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NONLINEAR SATURATION OF STATIONARY CROSSFLOW VORTICES IN A THREE-DIMENSIONAL BOUNDARY LAYER

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ABSTRACT

Stability experiments are conducted in the ASU Unsteady Wind Tunnel on a 45° swept airfoil. The test-section floor and ceiling are contoured to simulate an infinite span, and the pressure gradient is designed so that the boundary layer is subcritical to Tollmien-Schlichting instabilities. Uniform stationary crossflow vortices are generated by placing arrays of micron-sized roughness elements near the attachment line. Roughness spacing and Reynolds number are varied to examine the behavior of multiple wavelengths and harmonics. Spectral decompositions isolate single-mode growth rates. The measurements show a clear nonlinear distortion of the mean flow and saturation of the stationary structure at considerably lower amplitude than predicted by linear theory. Comparisons with nonlinear PSE calculations show good agreement in the growth rate and amplitude saturation.

THE EXPERIMENT

Motivation

The present swept-wing research program experimentally investigates the fundamental nature of the crossflow instability which leads to transition in three-dimensional boundary layers.

In earlier ASU experiments, Dagenhart et al. (1989) found that naturally occurring stationary crossflow waves of moderate amplitudes have lower growth rates than predicted by linear theory. Under the same conditions, Radeztsky et al. (1993) investigated the sensitivity to surface roughness and observed (but did not quantify) the early saturation of the stationary disturbance amplitude. Later experiments by Radeztsky et al. (1994) examined the growth of very weak crossflow waves in an attempt to close the gap between prior experimental results and linear theory. Linear theory failed to predict the disturbance growth for these weak waves.

This experiment builds on the work of Dagenhart and Radeztsky—along with improved measurement techniques—to provide a detailed and accurate experimental database for the growth of stationary crossflow disturbances.

Parallel investigations on the saturation phenomena have been conducted at DLR-Göttingen. The most recent results are summarized by Deyhle and Bippes (1995).

Facility and Model

The Unsteady Wind Tunnel at Arizona State University is a low-speed, low-turbulence, closed-circuit facility used to study the stability and transition of laminar boundary layers (Saric, 1992). As in the previous experiments, the NLF(2)-0415 airfoil is used (Somers and Horstmann, 1985). The model is mounted vertically in the $1.4\ \mathrm{m} \times 1.4\ \mathrm{m} \times 5\ \mathrm{m}$ test section. Floor and ceiling contours produce an infinite-span swept-wing flow. With an angle of attack of $\alpha = -4°$, a strong, favorable pressure gradient produces moderate-amplitude stationary crossflow waves while suppressing T-S modes. The solid aluminum model is polished to 0.2 μm rms surface finish. A high-resolution, computer-controlled, three-dimensional traverse allows precise placement of the hot wires within the test section.

Wall-Normal Scans

Wall-normal boundary-layer scans provide a detailed map of the stationary structure. These maps are constructed by taking a spanwise series of mean-flow boundary-layer profiles normal to the wing surface. Once the scans are aligned along the span, disturbance profiles are generated from which a stationary crossflow wave mode shape is computed. The dis-

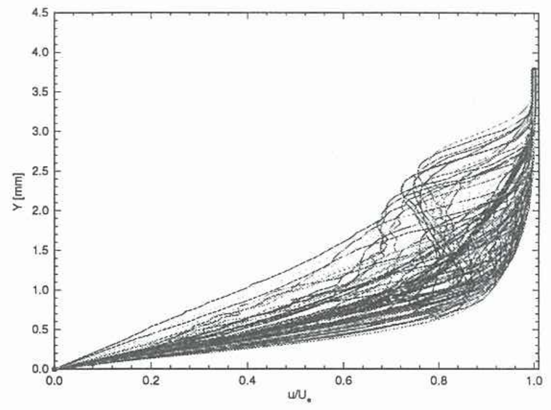

FIGURE 1: SPANWISE ARRAY OF BOUNDARY-LAYER PROFILES AT $x/c = 0.50$, $Re_c = 3.0 \times 10^6$. NO ARTIFICIAL ROUGHNESS. THE DOTS INDICATE THE MEAN OF THE PROFILES.

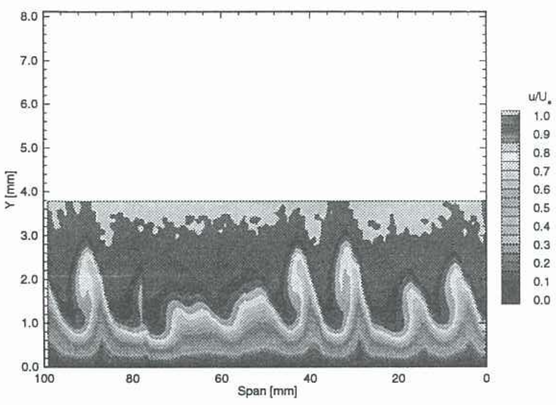

FIGURE 2: STREAMWISE VELOCITY CONTOURS AT $x/c = 0.50$, $Re_c = 3.0 \times 10^6$. NO ARTIFICIAL ROUGHNESS.

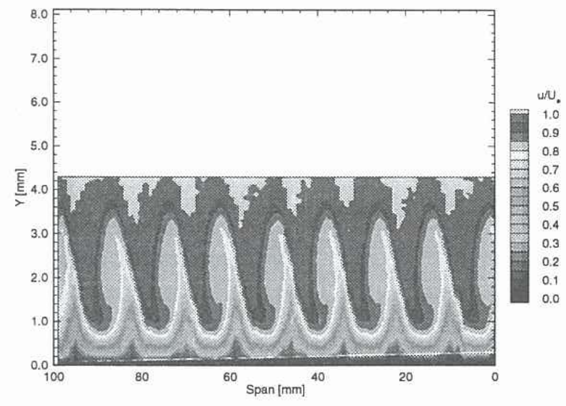

FIGURE 3: STREAMWISE VELOCITY CONTOURS AT $x/c = 0.50$, $Re_c = 2.4 \times 10^6$. A FULL-SPAN ARRAY OF 6 μm ROUGHNESS WITH 12 mm SPACING IS AT $x/c = 0.023$.

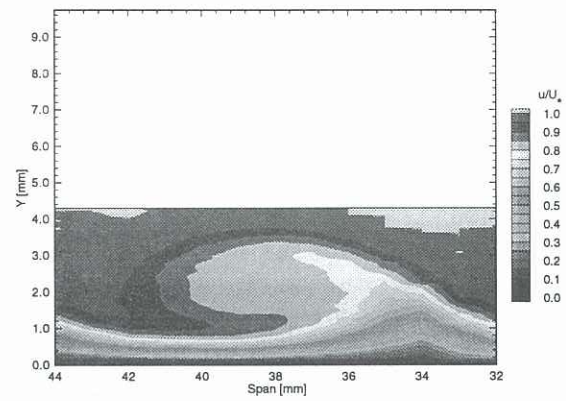

FIGURE 4: STATIONARY CROSSFLOW VORTEX ISOLATED FROM FIGURE 3. UNIT ASPECT RATIO.

turbance growth is computed by tracking the "size" of the mode shape at various chord positions. These results, however, cannot (in general) be quantitatively compared with single-wavelength linear predictions since *all* amplified stationary modes are lumped into a single mode shape.

Single wavelength information can be extracted by "slicing" across the boundary-layer profiles at a constant height above the wing surface, and using spectral techniques to resolve the wavenumber content. Reasonable resolution in the wavenumber domain, however, requires a large spanwise extent of the measurement region.

Spanwise Scans

A spanwise scan at constant height above the wing surface provides single-wavelength information in a fraction of the time required for a set of boundary-layer profiles. These scans are easy to perform and are well-suited for spectral analysis and single-mode measurements. The boundary-layer height at which to scan is chosen by consulting a corresponding mode shape produced by a set of wall-normal scans.

RESULTS

Boundary-Layer Maps

Figure 1 shows a set of 100 boundary-layer profiles covering a span of 99 mm. These scans are taken with no artificial roughness on the wing. It should be emphasized that these are mean profiles and not an unsteady oscillation in the boundary layer. One can clearly see how the stationary structure has distorted the mean flow, resulting in accelerated, decelerated, and doubly inflected profiles existing millimeters apart. A contour plot of the same data shows the nonuniformity of the naturally occurring stationary waves resulting from sub-micron surface irregularities near the leading edge (Figure 2). This plot shows the streamwise velocity u/U_e in the (y, z) plane. The flow is toward the reader, and the stationary vortices are turning in the right-handed sense.

The initial conditions are controlled by applying a full-span array of 6 μm roughness elements at $x/c = 0.023$. The spanwise spacing of the elements is 12 mm, corresponding to the most amplified wavelength according to linear theory. Figure 3 shows the streamwise velocity contour with the roughness in-

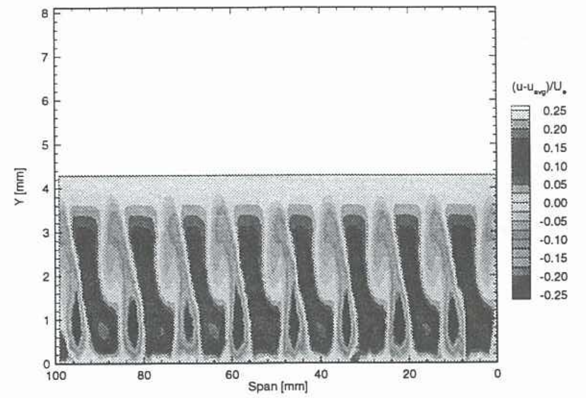

FIGURE 5: DISTURBANCE VELOCITY CONTOURS AT $x/c = 0.50$, $Re_c = 2.4 \times 10^6$. A FULL-SPAN ARRAY OF 6 μm ROUGHNESS WITH 12 mm SPACING IS AT $x/c = 0.023$.

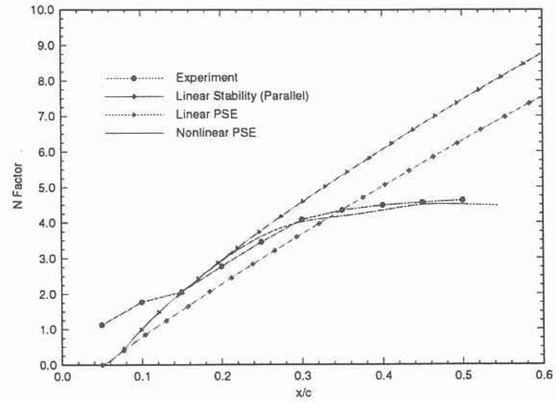

FIGURE 7: MEASURED AND THEORETICAL RELATIVE N-FACTORS FOR $\lambda_s = 12$ mm, $Re_c = 2.4 \times 10^6$. THE REFERENCE POINT FOR THE EXPERIMENTAL DATA IS $x/c = 0.15$.

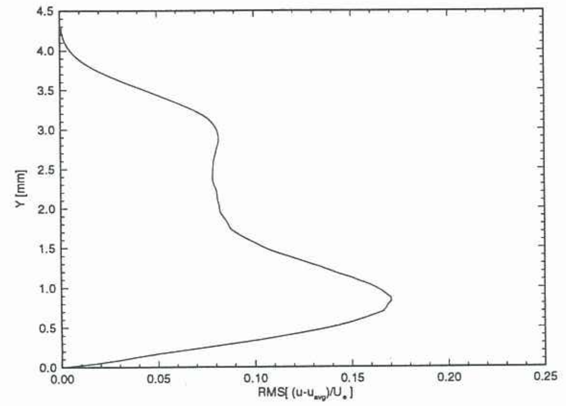

FIGURE 6: STATIONARY CROSSFLOW MODE SHAPE AT $x/c = 0.50$, $Re_c = 2.4 \times 10^6$. A FULL-SPAN ARRAY OF 6 μm ROUGHNESS WITH 12 mm SPACING IS AT $x/c = 0.023$.

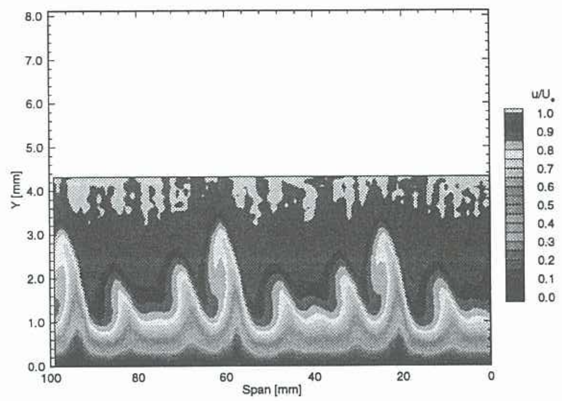

FIGURE 8: STREAMWISE VELOCITY CONTOURS AT $x/c = 0.45$, $Re_c = 2.4 \times 10^6$. A FULL-SPAN ARRAY OF 6 μm ROUGHNESS WITH 36 mm SPACING IS AT $x/c = 0.023$.

stalled. The dominance of the 12 mm mode is striking, as is the uniformity of the disturbance. Isolating a single vortex shows the "rollover" of the mean boundary-layer flow (Figure 4). Disturbance contours are generated by computing the velocity surplus and deficit with respect to the mean of the profiles (Figure 5). The crossflow wave mode shape is computed by taking the spatial rms of the disturbance profiles (Figure 6). The nonlinear growth is indicated by the distortion of the mode shape.

Since 12 mm forcing produces an overwhelmingly dominant 12 mm mode, growth rates can be computed by tracking the size of the mode shape at various chord locations. Figure 7 compares the experimental N-factor (log of the amplitude ratio) with the linear and nonlinear predictions of Haynes and Reed (1995). The saturation phenomenon is clearly evident, and the agreement with the nonlinear calculations is excellent. In contrast to Radeztsky et al. (1994), the early growth shows qualitative agreement with linear theory even though the present mean-flow distortion is an order of magnitude larger. This may indicate that the large roughness used by Radeztsky et al. caused the linear regime to be bypassed.

Wavelength Separation

Multiple-wavelength crossflow waves are produced by increasing the space between the roughness elements. Figure 8 shows the streamwise velocity contour obtained with a roughness spacing of 36 mm. The primary structures are 36 mm apart corresponding to the roughness spacing. Unlike the 12 mm forcing, however, superharmonics are present at integer multiples of the primary wavenumber. A mode shape similar to Figure 6 can be computed, but the individual wavelength information would be lost. Instead, these configurations are analyzed using the spanwise scan technique discussed above.

Figure 9 shows a spanwise scan taken at y = 1.0 mm above the wing surface. The strong mean-flow distortion is evident, and it is clear that the signal contains multiple wavelengths. Amplitude information is obtained by computing the FFT-based spatial power spectrum of the spanwise scan (Figure 10).

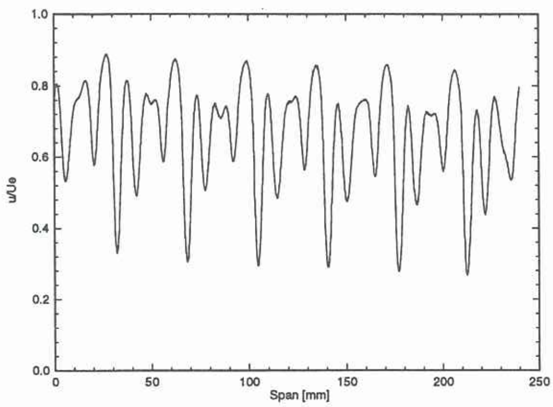

FIGURE 9: SPANWISE HOT-WIRE SCAN AT $x/c = 0.45$, $Re_c = 2.4 \times 10^6$, $y = 1.0$ mm. A FULL-SPAN ARRAY OF 6 μm ROUGHNESS WITH 36 mm SPACING IS AT $x/c = 0.023$.

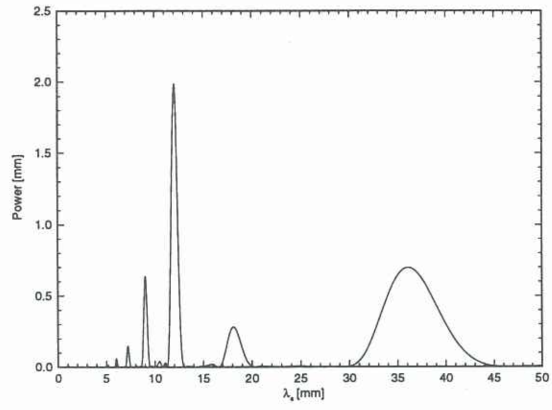

FIGURE 10: FFT-BASED SPATIAL POWER SPECTRUM OF SPANWISE HOT-WIRE SCAN SHOWN IN FIGURE 9.

Harmonics are amplified at wavelengths of 18 mm, 12 mm, and 9 mm. There appear to be no amplified subharmonics of the primary roughness spacing. It should be noted that the apparent width of the 36 mm peak is an artifact of plotting the spectrum in the wavelength instead of the wavenumber domain.

Single-mode growth rates are obtained by tracking the spectral power in each peak at various chord positions. Figure 11 shows the N-factors for wavelengths amplified by the 36 mm forcing. Some characteristics of linear theory qualitatively apply, such as the early growth, then decay, of shorter wavelengths. However, the persistence of the long wavelengths is not predicted.

CONCLUSIONS

Stationary crossflow disturbances are investigated with detailed hot-wire measurements on a swept airfoil. Micron-sized roughness near Branch I introduces known initial conditions without saturating the initial disturbance amplitude. Disturbance profiles, amplitudes, and growth rates are obtained, and spectral techniques are used to extract single-mode growth rates.

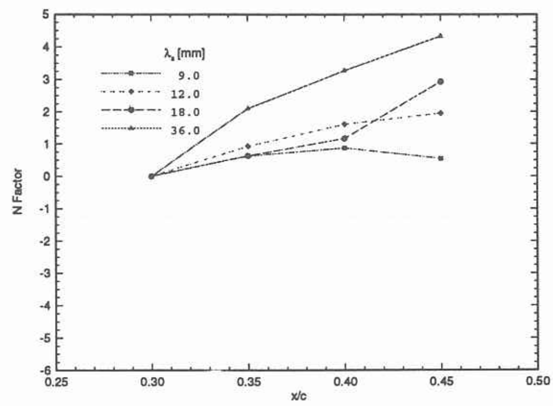

FIGURE 11: MEASURED RELATIVE N-FACTORS AT $Re_c = 2.4 \times 10^6$, $y \approx 1.0$ mm. THE REFERENCE POINT IS $x/c = 0.30$.

These data continue to illustrate the extreme sensitivity of stationary crossflow instabilities to leading-edge roughness. Nonlinear distortion of the mean flow is observed, as is the nonlinear saturation of the disturbance amplitude. Although there is evidence of early linear growth, only select features of linear stability theory apply. Nonlinear PSE calculations agree well with the experimental results.

ACKNOWLEDGEMENTS

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REFERENCES

Dagenhart, J.R., Saric, W.S., Mousseux, M.C., and Stack, J., 1989, "Crossflow-Vortex Instability and Transition on a 45-Degree Swept Wing", *AIAA Paper No. 89-1892.*

Deyhle, H., and Bippes, H., 1995, "Disturbance Growth in an Unstable Three-Dimensional Boundary Layer and its Dependence on Environmental Conditions", *J. Fluid Mech. in press.*

Haynes, T.S., and Reed, H.L., 1995, "Nonlinear Saturation of Stationary Crossflow Vortices in a 3-D Boundary Layer: Computational Analysis", *submitted to Physics of Fluids.*

Radeztsky, R.H. Jr., Reibert, M.S., and Saric, W.S., 1993, "Effect of Micron-Sized Roughness on Transition in Swept-Wing Flows", *AIAA Paper No. 93-0076.*

Radeztsky, R.H. Jr., Reibert, M.S., and Saric, W.S., 1994, "Development of Stationary Crossflow Vortices on a Swept Wing", *AIAA Paper No. 94-2373.*

Saric, W.S., 1992, "The ASU Transition Research Facility", *AIAA Paper No. 92-3910.*

Somers, D.M., and Horstmann, K.H., 1985, "Design of a Medium-Speed Natural-Laminar-Flow Airfoil for Commuter Aircraft Applications", *DFVLR-IB/29-85/26.*