FOR AEROSPACE MANUFACTURERS, particularly those in the business of building transports, the Holy Grail of their continuing quest is to reduce the drag—creating effects of friction on the skins of their aircraft.

Friction accounts for half the total drag on a modern jet transport; the rest comes from pressure—induced and wave drag. An aircraft’s need to generate lift in order to stay in the air creates these latter three forces, so not a great deal can be done to minimize their effects. Wing fences or winglets can shave only a few percentage points off an aircraft’s induced drag budget, and only if the plane remains cruising long enough.

However, if skin friction can be reduced appreciably, an aircraft will achieve a proportional saving in the amount of fuel it burns, conferring benefits on range and operating cost. This is the reason for the industry’s fascination with laminar flow control.

If greater amounts of boundary-layer air can be made to flow over an aircraft’s wing, fuselage, and empennage without becoming turbulent, the plane will burn proportionally less fuel.

About half the total skin friction experienced by an aircraft is on its fuselage and empennage, and about half is on its wings, says William Saric, a professor at Texas A&M University’s Dept. of Aerospace Engineering and the director of its Flight Research Laboratory. Recently, companies have experimented successfully with riblets—raised rib-like protuberances applied along fuselages and empennages in areas where aircraft have turbulent boundary-layer air—to reduce skin friction (and fuel burn) by 2-5%.

Fuel savings from laminar flow

According to Saric, achieving wing laminar flow would complement the use of riblets elsewhere on an aircraft and would yield additional fuel savings. He estimates that wing laminar flow control potentially offers fuel—burn savings of 10% to 12%—roughly equal to the savings a new generation of turbofan engines offers compared with the preceding generation.

The calculation is simple: Skin friction accounts for half the drag on an aircraft, and the wings account for half of that skin friction—hence they represent a quarter of the total friction drag. But not all skin friction on the wings can be nullified: Saric notes there is a limit to the degree of wing laminar flow that can be achieved.

Laminar flow breaks down as a result of disturbances within boundary-layer air. As these disturbances grow and become more unstable, they create turbulence. The boundary layer can remain laminar as the flow accelerates to its minimum pressure at about 60% of chord. However, the air must decelerate efficiently to atmospheric pressure by the time it reaches the wing’s trailing edge; this ensures that boundary-layer disturbances create turbulence in the pressure recovery region over the control surfaces.

Since laminar flow is only possible over about 60% of the wing, total wing friction can potentially be reduced by only 60% at most—or about one-eighth of total skin friction on the aircraft. Saric says laminar flow over the wing’s upper surface would produce about 60% of the wing friction reduction benefit, and laminar flow over the lower surface about 40%.

Tried and tested techniques

Various approaches have sought to achieve laminar flow control, and some have seen fair success. Creating a 2D airfoil (a very thin airfoil with a sharp leading edge), and ensuring the wing leading edge and surface are highly polished, is the best known way to achieve natural laminar flow.
Saric says it is also much easier to achieve it on a wing with no sweep angle, or only a small one, than on a transonic or supersonic swept wing.

Another option is to use weak suction at the surface. Boeing used this technique successfully in the 1990s in an experiment with a 757. This approach combined natural laminar flow control—using an accelerating pressure gradient in the swept-wing airfoil—with tiny holes in the leading edge of the wing. Suction applied through those holes helped control leading-edge airflow contamination and crossflow instabilities.

But in a swept wing that carries fuel and features high-lift leading-edge devices, installing the ducting needed to produce leading-edge suction presents engineering problems that may not be solved easily (or cheaply) in a production aircraft. Saric’s team at Texas A&M is pursuing a different approach that, while still at the technology demonstration stage, might eventually offer a simpler way to produce laminar-flow control benefits.

Controlling crossflow instabilities
Swept wings create an imbalance between the centripetal acceleration and pressure gradient experienced by air in the layer above the boundary layer, compared with the air within the boundary layer. This imbalance creates a secondary crossflow of air in the boundary layer, which runs in waves along the wingspan, perpendicularly to the air streaming over the chord. In attempts to achieve laminar flow, these crossflow waves are particularly difficult to control.

In two separate research initiatives—one a NASA Environmentally Responsible Aviation (ERA) project and the other an AFRL-funded effort with Lockheed Martin and Texas A&M—Saric’s team has experimented to suppress the most unstable crossflow wavelengths in different flight and wing conditions.

Their approach has been to interfere with those unstable waves by inducing waves of other wavelengths along the span using two different techniques. The team’s experiments have used wind tunnels and the laboratory’s own Cessna O-2 testbed, fitted to carry a 30-deg swept airfoil section perpendicularly under its wing. The initial results have been promising.

Discrete roughness elements
One technique, funded under NASA’s ERA project, has been to use periodic discrete roughness elements (DREs) placed spanwise at regular intervals within the first 1% of the chord of the wing, to create interference waves. These DREs are tiny bumps, no more than 10-12 µm high and no more than 1 or 1.5 mm in diameter. They are spaced so the distances between their centers are from one-half to two-thirds of the wavelength of the most unstable crossflow wave, to create the maximum of interference with it.

In flight testing of the swept-wing airfoil—carried under the Cessna O-2 and painted to simulate a typical operational aircraft surface—the Texas A&M researchers found that the DREs suppressed the most unstable wave enough to move the transition point between laminar and turbulent airflow from 30% of chord to 60%.

Saric says the wavelength of the most unstable crossflow wave on a particular wing depends on the airfoil of the wing, the radius of its leading edge, the aircraft’s speed, and its condition of flight. (For instance, the most unstable wavelength might change with the aircraft’s angle of attack.)

In wind tunnel testing, Saric’s team found that the most unstable crossflow wavelength for their swept-wing airfoil model was 12 mm. However, in a wing-glove test on a Gulfstream 3 flying at Mach 0.75, the most unstable crossflow wavelength may be 7 mm;
on the flight test model carried on the Cessna O-2 testbed the most unstable wavelength is 4.5 mm. Testing at Mach 1.85 with an F-15B had a 4-mm most unstable wave.

“My guess, if we had to make a transport wing, is that the most unstable wave would be in the 6-8-mm range,” says Saric. The ‘magic number’ of the wave needed to interfere with the most unstable wave would be from half to two-thirds of the most unstable wavelength, so the distance between the centers of the DREs would be from 3.5 mm to 4 mm.

**Different kinds of DREs**

To date the only DRE shape tested has been a circle. However, Saric says Russian research has suggested a rectangular shape with rounded corners might be even more effective, the DRE extending in the direction of the airstream over the wing and its diameter being from one-quarter to one-third of the most unstable crossflow wavelength.

For some experiments, the Texas A&M researchers have used DREs stuck on the airfoil surface as an appliqué from a specially printed transfer sheet. In other tests, they experimented with pneumatic roughness elements, stretching membranes over tiny holes in the airfoil and applying pneumatic pressure from within. One advantage of using pneumatic elements was that the scientists could easily vary the height of the elements to determine the best height for disrupting the unstable interference wave.

The team also applied vacuum to create dimples in the membranes over the holes, producing a surface that looked rather like that of a golf ball. They found that the two other approaches “seemed to work as well as the appliqué,” says Saric. On production aircraft, anodized aluminum DREs might be the most practical solution, he believes.

One disadvantage of DREs is that their positions are fixed, and a given DRE spacing is designed for a particular flight condition. As Saric notes, a widebody aircraft on a long-haul flight will start off fully loaded and flying at a particular altitude and angle of attack. However, as it burns off fuel, it has to bleed off lift by changing altitude or changing its angle of attack, so its flight condition changes. In changing flight conditions, DREs can be of only limited use.

**DBDP jets**

In response to this, the Flight Research Laboratory is building on work initially performed in 2001-2002 with tiny solid-state dielectric barrier discharge plasma (DBDP) elements mounted in or near the wing leading edge. Each DBDP sends current between its conductor and dielectric element to create jets of air parallel or perpendicular to the direction of travel, to mimic DREs.

Together with Lockheed Martin, Saric’s team is working to develop and test plasma actuators that can be set in an array along a wing. Different actuators in the array could be activated during different flight conditions, so that the spacing of active DBDPs could be changed in order to suppress crossflow interference waves of different wavelengths.

During DBDP development, the team used a technique called micro-particle image velocimetry to trace the trajectories of the particles within each jet and thus derive a velocity vector for it. This technique produced “some really interesting results” that “gave us an idea for a different design for the plasma actuators,” Saric says.

The Flight Research Laboratory plans to continue its joint research with Lockheed Martin on using DBDPs to achieve laminar flow control, says Saric, “probably beginning this fall,” and, he hopes, with AFRL backing. The work “would encompass wind tunnel tests, flight tests, and detailed lab measurements and computations of what these things are doing.”

NASA ERA-supported work continues with a laminar flow wing glove, using an appliqué, on a Gulfstream III. In this way, flow parameters approaching transport conditions will be achieved and the technical readiness level of the DREs will be raised. These flights are scheduled for 2014.

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