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Technical Notes

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Origin of Surface-Shear-Stress Pulses in Turbulent Boundary Layers

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I. Introduction

INFORMATION related to the large magnitude pulses of surface shear stress that are present in all turbulent boundary layers [1] is sketchy. It has been demonstrated [2] that the pulses are related to the coherent events that make up the turbulent boundary layer. Recent computer simulations [3] related to "vortical" induced transition of laminar-to-turbulent boundary layers predict the occurrence of turbulent "spots" in the outer region of the layer, which in turn produce large pulses in the underlying surface shear stress. Although the transition turbulent spots differ from the coherent structures within the turbulent boundary layer, the process that produces the high-velocity pulses near the surface is expected to be similar. Flow visualization studies [4] for laminar-turbulent transition starting from Tollmien–Schlichting wave instability demonstrate a spectrum of "sweep" pulses first associated with a Λ vortex and progressing to much stronger sweeps (stage 3) in the final stage of transition.

The present experimental study examines the development of the time-dependent surface-shear-stress pulses and/or the near-surface velocities for transition flows with moderate, 1.2–2.7% freestream turbulence levels. A *bypass* laminar-to-turbulent transition occurs, which is similar to the computer simulation flows.

II. Experimental Study

A series of measurements was made in boundary layers transitioning from laminar-to-turbulent flow in a small, closed return, 6.9×16.5 cm inlet wind tunnel. The freestream velocity distribution (Fig. 1) at the measuring station, 53.3 cm downstream of the inlet, was favorable (i.e., the Hartree parameter β varied from 0.1 to 0.05, where the freestream velocity U_e was approximated as $U_e = Cx^{\beta(2-\beta)}$). For the initial measurements, the inlet turbulence intensity, in Fig. 2, varied from 0.012 to 0.017, depending on the flow velocity. For the laser velocimeter measurements (requiring seeding), it was necessary to remove the filter paper from the inlet, resulting in an increase of the inlet turbulence intensity to approximately 0.025. The boundary-layer thickness δ ranged from laminar values of $\delta/h \approx 0.17$ to turbulent values of 0.35, where h (=44 mm) is the vertical half-width of the tunnel at the measuring station. The laminar-turbulent transition was of the bypass type (i.e., no evidence of Tollmien–Schlichting instability).

Typical time traces of the surface shear stress for a number of Reynolds numbers are shown in Fig. 3. The Reynolds number was varied by changing the freestream velocity. The time-dependent surface-shear-stress traces were obtained using a 0.01 mm (0.0004 in.) diameter platinum-8% tungsten hot wire mounted directly on the surface. Details of the surface hot wire, substrate, and heat transfer characteristics were reported previously [1]. For the traces in Fig. 3, the wire was operated at a constant temperature using a commercial feedback anemometer and a power law linearizer (with an exponent of approximately six). The response time of the sensor, anemometer, and linearizer together was approximately 10^{-5} s. The surface hot wire was calibrated using a fully developed channel flow calibrator, which was mounted directly over the sensor. The extremely small values of $\bar{\tau}_w$, particularly in the laminar flow, resulted in uncertainties of 12–15%.

The surface sensor cannot distinguish between positive and negative shear stress. However, laser velocimeter measurements definitely indicated that the large pulses were always positive, Fig. 4. As the Reynolds number was increased, the population of the pulses increased. The last vestige of laminar flow appears as small patches of velocity decaying to near the laminar values. The surface-shear-stress pulses occur at the onset of the laminar-turbulent transition process. Although there is a spectrum of pulse shapes and magnitudes, many show a discreet and very rapid initial rise in shear with a slower rate of decay.

Figure 5 shows the comparison of a surface-shear-stress sensor time trace with that of a corresponding time trace for a hot wire located at $y/\delta = 0.76$ above the surface. The outer hot-wire trace shows dominant negative velocity "spikes" which were taken as an indication of the breakdown of the laminar flow in the outer region. These negative velocity spikes appear similar to the spikes reported by Klebanoff et al. [5]. The outer negative velocity spikes always preceded the surface-shear-stress pulses. Although not all of the outer flow disturbances produced a response at the surface, the surface-shear-stress pulses always followed an outer flow disturbance. Thus, it is evident that the surface pulses are a direct response to the negative velocity spikes.

The insert in Fig. 5 shows an expanded time scale trace of one of the shear pulses. (Note: the zero time was arbitrarily selected to correspond to the approximate beginning of the disturbance.) This surface-shear-stress pulse was 2.7 times greater than the mean value of the surface shear. Durbin and Wu [3] show a plot of the instantaneous values of the surface shear stress as a function of Reynolds number (i.e., their Fig. 11), obtained from the computer simulation, with peak values 2.6–2.8 greater than the mean value. Note that the present measurements are time traces at a fixed Reynolds number, whereas the computer traces are of Reynolds number at a fixed time.

The initial shear decay rate for the pulse on the insert of Fig. 5 was approximately $\Delta t^{-0.23}$, where Δt is the time measured from the maximum of $\tau_w(t)$. This decay rate is smaller than the $t^{-0.5}$ (or greater) decay obtained from similar solutions of the impulse equation [6], and also for the Blasius solution (using $t = x/U_e$). For the turbulent boundary layer [7], the initial decay rates appear to be more rapid than those shown in Fig. 5.

The laser velocimeter measurements (Fig. 4) made for a flow with a higher turbulence level, $(u'/Ue \approx 0.027)$, indicating that not only were the large velocity peaks (and resulting large

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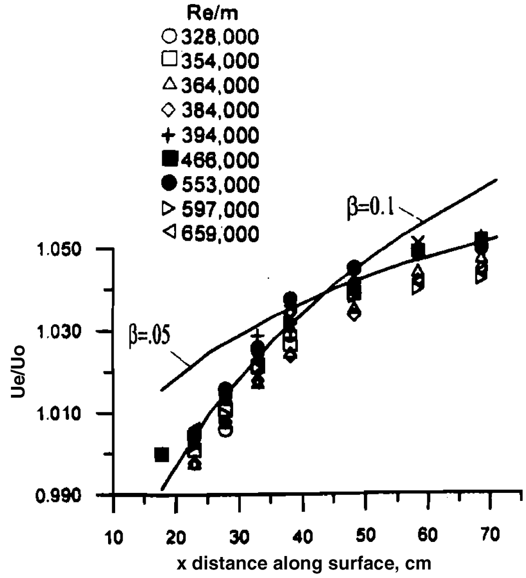

Fig. 1 Freestream velocity variation.

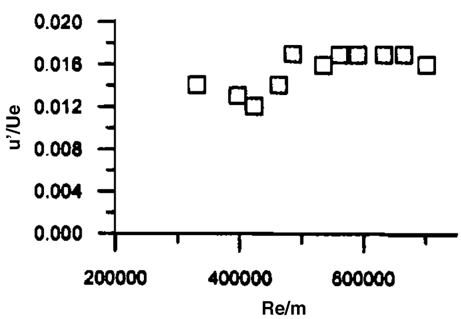

Fig. 2 Freestream turbulent intensity.

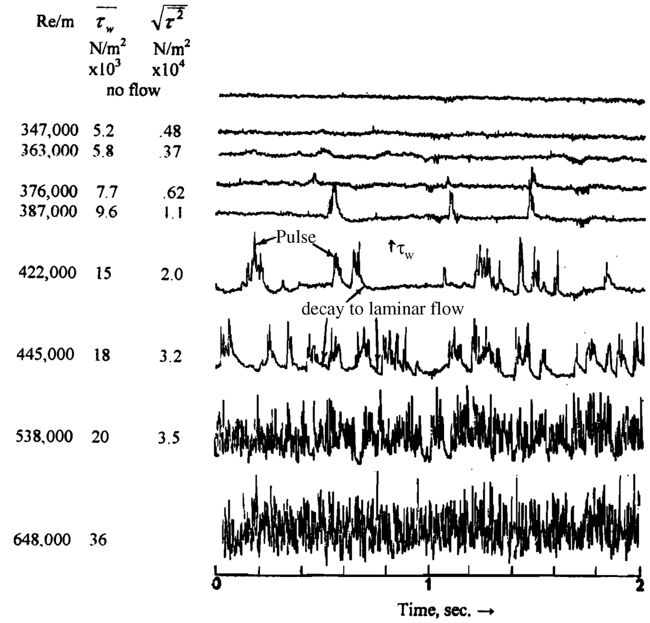

Fig. 3 Surface-shear-stress traces, $x = 53.3$ cm.

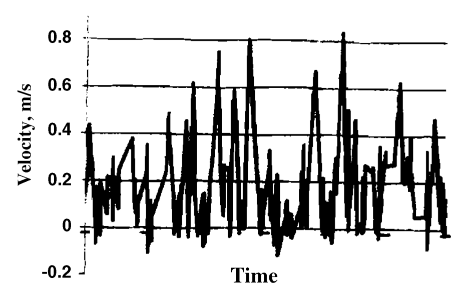

Fig. 4 Laser velocimeter time trace, $y = 0.1$ mm, $Re/\mathrm{m} = 336,000$.

surface-shear-stress pulses) always positive, but also that small *negative* velocities were present.

Alteration of the inlet turbulence level in the tunnel, from as low as 0.7–2.5%, did not appear to change the overall characteristics of the bypass transition, although the transition Reynolds numbers decreased with increasing turbulence. The drive blower of the tunnel operated at approximately 350 rpm, and was the major contributor to the freestream turbulence at the 0.7% level. Although the blower frequency was seen in the freestream measurements, it was not discernible in the output of either the outer layer or the surface sensors. As discussed by Durbin and Wu [3], the boundary-layer shear flow has a filtering effect on the freestream disturbances.

Cross-correlation measurements were made for two hot wires, one at a fixed distance in the outer part of the boundary layer, and the second wire at several y distances closer to the surface (for the 2.5% turbulence level flow). The insert in Fig. 6 shows a typical correlation when the inner wire was close to the surface. The negative correlations were present only when the inner wire was close to the surface and the outer wire signal was delayed with respect to the inner wire. The negative correlations changed abruptly to a positive correlation at $y_{\mathrm{inner}}/\delta \approx 0.18$.

Figure 6 is a plot of the *maximum* values of the cross correlation as a function of $y_{\mathrm{inner}}/\delta$ (outer sensor delayed). The abrupt change in the correlation from negative to positive might suggest that the flow close to the surface is not an integral part of the outer flow breakdown. Note that the correlations were from the direct voltage output of the sensors. Any nonlinear distortion (due to the wires' operation at different velocities) that might slightly alter values of the correlations was not expected to change the location of the "jump" from negative to positive. It was also found that the delay time to maximum correlation decreased sharply at the same y distance.

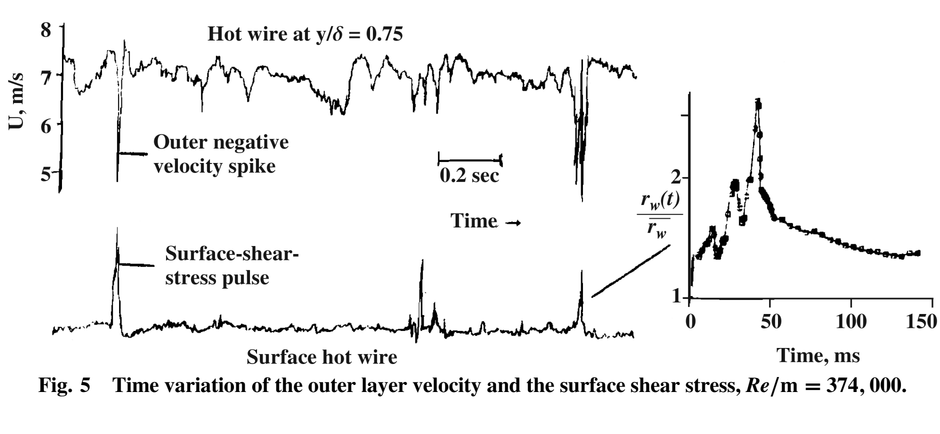

Fig. 5 Time variation of the outer layer velocity and the surface shear stress, $Re/\mathrm{m} = 374,000$.

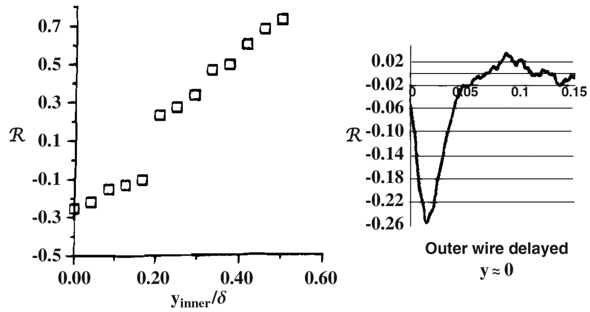

Fig. 6 Maximum values of the cross-correlation outer sensor at $y/\delta = 0.54$, $R_\theta = 400$.

III. Discussion

The present bypass transition quickly developed a negative velocity spike in the outer region of the laminar boundary layer, followed by the appearance of a surface-shear-stress pulse. These two features appear to be the dominant events for the present transition. Flow visualization [4] indicates that "extremely strong sweep events" occur in the *final* stages of transition, which best describes the present flow. A simplified model for the surface-shear-stress pulse in turbulent boundary layers [2] proposes that the quasi-irrotational flow in the boundary layer was forced to go around and/or beneath the "coherent structures." The present measurements are consistent with the proposed model, although the transition turbulent spots *are not* coherent structures present in turbulent boundary layers. Flow visualization studies [8] observe "elongated high-speed streaks" related to Λ vortices, occurring soon after Tollmien-Schlichting instability waves, which might more closely model the coherent structure-shear pulses.

The computer simulation of Wu et al. [9] (see their Fig. 11) indicates that the leading portion of the outer flow disturbance is a discrete vortex. For the present study, the spikes were employed as a flow marker, although the spikes have received considerable attention in the literature [8,10–12].

Direct numerical simulation (DNS) by Borodulin et al. [12] was able to produce the Λ vortices. The DNS study [12] also found that "ringlike vortices (associated with the well-known spikes) induce some rather intensive velocity fluctuations (positive spikes) in the near wall region." Although not explored in the present study, the DNS calculations and flow visualization [12] also indicate up to three well-defined negative spikes that can occur within a given disturbance.

It was noted by Durbin and Wu [3] that the turbulent spots generated by the bypass transition simulations were unlike those found for artificially produced (mature?) turbulent spots. Because the turbulent spot first appeared in the outer flow, this suggests that the rapid increase in surface shear stress, although due to the spot, is not necessarily an integral part of the outer vortex.

The computer simulations found that the turbulent surface-shear-stress pulses depend on the freestream turbulent characteristics. The surface-shear-stress values computed by Jacobs and Durbin [13] are much larger in magnitude than those reported by Durbin and Wu [3] or found in the present study. As noted for the present study, variation of the freestream turbulence level did not appear to alter the general development of the pulses.

The cross-correlation measurements indicate a marked change in the flow very close to the surface, which is consistent with the concept that the high-speed pulses are not an integral part of the outer packet of vorticity. The cross correlations appear to reflect mainly the decay region downstream of the pulse, because the duration of the pulses is very short. The recent measurements of Hernon et al. [10] employed local velocity maximums and skewness to define the penetration of the outer turbulent spots into the boundary layer.

Initially, it was suggested that the shear pulses might be due to the outer packet of vorticity producing a stagnation point at the surface. However, because the shear pulses were found to lag the center of the negative velocity spike, it is difficult to envision a pronounced stagnation point. The smaller shear increases that precede the larger shear pulse, shown in the insert of Fig. 5, could be an indication of the downward motion induced by the outer disturbance.

The present model implies that the higher momentum flow in the outer part of the boundary layer is diverted toward the surface. At very low Reynolds numbers [7], the pulses were the major contributor to the *mean* surface shear stress in the turbulent boundary layer. At higher Reynolds numbers, where the "packets of vorticity" (i.e., coherent structures) were dominant, the pulses were estimated to have contributed less than 20% to the mean value. The downward deflection of the outer flow momentum, although not originally foreseen in the early turbulence models, obviously must be a part of the "turbulent mixing length" concept near the surface.

The observation of local instances of reverse flow (Fig. 4) in the laminar-turbulent transition region was not reported for the computer simulations. For the present measurements, the reversals usually occurred at the end of the pulse decay. The reversals were of short duration, and so they had only minimal effects on the hot-wire measurements.

IV. Conclusions

The origin of time-dependent surface-shear-stress pulses in the transition region from laminar-to-turbulent boundary-layer flow was experimentally explored. Outer boundary-layer flow disturbances, characterized by negative spikes of velocity, were found to be the precursor for large positive surface-shear-stress pulses. The present results are similar to predictions obtained for computer modeling of the bypass transition process.

The measurements are consistent with a proposed model showing that the near-surface-velocity pulses, and the corresponding surface shear pulses, are the result of a higher speed, quasi-irrotational flow being forced to go around and/or beneath the packets of vorticity created by the outer flow turbulent spots.

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