

Inflectional Instabilities in the Wall Region of Bounded Turbulent Shear Flows

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Objective

The primary thrust of this research was to identify one or more mechanisms responsible for strong turbulence production events in the wall region of bounded turbulent shear flows. Based upon previous work in a transitional boundary layer (Swearingen & Blackwelder 1987), it seemed highly probable that the production events were preceded by an inflectional velocity profile which formed on the interface between the low-speed streak and the surrounding fluid. In bounded transitional flows (Swearingen & Blackwelder 1987, Finlay, Keller & Ferziger 1987), this unstable profile developed velocity fluctuations in the streamwise direction and in the direction perpendicular to the sheared surface. The rapid growth of these instabilities leads to a breakdown and production of turbulence. Since bounded turbulent flows have many of the same characteristics, i.e., strong shear, low-speed regions, oscillatory motions, etc., they may also experience a similar type of breakdown and turbulence production mechanism.

Methodology

From the turbulent-boundary-layer direct numerical simulation of Spalart (1988), the instantaneous velocity, pressure, and vorticity fields were readily available. The first effort was devoted to examining these fields visually through the wonders of the IRIS workstation. The spanwise shear, $\partial u / \partial z$, was examined as well as the related normal vorticity, ω_y . The inflectional profile associated with the shear layer with this orientation may be unstable in the Kelvin-Helmholtz sense and produce u and w fluctuations. Hence, the role of the spanwise velocity fluctuations was deemed to be important. Secondly, these fluctuations were studied to see whether the average structure associated with w indicated turbulence production. A detection method based on w using a VISA and quadrant technique was obtained by modifying existing software programs within the CTR. Thus, the shear $\partial u / \partial z$, etc., could be conditionally averaged to educe the relevant parameters leading up to and associated with the turbulence- production events.

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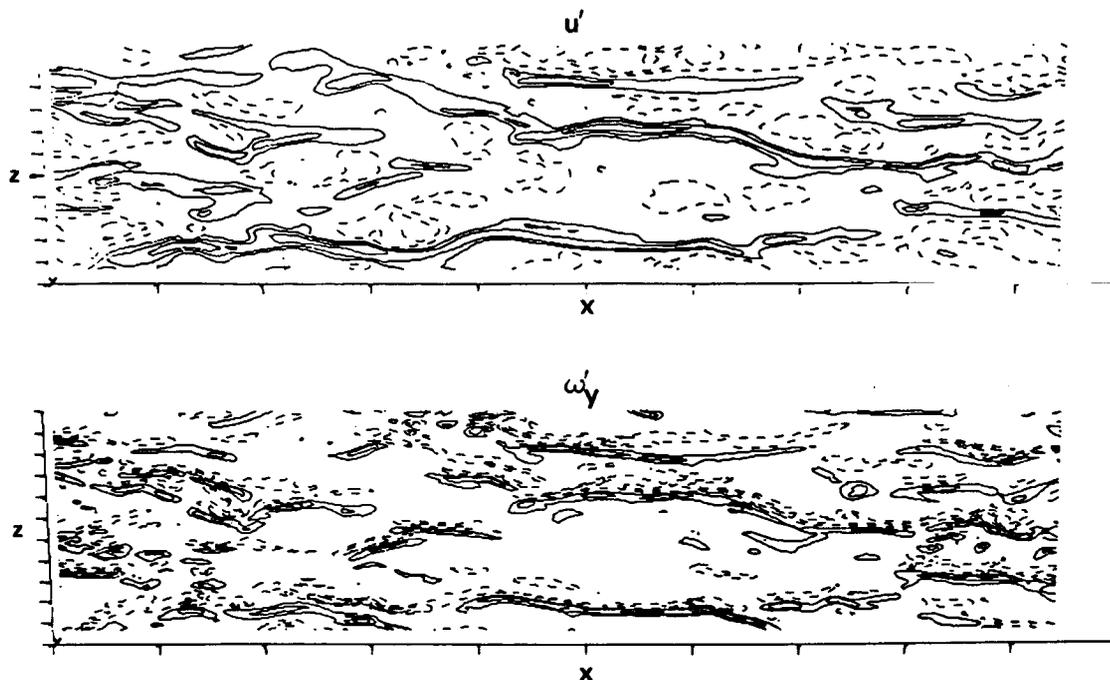


FIGURE 1. Contours in an $x - z$ plane. a) Streamwise velocity fluctuations u' ; b) normal vorticity ω'_y

Results

All of the results reported here were obtained from the boundary-layer-simulation data of Spalart (1988) for $R_\theta = 670$. The visual observations of the instantaneous velocity field near the wall revealed that the low-speed streaks were surrounded by regions of strong shear. On both sides of the streak (see Fig. 1), $|\partial u^+ / \partial z^+|$ was typically between 0.2 and 0.5 with opposite signs on the two sides. Above the streaks, $\partial u^+ / \partial z^+$ was also large and had similar values. Three-dimensional plots of the modulus

$$\left(\frac{\partial u^{+2}}{\partial y^+} + \frac{\partial u^{+2}}{\partial z^+} \right)^{1/2}$$

showed that in the region $15 < y^+ < 80$ it had its largest magnitude and was typically beside and above the low-speed streak.

In many instances, the low-speed region undulated, i.e., moved in the spanwise direction with a wavy motion. This movement was similar to those observed by Swearingen & Blackwelder (1987) and Finlay *et al.* (1987), and had a streamwise wavelength of $100 - 200 \nu / u_\tau$. As a time sequence of the low-speed region was followed, the undulating motion was seen to grow in amplitude and finally break up into chaotic motion.

Closer study of this motion revealed that the undulation was associated with strong w fluctuations. Data at $y^+ = 15$ were used to examine this aspect of the

low-speed streaks. A quadrant technique program was developed to plot the intense regions in quadrants 2 and 3 of the uw plane; i.e., those regions whose magnitude exceeded $4 u_\tau^2$ were plotted. The instantaneous field had three important characteristics: first, those spatial regions where quadrant-2 events were occurring had a preferred direction that made an angle with the streamwise direction of 10 to 15° in the $x - z$ plane. Similar quadrant-3 events were aligned at -10 to -15° forming a cone opening downstream and extending over a streamwise extent of 600 to $1200 \nu/u_\tau$. Secondly, the exact locations of the quadrant-2 and -3 events were often aligned with the locations where the low-speed streaks were turning in their undulatory motion; i.e., at the corners where the low-speed streak changes its direction. Thirdly, by plotting the quadrant-2 and -4 uv events (i.e., the high-production events in the Reynolds average sense) from the same data, the uw events were observed to occupy a much larger spatial extent than the corresponding uv events; i.e., the uw events had longer scales.

It was also observed that the corners of the undulating streaks were often in the process of being lifted away from the wall. A similar quadrant technique was used to examine the simultaneous v and w motions; namely, quadrants 1 and 4 in the vw plane. This motion, which had large amplitudes in these quadrants with $v > 0$, were compared with the streaks of the same data. The vw events were much less frequent than either the uw or the uv events. When they occurred, however, they generally denoted regions of the streaks near the corners that had been lifted. As these events were followed visually downstream, they broke up into chaotic motion.

Auxiliary results

If the turbulence production is associated with inflectional velocity profiles, then any disturbance at the inflection point should begin growing where an inflection occurs. The rate of growth is directly proportional to the shear at the inflection point, as described by Drazin & Reid (1984). Thus $U(z)$ data in the $y^+ = 15$ plane were searched for points of inflection, and the value of the gradient $\partial u/\partial z$ was recorded. Similar results were obtained for the values of $\partial u/\partial y$ at the inflection points in the $x - y$ plane in the range $10 < y^+ < 20$. These data were used to construct the conditional probabilities of the shear at the inflection points shown in Fig. 2. The conditional probability of $\partial u/\partial z$ is close to being symmetrical about the origin, consistent with spanwise symmetry, and has peaks at $\pm 0.16 u_\tau^2/\nu$.

The joint probability distributions of uw , uv , and vw were recorded to ascertain whether the embedded undulating motion described earlier could be detected in the standard statistics. The uw distributions were symmetrical about the $w = 0$ axis, as expected, but were asymmetrical about the $u = 0$ axis. Similar results were obtained for the vw joint distribution.

A preliminary attempt was made to determine where the largest changes in the flow structure occurred as the flow was convected downstream. The convection velocity, U_c , was obtained by comparing two data planes at the same y^+ value but displaced in time by $\Delta t^+ = 9$. The second plane was shifted in the x direction by a distance of $U_c \Delta t$ to form the function $f(x + U_c \Delta t, t_o + \Delta t)$ and the difference $\delta(x)$

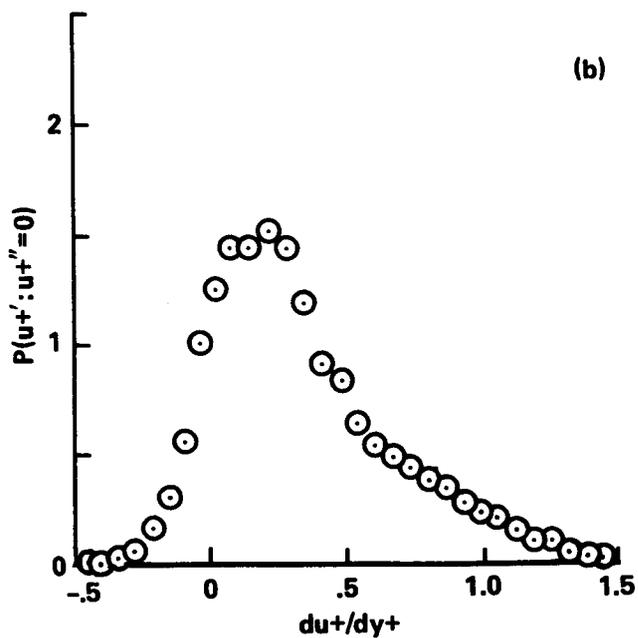
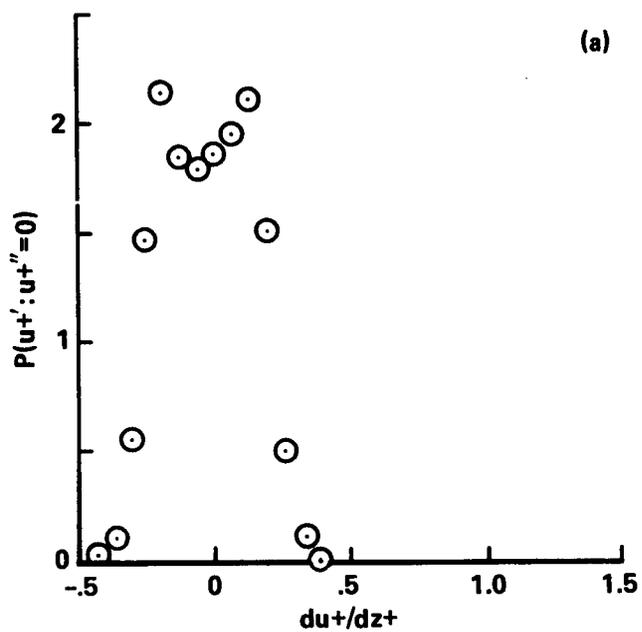


FIGURE 2. Conditional probability distributions at inflection points: a) du^+/dz^+ ; b) du^+/dy^+

with the first plane $f(x, t_o)$ obtained. The minimization of the mean square of the differences, δ , was used to determine the convection velocity U_c . The convection velocity in the logarithmic and outer region of the flow followed the mean velocity within the accuracy of the calculation. However, for all values of $y^+ < 10$, the convection velocity was constant at $U_c \approx 10 u_\tau$ for all flow variables; i.e., the velocities, vorticities, and pressure. This result could be very important for understanding the physics and for modeling and should be pursued further.

Summary

The results support the idea that an inflectional instability may be associated with and responsible for the disintegration of the low-speed streaks in the wall region. There was often a strong shear and an inflectional velocity profile surrounding the low-speed region. The time sequences indicated that this condition persisted up to $60 \nu/u_\tau^2$, indicating sufficient time for an instability to develop. The low-speed streaks developed an oscillatory motion which increased as time progressed, also indicative of an instability. The v and w velocity components became large during this motion, in accordance with an instability mechanism. In the last available time frame of the data observed in detail, the undulating portion of the streaks appeared to be breaking up into chaotic motion.

Future work

The work has been based primarily upon a study of the instantaneous data. In the future, one hopes to be able to apply conditional sampling to the data. The 1st and 4th quadrants of vw seemed to be the best detection function to pursue.

The fact that the convection velocity in the wall region was found to be constant at about $10 u_\tau$ has important implications for the wall structure, as well as modeling. It is hoped that this work can also be continued in conjunction with J. Kim.

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