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STRUCTURE OF SPANWISE VORTICITY IN A LOW REYNOLDS NUMBER TURBULENT BOUNDARY LAYER

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ABSTRACT

The spanwise (ω_z) component of fluctuating vorticity in a low Reynolds number turbulent boundary layer was measured using a four hot wire vorticity probe. A single hot wire, mounted on a plug and placed inside the sublayer provided a reasonable estimate of ω_z near the wall. The distribution of rms ω_z, skewness and flatness factors are in good agreement with other measurements and direct numerical simulation results at a comparable Reynolds number. Correlations between u and ω_z, v and ω_z, ω_z and its approximation at the wall, as well as conditional averages of the velocity field associated with both positive and negative detections of ω_z yield some useful insight into the vortical structure of the flow in the wall region of the layer.

INTRODUCTION

Vorticity is an important defining property of turbulence. The existence of organised, vortical motions in a turbulent bounday layer associated with ejections, sweeps and low speed streaks is now well established, based on extensive experimental investigations and numerical simulations. These organised motions make a significant contribution to mass, momentum and heat transfer in a turbulent boundary layer. In view of its importance, the measurement of one or more components of vorticity has been the focus of several investigations using different types of probes (see Foss and Wallace, 1989 for a review). Simultaneous measurements of all three vorticity components were made by Balint et al. (1991) using a nine-wire probe whereas the measurement of either the lateral (ω_y) or transverse (ω_z) component can be made using a four-wire probe consisting of an X-wire straddled by two parallel single wires (e.g. Haw et al., 1988; Antonia and Rajagopalan, 1989,1990). The performance of such a probe was verified by making spanwise vorticity fluctuation measurements in a wake (Antonia and Rajagopalan, 1990) and in a fully developed channel flow (Klewicki, 1989).

In the present investigation, statistical properties of ω_z were obtained from a four-wire probe in a low Reynolds number turbulent boundary layer and compared with other measured and numerical simulation data. A single hot wire probe, mounted on a plug and placed near the edge of the sublayer provided (simultaneously) an approximation to the instantaneous wall shear stress (and therefore ω_{zp} near the wall where the subscript p denotes the plug probe). The relationship between ω_z and ω_{zp} was studied using spatio-temporal correlations. Conditional averages of the longitudinal (u) and lateral (v) velocity fluctuations based on relatively large amplitude positive and negative peaks of ω_z were obtained to gain an insight into the flow structure in the near wall region.

EXPERIMENTAL CONDITIONS

The experiments were carried out in a zero pressure gradient turbulent boundary layer on the smooth wall of a wind tunnel. The boundary layer was tripped at the beginning of the test section by a 3 mm diameter wire followed by 10 cm wide coarse grain sand paper. The momentum thickness Reynolds number R_θ ($\equiv U_1\theta/\nu$, where U_1 is the free stream velocity, θ is the momentum thickness and ν is the kinematic viscosity) is 1450. The free stream velocity was 2.4 m/s and the friction velocity U_τ ($\equiv \tau_w^{\frac{1}{2}}$, where τ_w is the kinematic wall shear stress) was 0.1 m/s. The vorticity probe was made of 5 μm Pt-10% Rh wire with a sensing length of nearly 0.6 mm. The distance Δy between the parallel wires was 0.8 mm and the separation Δz between the two wires of the X-probe was 1.06 mm. This probe was mounted on a traverse to facilitate movement in the y-direction. A single hot wire was mounted on a plug and placed at 0.71 mm from the wall ($y_p^+ = 4.7$) at the same x and z locations of the vorticity probe. The calibration of the X-wire and the parallel wires of the vorticity probe was done in the free stream whereas the plug probe was calibrated indirectly by assuming that the mean velocity at the wire location is known. The signals from the hot wire were digitised at 2.5 kHz/channel using a 12 bit A/D converter with a simultaneous sample and hold unit on a personal computer. Data processing was done on a VAX 8550 computer. The instantaneous ω_z component was estimated by

$$\begin{aligned}\omega_z &= \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \\ &= -\frac{1}{\overline{U}}\frac{\partial v}{\partial t} - \frac{\Delta u}{\Delta y} \qquad (1)\end{aligned}$$

using Taylor's hypothesis to estimate $\partial v/\partial x$ and a finite difference method to evaluate $\partial u/\partial y$. The influence of Δy on the measurement of ω_z has been considered by Rajagopalan and Antonia (1992).

RESULTS AND DISCUSSION

Statistics of ω_z

The present distribution of ω_z' near the wall normalised by wall units (a prime denotes an rms value) shows good agreement with the measurement of Balint et al. (1991) and Klewicki and Falco (1991) and the simulation results of Spalart (1988) at a comparable Reynolds number (Figure 1). A more detailed discussion of the comparison is given in Rajagopalan and Antonia (1992). Skewness and flatness factor distributions (not shown here) also showed good agreement with the results of Balint et al., Klewicki and Falco and Spalart. The skewness of ω_z is negative throughout the layer, which indicates the dominance of negative ω_z peaks compared to the positive ω_z peaks. It was observed that $(\partial u/\partial y)$ makes a larger contribution to ω_z' than $\partial v/\partial x$; this contribution is a maximum near the wall and decreases as y increases. This suggests that large amplitude negative ω_z excursions can be essentially identified with positive $(\partial u/\partial y)$ or sweep-like motions which appear to dominate throughout the layer. Eckelmann et al. (1977) observed that at $y^+ = 15$, large, negative excursions in ω_z were essentially associated with a sweep-like motion having a large value of $(\partial u/\partial t)$.

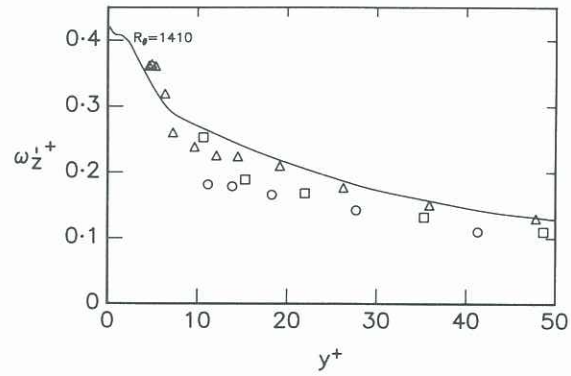

Figure 1 Distribution of rms ω_z in the wall region normalised using wall scaling. □, Present; Δ, Klewicki and □, Present; Δ, Klewicki and Falco ($R_\theta = 1010$); ◇, Balint et al. ($R_\theta = 2655$); ——, Spalart ($R_\theta = 1410$).

Correlation Between u or v and ω_z

The distribution of the correlation coefficients

$$\rho_{\alpha\omega_z} = \frac{\overline{\alpha(t)\omega_z(t)}}{\alpha'\omega_z'}$$

where $\alpha \equiv u$ or v are shown in Figure 2. Near the wall $\rho_{u\omega_z}$ is large and negative. In the limit $y \to 0$, $\omega_z \to -u/y$ and hence $\rho_{u\omega_z} \to -1$. The correlation coefficient $\rho_{v\omega_z}$ is positive but smaller in magnitude compared to $\rho_{u\omega_z}$. It can be shown, using a Taylor series expansion, that the value of $\rho_{v\omega_z}$ tends to ρ_{uv} as y decreases. In the outer region the magnitude of $\rho_{v\omega_z}$ is greater than $\rho_{u\omega_z}$. Near $y^+ \simeq 20$, both $\rho_{u\omega_z}$ and $\rho_{v\omega_z}$ change sign. A mixing length type argument appears to be consistent with the signs of $\rho_{u\omega_z}$ and $\rho_{v\omega_z}$ in the outer layer but not in the wall region.

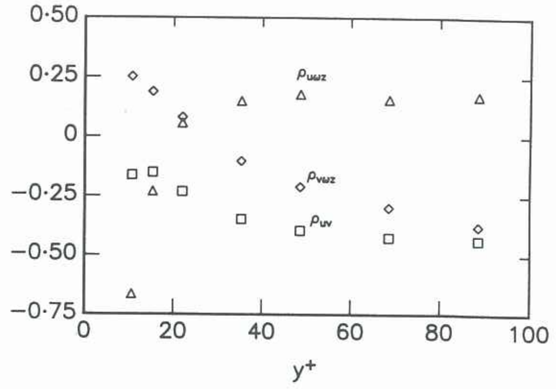

Figure 2 Distribution of normalised correlation between u and ω_z and v and ω_z. Δ, $\rho_{u\omega_z}$; ◇, $\rho_{v\omega_z}$; □, ρ_{uv}.

Correlation Between ω_z and u_p

The signal u_p from the single hot wire mounted on the plug at $y^+ = 4.7$ can be interpreted as instantaneous shear stress as $\partial u/\partial y \to u/y$ as $y \to 0$ as well as a reasonable approximation to ω_{zp} since $\partial v/\partial x \to 0$ as $y \to 0$. The correlation between u_p and ω_z, shown in Figure 3 should be -1 for $\Delta y^+ = 0$. The correlation is positive at small Δy^+ but becomes negative as Δy^+ increases. This suggests that on average, vorticity fluctuations in the sublayer are of opposite sign to those outside the sublayer. Two point ω_z correlation results of Klewicki (see Falco et al., 1990) and Kim (private communication) — the latter obtained from DNS data in a turbulent channel flow — indicate a similar trend. Falco et al. interpreted the negative sign of the two point correlation as due to the arrival of a "typical eddy" with positive ω_z at the location of the upper probe and fluid with $-\omega_z$ at the location of the lower probe. However, other interpretations are possible : for example, a vortex with strong negative ω_z at the upper probe could induce ω_z vorticity of the opposite sign at the lower probe.

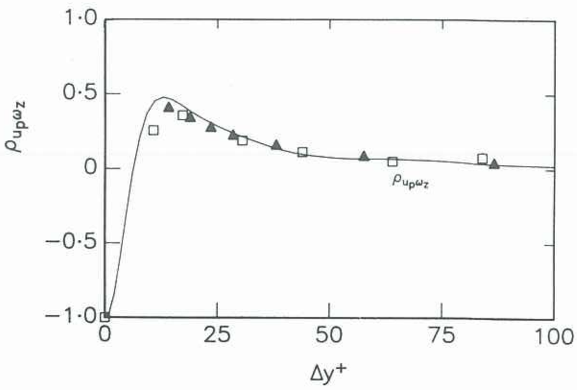

Figure 3 Space-time correlation between ω_z and u_p. □, $\rho_{u_p\omega_z}$; ——, DNS (Kim); ▲, $-\rho_{\omega_z\omega_{zp}}$ (Falco et al.);

Conditional Averages

It is of interest to obtain the conditional averages of u and v based on the detection of local positive and negative peaks of ω_z. An instantaneous quantity F can be written as

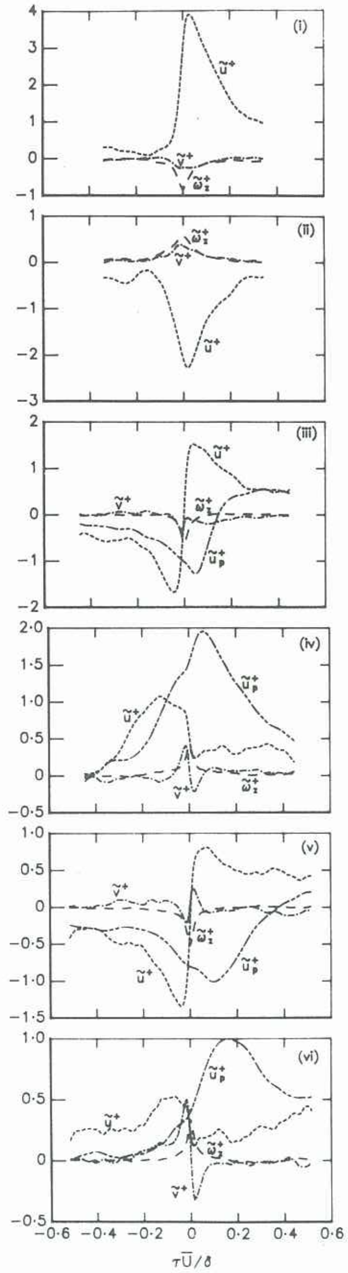

Figure 4 Conditional averages of u, v, u_p and ω_z. (i)–(ii) $y^+ = 10.7$; (iii)–(iv) $y^+ = 22$; (v)—(vi) $y^+ = 35$. ----, u; — - —, v; — —, ω_z; — - - —, u_p.

$$F = \overline{F} + \tilde{f} + f_r$$

where $\overline{F}$ is the mean value, f is the fluctuation (u, v, ω_z or u_p), $\tilde{f}$ is the component of f associated with the detected motion and f_r is the remainder.

The quantity

$$\tilde{f}(t) \equiv <f> = \frac{1}{N}\sum_{i=1}^{N} f(d_i + t)$$

where $<>$ denotes conditional averaging, N is the number of events detected and d_i ($i = 1, 2, ...N$) are the detection instants. A detection is recorded when $|\omega_z| > \beta$, where β is a threshold level, and reaches a local maximum.

Conditional averages of u and v associated with $\pm\omega_z$ detections are shown in Figures 4i–vi for $y^+ = 10.7$, 22 and 35. At $y^+ = 10.7$, $\tilde{u}$ is essentially positive and $\tilde{v}$ is negative when the detection is based on $-\omega_z$ and the signs of $\tilde{u}$ and $\tilde{v}$ are reversed when the detection is based on $+\omega_z$ (Figure 4i–ii). It appears that large $-\omega_z$ is associated with sweep-like motions near the wall ($u > 0$, $v < 0$) whereas large positive excursions of ω_z could be associated with either ejection-like motions or the lifting of low-speed streaks ($u < 0$, $v > 0$). Compared to $\tilde{u}$, $\tilde{v}$ exhibits a dramatic change in distribution and the distributions of $\tilde{u}$ and $\tilde{v}$ at $y^+ = 22$ and 35 (Figures 4iii–vi) may be interpreted as the signature of a spanwise vortex. The distribution of $\tilde{v}$ based on $+\omega_z$ also suggests the presence of such a vortex but with an opposite sense of rotation. This vortex-like characteristic of the conditional average was evident up to $y^+ \simeq 100$. While it appears that conditional averages, based on ω_z, can identify vortex-like structures in the wall region, a more complete description would require the simultaneous measurement of the longitudinal component ω_x in addition to ω_z.

CONCLUSIONS

The measurement of the spanwise vorticity component ω_z using a compact, four-wire probe in a low Reynolds number turbulent boundary layer shows good agreement with the measurements of Balint et al. and Klewicki and Falco and the direct numerical simulation results of Spalart. A single wire probe mounted on a plug and placed in the sublayer at a fixed distance from the wall provided a reasonable approximation to ω_z in the sublayer as well as the wall shear stress. The correlation between v and ω_z near the wall is positive, suggesting the presence of sweep-like motions. Conditional averages, based on the detection of peaks of ω_z of either sign suggest that, in the sublayer ($y^+ = 10.7$), large and negative ω_z excursions are associated with sweep-like motions. Conditional averages of $\tilde{u}$ and $\tilde{v}$ in the buffer and log regions suggest the presence of spanwise vortices with a sense of rotation opposite to that of the near-wall spanwise vorticity.

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