Of Wings and Things

Understanding NASA's Supercritical Wings, Winglets and Oblique Wings

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Almost two decades of space exploration has led to the evolution of rocket engines that produce millions of pounds of thrust. All they require is a massive diet of exotic fuel.

Aviation also has the power it needs, but *not* the fuel. As a result, NASA (National Aeronautics & Space Administration) has been working to develop aerodynamic improvements that increase fuel efficiency.

This is an extremely challenging assignment because an airplane wing is already so remarkably efficient.

Consider, for example, the theoretical lightplane in Figure 1. Its right wing is conventional, but the left consists only of a straight wire that has a diameter of one-half inch. Both "wings" have the same span.

It may seem incredible, but in cruise flight (if such a thing were possible), the slender wire would create as much parasite drag as the entire wing on the other side.

If the conventional wing were perfectly clean and flawlessly built with a laminar-flow airfoil, then the wire would need to have only a one-quarter-inch diameter to create as much drag as the wing.

When a wing is this efficient, improvements don't come easily or in quantum leaps. But thanks to NASA and a core of dedicated scientists, advances are being made. Notable examples include supercritical wing technology, winglets and oblique wings.

Although these concepts have been given considerable attention by the aviation press, little effort has been made to explain their aerodynamic principles in lay terms. Relying on some simplification, that is what we shall strive to achieve here.

First, the supercritical wing. Although this design was intended originally for high-speed flight, it has evolved into an efficient, low-speed airfoil for general aviation.

"Supercritical" research began in the late fifties when the military expressed the need to increase aircraft speed without additional power and fuel flow.

One of those to accept the challenge was NASA's Richard Whitcomb, the brilliant aerodynamacist who had discovered and verified the principle of *area rule.* This, he claims, resulted from his musings over the shape of a Coke bottle.

The search for increased efficiency eventually led Whitcomb to the invention of the supercritical wing, a concept that is not difficult to grasp as long as the reader isn't shy about dealing with Mach numbers.

Simply stated, a Mach number ex-

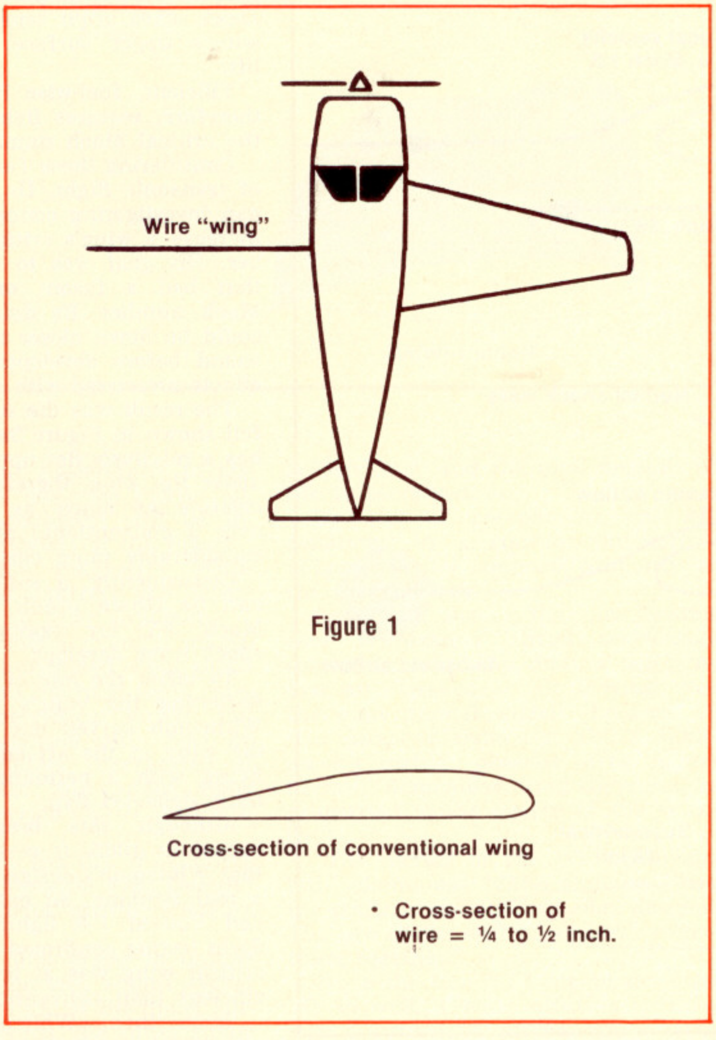


Figure 1

presses the speed of an object with respect to the speed of sound. Mach .5, for example, represents 50% of the speed of sound, Mach 1 *is* the speed of sound, Mach 1.2 represents 1.2 times the speed of sound, etc.

Figure 2a is a conventional airfoil flying at Mach .85 (15% below the speed of sound). But because of wing camber (curvature), air above the wing is actually moving faster than the wing itself.

It is entirely possible, therefore, that even though the wing is cruising at Mach .85, local air velocities above the wing may reach Mach 1.

When the velocity of air above a wing reaches Mach 1, the wing is said to be flying at its "critical Mach number." In the previous paragraph, for example, air above the wing reaches a local speed of Mach 1.0 even though the airplane is flying at only Mach .85. In such a case, the critical Mach number of the airplane is .85.

In this age of fuel consciousness, the critical Mach number of an airplane is particularly significant. When an airplane is flown in excess of this speed, a part of the wing is forced to become supersonic. At such a time, a shock wave forms above the wing (Figure 2b). This results in a rapid drag rise and requires a disproportionately large increase in power and fuel flow. Also, air flowing behind the shock wave often separates from the wing's upper surface, which erodes lift.

Efficient, fuel-wise flight planning, therefore, requires flying slower than the critical Mach number.

Considering these (and other) facts of transonic flight, Dr. Whitcomb began investigating concepts that might increase a wing's critical Mach number. His goal was to design a wing that had a faster, or *supercritical*, Mach number. By doing so, a wing could be flown closer to the speed of sound before developing the adverse effects associated with a shock wave.

The result was the supercritical airfoil shown in Figure 2c, a design that has a relatively flat upper surface. Air above the wing, therefore, doesn't accelerate as much as when flowing over a conventional airfoil that has considerably more camber.

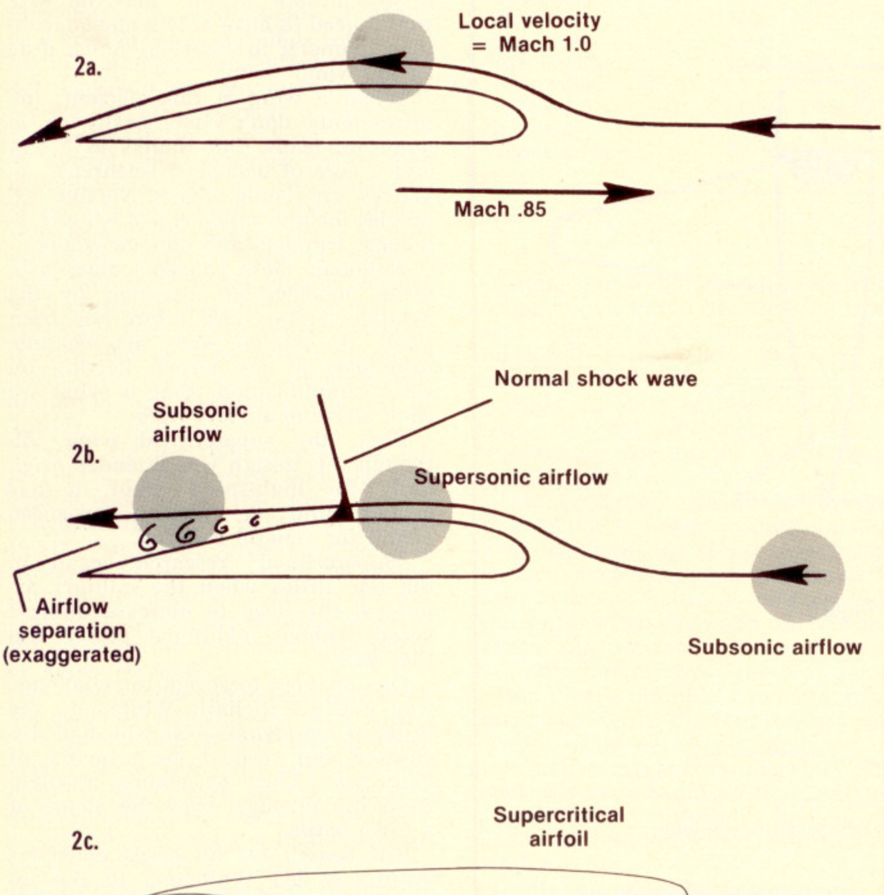
Consequently, a supercritical wing can be flown much faster (up to Mach .95, for example) before a shock wave develops.

To offset the loss of lift caused by flattening the wing's upper surface, Whitcomb carved out a cusp under the wing at the aft end. This is like flying with a permanently and partially deflected flap.

Although this breakthrough occurred in 1965, it wasn't until 1971 that Whitcomb's design was applied to a real airplane, an extensively modified Vought F-8 fighter. Subsequent flight testing confirmed that the supercritical wing was at least 50% more efficient than conventional airfoils.

Since then, Whitcomb's creation

Figure 2



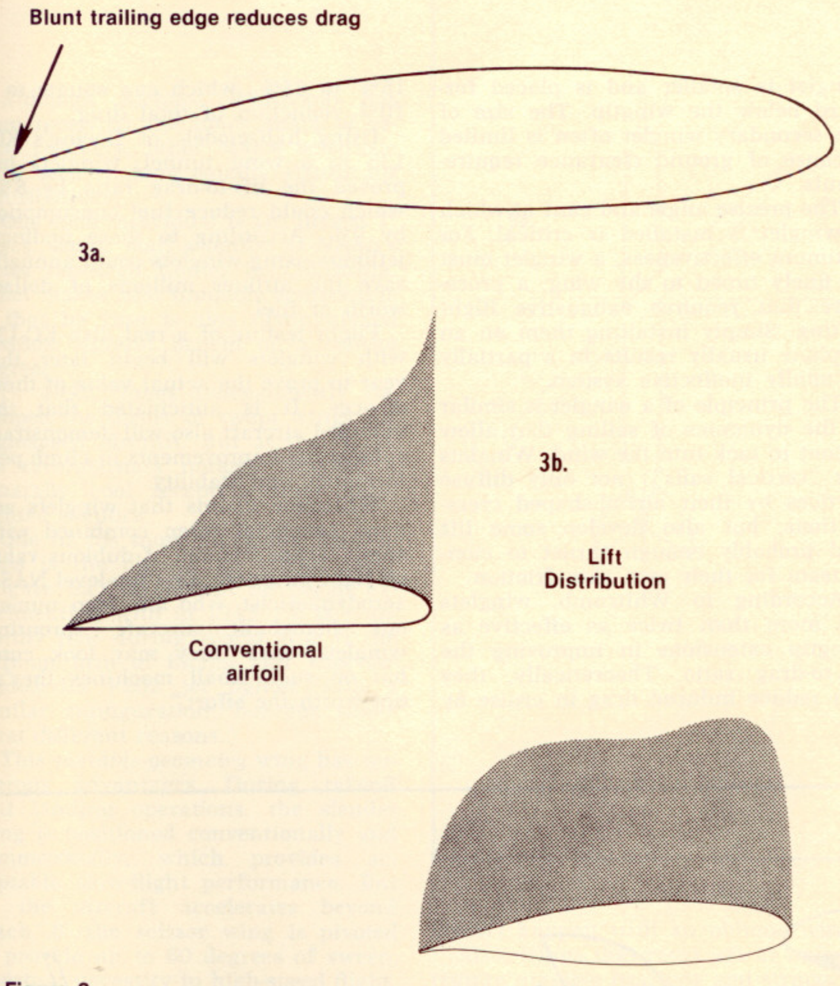


Figure 3

has been applied successfully to numerous business jets (the Falcon 50, et al.) and undoubtedly will be incorporated on jetliners of the future.

Ultimately, the innovative Whitcomb considered applying the supercritical concept to light airplanes.

Since most general aviation manufacturers aren't concerned about shock waves, Whitcomb returned some camber to the supercritical airfoil, but retained the underside cusp. Also, he increased the radius (curvature) of the leading edge and added some droop (a la Robertson's STOL modification).

The result was the GA(W)-1 (General Aviation-Whitcomb, First Design) similar to the airfoil shown in Figure 3a.

What makes this shape so unique is that lift is generated almost evenly along the full length of the upper surface. In other words, the entire airfoil is "working" and the total amount of lift is increased.

By way of comparison, the lift generated by a conventional airfoil (Figure 3b) is confined primarily to the forward half.

Important also is that air flowing over Whitcomb's airfoil accelerates more gradually and doesn't reach as fast an airspeed as air flowing over the conventional airfoil. Because of this airspeed reduction above Whitcomb's airfoil, parasite drag is reduced. (Remember, drag increases in proportion to the square of the velocity.)

"The secrets of the Whitcomb airfoil," claims one NASA engineer, "are the leading and trailing edge designs. The rest of the airfoil just holds everything together."

Since the GA(W)-1 airfoil develops lift so well, a wing utilizing this design doesn't need quite so much wing area. Consequently, wing chord can be reduced, which results in a higher aspect ratio wing and less induced drag. Also, a smaller wing costs less to build and weighs less, which allows increasing aircraft payload. Additionally, a wing with less surface area (greater wing loading) provides a smoother ride in turbulence because it is less affected by gusts.

The GA(W)-1 airfoil is somewhat thick, a feature that allows for larger fuel tanks, rugged construction and roomier wheel wells for retractable legs.

The first airplane to incorporate the GA(W)-1 airfoil was a highly modified Piper Seneca that was called ATLIT (Advanced Technology Light Twin). Subsequent flight testing demonstrated the feasibility of Whitcomb's airfoil and led to the development of a family of low-speed, or LS airfoils. Such designs have been used by Beechcraft (Model 77), Cessna (Model 303), Piper (Tomahawk), and others.

According to one of NASA's aerodynamicists (who prefers to remain anonymous), "the new airfoils are not a panacea, but they are a positive step in the right direction. Although stall characteristics are very mild, for example, the blunt leading edge has one negative feature; it is more prone to flat-spinning."

Whitcomb and company also have devoted considerable attention to vortex (wake turbulence) hazards. Somehow, they reasoned, it must be possible to thwart the formation of these invisible tornadoes.

Since wingtip vortices are intricately related to induced drag, it seemed logical to assume that inhibiting vortex development also would lead to drag reduction and fuel savings.

One way to partially achieve this result has been to increase wing span. But this is often unsatisfactory because of additional manufacturing costs, weight penalties and wing-bending moments (which require additional wing-root strength, etc.).

Another, less popular technique has been to install a flat plate at each wingtip. But these rarely are worth the drag they create. End plates do eliminate some induced drag at large angles of attack, but they are usually detrimental to cruise performance.

It is generally conceded that extended wingtips are more efficient than end plates.

continued

Figure 4a illustrates how a vortex is spawned. High-pressure air from beneath the wing tends to *curl* over the tip toward the area of low pressure above the wing.

One way to inhibit this vortex development, therefore, is to somehow "block" this curling action. Clearly, something like an end plate is required but, to be effective, the device must at least compensate for its own drag.

A few years after beginning their study of these problems in 1970, the Whitcomb team arrived at an effective solution: winglets, or vortex diffusers that control (or partially block) spanwise airflow (curling) at the wingtip.

Winglets really are small wings mounted almost vertically at the wingtips. The primary winglet (Figure 4b) is a relatively large surface mounted rearward above the tip; the secondary winglet is smaller and is placed forward below the wingtip. The size of the secondary winglet often is limited because of ground clearance requirements.

The precise angle and cant at which a winglet is installed is critical. For optimum effectiveness, a winglet must be finely tuned to the wing, a procedure that requires exhaustive flight testing. Simply installing them on an airplane usually results in a partially or totally ineffective system.

The principle of a winglet is similar to the dynamics of sailing that allow a boat to tack into the wind. Winglets (or "vertical sails") not only diffuse vortices by their airfoil-shaped cross-sections, but also develop some lift and probably enough thrust to compensate for their own skin friction.

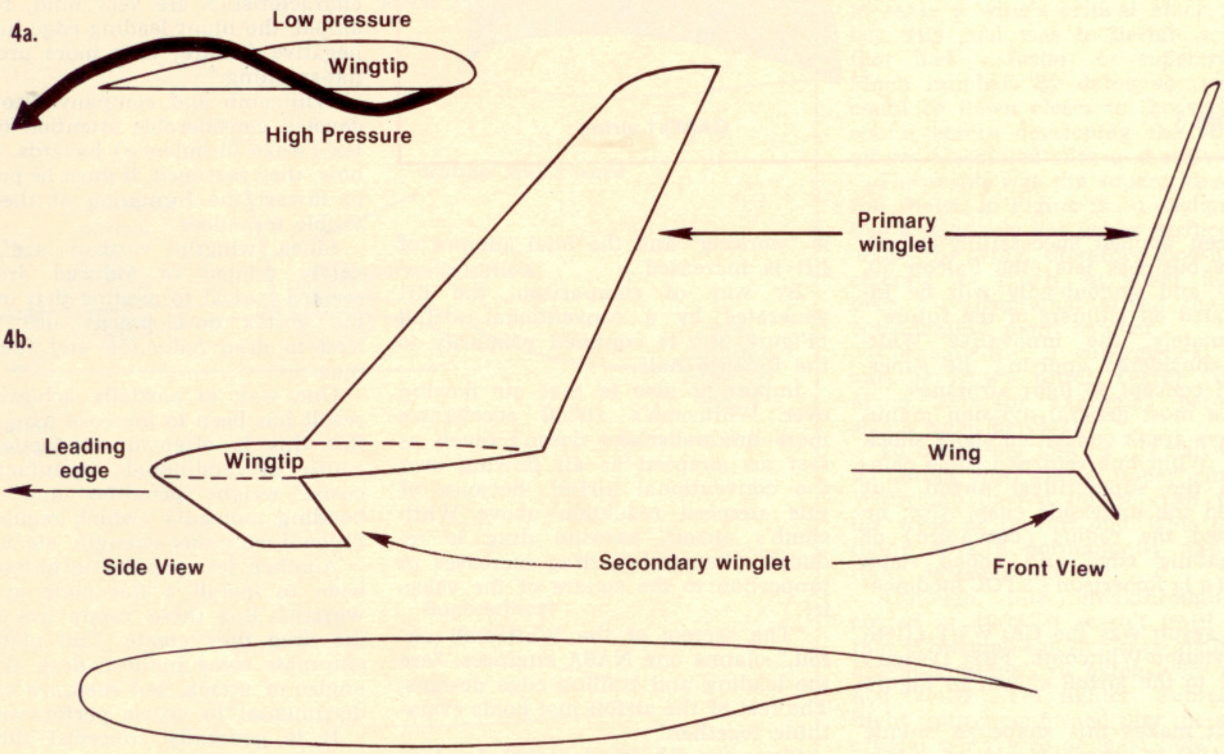
According to Whitcomb, winglets are more than twice as effective as wingtip extensions in improving the lift-to-drag ratio. Theoretically, they can reduce induced drag in cruise by 15% to 25%, which can equate to a 10% reduction of total drag.

Using half-models of Boeing's KC-135 in a wind tunnel, winglets improved the lift-to-drag ratio by 8%, which could reduce fuel consumption by 9%. According to these findings, jetliners using winglets could annually save the airlines millions of dollars worth of fuel.

Flight testing of a real, live KC-135 with winglets will begin later this year to prove the actual value of these devices. It is anticipated that the modified aircraft also will demonstrate substantial improvements in climb performance and stability.

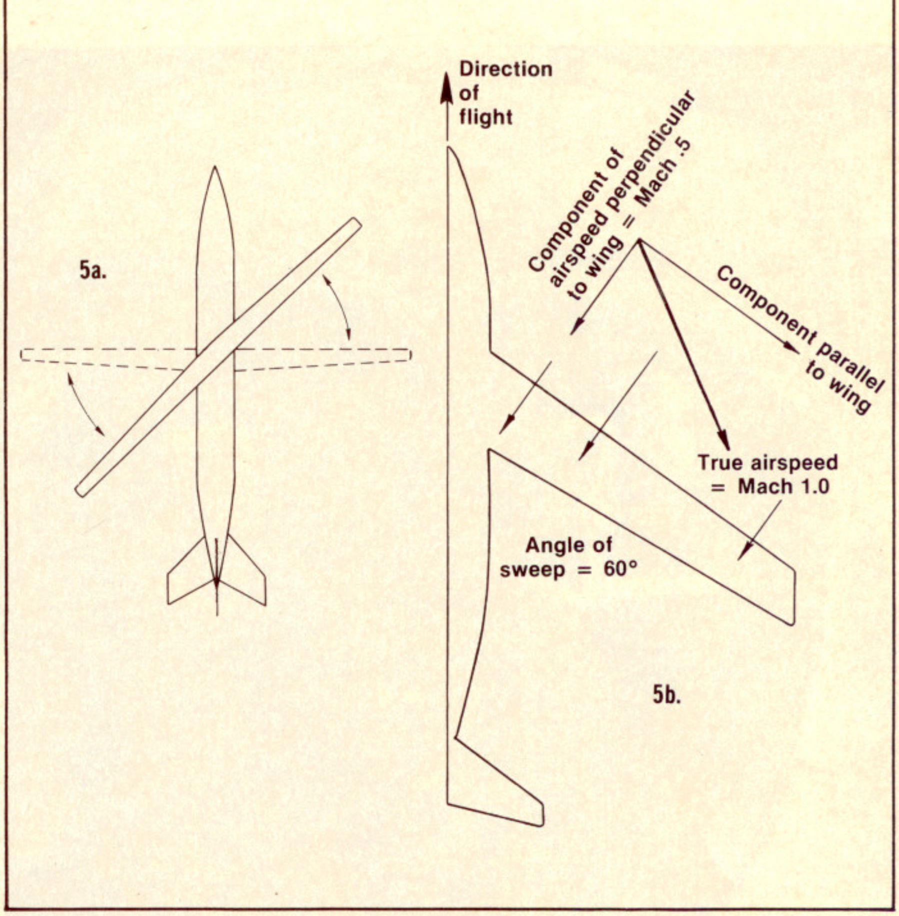
Whitcomb claims that winglets are most beneficial when combined with swept wings and are of dubious value on light airplanes. One top-level NASA aerodynamicist, who has seen numerous homebuilt aircraft sprouting winglets, says "they may look cute, but on such small machines they're not worth the effort."

Figure 4



Typical winglet cross-section

Figure 5



Although Richard Whitcomb has been receiving the lion's share of recent publicity, other NASA scientists have been making equally significant contributions.

One such individual is Dr. Robert T. Jones, senior staff scientist at NASA's Ames Research Center in California. What makes him uniquely remarkable is that he rose to this distinguished position without benefit of a college degree.

In 1945, Jones independently developed the theory of swept wings for high-speed aircraft. But at that time, his revolutionary notions received a generally cool reception from near-sighted skeptics.

One of his most intriguing innovations is the oblique or *scissor* wing (Figure 5a), a concept he began experimenting with in 1945. (It is noteworthy that during World War II the German firm of Blohm and Voss designed its P202 jet fighter with a similar configuration, but for somewhat different reasons.)

This *variable-geometry* wing has numerous advantages. During takeoff and landing operations, the slender wing is positioned conventionally and symmetrically, which provides acceptable slow-flight performance. But as the aircraft accelerates beyond Mach .8, the scissor wing is pivoted to provide up to 60 degrees of sweep, a virtual necessity in high-speed flight. Such a configuration takes on the appearance of a child's balsa glider that had its wing knocked askew by flying into a telephone pole.

The purpose of a swept wing is to fool the air into believing that it is flowing more slowly than it really is. Notice in Figure 5b that, although the swept wing is cruising at Mach 1, the airflow component perpendicular to the wing is much less. The wing feels and behaves as though it were flying at only Mach .5. As a result, the rapid drag rise of transonic flight is avoided. And as far as the air is concerned, it doesn't matter whether the wing is swept forward or aft.

But why use an oblique wing? After all, the Air Force's F-111 has a variable-geometry configuration that allows both wings to sweep aft simultaneously to maintain symmetry. Well, there are several disadvantages to this design.

First of all, when both wings are positioned aft, the center of lift also shifts rearward which tends to unbalance the aerodynamic forces. This doesn't happen with an oblique wing.

Also, wings that move aft in unison require massive bearings and structure to contain the bending loads that attempt to separate the wings from the machine. This adds considerable weight and complexity.

Conversely, an oblique wing can be constructed as one piece with a continuous spar. All that's required is a pivot point and some machinery.

Although the oblique wing looks weird and might take time to win public aceptance, flight tests of a radio-controlled model indicate that the scissor wing has normal flight and handling characteristics during conventional maneuvering.

To further test Jones' theories, however, NASA is building a small, jet-powered, single-place airplane (the AD-1) that could be a stepping stone toward second-generation SSTs.

One problem, of course, is the sonic boom. But an oblique-wing SST could fly at Mach 1.15 at altitude without leaving a sonic footprint. Because of the temperature difference between the stratosphere and sea level, such a boom would dissipate before reaching ground level. Over water, however, such an SST could go considerably faster.

But even at Mach 1.15 (about 750 mph at altitude), transcontinental flying time would be reduced by almost two hours. And at 1,000 mph (over water), Jones claims an oblique wing SST would be twice as fuel efficient as either the Concorde or TU-144.

An oblique wing SST would not, however, be as fuel efficient as present wide-body jetliners. For this reason, Jones believes that a supersonic business jet may be the first to employ his concept.

Although Jones is 67 and has devoted his life to advancing the aeronautical sciences, only recently has he begun learning to fly. His lessons are being taken in an Ercoupe, an airplane he helped to design.

Jones' expertise in aerodynamics also has been applied to the design of artificial hearts. And why not? The only significant difference between blood and air is color and viscosity; both are fluids.

So if a problem relates to fluid flow —whether through your heart or over your wings—someone at NASA probably can find the answer. □