AIAA 2001-0271
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39th Aerospace Sciences Meeting & Exhibit
8–11 January 2001
Reno, Nevada
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Abstract

The transition process on crossflow-dominated swept wings undergoes three distinct stages: receptivity, disturbance growth, and breakdown. The details of the physical mechanisms active in each render the common industrial tool for transition prediction, the \( e^N \) method, unable to produce acceptable results. An alternative method that accounts for the physical mechanisms of crossflow transition is required if better results are to be obtained. Experiments at the Arizona State University Unsteady Wind Tunnel have been performed to investigate each stage. Results from receptivity and breakdown experiments are presented here. The experiments show that the most important feature of the receptivity phase is mode selection and that selection of traveling- or stationary-wave-dominated transition depends on both turbulence intensity and surface roughness. The breakdown experiments elucidate the role of the high-frequency secondary instability as the breakdown mechanism and find that destabilization of the secondary instability is a useful transition criterion. The experimental results are used to suggest an alternative prediction method.

1 Introduction

The problem of predicting transition in swept-wing crossflow boundary layers is of significant importance because of the prevalence of swept-wing aircraft. Currently, the industrial approach to transition prediction, the \( e^N \) method, does not account for many of the advances made in the understanding crossflow transition in the past decade. And the bulk of these advances suggests that the \( e^N \) method cannot be successfully applied to crossflow transition.

The basic assumptions of \( e^N \)-based transition prediction are that there is an essentially uniform distribution of disturbance inputs to the boundary layer, that these disturbances grow linearly, and that transition occurs once any disturbance mode reaches a threshold amplitude. In practice, one computes \( N \) factors of all possible disturbance modes using linear theory and uses an experiment to determine the \( N \) factor that causes transition. The value of \( N \) incorporates the receptivity process and any nonlinear behavior prior to breakdown of the particular experimental setup. The \( N \) factor is then applied to somewhat different situations to predict the transition location. This method was first proposed\(^1,2\) for situations where Tollmien–Schlichting (T–S) waves are the dominant instability mode. The method is somewhat successful in those situations because each stage of the transition process, receptivity, disturbance growth, and breakdown does not deviate too significantly from the assumptions made by the \( e^N \) method. However, the same cannot be said for crossflow transition. For crossflow, none of the stages are correctly captured by an \( N \)-factor correlation. Successful transition prediction for crossflow-dominated boundary layers demands a completely different approach that reflects the physical transition mechanisms of crossflow.

A fundamental feature of swept-wing boundary layers is that the combined influences of wing sweep and pressure gradient produce curved streamlines at the boundary-layer edge. The curvature produces a secondary flow in the boundary layer that is directed perpendicular to the external streamline, toward the streamline’s center of curvature. The secondary flow is called crossflow. The crossflow velocity profile has an inflection point and is therefore subject to an inviscid instability that produces both stationary \((f=0)\) and traveling waves of nearly streamwise vorticity. This means that the instability mechanism for swept wings is fundamentally different from that of unswept wings because the unswept configuration is subject to the viscous T–S instability mechanism. One should not expect that a transition prediction strategy designed for T–S waves would be applicable to crossflow.
What is especially confounding to the $e^N$ approach is that although according to linear theory the most amplified mode is a traveling mode, in nearly all experiments that approach flight conditions (i.e., with low freestream turbulence), a stationary mode, not the most amplified traveling mode, is observed to dominate transition. There are two reasons for this. First, receptivity theory shows that in low-disturbance environments the initial amplitudes of stationary disturbances are much larger than those of traveling disturbances. Second, because the stationary vortices are nearly aligned with the inviscid streamlines, the same $u', v'$ disturbance acts on a fluid element along its entire trajectory. The result is a strong integrated effect that results in significant mean-flow modification, despite the relative low amplitude of the stationary disturbance. The fact that modification of the boundary layer occurs means that its stability is not well described by linear theory when stationary waves dominate. Instead a nonlinear model is required to understand crossflow boundary-layer stability for nearly the entire boundary layer.

Work at ASU by Radeztsky et al., Reibert et al. and Saric et al. has shown that when stationary modes dominate the transition process, amplitude saturation can occur if sufficiently high-amplitude surface roughness is present. In the cases examined where saturation did occur, it did so well upstream of the transition location, where linear theory indicates that the stationary mode should still be strongly amplified. The amplitude at which the fundamental mode saturates depends only on Reynolds number and the mode’s wavelength; it is independent of the initial amplitude (provided the amplitude is sufficiently high). Radeztsky et al. worked with low-amplitude distributed roughness that did not lead to saturation. Reibert et al. and Saric et al. worked with roughness arrays of higher amplitude that did lead to saturation. This process is well understood and has been successfully modeled by nonlinear parabolized stability equation (NPSE) codes by both Malik et al. and Haynes and Reed.

If traveling waves dominate the boundary layer, linear theory can be successful because there is not a mean-flow modification. This can be observed in situations with high freestream turbulence where there is a higher amplitude input to traveling waves. Deyhle and Bippes found that traveling waves dominate beyond $Tu = 0.0015$. Perhaps surprisingly, Deyhle and Bippes also discovered that if traveling waves dominate and the turbulence intensity is not too high, $0.0015 < Tu < 0.0020$, transition is actually delayed relative to stationary-wave transition. For comprehensive reviews of the recent experimental work see, Bippes for the DLR effort and Saric et al. for that of ASU. Other more general reviews are by Arnal, Crouch, Herben, Kachanov, and Reshotko.

The difficulties in applying the $e^N$ method to boundary layers with crossflow are demonstrated in a recent paper by Schrauf et al. In that paper, the authors attempt to correlate flight test data on swept-wing transition to $N$ factors obtained from linear stability codes with and without curvature and compressibility. Although a number of different variations on the method are attempted, including the envelope approach and a two-$N$-factor approach, there is no case for which a clear result is obtained. Moreover, the authors state that there are a number of pathological cases that must be removed prior to obtaining the correlations that are presented in the paper. It seems clear that the physics of crossflow transition are not amenable to $e^N$-based prediction.

To account for some of the difficulties in crossflow transition prediction using an $e^N$ method, Crouch and Ng recently presented a compromise approach that provides a variable $N$ factor that incorporates the results of the crossflow receptivity experiments by Radeztsky et al. at ASU and Deyhle and Bippes at DLR Göttingen. The form of this relationship is $N = N_0 - \ln \delta$, where $\delta$ is a roughness, suction, or turbulence parameter that captures the receptivity effects. Crouch and Ng argue that there should be a hierarchy of transition prediction methods ranging from simple approaches that provide crude transition estimates to highly accurate estimates that require very intensive calculations. The variable $N$-factor approach is intended to provide an intermediate level of such a prediction hierarchy. The authors correctly warn that in practical situations, additional computational effort is wasted if the initial disturbance conditions are not known to a very good (perhaps unobtainable) level of certainty.

Although a general hierarchical approach to transition prediction is appropriate, and the results Crouch and Ng present are quite good, the crossflow stability experiments at ASU since those of Radeztsky et al. suggest that other approaches to transition prediction that better reflect the physical mechanisms of crossflow transition may be more appropriate than a variable $N$-factor method. The purpose of this paper is to present the results of several such recent experiments at the ASU Unsteady Wind Tunnel and to use those results to argue for an alternative transition prediction methodology based on more-physical criteria than the $e^N$ method. The layout of the paper is as follows. The design of the ASU experiment is described in Section 2. Sections 3 and 4 present recent results on the receptivity and breakdown stages of crossflow transition. The nonlinear growth of the primary instability is not discussed in detail because those results have been more widely disseminated than the receptivity and breakdown results. Finally, in Section 5, an outline of an alternative transition prediction methodology is presented that reflects the physical transition mechanisms demonstrated by the results.
2 The ASU Swept-Wing Experiment

In the course of the ASU crossflow transition experiments, two swept-wing models have been used. Both share a design philosophy that has its origins with the work of Dagenhart. The objective is to provide an experimental platform that captures all of the essential features of a swept wing, undergoes crossflow-dominated transition, and yet provides the simplest possible experimental and computational problem. If all of the important physics are included in the experiment and good agreement with computations is achieved, then the computations can be used with confidence to obtain results with more realistic operating conditions. This implies that a swept wing is preferable to a swept flat plate because the wing provides surface curvature, and the results of Haynes and Reed indicate that even though the curvature is quite small, it is an essential element for correctly predicting stationary-mode growth rates. The model is not tapered, so a spanwise-uniform basic state can be established, greatly simplifying both the experiment and stability calculations.

What is needed for a successful experiment is a model with boundary layers that are sufficiently thick to allow for relatively easy and well-resolved boundary-layer velocity measurements and to simultaneously provide sufficient crossflow to cause transition. These requirements conflict because thick boundary layers can be achieved by restricting the experiment to low Reynolds numbers, but at too low a Reynolds number the instability would not be strong enough to produce transition. One of the first means of improving the prospect for strong crossflow and a thick boundary layer is to select a pressure gradient that locates the pressure minimum as far back on the model as possible. This permits the boundary layer to develop over the longest possible distance without becoming unstable to T–S waves and without the crossflow direction changing at the pressure minimum. The pressure gradient can also be used to enhance the crossflow by making the pressure gradient as strong as possible. Although this implies that strong negative lift is preferable, experience at ASU has shown that the wall liners used to maintain spanwise-uniform flow are difficult to construct and maintain when there is strong lift. Therefore, a pressure contour that provides a strong pressure gradient with a late pressure minimum at zero lift is the optimum configuration. Enhanced crossflow can also be produced by increasing the sweep angle of the wing. However, exceeding $\Lambda = 45^\circ$ is impractical for the hotwire traverse system.

The earlier ASU crossflow experiments employed a swept-wing model with an NLF(2)-0415 profile, a 1.83 m unswept chord length, and $45^\circ$ sweep. The profile locates the suction-side pressure minimum at 71% chord. Transition on this model is always observed upstream of the pressure minimum, so the T–S instability does not contribute to transition, nor does the Görtler instability, because the concave region also occurs downstream of 71% chord. The nose radius and sweep are such that leading-edge contamination is not present. Recently a new model, designated the ASU(67)-0315, was designed by Reibert around the same principles with the additional feature of generating significant crossflow at zero lift. The ASU wing has the same chord length, sweep angle, and suction-side pressure minimum location as the NLF wing. The ASU wing is operated at $0^\circ$ angle of attack, the zero-lift angle. A comparison of the measured pressure gradient on the ASU wing to the theoretical contour is shown in Figure 1. Other details of the experimental setup and procedures is available from White.

3 Receptivity

The receptivity of crossflow vortices to surface roughness and acoustic disturbances has been investigated at ASU since the work of Radetzsky et al. Receptivity to freestream turbulence has been investigated by Deyhle and Bippes who determined that turbulence intensity is a mode selection mechanism that controls whether stationary or traveling waves dominate the transition process. Recent work at ASU has suggested that the mode selection process may depend on both surface roughness and turbulence intensity and an experiment was performed to investigate this possibility. The suggestion that traveling waves result from an interaction of roughness and freestream fluctuations has been made by both Crouch and Choudhari. This is the first experiment that explicitly demonstrates the interaction.

The experiment consists of placing a turbulence generator in the wind tunnel to raise the turbulence intensity to $Tu = 0.003$, much higher than the nominal level of the Unsteady Wind Tunnel, but typical of many general-purpose wind tunnels that do not take the special flow-quality precautions necessary for conducting stability experiments. This level exceeds the Deyhle and Bippes criterion of $Tu = 0.0015$. For nominal surface roughness conditions, polished aluminum with an rms surface roughness less that 0.5 µm and $Re_c = 2.4 \times 10^6$, transition is observed in the naphthalene flow visualization photograph shown in Figure 2 to occur between $x/c = 0.40$ and $x/c = 0.50$ for the center region of the model. The transition front in the figure displays the saw-tooth pattern typical of stationary-wave dominated transition. The turbulent wedges that extend as far upstream as $x/c = 0.30$ result from surface irregularities at the leading edge associated with the variable roughness actuator. (See White and Saric for a description of the actuator.)
The roughness actuator is activated in the second part of the experiment to produce an array of 50-μm-high roughness elements on an 8-mm spacing at \( x/c = 0.025 \). These are conditions that Saric et al.\(^5\) showed can lamellarize the wing to chord locations beyond the pressure minimum at low turbulence levels. Subsequent experiments have shown that the techniques is effective at low turbulence levels with background surface roughness as high as 10–30 μm. In this case however, Figure 3 shows that transition is moved forward from \( x/c = 0.50 \) to \( x/c = 0.35 \) and that the saw-tooth pattern has disappeared. These two features indicate that for these conditions, the addition of “control roughness” has actually triggered earlier transition by forcing traveling waves that are more amplified than the stationary waves of all of the previous ASU transition-control experiments.

Two important conclusions should be drawn from these results. The first is that although the control technique of Saric et al.\(^5\) appears to be quite robust to random background surface roughness, it may not be as robust to enhanced freestream turbulence. Therefore, additional care is required in designing such a system for a real configuration. The second is that selection of traveling or stationary modes in crossflow boundary layers does indeed involve an interaction of freestream turbulence and surface roughness. Currently, additional experiments are underway that will establish a more detailed database of conditions for which one or the other type of mode dominates. This mode selection process clearly impacts the prospects for \( e^N \) transition prediction for crossflow. The traveling and stationary waves undergo different transition processes, so one must use the receptivity results to establish which type of mode will dominate and choose an appropriate transition prediction method on that basis. The ultimate conclusion may be that if traveling waves dominate, a modified \( e^N \) method is acceptable because for these situations, linear growth is observed. However, for the more common case where stationary waves are most important, there is a need for an alternative approach.

## 4 Breakdown

Since work of Kohama et al.\(^24\) at ASU on the secondary instability of crossflow vortices, it has been known that high-amplitude crossflow waves are subject to a high-frequency secondary instability preceding breakdown to turbulence. Recently, a detailed series of experiments has been carried out at ASU to investigate this phenomenon in more detail and to verify that it is the secondary instability, and not an absolute instability, that leads to crossflow vortex breakdown. Some preliminary secondary instability results of the ASU team were presented by White and Saric.\(^{23} \) Results of swept flat plate experiments of other groups have been presented by Kohama et al.,\(^25\) Lerche and Bippes,\(^26\) and Kawakami et al.\(^27\) The primary instability was shown to be a convective and not an absolute instability in a separate series of experiments by White.\(^20\)

The secondary instability experiments consist of hotwire velocity fluctuation measurements that are obtained for a grid of points in the spanwise–wall-normal plane for a single stationary crossflow vortex at various chord stations throughout the transition region. The velocity fluctuations are analyzed using a Fourier transform to identify individual modes of the secondary instability and traveling modes of the primary instability. Amplitude growth of the modes is obtained by integrating the fluctuations across one wavelength of the stationary crossflow vortex in \( z \) and from the wall to the freestream beyond where the fluctuations cannot be detected in \( y \).\(^1\)

Four cases are considered. The first is a baseline case at \( Re_c = 2.4 \times 10^6 \) with an array of 18-μm-high roughness elements on a 12-mm spacing (denoted \([18][12] \) roughness) applied at \( x/c = 0.025 \) (near the branch I neutral point). The second case examines the role of roughness height; it is also at \( Re_c = 2.4 \times 10^6 \) but with \([54][12] \) roughness. The third and fourth cases examine the role of Reynolds number and feature \([54][12] \) roughness at \( Re_c = 2.0 \times 10^6 \) and \( Re_c = 2.8 \times 10^6 \), respectively. The baseline case was presented in detail by White and Saric.\(^{23} \) Here cases two, three, and four will be discussed in more detail as they have now been more thoroughly investigated and are better understood. One important correction to the White and Saric paper\(^{23} \) is that the roughness amplitudes cited there are incorrect. That paper discussed 6- and 18-μm-high roughness, while the actual roughness heights for both that paper and the present work are 18 and 54 μm.

To review the results for the baseline \( Re_c = 2.4 \times 10^6 \), \([18][12] \) case, measurements begin at \( x/c = 0.30 \) where the mean flow has undergone mild distortion but has not yet developed the characteristic roll-over character of the highly distorted stationary vortices, nor does it display secondary instability behavior. By \( x/c = 0.40 \), the stationary vortex has saturated, and at \( x/c = 0.42 \), a 3.0-kHz disturbance begins to grow. The 3.0-kHz mode grows very rapidly and by \( x/c = 0.46 \) localized breakdown occurs. Full-field breakdown occurs within the next several percent chord. The amplitude growths of the stationary, 200-Hz (most-amplified) traveling primary, 3.0-kHz secondary, and 6.1-kHz secondary modes are given in Figure 4. Contour plots of the mean flow, the 200-Hz traveling crossflow mode, and the 3.0-kHz secondary mode at \( x/c = 0.40 \) are given in Figures 5–7. The 6.1-kHz mode is

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\(^1\) The coordinate direction \( z \) is in the span direction, parallel to the leading edge. \( Y \) is a global wind tunnel coordinate that is perpendicular to \( z \) and nearly aligned with the surface normal direction.

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spatially coincident with the 3.0-kHz mode, although the growth rates indicate that it is a distinct mode and not a harmonic.

The basics of the stationary vortex behavior for case two, \(Re_c = 2.4 \times 10^6\) with \([54][12]\) roughness, are nearly the same as for the baseline case. One would expect this based on the result of Reibert et al.\(^4\) that saturation amplitude does not depend on the roughness-array amplitude, provided it is sufficiently large. Two items substantially differentiate this case from the baseline, however. The first is that the total disturbance energy contained in the traveling modes of the primary instability is much larger than before. This result reinforces the conclusion of the previous section that the determination of whether stationary or traveling waves needs to include both turbulence intensity and surface roughness. The other significant difference present in case two is that in this case another secondary instability mode can be extracted from the data. This mode is at 6.1 kHz, as in the baseline case, except now the mode is located in the wall-normal velocity gradient region on the top of the overturning structure. The structure of the mode at \(x/c = 0.39\) is given in Figure 8. (The position of the underlying stationary vortex relative to the figure’s axes is equivalent to that in Figure 5.) The 3.0-kHz mode of the previous case is denoted a type-I or \(z\) mode and the 6.1-kHz mode of the type shown in Figure 8 is denoted a type-II or \(y\) mode,\(^6\) where \(y\) or \(z\) indicates the particular mean-flow velocity gradient that is most important for the disturbance mode’s energy production.

For the high-amplitude roughness case localized breakdown occurs first at \(x/c = 0.40\). Breakdown in this case is 6% chord upstream of the baseline case, but the difference is within the variation of the breakdown location of a single case, so the difference should not be considered significant. The growth of the stationary, 200-Hz, and 3.0-kHz modes are shown in Figure 9. The 6.1-kHz mode is not included in the figure because it did not persist for a long enough chord length to be meaningfully included. What is particularly interesting about the velocity fluctuations at breakdown for this case is that low-frequency fluctuations contain most of the disturbance energy, and yet it appears as if the destabilization of the secondary instability remains the breakdown trigger. Contours of the total fluctuation energy are shown in Figure 10, and the maximum is clearly located in the traveling crossflow wave region. In the baseline case an equivalent figure would show most of the energy concentrated in the same region as the 3.0-kHz type-I mode (see Figure 10 in White and Saric\(^{25}\)).

The results for the \(Re_c = 2.0 \times 10^6\), \([54][12]\) roughness case are the most difficult to interpret, yet the data are some of the most interesting. The roughness array in this case produces somewhat subcritical forcing, a mechanism that Saric et al.\(^5\) found could suppress transition. White and Saric\(^{23}\) reported that in the preliminary phase of the breakdown investigations at ASU, it appeared as if the vortex was eroded by high-amplitude laminar fluctuations because the velocity fluctuation spectra retained distinct mode structures rather than broadening and thereby indicating a breakdown to turbulence. White and Saric surmised that this combination of roughness and Reynolds number may be a marginal case for which transition suppression via subcritical forcing is almost effective. Some of the stationary vortices, however, are observed to undergo the same sort of rapid breakdown observed for the other cases, and these produce spreading turbulent wedges that eventually contaminate the entire boundary layer. Examination of one of the vortices that does undergo rapid breakdown reveals nearly the same behavior as the previous cases. Case three is an examination of one of these structures. The fluctuation growth curves for this case (Figure 11) show that the secondary instability does not trigger breakdown as rapidly in this case. The lowest frequency secondary instability at 2.4 kHz exists for slightly more than 10% chord prior to breakdown. The 4.9-kHz mode shown in the figure is likely a harmonic of the 2.4-kHz mode based on the growth-rate relationship. In the last few percent chord prior to breakdown, as many as five or six secondary instability modes can be observed in the fluctuation spectra, and all whose spatial distribution can be extracted appear to be type-I modes. At breakdown the fluctuation energy is nearly evenly divided between the traveling crossflow region and the mode-I region of the stationary vortex.

The fourth case, \(Re_c = 2.8 \times 10^6\) with \([54][18]\) roughness, presents a situation where the roughness array forcing is somewhat supercritical. The effect of this forcing appears to be a reduction of the spanwise mean-flow velocity gradients close to the wall. This is clearly visible in Figure 12, where the flow is nearly uniform in the span direction for \(Y < 0.75\) mm, especially on the left-hand side of the figure where the mode-I secondary instability is located. As a result of this somewhat different mean-flow distribution, the mode-II secondary instability is much more pronounced relative to the type-I modes in this case than in the others. The amplitude growth curves (Figure 13) show that in this case the type-II secondary-instability mode at 6.5 kHz undergoes growth equal to or greater than the 3.6-kHz type-I mode. Perhaps more important, the total fluctuation contours at breakdown shown in Figure 14 indicate that although most of the disturbance energy is in the traveling crossflow regions, a significant portion is in the mode-II location, and only an insignificant portion is located in the mode-I location.

In addition to these four cases, several tests were performed to determine whether the secondary instability could be forced directly via increased high-frequency
freestream fluctuations and whether such forcing could lead to accelerated breakdown. A number of tests were conducted both with acoustic forcing and enhanced freestream turbulence. Acoustic forcing at frequencies between 2 and 4 kHz as high as 125 dB for \( Re_c = 2.0 \times 10^6 \) and \( Re_c = 2.4 \times 10^6 \) with [54][18] roughness. No change in either the secondary-instability behavior or breakdown was observed in any of these tests. Tests using a turbulence generator located either in the settling chamber or in the contraction cone of the wind tunnel were also conducted. The grid was capable of producing freestream rms fluctuation levels as high as \( u'/U_\infty = 0.0029 \), high enough that traveling modes might be expected to dominate transition. \(^8\) But as before, no change in the secondary instability or breakdown behavior was observed.

The conclusion drawn from this series of secondary instability experiments is that breakdown of saturated stationary crossflow vortices is always preceded by rapid growth or one of more secondary-instability modes. It also appears that although lower-frequency disturbances may contain more total disturbance energy than the secondary instabilities, those disturbances are not the breakdown trigger. What is particularly encouraging about these results is that there is strong qualitative agreement with the secondary instability calculations of both Malik et al.\(^6\) and Koch et al.\(^28\) Both groups use linear, temporal approaches to the secondary-instability calculations using the saturated mean flow as a basic state. A rigorous comparison between the experimental results and the existing computations is not possible because they are for somewhat different conditions, but there is quite good qualitative agreement especially in terms of the appearance of both the type-I and type-II modes.

5 Crossflow Transition Prediction

The behavior of crossflow boundary layers suggest a wholly different approach to transition prediction than the e\(^N\) method. The physical mechanisms suggest that one first determine from a combination of \( Tu \) and surface roughness whether traveling or stationary waves will dominate the transition process. Then, if stationary waves dominate (as may be expected for flight situations), use an NPSE code to predict the saturation behavior of the most-amplified stationary modes. Last, using the meanflow solution provided by the NPSE code as a basic state, determine the chord location where the secondary instability destabilizes and use this location (or a location based on it) as the transition location.

While this more physical approach would certainly require more computational effort as Crouch and Ng\(^17\) suggest, the fact that the stationary disturbances saturate provided the initial input is of sufficiently high amplitude indicates that those efforts may not be wasted on uncertain initial conditions. Because the saturation amplitude appears to be independent of initial amplitude and the amplitude threshold for which saturation occurs is very low, acceptable initial conditions may simply be those that produce saturation. Reibert et al.\(^4\) observed saturation of 12-mm-wavelength disturbances at \( Re_c = 2.4 \times 10^6 \) triggered by an array of 6-\( \mu \)m-high roughness elements, and because roughness height is relative to the boundary-layer thickness, this level is certainly lower than any roughness amplitude that could be achieved on an actual aircraft. This may be a case where nonlinear effects actually simplify the analysis because a wide range of input conditions can be reduced to the same problem.

Using the destabilization of the secondary instability to determine the breakdown location should be a very robust criterion. In all the experimental cases of the breakdown experiment, where stationary waves dominated transition, breakdown occurred within a few percent chord of where the secondary instability could first be detected and the cases examined here show that this length may have a relatively simple dependence on the Reynolds number. Depending on the level of accuracy required, one could either use an \( N \)-factor approach based on the secondary instability as Malik et al.\(^6\) do or simply make the more conservative estimate that breakdown occurs at the point of destabilization as Högborg and Henningsson\(^29\) suggest. This sort of choice between simplicity and accuracy is exactly the sort described by Crouch and Ng’s hierarchical approach\(^17\) applied to a more physically realistic transition model. In either case, based on Malik et al.’s findings\(^6\) it appears that a linear, temporal secondary instability code is sufficient to determine the location of the secondary-mode destabilization.

This sort of method is not restricted to analysis of existing configurations of course, but can also be used as a design tool for laminar-flow wings. This is particularly relevant since Saric et al.\(^5\) have demonstrated that subcritical roughness arrays can completely suppress crossflow transition, but the results presented here indicate that some care must be taken to ensure that a roughness input designed to suppress transition does not do the opposite. A suitable design method would combine the information about the three stages to produce a control roughness configuration that would suppress the destabilization of the secondary instability while maintaining the importance of stationary waves.

Acknowledgements

This work was supported by AFOSR Grant F49620-97-1-0520. The authors wish to thank Dr. Helen Reed for her
assistance and encouragement and Dr. James Kendall for kindly allowing us to use his turbulence generator. Mr. Dan Clevenger provided invaluable technical assistance.

References


Figure 1: Theoretical and experimental pressure contours for the ASU(67)-0315 at $Re_c = 2.4 \times 10^6$ and $-3^\circ$ angle of attack.

Figure 4: Velocity-fluctuation rms growth, $Re_c = 2.4 \times 10^6$, [18][12] roughness.

Figure 5: Mean-flow velocity contours, $Re_c = 2.4 \times 10^6$, [18][12] roughness, $x/c = 0.40$, contour lines at $U/U_{edge} = 0.1$, 0.2, ..., 0.9.

Figure 6: 200-Hz velocity-fluctuation rms distribution, $Re_c = 2.4 \times 10^6$, [18][12] roughness, $x/c = 0.40$, 100–300 Hz bandpass. Lines are 10% contours of the maximum in this band.

Figure 7: 3.0-kHz velocity-fluctuation rms distribution, $Re_c = 2.4 \times 10^6$, [18][12] roughness, $x/c = 0.40$, 2.9–3.1 kHz bandpass. Lines are 10% contours of the maximum in this band.

Figure 8: 6.1-kHz velocity-fluctuation rms distribution, $Re_c = 2.4 \times 10^6$, [54][12] roughness, $x/c = 0.39$, 6.0–6.2 kHz bandpass. Lines are 10% contours of the maximum in this band.
Figure 2: Naphthalene flow visualization without $[50][8]$ roughness at $\text{Re}_e = 2.4 \cdot 10^6$ and $Tu = 0.003$.

Figure 3: Naphthalene flow visualization with $[50][8]$ roughness deployed at $\text{Re}_e = 2.4 \cdot 10^6$ and $Tu = 0.003$. 

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Figure 9: Velocity-fluctuation rms growth, $Re_c = 2.4 \times 10^6$, [54][12] roughness.

Figure 10: Total velocity-fluctuation rms distribution, $Re_c = 2.4 \times 10^6$, [54][12] roughness, $x/c = 0.40$, 20 Hz–8.0 kHz bandpass. Lines are 10% contours of the maximum rms fluctuations.

Figure 11: Velocity-fluctuation rms growth, $Re_c = 2.0 \times 10^6$, [54][12] roughness.

Figure 12: Mean-flow velocity contours, $Re_c = 2.8 \times 10^6$, [54][12] roughness, $x/c = 0.37$, contour lines at $U/U_{edge} = 0.1, 0.2, \ldots, 0.9$.

Figure 13: Velocity-fluctuation rms growth, $Re_c = 2.8 \times 10^6$, [54][12] roughness.

Figure 14: Total velocity-fluctuation rms distribution, $Re_c = 2.8 \times 10^6$, [54][12] roughness, $x/c = 0.385$, 20 Hz–12.0 kHz bandpass. Lines are 10% contours of the maximum rms fluctuations.