Streaky structures in a controlled turbulent boundary layer

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INTRODUCTION

Active control of turbulent boundary layers for skin-friction drag reduction has received a great deal of attention in fluid dynamics research community due to its significance in engineering applications. It has been widely accepted that large-scale coherent structures such as quasi-streamwise vortices and sweeping events in the near-wall region of a turbulent boundary layer (TBL) is closely connected to large skin-friction drag. Thus, manipulating these structures may affect the skin-friction drag. Recently, Bai et al. (2012) employed a spanwise-aligned PZT-actuator array (Fig 1.1) generating local surface oscillations to disturb the near-wall coherent structures in a TBL at Re_θ = 1000, based on momentum thickness (θ) and free-stream velocity U_∞ = 2.4 m/s [1]. The cantilever-supported actuators can oscillate individually when driven by a sinusoidal voltage and, given a phase shift $\varphi_{i,i+1}$ between two adjacent elements, a transverse travelling wave on the wall surface. The skin-friction drag downstream of the actuator was estimated by the slope of hotwire-measured streamwise mean velocity profile in the viscous sublayer. Under the optimum control parameters (i.e., A_o^+ = 2.22, f_o^+ = 0.65, and $\varphi_{i,\,i+1}$ = 18°, where A_o^+ is the peak-to-peak oscillation amplitude at the actuator tip and f_o^+ is the oscillation frequency), Bai et al. achieved a large reduction in local skin-friction drag by 50% at x^+ = 17 and, meanwhile, observed significantly impaired streaky structures near the wall. Superscript '+' denotes normalization in wall units in the absence of control. The altered near-wall flow structures were carefully examined based on extensive measurements via smoke-wire flow visualization, hotwire, hot-film, and PIV. This work aims to study further these altered streaky structures under the optimum control parameters, based on PIV-measured fluctuating velocity u^+ in the viscous sublayer using a velocity streak eduction procedure proposed by Schoppa & Hussain (2002) [2].

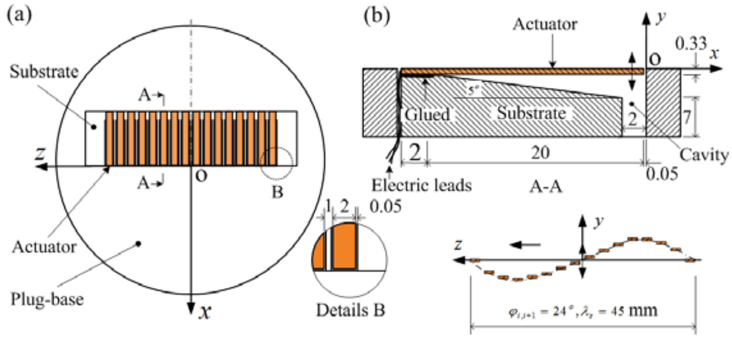

Fig. 1.1 (a) Layout of 16 PZT actuators, (b) the cantilever-supported actuator and one spanwise wave formed at $\varphi_{i,\,i+1}$ = 24° (λ_z = 45 mm or 312 wall units).

Table 1.1 Statistical results of low-speed streaks at y^+ = 5.5

	Natural TBL	Disturbed TBL
N	294,653	337,704
$\overline{S}^+$	83.8	72.5
$\overline{L}^+$	49.2	43.2

RESULTS AND DISCUSSION

Table 1.1 presents a comparison of the statistical results from the streak eduction between the natural and controlled flows, i.e., identified low-speed streak center numbers N, and averaged low-speed streak spacing $\overline{S}^+$ and width $\overline{L}^+$. The number of low-speed streak centers was increased by about 15%, whilst both the averaged width and spacing were reduced by about 12% by the wall-based oscillations.

Fig 1.2 shows histograms of the low-speed streak spacing S^+ and width L^+ with and without control. The distributions of S^+ (Fig 1.2a) and L^+ (Fig 1.2b) were greatly modified by the local surface oscillations. In the absence of control, the histogram of S^+ shows a positively-skewed distribution, with the highest value at $S^+ \approx 60$. Under control, the S^+-distribution was more positively-skewed, with its maximum shifted towards smaller S^+ ($\approx$ 50). For the low-speed streak width, the highest probability occurs at $L^+ \approx 30$ in the natural flow but is shifted towards smaller L^+ under control, suggesting impaired streaks. The observations are in line with results from smoke-wire flow visualization (Fig 1.3) and two-point cross-correlation function R_{uu} of u (Fig 1.4). Large-scale coherent structures appear broken up, resulting in considerably

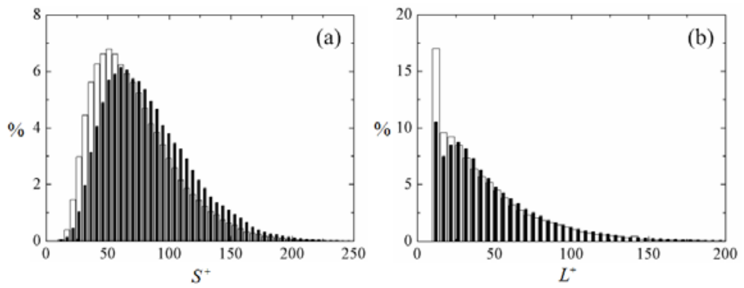

Fig. 1.2 Histograms of low-speed streak spacing S^+ (a) and width L^+ (b): ■, natural; □, controlled.

smaller-scale longitudinal structures (Fig 1.3). R_{uu} in Fig 1.4 indicates that lateral integral scale (areas under the curve) of the streaks was reduced by the wall-based oscillations.

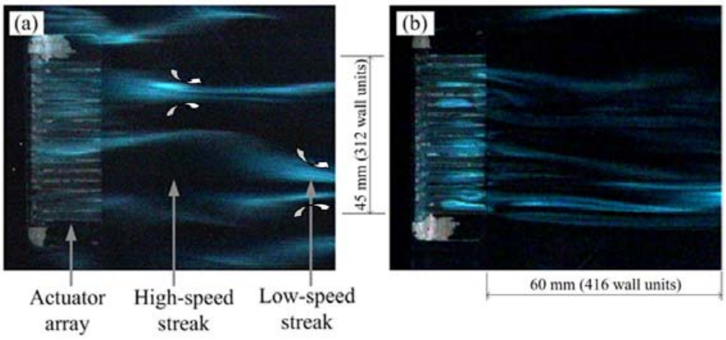

Fig. 1.3 Typical photographs of instantaneous flow structure in the *xz*-plane at $y^+ = 10$ from smoke-wire flow visualization: (a) uncontrolled, (b) controlled. Flow at $U_\infty = 1.5$ m/s is left to right. Circular arrows indicate streamwise vortices.

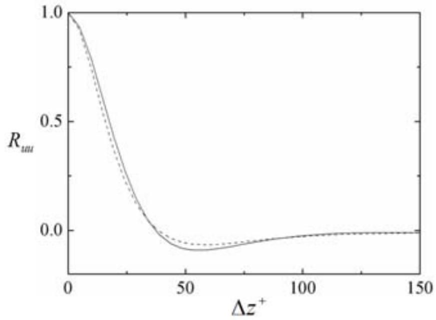

Fig. 1.4 Two-point cross-correlation function R_{uu} of u: —, natural; ----, controlled.

Figure 1.5 shows the histograms of $\partial u^+/\partial x^+$ and $\partial u^+/\partial z^+$ at the streak borders with and without control, which characterize the internal shear layer and streamwise vortex generation. The histogram (Fig 1.5a) appears positively-skewed in the absence of oscillations, due to the fact that the magnitude of positive $\partial u^+/\partial x^+$ decreases across the streak border when fluid particles move from the inside to outside of a low-speed streak. Once the control was introduced, the histogram is more symmetrical, which is attributed to the occurrrence of less coherent structures in the disturbed flow and thus consistent with observations from the flow visualization (Fig 1.3). The higher probability of large $\left|\partial u^+/\partial x^+\right|$ in the histogram tails in the disturbed flow suggests that the low-speed streaks become less aligned with the streamwise flow and probably more wavy, compared to the natural case.

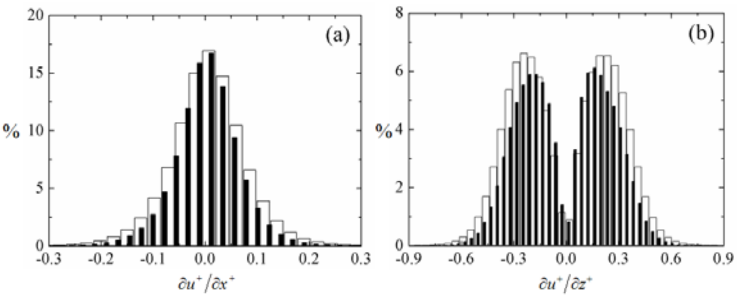

Fig. 1.5 Histograms of $\partial u^+/\partial x^+$ (a) and $\partial u^+/\partial z^+$ (b) at streak borders: ■, natural; □, controlled.

The histogram of $\partial u^+/\partial z^+$ (Fig 1.5b) was modified by the wall-based oscillations, with the distribution mainly shifted to larger $\left|\partial u^+/\partial z^+\right|$ compared to the natural case. The $\left|\partial u^+/\partial z^+\right|$ at the streak borders is an indicator of the streak strength. Thus, the alteration of $\partial u^+/\partial z^+$ histogram in Fig 1.5(b) suggests an increase in streak strength and an indication of strong formation of streamwise vortices due to the wall-based oscillations. This feature is distinct from that using other techniques.

CONCLUSIONS

The turbulent boundary layer is manipulated based on wall-normal oscillations generated by an array of 16 piezo-ceramic actuators flush-mounted to the wall surface; driven by a sinusoidal voltage, each oscillated independently and produced a perturbation to the flow. The maximum drag reduction reaches 50% at $x^+ = 17$ under the optimum control parameters for the first time using an array of discrete actuators. The low-speed streaks in the viscous sublayer of this manipulated flow have been examined and detected based on PIV-measured u^+ of $y^+ = 5.5$. It has been found that the streaks decrease by 12% in width and spacing, though their strength is increased, in distinct contrast with the observation by others [3].

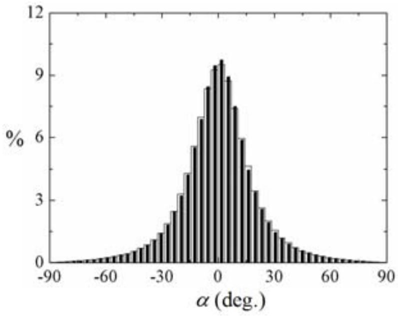

Fig. 1.6 Histograms of $(\nabla u)_{x,z}$ direction at streak borders: ■, natural; □, controlled.

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