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Toward Practical Laminar Flow Control— Remaining Challenges

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ABSTRACT

Different laminar flow control strategies are reviewed for the various instability mechanisms and their applications over the different flight regimes are discussed. Success stories are told and unresolved problems are discussed. Over the years, the crossflow instability has been the primary challenge for laminar flow control. Favorable pressure gradients used to stabilize streamwise instabilities destabilize crossflow. Alternatives to weak boundary-layer suction are discussed.

I INTRODUCTION TO STABILITY AND TRANSITION

To control skin friction or heat transfer, one either modifies the turbulence structure or prevents the boundary layer from becoming turbulent by limiting the growth of linear disturbances. The latter is known as Laminar Flow Control (LFC) and is effective principally in low-disturbance environments. For engineering applications, passive control (i.e. static manipulation of the boundaries or flow field) seems more feasible than active feedback control through wave cancellation (Saric 1994a).

The general principle that governs all flow-control implementation is that the flow-control strategy must be incorporated within the conceptual and preliminary design phases, and not just the final design of the aircraft. This optimizes the effects of control consistent with the design constraints of the aircraft. While it is generally accepted that it is not practical to laminarize the fuselage or the engines, there are possibilities to achieve some laminar flow on the wings and empennage and it is in these areas that the discussion is applicable. In a low-disturbance environment such as flight, transition to turbulence within the boundary layer occurs as a result of flow instabilities or attachment-line contamination. There are five basic instability mechanisms that can contribute to transition on a wing. These are described first before proceeding with the means for achieving LFC.

A *Curvature Induced Instabilities – Görtler Vortices*

Regions of concave curvature can give rise to a basic instability first recognized by Rayleigh. For boundary layers on concave surfaces in open systems, Görtler vortices appear. These are stationary, streamwise oriented, counter-rotating vortices that nonlinearly modify the mean flow and lead to secondary instabilities and turbulence (Saric 1994b). This mechanism is not considered important because it can be easily controlled by the appropriate profile design. Usually concave curvature, if used, is aft on the pressure side of the airfoil. If critical Görtler numbers are reached (and one should always do a sanity check on this) an informal suggestion by Pfenninger that locally alternates concave and convex curvature was shown to work by Benmalek and Saric (1994) because convex curvature is more stabilizing than the convex curvature is destabilizing.

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B *Attachment-Line Contamination and Instability*

The combination of leading-edge radius and sweep gives rise to attachment-line contamination and instability (Pfenninger 1977; Poll 1985) but can be controlled in a straightforward manner (Reed and Saric 1989). To avoid wing-root disturbances from propagating along the attachment line and feeding into and tripping the boundary layer, it is necessary to keep the attachment-line momentum-thickness Reynolds number, Re_θ, below 100. Following Pfenninger (1977) and Poll (1985), an approximate relationship for Re_θ is given in (1) as

$$Re_\theta = 0.404\left(\frac{U_\infty r \sin^2\Lambda}{(1+\varepsilon)\nu\cos\Lambda}\right)^{\frac{1}{2}} \tag{1}$$

where U_∞ is the freestream speed, r is the nose radius (perpendicular to the leading edge), Λ is the leading-edge sweep angle, ν is the kinematic viscosity, and ε is the ellipticity of an equivalent ellipse. For most applications, practical control is achieved by simply limiting the nose radius for a specific sweep angle. Difficulties arise in supersonic cruise when the sweep angle is large and the airfoil thickness becomes small. This will be discussed later in the case of supersonic flight.

The flow along the attachment line can also undergo a shear-layer instability but this occurs at a higher value of Re_θ. There is a roughness sensitivity that needs to be addressed but this is also not a major problem. See Reed and Saric (1989) for a review of both of these issues.

C *Receptivity and Streamwise Instabilities – Tollmien-Schlichting Waves*

Streamwise instabilities related to the Tollmien-Schlichting mechanism result in the appearance of the so-called T-S waves. This was, for years, the prototype instability that dominated transition to turbulence thinking for much of the 20th century and is the order-one problem for LFC because it is important for both swept and unswept wings under all flight conditions. In fact, most of the progress was made in the last decade of that century (Reshotko 1997). The instability waves are slow growing and their behavior is governed by the Orr-Sommerfeld equation (OSE) with some modification for nonparallel effects. However, T-S waves are very sensitive to freestream conditions and should really be governed by an initial-value problem (parabolized stability equations) rather than and eigenvalue problem (OSE). The initial amplitudes of the waves come from the freestream and the transfer function is called receptivity. A recent review by Saric et al (2002) discusses the progress in this area. Receptivity issues will always confuse the conversion of wind-tunnel data to flight. This is especially true of supersonic tunnels. The T-S mechanism is especially sensitive to freestream sound and to 2-D roughness (steps and gaps) so care must be exercised in these cases.

T-S waves typically occur in the mid-chord region and transition induced by T-S can be reasonably correlated with linear stability theory (Reed et al 1996). There is no dearth of important papers on the actual breakdown process itself but these are of little interest in LFC. The basic idea of LFC for T-S waves is to control linear disturbances. Once the nonlinear and 3-D effects are present, only heroic efforts can re-laminarize the boundary layer.

Since linear theory of T-S waves, with an accountability for non-parallel effects in the form of parabolized stability equations (PSE), is a reliable tool (Herbert 1997a,b), one can now concentrate on control with serious attention paid to freestream disturbances. Successful control strategies for T-S waves are discussed in the first part of section II.

D *Receptivity Crossflow Instabilities*

The combination of sweep and pressure gradient create a flow within the boundary layer that is perpendicular to the inviscid streamlines. This velocity profile is inflectional and undergoes an instability at low x-Reynolds numbers. The instability takes the form of co-rotating vortices aligned approximately in the inviscid flow direction. Both traveling and stationary waves can be present – the former excited by freestream turbulence and the later by micron-sized surface roughness.

Transition to turbulence in crossflow-dominated, swept-wing boundary layers has received considerable attention over the past decade or so. The reason is the obvious engineering benefit that would result from enabling laminar flow over most of the wing. The difficulty faced in confronting this problem has been the strongly nonlinear nature of the crossflow instability. Linear methods have provided almost no useful results in predicting transition and therefore tremendous effort has been given to understanding the nonlinear aspects of the phenomenon. The basic review of swept wing stability was given by Reed and Saric (1989) while recent reviews of crossflow efforts have been given by Arnal (1997), Bippes (1997, 1999), Crouch (1997), Haynes and Reed (2000), Herbert (1997a, 1997b), Kachanov (1996), Reshotko (1997), and Saric et al (1998a,b; 2003). The relevant review for this paper is Saric and Reed (1993).

The primary instability region is now very well understood and excellent agreement between the NPSE (nonlinear parabolized stability equations, Herbert 1997a) computations of Reed et al (1998) and Haynes and Reed (2000) and the experiments of Reibert et al (1996) and Saric et al (1998b) has been achieved. The quality of the agreement suggests that all the features important for the primary instability, including curvature and details of the nonlinear effects, are adequately modeled and other crossflow-dominated configurations can be computed with some confidence.

The location at which the saturated vortices produced by this instability break down and lead to turbulence is not nearly as well documented. What is observed in stationary-wave-dominated transition experiments is that, at some point aft of where the vortices saturate, breakdown to turbulence occurs very rapidly along a jagged front. This behavior is particularly well-illustrated in flow-visualization studies such as that by Dagenhart and Saric (1999). These studies suggest that the final stage of transition occurs over a very short streamwise distance and is the result of a secondary instability initially described experimentally by Kohama et al (1991) and analytically/computationally by Malik et al (1994, 1996, 1999) and Janke and Balakumar (2000). Recent DNS work by Wasserman and Kloker (2002) and experimental work by White and Saric (2004) has put the secondary instability on firm ground. The net result of these efforts is a very complete understanding of the primary crossflow instability, including details of the nonlinear saturation of the dominant stationary mode and the growth of harmonics. An important consequence is that a means of transition suppression has been developed by Saric et al (1998b) that exploits the nature of the nonlinearities.

Detailed physical receptivity mechanisms for crossflow have not been investigated experimentally. However, recent work has provided a parametric understanding of receptivity. Surface roughness is an important crossflow receptivity mechanism and one is referred to work on distributed random roughness and isolated static roughness elements (Radeztsky et al 1999) and spanwise-periodic, static roughness arrays (Reibert et al 1996). The Deyhle and Bippes (1996) experiments established that for low levels of freestream turbulence, the transition process is dominated by stationary crossflow waves, while at high disturbance levels, traveling waves dominate because of the larger amplitude unsteady initial conditions. These traveling waves have the tendency to wash out the stationary structure. However, the stationary modes may be the most important practical case because of the low freestream turbulence observed in flight situations.

E *Transient Growth*

Transient growth is fundamentally different from T-S wave growth because it results from an inviscid rather than viscous mechanism and produces algebraic rather than exponential disturbance growth. This is due to the fact that the Orr-Sommerfeld equation is not self-adjoint and thus the eigenvectors, although linearly independent, are not orthogonal. Thus, the sum of two stable modes governed by the OSE-Squires system can experience algebraic growth. Disturbances that experience this algebraic growth eventually decay exponentially, but prior to this decay they are capable of undergoing very significant growth upstream of first branch of neutral curve. Therefore, since the growth factors can be large and since the mechanism is active upstream of T-S waves, transient growth may play a significant role in the transition process under certain conditions. See Reshotko (2001) for an up-to-date review on the subject that has relevance to practical systems.

It is generally accepted that transient growth plays an important role in the transition process when surface roughness and freestream turbulence are present (White and Reshotko 2002). At this time, we are assuming that

LFC surfaces will not have significant roughness and that the flight environment will have low turbulence levels. This assumption will have to be re-addressed of course if flight data for LFC systems show otherwise.

II LAMINAR FLOW CONTROL

Since linear-stability behavior can be easily calculated, passive control schemes are usually designed based on LST. However, since the initial conditions (receptivity) are not generally known, only relative comparisons between control schemes are possible and must be between systems with similar environmental conditions.

Experience with LST shows that a fuller boundary layer (more negative $\partial^2U/\partial y^2$) usually results in lower disturbance growth. Following Reshotko (1984) and re-writing the boundary-layer equation near the wall as in (2),

$$\mu\frac{\partial^2 U}{\partial y^2} = \rho V_0\frac{\partial U}{\partial y} + \frac{dp}{dx} - \frac{d\mu}{dT}\frac{\partial T}{\partial y}\frac{\partial U}{\partial y}, \quad y \approx 0 \tag{2}$$

anything that makes the left-hand-side of (2) more negative will stabilize the boundary layer. Thus, wall-normal suction ($V_0 < 0$), accelerating pressure gradients ($dp/dx < 0$), wall cooling in air ($\partial T/\partial y > 0$; $d\mu/dT > 0$), or wall heating in water ($\partial T/\partial y < 0$; $d\mu/dT < 0$) are possibilities as control schemes for LFC. Here, T is the local temperature, p is the pressure, and μ is the dynamic viscosity. The early work is reviewed by Bushnell and Tuttle (1979), Mack (1984), Arnal (1984, 1992), Saric (1992), Reed et al (1996), and Herbert (1997b) and the reader is asked to consult these papers for more details.

Natural Laminar Flow (NLF) control involves the tailoring of the favorable pressure gradient region to control disturbances and delay transition far back along the chord of a 2-D airfoil. The combination of suction in the leading-edge region and NLF (in the mid-chord region) is then termed Hybrid Laminar Flow Control (HLFC).

A new technique for swept wings is proposed (Saric at al 1998a,b, Saric and Reed 2003), Swept Wing Laminar Flow Control (SWLFC), that capitalizes on the nonlinear nature of crossflow and suggests a passive and simple control scheme. Whereas LFC, NLF, and HLFC discourage the growth of crossflow and control T-S, SWLFC naturally stabilizes T-S and the attachment line and promotes the growth of selected stationary crossflow vortices to delay transition. This is discussed in sections II.B and II.C.

A *Suction and Thermal Control*

The paper by Joslin (1998) reviews the state of the art of LFC from the 1930's through the 1990's and as such is recommended as a complement to this paper. He discusses studies of the benefits of LFC for subsonic and supersonic aircraft, early studies related to manufacturing tolerances and insect contamination, and results of concept studies in wind tunnels and in flight. Reported are flight-test results from major United States programs under the LFC project (under the NASA Aircraft Energy Efficiency – ACEE program) which was formed to help improve aircraft cruise efficiency: the Jetstar LFC test (Fischer et al 1983; Maddalon and Braslow 1990), the B-757 HLFC flight test at high Reynolds numbers (Collier 1993), and the GEAE CF6-50C2 engine nacelle modified to incorporate two HLFC panels and installed on the right wing of an Airbus A300/B2 transport (Collier 1993). The Jetstar test in fact made some of the most significant contributions to the advancement of LFC because it demonstrated that LFC could be operated in an airline-type operational environment. Details of the successful F-16XL supersonic LFC suction-glove flight tests conducted by NASA, Rockwell, Boeing, and McDonnell Douglas are not available as well as other restricted experiments. Joslin (1998) also reports flight-test results from Europe's ELFIN (European Laminar Flow Investigation) program which concentrated on the development of laminar flow technology for application to commercial transport aircraft: the Dassault Falcon 50 HLFC Flight Tests which used suction and a Gaster bump to prevent attachment-line contamination (Gaster 1965), the HLFC Nacelle Demonstration flight test on the VFW-614/ATTAS aircraft, and the A320 Laminar Fin HLFC flight test program. These programs show that laminar flow can be maintained under operational conditions, at high Reynolds numbers, and at both subsonic and supersonic conditions. Joslin then points out that opportunities will now be innovations in addressing the need for added systems, uncertainty in maintenance requirements, long-term structural integrity, and long-term operational and reliability characteristics.

As far as the effects are concerned, for 3-D boundary layers, LST shows that cooling the wall has a stabilizing effect in air. However, the effect is very small because crossflow instability is a dynamic instability due to the presence of an inflection point away from the wall in the crossflow-velocity mean-flow profile. The properties of the inflection point are hardly affected by the wall conditions. Consequently, the effect of cooling is large for T-S disturbances, it is essentially inconsequential for crossflow disturbances. For the same reason, larger values of suction are required for 3-D boundary layers, compared with the 2-D case, for stabilization. See Pfenninger et al (1980), Lekoudis (1980), Mack (1980, 1981), Bushnell and Malik (1987), and Balakumar and Reed (1991). Also, whereas suction can completely eliminate T-S waves, it only reduces the development of crossflow disturbances. Consequently, when crossflow and T-S disturbances are present simultaneously without suction, only (damped) crossflow waves survive when suction is applied.

Because a pressure gradient is the cause for instability on a 3-D wing, NLF is unfeasible to control crossflow. Crossflow instability increases with increasing sweep angle (Schrauf et al 1992). Also, full-chord LFC is very expensive and adds system complexity. Therefore, HLFC has been and is being considered for swept wings. A quick acceleration of the flow over a few percent chord accompanied by suction at the leading edge is expected to minimize the growth of crossflow. Then the geometry is tailored for NLF in the mid-chord region (Collier 1993).

As a caution for HLFC and in fact all techniques, considering the extreme sensitivity of crossflow to leading-edge roughness (as discussed in previous sections), the application of any control at the leading edge must be done with care. Any nonuniformity will likely act as roughness and enhance crossflow instabilities.

B *Passive Swept-Wing Laminar Flow Control - SWLFC*

The crossflow instability has been the primary Chimera holding back LFC. Favorable pressure gradients used to stabilize streamwise instabilities destabilize crossflow. For years, it seemed as though the only solution to crossflow control was surface suction. Despite the success of suction (Joslin 1998), the perceived complications with moving parts and additional maintenance were always discouraging factors toward using this for laminarizing swept wings.

In low-disturbance environments such as flight or special low-turbulence wind tunnels, the dominant crossflow instability is a stationary co-rotating vortex structure. Contrary to streamwise instabilities, this instability is not sensitive to 2-D roughness or freestream sound. Extensive tests with freestream sound and roughness in the ASU experiments have verified this behavior. On the other hand, also contrary to streamwise instabilities, crossflow is highly sensitive to 3-D roughness and freestream vorticity. In high-Mach-number flow, therefore, the more conventional blowdown tunnels with sound the prevailing disturbance can be used for crossflow tests on wings whose leading edges are swept beyond the Mach angle and one need not use a “quiet” supersonic tunnel. Of course, if one were to study streamwise instabilities or blunt-body effects, one must use a quiet facility. Also, sound passing through a bow shock will produce vorticity, so that in cases where the leading edge is unswept or swept ahead of the Mach angle, a quiet facility is also suggested.

Experiments with periodic discrete roughness elements (DRE) on a swept wing demonstrated a scheme for laminarization. Two important observations concerning the DRE results of Reibert et al (1996) are: (1) unstable waves occur only at integer multiples of the primary disturbance wavenumber; (2) no subharmonic disturbances are destabilized. Spacing apart the roughness elements with wavenumber $k = 2\pi/\lambda$, excites harmonic disturbances with spanwise wavenumbers of $2k$, $3k$, $\cdots$, nk (corresponding to $\lambda/2, \lambda/3, \cdots, \lambda/n$) but does not produce any unstable waves with “intermediate” wavelengths or with wavelengths greater than λ. Thus, excitation of subcritical wavelengths cause these waves to grow and prevent more unstable waves from growing. The subcritical waves eventually decay leaving nothing. See Saric et al (1998a,b) and Saric and Reed (2003) for details. Subsequent to the experiments, the NPSE results (Haynes and Reed 2000) confirmed this effect. In a DNS solution, Wassermann and Kloker (2002) have shown the same stabilization due to subcritical forcing. Using the same independent approach regarding the calculation of the basic state, they demonstrated the stabilization due to subcritical roughness. Saric and co-workers also showed that holes and glow discharge work equally as well as bumps, and that bump shape is not important just the spacing and height. Providing the initial 3-D biasing to the flow is the key.

C *Airfoil Design Criteria for SWLFC*

According to Saric and Reed (2002), the main ideas to consider during the design of the airfoil are to encourage crossflow, eliminate streamwise and attachment-line instabilities, and allow shorter wavelengths to grow sufficiently, early enough for control of the most unstable wavelength. The initial part of the design procedure is to have an accelerated flow that is nearly subcritical to T-S waves. When considering natural or passive LFC under flight Reynolds numbers of 15 million or more, it is injudicious to work at the margins of T-S instability. The present design philosophy is to eliminate or minimize T-S instabilities and concentrate on meanflow modifications to reduce the growth of crossflow waves.

To implement distributed roughness (or holes or glow discharge) for laminar flow control, one recognizes that in the flight environment, stationary crossflow is the dominant instability. One first identifies the most unstable stationary crossflow wavelength, λ_{crit} (again, it is easiest to reference this length as being parallel to the leading edge). Linear stability theory accurately predicts this critical wavelength and the location at which it first becomes unstable (neutral point). Then one studies stationary crossflow of shorter, *subcritical* wavelengths, λ_{sub}. These are the waves we will force by roughness for control. Therefore it is necessary that these waves grow strongly earlier than the critical wave, but then decay downstream after O(40%) chord. The observation is that the C_p distribution can be so designed that waves of about half the wavelength of the most unstable wave will grow sufficiently and then decay, thus changing the basic state and not allowing the most unstable wave to take hold. One must be cautious in C_p design that the stability N-factors do not become too large.

Therefore, an airfoil conducive to laminar flow control by distributed roughness must feature uniformly accelerated flow so that T-S waves are stable. With wing sweep, this favorable pressure gradient will be very unstable to crossflow. The associated C_p distribution must allow shorter-wavelength disturbances to grow sufficiently in the leading-edge region to nonlinearly modify the basic state and inhibit the growth of the longer-wavelength most-unstable disturbance. Thus transition will be delayed.

Traveling crossflow waves are more unstable (larger growth rate) than stationary crossflow waves according to linear stability theory. However, everything is forced at the shorter wavelength, λ_{sub}, and these traveling-wave growth rates are much lower and should not lead to transition. Traveling crossflow is not an issue with the distributed roughness. This has been confirmed in the low-speed experiments and reported in Gladden (2001).

The control proposed is to be applied at the leading edge within the first 2-5% chord. Radeztsky et al (1999) showed that small roughness placed downstream has no effect on the boundary layer and small roughness at the leading edge dominates crossflow transition. Because we are applying roughness for control, we have to pay attention that the roughness is not high enough to locally trip the boundary layer to turbulence. Here we are guided by Braslow's criterion that if the roughness Reynolds number, Re_k, is greater than 150, the flow is tripped (von Doenhoff and Braslow, 1961). Our proposed roughness is characterized by $Re_k = O(1)$, we are well below the limit.

D *Comment on Design Tools*

Linear stability theory accurately predicts which wavelengths are most unstable and which are appropriate for control, and is therefore very useful for SWLFC airfoil and wing design. However, due to the nonlinearities associated with crossflow, these calculations cannot be used to predict actual transition location for various operating and roughness conditions. Additional information is needed to assess the relevant parameters and actual impact on the drag. NPSE has been shown to accurately predict the growth and saturation amplitude of crossflow vortices and breakdown location.

III PRACTICAL LFC IN DIFFERENT FLIGHT REGIMES - CHALLENGES

A limited number of test cases are introduced with some thoughts on LFC in each case.

A *Lowspeed – General Aviation and UAVs*

For unswept wings, one can achieve passive LFC by designing an airfoil with a pressure minimum at say 70% chord and achieve laminar flow over the entire accelerated flow region. Crossflow and attachment-line problems do not exist and it is easy to keep T-S waves subcritical on the pressure side and sub-transitional (not marginal) on the suction side. Some care has to be taken with surface roughness – in particular 2-D steps or gaps, but in general, the analysis tools and technology are available. LFC is of particular interest for an increase in loiter time for UAVs and a reduction of fuel costs for general aviation.

Challenges: The challenge is to inform the designer that the solution of the Orr-Sommerfeld equation is not the formidable task as it once was. These airfoils can be designed and made to fly with significant laminar flow.

B *Subsonic – SensorCraft Type Aircraft and Business Jets*

For a SensorCraft type vehicle, time “on station” is an important consideration and LFC can make a contribution if it is simple and passive. Assume a prototype flight envelope of: Mach 0.6 – 0.7; altitude 60 – 70 kft; chord Reynolds number 6 – 7 million; sweep angle 25 – 35 deg. Under these conditions, one expects both T-S and crossflow. Because of the modest sweep and Reynolds numbers, the T-S and crossflow both can be controllable by design to give significant laminar flow runs. The design is not trivial since it must be based on integrated stability calculations and flowfield calculations within the C_L and C_M constraints. The use of passive SWLFC (periodic discrete roughness elements or DRE) for crossflow control will extend laminar flow beyond the natural case and could be limited by the pressure-recovery region. Moreover, success with this simple method could lay a foundation for extending LFC applications to other areas.

Challenges: The Transition Study Group Guidelines recommend not going to flight unless there is nothing left to do in a wind tunnel. Although this example is a tailor-made solvable problem, it has been demonstrated that only preliminary results can be obtained in a wind tunnel because the unit Reynolds numbers and the turbulence levels are higher than flight. This may be a case for which it is now justified to go to flight to demonstrate passive SWLFC even though flight experiments have limited diagnostic capability.

The challenge is to do a modest, single-point flight demonstration of passive SWLFC with limited instrumentation such as IR thermography and hot films. This could be followed by a more detailed research effort covering off-design sensitivity studies with actual airfoils.

C *Transonic Transports*

This flight envelope has Mach 0.8; altitude 30 – 40 kft; chord Reynolds number up to 25 million; sweep angles up to 35 deg. This is a more difficult problem because both crossflow and T-S are strongly amplified. The review of Joslin (1998) indicates that the technology, if not ready, could be made ready. Pfenninger et al (1980) suggests a possible design. One would have thought that the projected 25% savings in fuel would have kept this work active.

Challenges: Wind tunnel experiments are extraordinarily difficult in the Mach number range and flight tests are expensive and limited. However, if passive SWLFC can be demonstrated in the previous example, a renewed interest in this problem could arise.

D *Supersonic Transports*

During FY02 to FY05, DARPA supported the Quiet Supersonic Platform (QSP) program which, besides the shaped sonic boom studies, had a strong element of LFC. This flight envelope had Mach 2.4; altitude 40 – 50 kft; chord Reynolds number up to 50 million; and typically sweep angles beyond 67 deg. (subsonic leading edge). However, the group led by Richard Tracy (Reno Air/Directed Technologies) and Ilan Kroo (Stanford/Desktop Aero) worked on an almost-unswept design that was principally T-S unstable which was controlled by the *Cp* distribution (Kroo et al 2002). Preliminary tests were conducted at NASA-DFRC on the F-15B that validated the basic idea. By avoiding crossflow altogether and "biting the bullet" on the bow-shock drag, a simpler solution to LFC was suggested. Unfortunately, this work was not continued. The ASU group worked on experiments in the ASU supersonic tunnel at M = 2.4 (Saric and Reed 2002), flight tests on the F-15B at M = 1.85, and tests in the NASA-LaRC 4x4 UPWT at M = 2.17. Some success for passive SWLFC (periodic DRE) was shown in the ASU tunnel (Saric and Reed 2002) that was not duplicated in the other work for a variety of reasons.

The flight tests at NASA-DFRC were done on a bi-convex airfoil with a 30-degree leading-edge sweep. It appeared as though the periodic discrete roughness elements worked in one region. However, the result was not consistent. A detailed Euler computation of the F-15B with the model revealed a pylon shock that bled over the splitter plate on to the model. This shock was not washed away until the Mach number exceeded 1.8. Moreover, the flow field under the fuselage caused a spanwise-nonuniform sweep angle.

The wind tunnel tests at the NASA-LaRC UPWT were complicated by a variety of issues. Basically, the model had to be mounted on the back door of the tunnel and differential blockage between each side of the model caused an angle of attack change because of the subsonic leading edge. The 3% thick model and the corresponding sharp nose designed for a unit Reynolds number of 7 million/ft caused a leading-edge separation bubble that tripped the flow. A re-design and angle-of-attack changes did not solve the problem.

Challenges: Wind tunnels may be out of the question unless small models are used in huge tunnels. The large sweep angles to achieve a subsonic leading edge make the attachment-line Re_θ marginal at high unit Reynolds numbers. On the other hand, if a supersonic leading edge is used to reduce the sweep-angle secant term in Equation (1), the bow shock will create vorticity from the sound field which will acerbate the crossflow problem.

A flight test program may be in order here but perhaps not with a model mounted under the fuselage. A wing glove on a removable wing may be the solution. A continuation of the work with supersonic leading edges at low sweep angles to eliminate crossflow and 3-D roughness sensitivity is also a possibility.

It should be noted that perhaps the logical progression would be to demonstrate passive control of crossflow at modest subsonic Mach numbers such as the SensorCraft program. One can then seek applications in the transonic region before tackling supersonic flight.

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