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CROSSFLOW INSTABILITIES – THEORY & TECHNOLOGY

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ABSTRACT

Over the years, the crossflow instability has been the primary challenge for Laminar Flow Control (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. The perceived complications with moving parts and additional maintenance were always discouraging factors toward laminarizing swept wings.

This final hurdle may have been overcome with Arizona State University's (ASU's) technique of *passive nonlinear biasing of stationary crossflow wave growth*. The past decade or so has seen significant advances in experimental methods and computational tools and in the identification of important factors such as: environmental conditions on the appearance of stationary and traveling waves; secondary instability causing local transition in stationary-crossflow-dominated flows; extreme sensitivity of the stationary disturbance to leading-edge, very small, surface roughness; nonlinear effects and modal interaction; and extreme sensitivity of stationary wave growth to very weak convex curvature. By carefully studying the basic physics, these advances have lead to a new and promising opportunity for transition delay. Termed *"Swept Wing Laminar Flow Control (SWLFC)"*, this can be accomplished by distributed roughness, holes, or glow discharge applied at the leading edge. This promising technique is currently also being evaluated for supersonic flight (Saric and Reed 2002a,b).

INTRODUCTION TO CROSSFLOW INSTABILITY

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), Reibert and Saric (1997), Reshotko (1997), and Saric et al. (1998a,b; 2003).

The net result of the previous 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.

Four basic instability mechanisms can contribute to transition on a swept wing. Concave curvature can give rise to Görtler instabilities (Saric 1994a) but this can be controlled by the appropriate profile design. Leading-edge radius and sweep give rise to attachment-line contamination and instability (Pfenninger 1977; Poll 1985) but can be controlled by keeping the leading-edge radius below a critical value. Streamwise instabilities related to the Tollmien-Schlichting mechanism typically occur in the mid-chord region and transition can be reasonably correlated (Reed et al. 1996). It is now well known that using a favorable pressure gradient and minimizing the extent of the pressure-recovery region both contribute to the control of these instabilities. 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. The perceived complications with moving parts and additional maintenance were always discouraging factors toward laminarizing swept wings. This final hurdle may have been overcome with *passive nonlinear biasing of stationary crossflow wave growth*.

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Receptivity and the primary crossflow instability

Detailed physical receptivity mechanisms for crossflow have not been investigated experimentally. However, Radeztsky et al. (1999) and Deyhle and Bippes (1996), provide a parametric understanding of receptivity.

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.

Surface roughness is the other important crossflow receptivity mechanism. Three configurations have been investigated experimentally at Arizona State University (ASU) in a low-disturbance freestream environment and stationary-wave-dominated boundary layer. The model is an NLF(2)-0415 airfoil swept 45° and features a favorable pressure gradient back to 71% chord to stabilize streamwise instabilities and destabilize crossflow. The configurations tested include distributed random roughness and isolated static roughness elements (Radeztsky et al. 1999), and spanwise-periodic, static roughness arrays (Reibert et al. 1996). For random, natural-surface roughness, dramatic transition improvements were obtained by decreasing the rms roughness level from 3.3 μm to 0.2 μm. For chord Reynolds number $Re_c = 2.4 \cdot 10^6$, this roughness decrease delayed transition from 45% to 65% chord. The isolated roughness element studies established that stationary crossflow features are generated by particular 3-D roughness elements at 1–3% chord near the first neutral point of the crossflow instability – small 3-D roughness placed further downstream and 2-D roughness both have no effect. The most effective spanwise scale for an isolated roughness element is about one-fourth the most amplified stationary crossflow wavelength.

The primary instability studies that employed spanwise-periodic roughness arrays established a number of crossflow-transition features. First, Reibert et al. (1996) showed that primary stationary waves quickly become subject to nonlinear evolution. Nonlinearities are important early on because, although the stationary disturbances are small, they transfer O(1) momentum and produce a large integrated effect in the streamwise direction. This results in a severely distorted mean flow. The distortion results in saturation of the primary wave and growth of harmonics. Saturation appears well before transition. The saturation amplitude appears to be independent of the leading-edge roughness amplitude. As the primary wavenumber disturbance saturates, a rich spectrum of harmonics of the primary are produced, but no subharmonics appear (i.e. harmonics and subharmonics in wavenumber space). For the ASU wing, the most unstable stationary crossflow wavelength predicted by linear stability theory (LST) is 12 mm – it is most convenient to reference this length as being parallel to the leading edge. For 12-mm-wavelength roughness arrays applied at the leading edge, wavelengths of 12, 6, 4, and 3mm are observed but 24-mm waves are not. For 36-mm-wavelength roughness arrays, wavelengths of 36, 18, 12, 9, 7.2, 6, 5.1, and 4.5 mm are observed. A key feature of this is that any initial disturbance with spectral wavelength content *at or greater than* the most amplified wavelength will produce strongly amplified waves. Roughness heights from 8 to 48 μm corresponding to $Re_k = O(1)$ were tested. Here, Re_k is the roughness Reynolds number based on roughness height, and the local velocity and kinematic viscosity at the top of the roughness element.

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 Kawakami et al. (1999) 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 (2003) has put the secondary instability on firm ground.

LAMINAR FLOW CONTROL

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 only 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 1994b).

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 $\partial^2 U/\partial y^2$) usually results in lower disturbance growth. If the boundary layer equation is re-written near the wall as in (1),

$$\mu \frac{\partial^2 U}{\partial y^2} = \rho V_0 \frac{\partial U}{\partial y} + \frac{dp}{dx} - \frac{d\mu}{dT}\frac{\partial T}{\partial y}\frac{\partial U}{\partial y}, \quad y \approx 0 \qquad (1)$$

anything that makes the right-hand-side of (1) 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), and Reed et al (1996) 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 LFC (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, 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.

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. At that time of Joslin's paper, details for the F-16XL supersonic LFC suction-glove flight tests conducted by NASA, Rockwell, Boeing, and McDonnell Douglas were not available and the paper by Parikh (2003) will discuss the results. 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 midchord 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.

Swept Wing Laminar Flow Control - SWLFC

In this section we describe an opportunity for LFC for swept wings capitalizing on the nonlinear behavior associated with crossflow instability evolution and breakdown. The principal control problem on a swept wing concerns crossflow instability, which up to now was thought to be controlled only by boundary-layer suction. The recent experiments at ASU show that *passive nonlinear biasing of stationary crossflow wave growth* near the attachment line can maintain a laminar boundary layer.

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 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.

Two important observations concerning the distributed roughness 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 the roughness elements with wavenumber $k = 2\pi / \lambda$ apart, 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.

For the ASU low-speed wing, the most unstable stationary crossflow wavelength predicted by LST is 12 mm (parallel to the leading edge). For the baseline, highly polished, 0.2-μm-rms random roughness case, transition occurred at 65% chord. For 12-mm-wavelength roughness arrays applied at the leading edge, wavelengths of 12, 6, 4, and 3 mm were observed but 24-mm waves were not, and transition occurred at 45% chord. For 36-mm-wavelength roughness arrays, wavelengths of 36, 18, 12, 9, 7.2, 6, 5.1, and 4.5 mm were observed and transition occurred at 45% chord. This means that any initial, unstable disturbance with a wavelength at or an integer multiple of the most amplified wavelength will produce strongly amplified waves. Roughness heights from 8 to 48 μm corresponding to $Re_k = O(1)$ were tested and transition location was found to be invariant with initial roughness height. Next, a roughness spacing of 18 mm was used with the result that the 18, 9, 6, 4.5, 3.6, and 3 mm waves were observed. However, the subharmonic at 36 mm was not excited and, even more importantly, the most unstable linear mode at 12 mm was not observed. This shows that an appropriately designed roughness configuration can, in fact, inhibit the growth of the (naturally occurring) most-unstable disturbance.

When the roughness spacing was changed to 8 mm, the 8 and 4 mm modes were observed and transition moved back beyond 80% chord - beyond the pressure minimum (located at 71% chord) and onto the flap and out of view of the camera. The 8 mm mode grows early and then starts to decay around 30% chord. By itself, the 8 mm mode does not lead to transition, but during the rapid growth of this mode, the mean flow is changed and the 12 mm mode and higher wavelengths are suppressed, thus delaying transition. Subcritical forcing at 8 mm spanwise spacing *actually delays transition beyond that of the highly polished condition (0.2 μm), beyond the pressure minimum, and well beyond 80% chord* (the actual location was beyond view). Figures 1 and 2 show crossflow-vortex visualization via naphthalene applied to the airfoil surface for the ASU experiment. Figure 1 is the case with no control – natural transition is at 65% chord. Figure 2 is the case with distributed roughness of subcritical 8-mm spacing applied at the leading edge – laminar flow beyond 80%.

This experiment shows that transition control is possible using a passive roughness distribution near the attachment line. Later, Saric et al. (2000) demonstrated that 50 μm high roughness at a subcritical wavelength could suppress the effects of random background surface roughness in the range of 10 – 30 μm. In other words, the passive control technique would work for a standard aircraft finish.

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.

The main conclusion from the ASU experiments is that transition control is possible using *passive nonlinear biasing of stationary crossflow wave growth* near the attachment line, termed *"Swept Wing Laminar Flow Control – SWLFC"*. This can be accomplished by distributed roughness, holes, or glow discharge. This promising technique is currently being evaluated for supersonic flight (Saric and Reed 2002a,b).

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.

Airfoil Design Criteria for SWLFC According to Saric and Reed (2002a,b), 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 streamwise instabilities (Tollmien-Schlichting waves). When considering natural or passive LFC under flight Reynolds numbers of 50 million or so, it is injudicious to work at the margins of this instability. The present design philosophy is to eliminate streamwise 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 Tollmien-Schlichting 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.

For the ASU low-speed experiments, Figure 3 shows a representative C_p distribution conducive to SWLFC. Figure 4 shows the corresponding N-factor calculations (integrated growth rate) for stationary crossflow from LST. Each curve corresponds to a different fixed spanwise spacing (parallel to the leading edge). The most unstable wavelength is identified as 12 mm (parallel to the leading edge) and a candidate for control is 8 mm. Based on experience, a broad band of wavelengths in the neighborhood of the suggested control wavelength will work equally well in delaying transition.

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).

To avoid disturbances 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 as

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

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.

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 $Re_k = O(1)$, well below the limit.

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.

SUMMARY

Boundary-layer transition in 3-D flows is a complicated process involving complex geometries, multiple instability mechanisms, and nonlinear interactions. Yet significant progress has been recently made toward understanding the stability and transition characteristics of 3-D flows. Concerning the crossflow problem, the past decade has produced several important discoveries including tools such as:

- Instrumentation that can be applied to the flight-test environment.
- POD methods to interpret wind-tunnel and flight-test transition data.
- Validation with careful experiments of nonlinear PSE codes to predict all aspects of stationary disturbance growth.

and the identification of important factors such as:

- Environmental conditions on the appearance of stationary and traveling waves.
- Secondary instability causing local transition in stationary-crossflow-dominated flows.
- Extreme sensitivity of the stationary disturbance to leading-edge, very small, surface roughness.
- Nonlinear effects and modal interaction.
- Extreme sensitivity of stationary wave growth to very weak convex curvature.

In addition, by carefully studying the basic physics, these advances have lead to the promising application of *passive nonlinear biasing of stationary crossflow wave growth* at the leading edge to control the crossflow instability and delay transition on swept wings in flight. Termed *"Swept Wing Laminar Flow Control – SWLFC"*, this can be accomplished by distributed roughness, holes, or glow discharge. This promising technique is currently being evaluated for supersonic flight (Saric and Reed 2002a,b).

The study of 3-D-boundary-layer stability still offers challenges to the community. Important factors such as receptivity—the process by which external disturbances enter the boundary layer and create the initial conditions for an instability—are still not completely understood. Yet in spite of this, careful experiments and companion accurate computations have resulted in significant progress towards understanding a difficult problem and offer promise of even further advances in the future.

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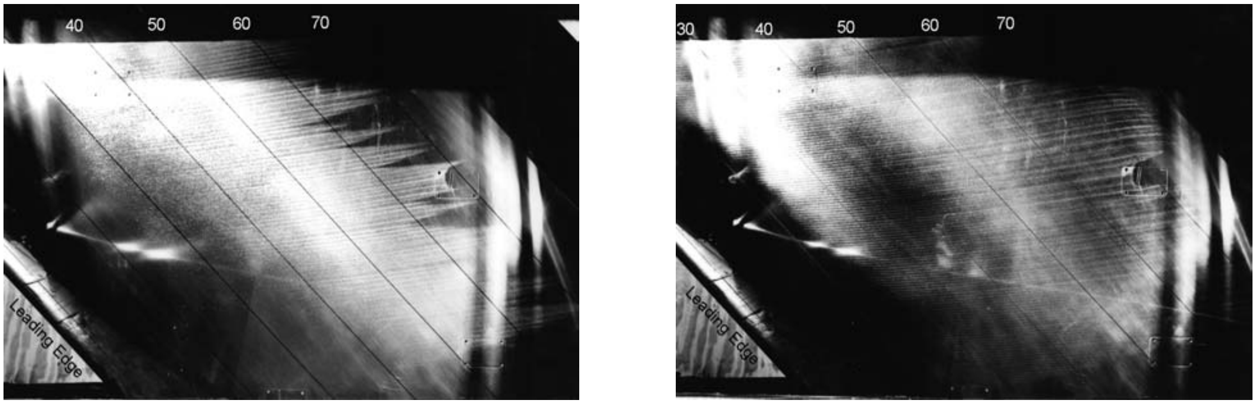

Figure 1. Natural transition at 65% chord.   Figure 2. Distributed roughness of 8-mm spacing at leading edge. Transition delayed beyond 80% chord.

Figures 1 and 2. Crossflow-vortex visualization via naphthalene applied to the wing surface. 45°-swept NLF(2)-0415 airfoil in ASU low-speed experiment. Flow from left to right.

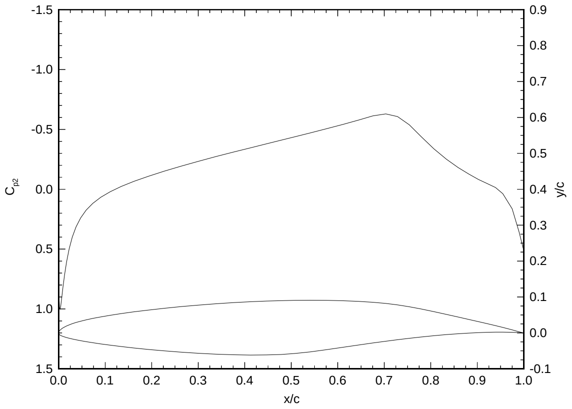

Figure 3. Upper surface C_p distribution for 45°-swept NLF(2)-0415 airfoil in ASU low-speed experiment.

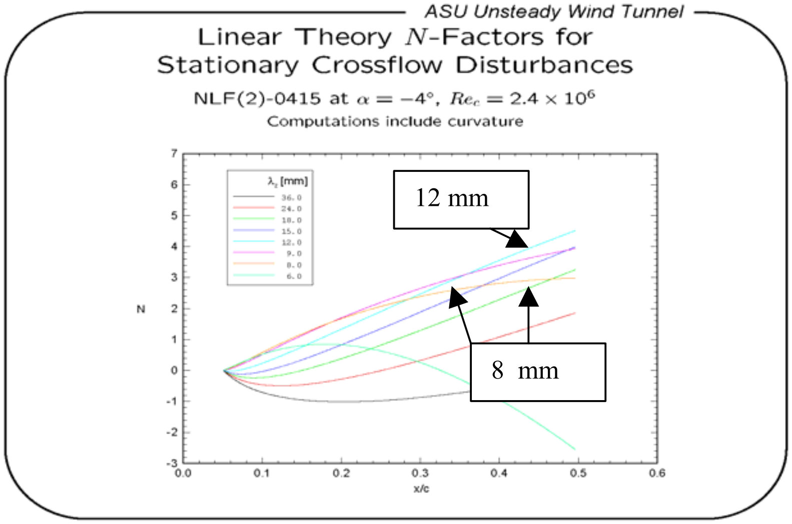

Figure 4. Stationary crossflow LST for 45°-swept NLF(2)-0415 airfoil in ASU experiment. Each curve a different spanwise spacing (parallel to leading edge). Most unstable wavelength 12 mm and candidate for control 8 mm.