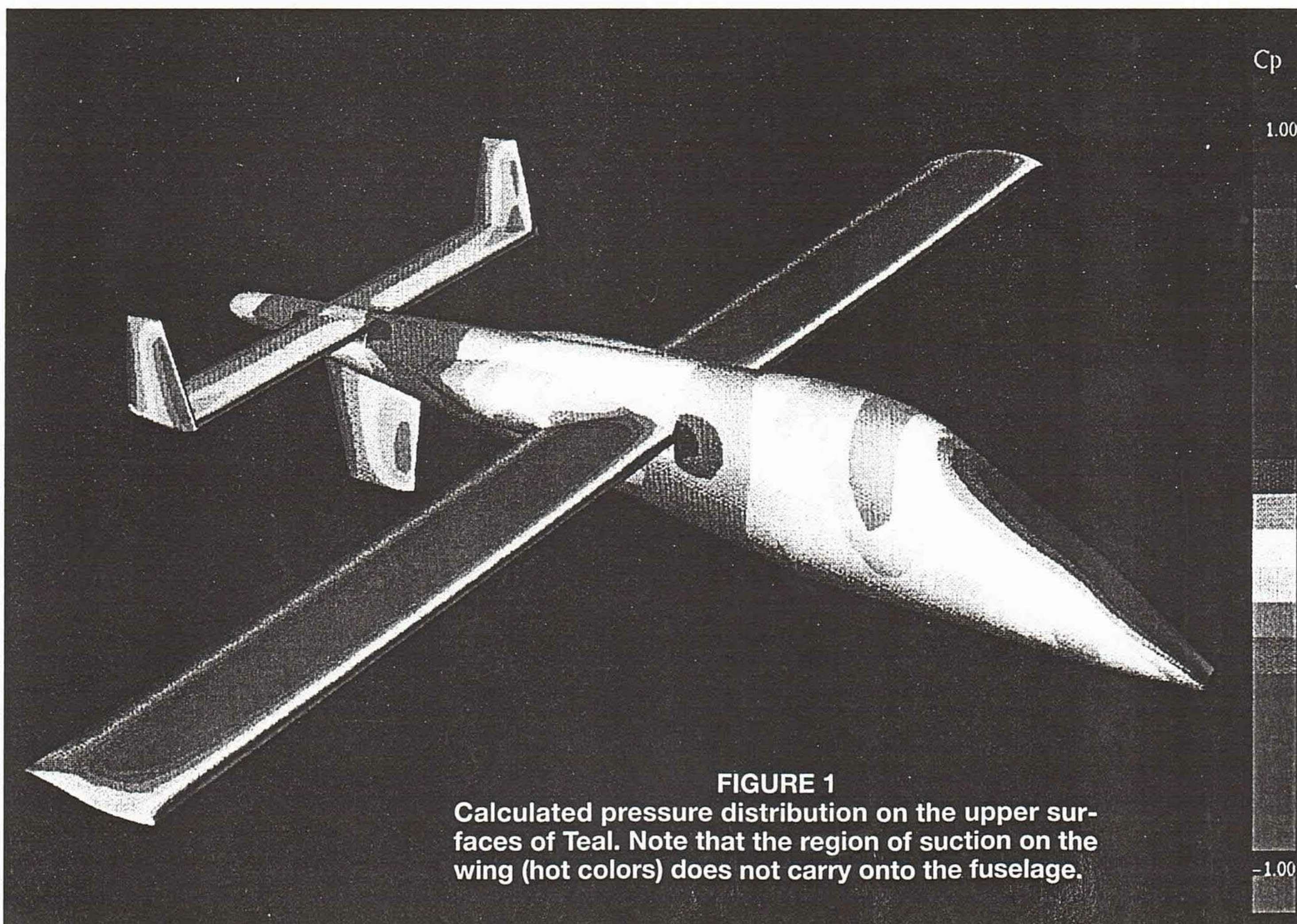


FIGURE 1
Calculated pressure distribution on the upper surfaces of Teal. Note that the region of suction on the wing (hot colors) does not carry onto the fuselage.

LESHER TEAL ANALYSIS

Teal was designed by Professor Ed Lesher, starting in 1962, with the intent of setting new records in the FAI C-1.a category for aircraft of gross weight not exceeding 500 kg (1,102 lbs). First flight was on April 28, 1965. Powered by a 100 hp Continental O-200, Teal quickly proved to be a real record setter. Professor Lesher, flying Teal, at one point held the following category C-1.a records:

- 3 km speed, 173.101 mph, September 29, 1973
- 15/25 km speed, 169.134 mph, September 30, 1973
- 500 km speed, 181.546 mph, May 22, 1967
- 1000 km speed, 162.211 mph, June 30, 1967
- 2000 km speed, 141.834 mph, October 20, 1967
- Straight line distance, 1835.459 miles, July 2, 1975

Many of these records stood for quite some time, but they have now all been broken. These records are now held by pilots flying VariEzes and Formula One air racers. Teal is unique in holding such a range of records.

Considering my admiration for Professor Lesher and his aircraft, it is perhaps surprising that I didn't analyze Teal long ago. The inspiration instead first came to me late one evening in 1996. Years ago, I had been given an EAA publication, Metal Aircraft Building Techniques, that contains articles on both of the airplanes Ed has designed and built, Nomad and Teal. Upon examination, I realized that Robert Pauley's drawings accompanying the Teal article had everything I needed to prepare a computer model of the aircraft. With this information, I was able to build the model in a week's worth of evenings.

The pressure distribution calculated on the model of Teal, trimmed in cruise is shown in Figures 1 and 2. As

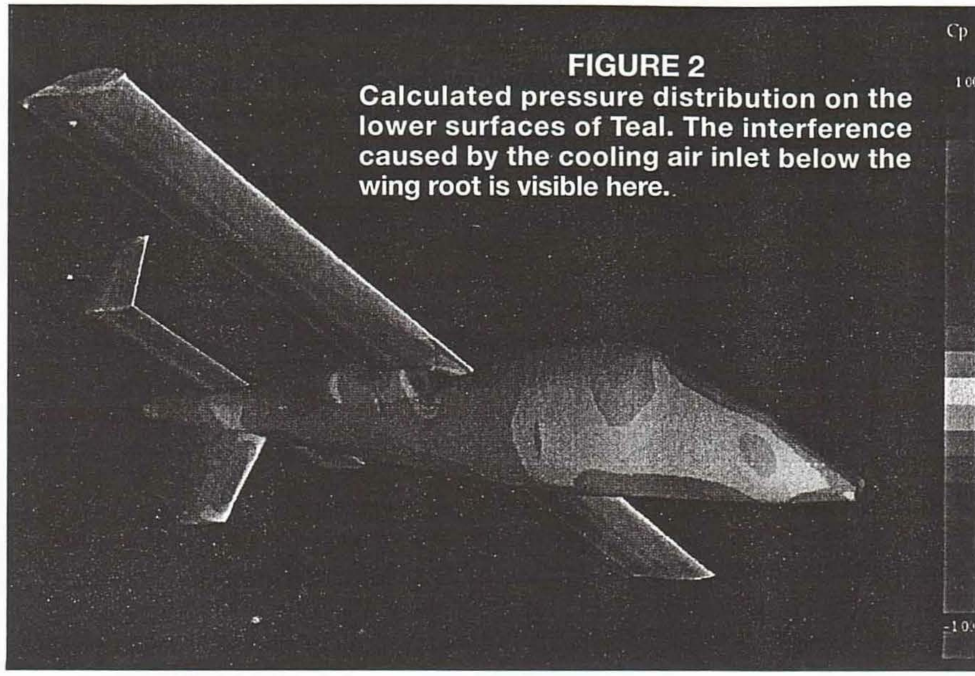


FIGURE 2
Calculated pressure distribution on the lower surfaces of Teal. The interference caused by the cooling air inlet below the wing root is visible here.

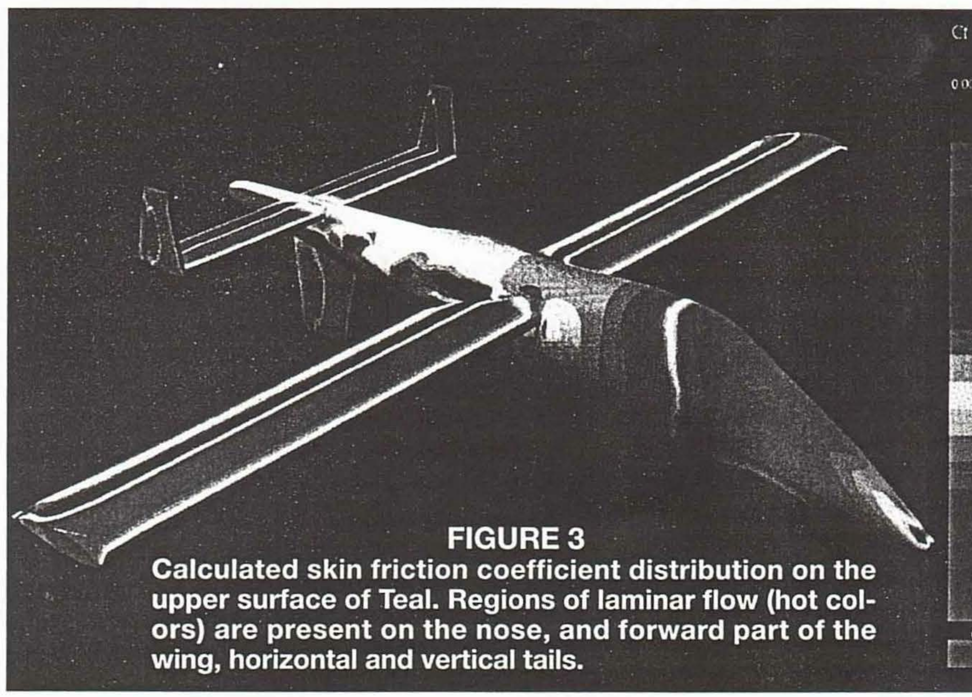


FIGURE 3
Calculated skin friction coefficient distribution on the upper surface of Teal. Regions of laminar flow (hot colors) are present on the nose, and forward part of the wing, horizontal and vertical tails.

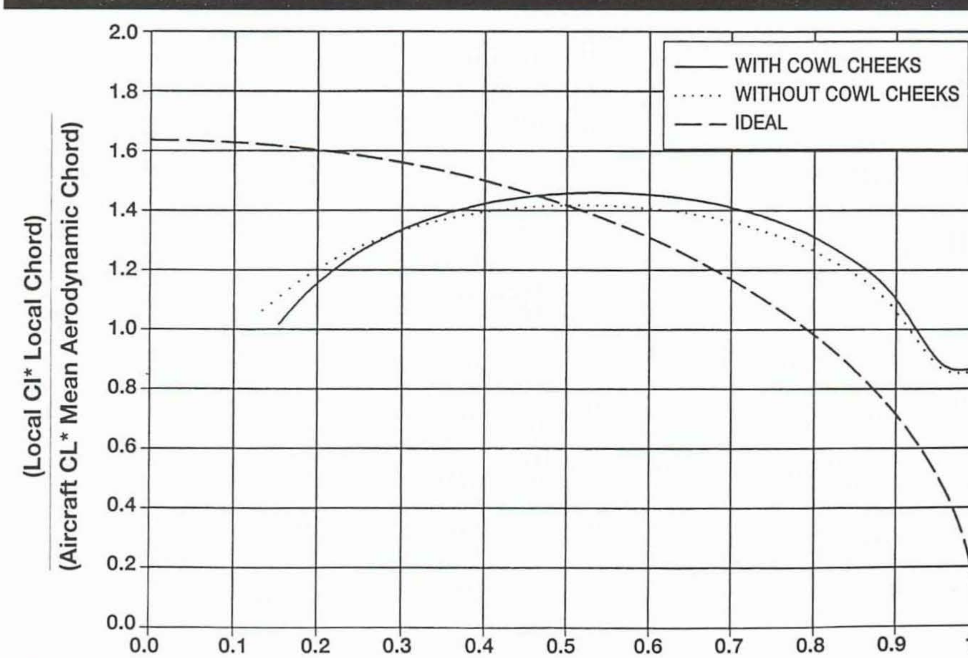


FIGURE 4

Calculated lift distribution on the wing of Teal, in cruise, with and without the cowl cheeks present. The distribution plotted here is actually that of non-dimensionalized circulation, but as the wing chord is constant, the lift coefficient distribution has the same shape. The optimal shape of this distribution would have the greatest values near the left side of the graph, instead of having the decrease seen here.

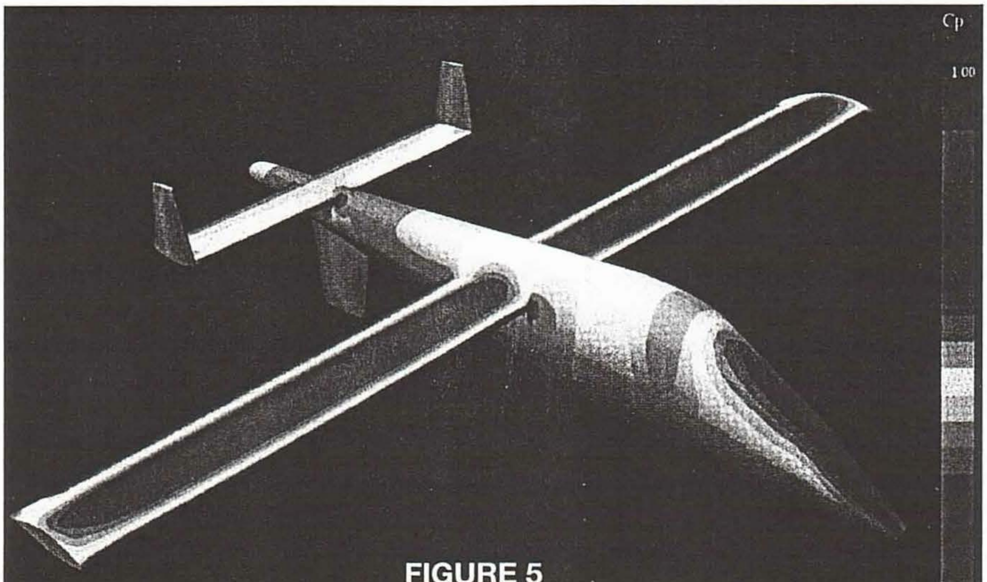


FIGURE 5
Calculated pressure distribution on the upper surface of Teal without cowl cheeks. Notice that the pressure distribution in the wing root region has changed only slightly and there is still no suction carrying over onto the fuselage.

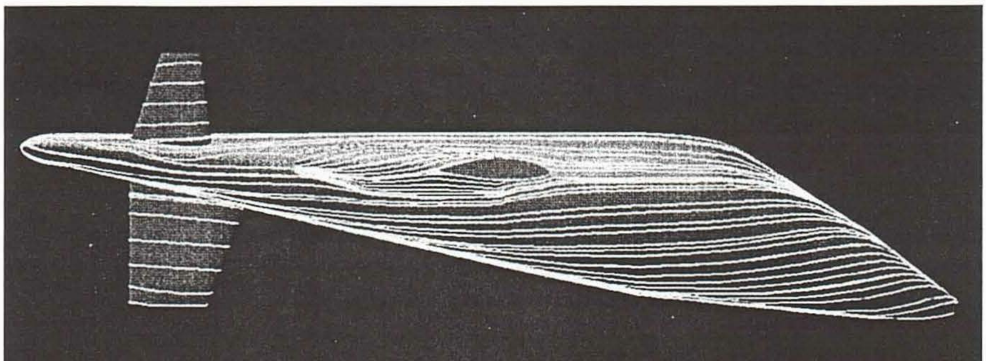


FIGURE 6
On-body streamlines calculated on Teal at cruise conditions (.64 degrees angle of attack). The downwards deflection of these streamlines in front of the wing, though slight, produces the reduced loading on the wing in the inboard region.

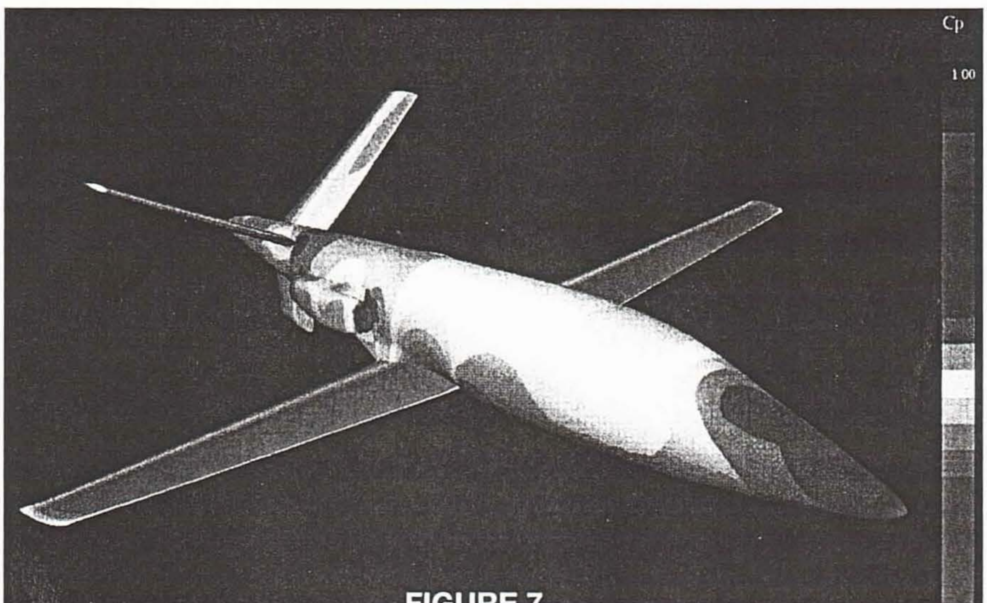
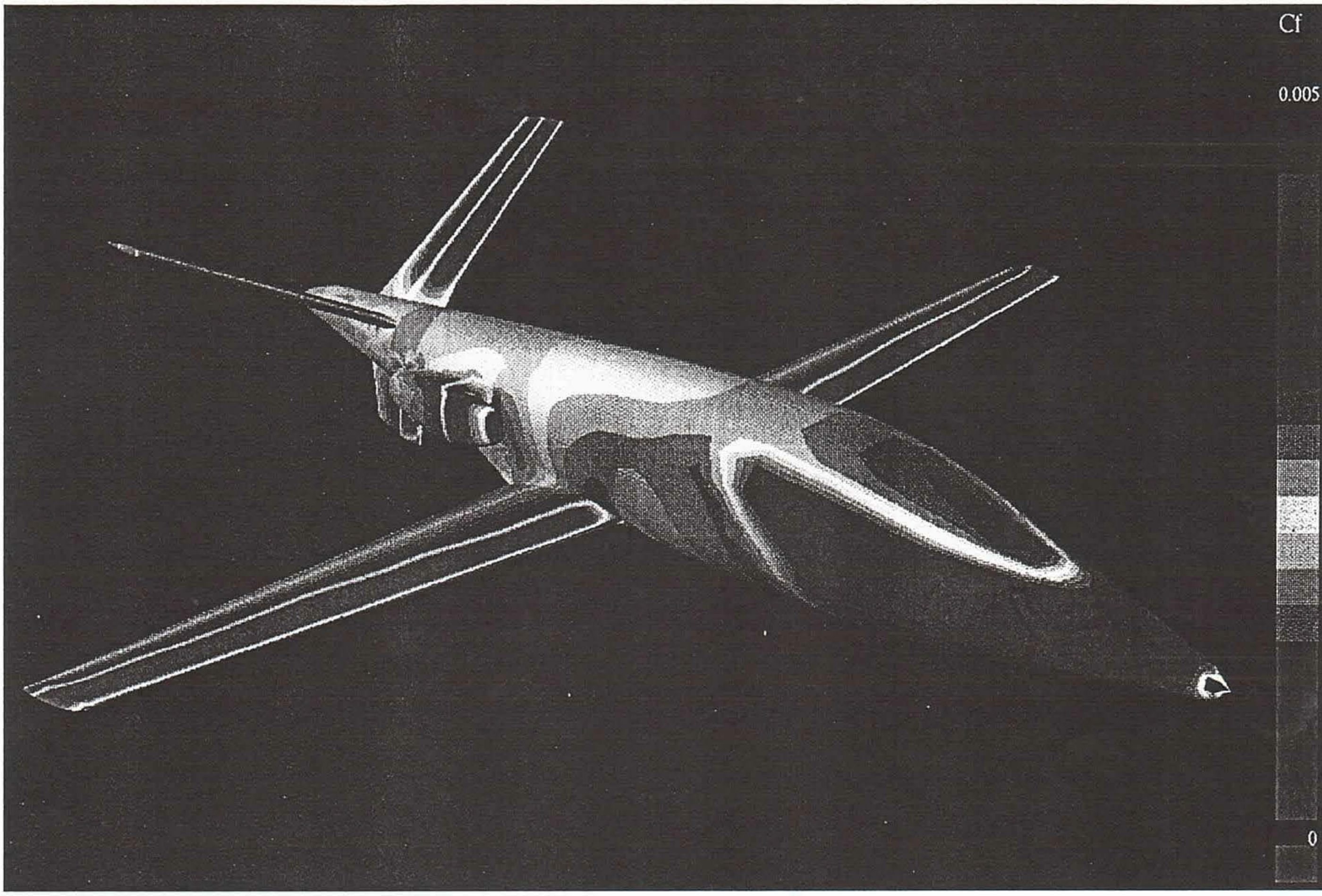


FIGURE 7
Calculated pressure distribution on the upper surface of the Lear Fan in cruise. Notice that on this aircraft, the wing upper surface suction carries over onto the fuselage.

the wing airfoil is a NACA 653-618, the maximum suction on the wing can be observed to extend to 50% of chord. This provides for the possibility of laminar flow on up to 50% of the wing chord. A look at the boundary layer solution (Figure 3) shows that this is indeed the case — laminar flow, with its low skin friction, is calculated to 50% of the wing chord.

An examination of the wing root region, on the upper and lower surfaces, shows the change in pressure distribution due to what appears to be the aerodynamic interference of the engine fairing with the wing. Checking the wing lift distribution (Figure 4), it can be seen that the wing lift drops off near the root, which is not desirable, as this makes the wing appear aerodynamically to be two wings, each with half the aspect ratio of the full wing. The end result of this is much higher induced drag. At first, it was believed that the location of the engine fairings is responsible for this. The computer model was modified by removing the engine fairings and was run again on the computer. The resulting pressure distribution (Figure 5) and lift distribution (Figure 4) show that this effect is still present. In the end, the calculated streamlines on the surface of the fuselage (Figure 6) explained the origin of this effect. To provide the necessary propeller clearance, the aft fuselage has to have a high upsweep angle. In cruise flight, this upsweep leads to the flow on the fuselage angling down to flow into this area. This local downwash area then leads to a lower local angle of attack inboard on the wing and lower lift in this region. This is a problem area that designers of pushers must keep in mind.

Ed's flight testing showed the power-on stick-fixed longitudinal Neutral Point to be at 49% of MAC and the power-on stick-free longitudinal Neutral Point to be at 39% MAC. The VSAERO calculations resulted in a power-off stick-fixed longitudinal Neutral Point at 47% MAC. As the power effects are stabilizing for pusher aircraft and 2% MAC is not an unreasonable value for this effect, the VSAERO results agree quite well with flight test. The stabilizing effect of the propeller is a useful feature of the pusher configuration. The 10% MAC destabilizing shift between stick-fixed (49% MAC) and stick-free (39% MAC) conditions gives a measure of how powerful this effect can be.



Skin friction distribution calculated on the Lear Fan in cruise. Large regions of laminar flow (hot colors) are present on the nose and forward parts of the wing, inlets, horizontal and vertical tails.

Additionally, Ed's flight testing yielded a flat plate drag area for Teal of 1.61 ft^2. The wetted area calculated by VSAERO is 274.5, which compares quite favorably with that of Formula One air racers such as Nemesis (253.7 ft^2), Madder Maxx (265.5 ft^2) and Shadow (270.1 ft^2). Dividing Teal's flat plate drag area by its wetted area gives C_{Dswet}, a measure of aerodynamic cleanliness. This value, .0058, is in the region of such aircraft as the P-51B Mustang (.0053), Spitfire IX (.0056) and P-63C King Cobra (.0060). In view of Teal's clean external design, it is likely that quite a bit of its drag is buried in the engine cooling system.

LEAR FAN 2100 ANALYSIS

The Lear Fan 2100 was designed by Bill Lear to be the first of a new generation of high performance turboprop business aircraft. Since the early 1950s, Bill Lear had advocated the safety of centerline thrust aircraft, as well as the performance gains of improved aerodynamics and pusher

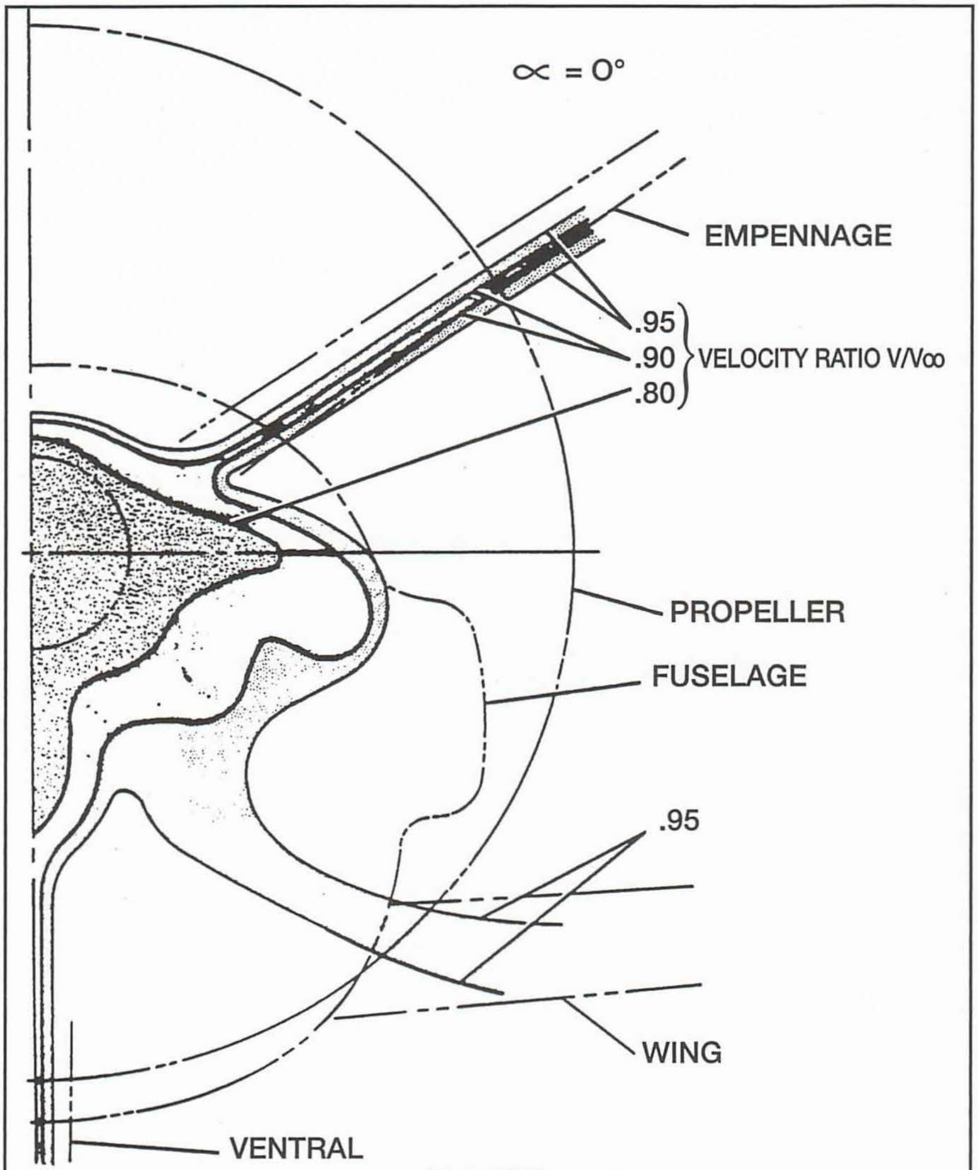
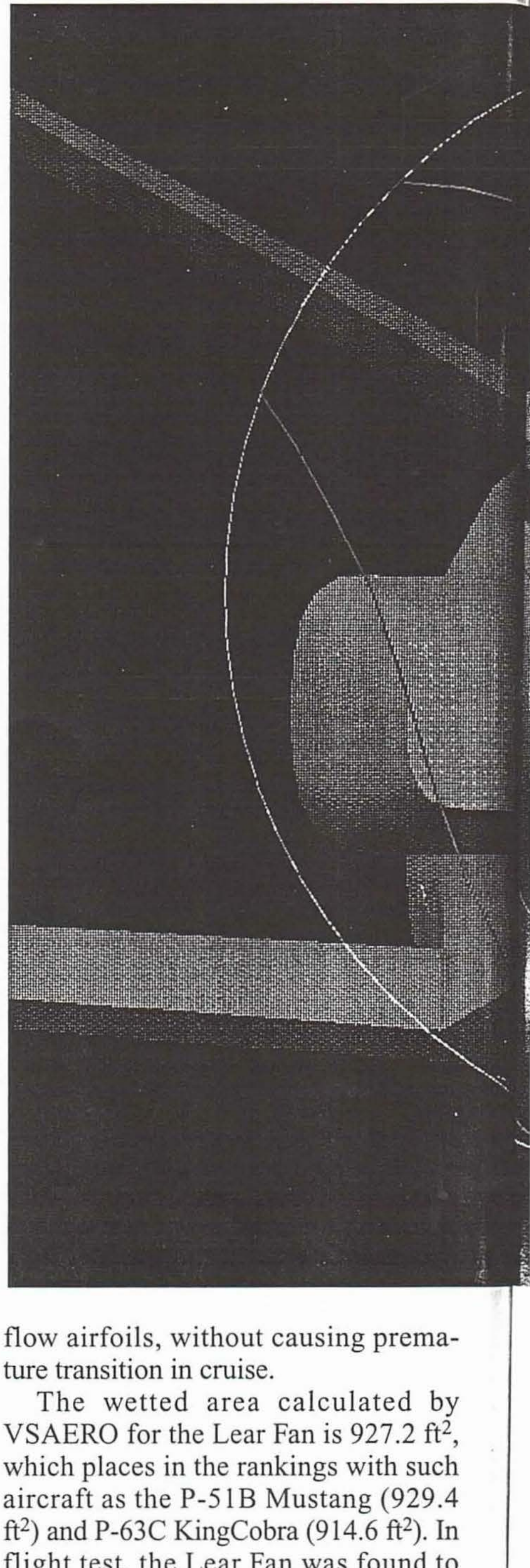


FIGURE 9

Regions of velocity deficit measured at the propeller plane of the Lear Fan in the wind tunnel. Most of these regions are due to boundary layer growth on surfaces upstream. (Figure from AIAA paper 83-2465, "High Speed Propeller for the Lear Fan 2100," by Ian Gilchrist)



configurations. In the late 1970s he initiated work on what would become the Lear Fan 2100. The prototype made its first flight on December 32, 1981. Unfortunately, development problems brought about the demise of the project in 1984. One of the prototypes survives in the EAA Museum in Oshkosh and another is in the Museum of Flight in Seattle.

Luckily, my co-worker Ian Gilchrist had saved a set of loft data on the aircraft after the demise of the Lear Fan company. With this information, I was able to build the computer model to use here. Due to the complexity of the geometry, this model took longer than Teal to be completed.

The calculated pressure distribution on the Lear Fan in cruise is shown in Figure7. The wing airfoil was designed for laminar flow over 50% of the wing chord, with a drag bucket extending over the cruise lift coefficient range of the aircraft. The pressure distribution shows that indeed, the maximum suction on the wing extends to 50% of chord and the calculated skin friction coefficient distribution (Figure 8) shows that the wing is capable of supporting laminar flow to approximately 50% of chord. The shaping of the forward fuselage can be seen to also produce a region of accelerating flow, which should have allowed laminar flow here too. Flight test drag polars revealed that the wing did indeed have extensive laminar flow. This laminar flow was achieved with B.F. Goodrich deicing boots and stall enhancing triangular leading edge vortex generators installed on the wing. The triangular leading edge vortex generators solved an abrupt stall, typical of many laminar flow airfoils, without causing premature transition in cruise.

The wetted area calculated by VSAERO for the Lear Fan is 927.2 ft^2, which places in the rankings with such aircraft as the P-51B Mustang (929.4 ft^2) and P-63C KingCobra (914.6 ft^2). In flight test, the Lear Fan was found to have an equivalent flat plate drag area (f) of 4.46 ft^2. Dividing this value by the wetted area gives a C_{Dswet} of .0048, less than that of Teal or the other aircraft mentioned previously. This verifies that the Lear Fan achieved the aerodynamic efficiency envisioned by its creator.

One concern surrounding pusher aircraft is the reduction in propeller efficiency due to the prop's ingested flow distorted by upstream components, such as the wing and horizontal tail. CFD can be used in an attempt to solve for this

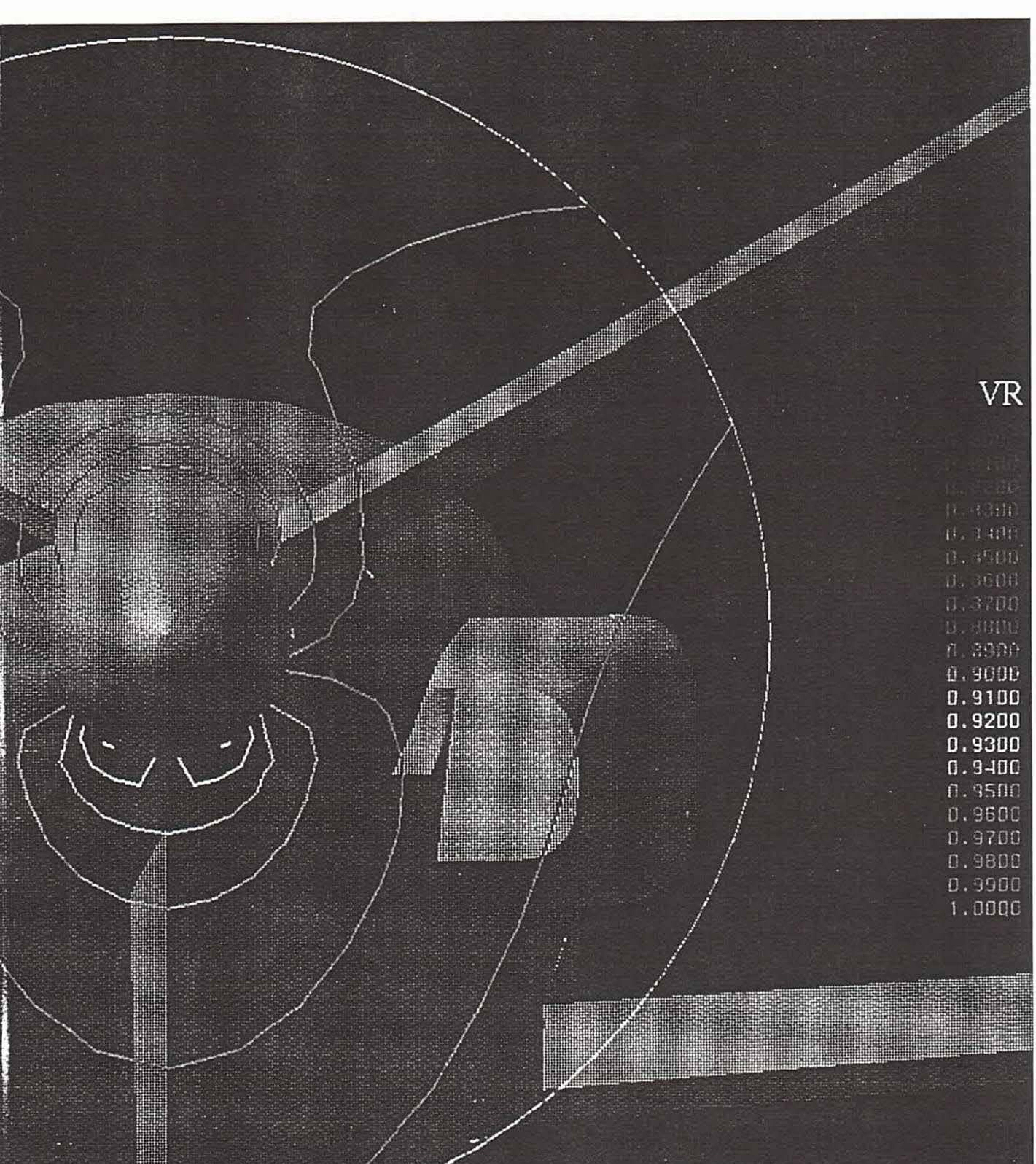


FIGURE 10
Regions of velocity deficit calculated by VSAERO. Lacking the means to model the thick, viscous wakes flowing from upstream surfaces, this distribution does not match that in Figure 9.

flow distortion at the propeller plane. For a tractor propeller, the result shows only minimal distortion and can be neglected. However, for a pusher propeller, the result can be quite significant.

During the development of the Lear Fan, measurements were made in the wind tunnel of the flow distortion at the propeller. The regions of reduced inflow velocity that were measured are shown in Figure 9. In comparison, the regions of reduced inflow velocity calculated at the same conditions by VSAERO are shown in Figure 10. It can be seen that majority of this deficit in inflow velocity is not calculated by VSAERO. This is because computer codes formulated like VSAERO generally ignore some of the physics of the flow, due to the simplifying assumptions used in the program. In particular, the thick, viscous wakes coming from the wing and horizontal tail are not modeled as they flow downstream. It is these wakes that produce the regions of reduced inflow velocity at the propeller. It should be noted that the flowfield distortion on the Lear Fan was found not to produce excessive propeller vibratory loads or to reduce the propeller's efficiency, which was measured to be 83% at 304 kts. and 35,000 feet.

In contrast to the difficulties in calculating the inflow velocity deficit, the flow angularity at the propeller of a pusher aircraft can be accurately calculated by VSAERO. As an example not connected with the Lear Fan, during development of the Beech Starship, the flow at the propeller plane was both calculated using VSAERO and measured in the wind

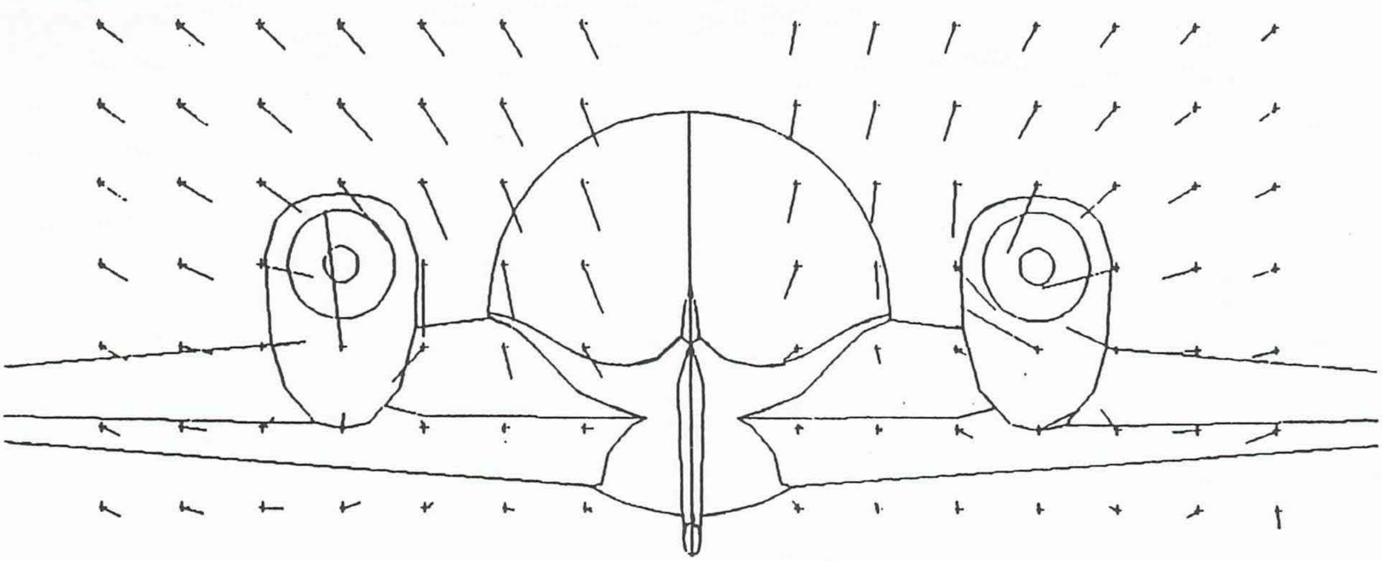


FIGURE 11

A comparison of flow angularity measured in the wind tunnel (left) and calculated by VSAERO (right) at the propeller planes of the Beech Starship. (Figure from AIAA Paper 88-2511, "Flowfield Study at the Propeller Disks of a Twin Pusher, Canard Aircraft," by Neal Pfeiffer)

tunnel. A comparison of the results from these two sources are shown in Figure 11. Similarly, during the development of the Rutan Voyager, flow distortion that I calculated at the rear propeller, using VSAERO, was an important input to John Roncz's propeller design effort. A contrast between the distortion at the front propeller and rear propeller of the Voyager is shown in Figure 12. While attempts were made on the Starship to improve the uniformity of the flow into the propellers, on the Voyager, the propellers were designed to cope with the existing nonuniformity. Obviously, this is another potential problem area that the designer of a pusher must keep in mind.

CONCLUSION

Two pusher aircraft have been analyzed here and their important design features have been discussed. While the off-stated advantages of pushers have not been refuted, light has been shed on problem areas associated with this configuration. I believe that carefully designed, a pusher configuration can offer superior performance to a tractor configuration. However, detailed analysis tools, such as CFD, are necessary to allow the full performance potential to be realized.

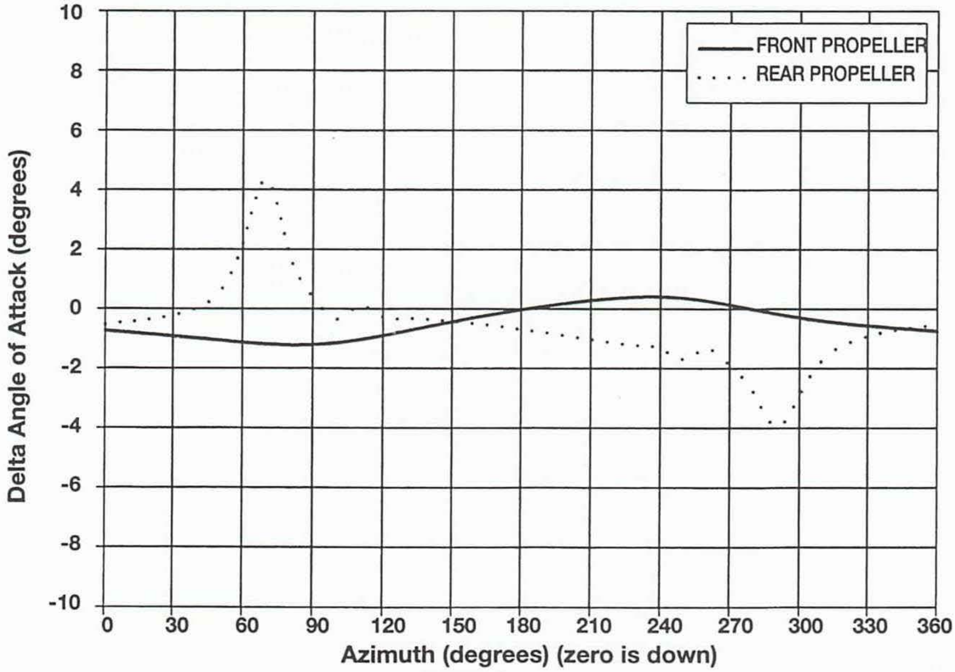


FIGURE 12

Changes in propeller blade angle of attack calculated by VSAERO on the Rutan Voyager at 75% radius. Note that while the front blade experiences only small changes to its angle of attack as the blade revolves, the rear blade sees large and sudden changes in angle of attack.

Author's Note

As noted at places in the text, I have had personal connection to both of these aircraft, and the Beech Starship and Rutan Voyager, which were mentioned in passing. During my time in engineering school at the University of Michigan, Ed Lesher was one of the primary influences in shaping the direction of my career and I have always admired the aircraft he designed and built. This inspired my interest in modeling Teal. A co-worker of mine, Ian Gilchrist, who prior to working at Analytical Methods, worked on the development of the Lear Fan, is my connection to this aircraft. Through Ian, I have been privileged to meet Moya Lear, Richard Tracy, Jim Chase and many of the other engineers involved with this aircraft. Lastly, during my time working for John Roncz, I was involved with the development efforts on the Beech Starship after it first flew and the Voyager. Unfortunately, the pattern here is that I developed connections with and analyzed all of these aircraft after they were designed and built!

As noted in the first article in this series, I am an aeronautical engineer, specializing in applied computational fluid dynamics. Based in Redmond, Washington, I work for Analytical Methods, Inc. My aerodynamic (and hydrodynamic) consulting projects at AMI have included submarines, surface vessels, automobiles, trains, helicopters, aircraft and space launch vehicles. I can be reached at: dave@amiwest.com or: Analytical Methods, Inc., 2133 152nd Ave NE, Redmond, WA 98052. ◆

PROPELLER, PUSHER DESIGN

Alex Strojnik convincingly demonstrated that a pusher configuration is necessary for ultimate drag reduction. Why? Well, in order to go, say, 200 mph in a tractor engined aircraft, the air stream along the fuselage will have to go 220 mph. That adds up to over 20% increase in skin drag. Add to that the horribly dirty front-end, the disturbed and turbulent airflow over the fuselage, and you are wasting a very significant part of the available thrust.

But pushers have their own dirty little secrets. Their major drawback is that the airframe disturbs the air before it reaches the propeller. This causes the prop to go into all sorts of undulations that wastes power and can lead to catastrophic failure. Have you ever noticed that all canard style aircraft have a unique slapping prop noise? Well, that is the sound of the prop fighting with the dirty air from the engine cowling behind the aircraft.

My recommendation is that props that are used on pushers for any extended period of time are made of wood. Many attempts have been made to run various composite and metal props. Composites and metal don't seem to be able to handle that kind of flexing.

So we have to run a fixed pitch wood prop on pushers.

There are ways to limit the amount of turbulence in the air entering the pusher prop disk. NASA's research on cruise missiles and RPVs shows that the trick is to increase the distance between the flying surfaces in front of the prop to one chord length. This gives the disturbed air a little more distance to calm down before it hits the prop. A slim fuselage in front of the prop helps a lot too.

The bottom line is that a well-designed pusher airframe should require less thrust than a tractor configuration.

My thanks go to the pioneers, Molt Taylor, Ed Lesher, Alex Strojnik and Burt Rutan. The air is less disturbed behind them! ◆