MEASUREMENTS OF HIGHER-ORDER TURBULENT STATISTICS IN A TURBULENT BOUNDARY LAYER SUBJECTED TO A SHORT ROUGHNESS STRIP

by

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Original scientific paper
UDC: 532.517.4
BIBLID: 0354-9836, *11* (2007), 4, 41-48

Hot-wire measurements have been undertaken in a turbulent boundary layer which is subjected to an impulse in form of a short roughness strip with the aim of determining its effect on turbulence structure. The quantifications were made through the measurements of higher-order turbulent statistics. The changes observed in the distributions of correlation coefficient, third-order moments, skewness and flatness factor relative to the smooth wall suggests that the turbulence structure is modified downstream of the short roughness strip. Relative to the undisturbed smooth wall, the third-order moments were increased in the region between the two internal layers. This increased extends to significant portion of the outer region of the boundary layer. While a gain in turbulent kinetic energy by diffusion occurs throughout the boundary layer for a flow over the short roughness strip, those of the smooth wall occur near the wall.

Key words: *measurements, turbulent, boundary layer, roughness strip*

Introduction

The response of a turbulent boundary layer to a sudden perturbation possesses interests from practical and fundamental context. From a fundamental context, such study can improve our basic knowledge of dynamical response of a turbulent boundary layer to a sudden change in boundary condition. For example, as discussed by Clauser [1] via the black box analogy, such study offers the real possibility of identifying key constituents of the dynamics of the flow. Moreover, from the practical context, such study can lead to an improvement in the effectiveness of the flow control strategies Bushnell and McGinley [2]. An interesting result that emerged from flow subjected to perturbation as reviewed by Smith and Wood [3] is the relative quick response of the inner layer as compared with the outer layer. Thus, reflecting difference time scales. Pearson *et al.* [4] used laser Doppler velocimetry (LDV) to quantify the effect of a short roughness strip on a boundary layer through the measurements of skin friction and second-order turbulent statistics. They concluded that relative to smooth wall, the streamwise vortical structures are interfered with by the roughness strip as observed by changed in the skin friction and

DOI: 10.2298/TSCI0704041O

Reynolds stresses distributions. This was later confirmed by their flow visualizations results. These authors did not measured third and higher-orders turbulent statistics. The measurements of higher-order turbulent statistics should be more reliable than the second-order moments since they are more sensitive to a change in boundary and flow conditions. Recently, Oyewola [5] quantified the effect of short roughness strip on the higher-order turbulent statistics. Unfortunately his measurements were not wide in scope to assess the full impact of the short roughness strip on the higher-order statistics. The aim of the present study, which extends the work of Oyewola [5], is to further examining the effect of short roughness strip in a turbulent boundary layer. The quantification is implemented through the measurements of correlation coefficient, turbulent transport of the Reynolds stresses (third-order turbulent statistics), turbulent kinetic energy diffusion, skewness and flatness factor for flow over the smooth and roughness strip.

Measurement method and conditions

Measurements were made in a newly constructed boundary layer wind tunnel, driven by a single-inlet 15 kW centrifugal fan, which is able to deliver up to a free stream velocity of 40 m/s. Air enters the working section (fig. 1) through a two-stage two-dimensional diffuser into the 1.6 0.9 m^2 settling chamber. The chamber consists of six evenly spaced wire mesh screens and a 5 mm aluminum honeycomb.

The settled air then flows through a 9.5:1 2-D contraction. A turbulent boundary layer developed on the floor of the rectangular working section (see schematic arrangement in fig. 1) after it was tripped at the exit from the contraction using a 100 mm roughness strip and this ensured fully turbulent state to be reached. The 2-D of the flow was checked by measuring mean velocity profiles at a number of spanwise locations for some streamwise locations. There were no systematic spanwise variations (maximum deviation was within 4% of the centreline velocity). Because the working section was designed initial for suction measurements, a dummy plate was mounted flux with the working section to cover the suction part. The short roughness strip made up of uniform sandpaper (40 grade) of 40 mm long in the streamwise direction and 1 mm above the smooth wall is placed at about 1200 mm downstream of the tripping device.

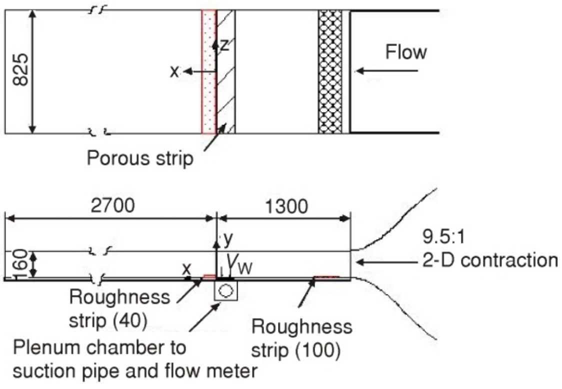

Figure 1. Schematic arrangement of the working section

The free-stream velocity U_1 is 7 m/s and the corresponding momentum thickness Reynolds number R_θ ($\equiv U_1\theta/\nu$, where, θ is the boundary layer momentum thickness) is 1400. Measurements of the velocity fluctuations were carried out at $x/\delta = 3$ (downstream of the trailing edge of the roughness strip, the origin for x being the strip trailing edge) with crossed-hot wire probe operated with in house constant temperature anemometers at an overheat ratio of 1.5. The etched portion of each wire (Wollaston, Pt-10% Rh) had a diameter of 2.5 μm, and a length to diameter ratio of about 200. The analog output signal of the hot wire was low pass filtered at 3000-5000 Hz, offset and amplified to within 5 V, then sampled and digitized at 6000-10000 Hz. A 40 s data record was used at each measurement station to ensure the convergence (to within 0.5%) of mean velocity and velocity fluctuation.

Correlation coefficient

Before considering the higher-order statistics, the variations of the correlation coefficient $R_{\rm uv}$ ($= -\langle u'v'\rangle/\langle u'^2\rangle^{1/2}\langle v'^2\rangle^{1/2}$), which is a measure of the extent of correlation between u and v fluctuations are plotted in terms of y/δ in fig. 2 for flow over smooth wall and short roughness strip. Interestingly, the maximum value of $R_{\rm uv}$ is unaltered for the smooth and perturbed layers and is around 0.45, which is in close agreement with the generally accepted value for a zero pressure gradient turbulent boundary layer. Relative to smooth wall data, $R_{\rm uv}$ increases in the region $y/\delta < 0.2$, collapses in the region $0.2 < y/\delta < 0.7$), and decreases sharply in the other part of the boundary layer. The behavior shows that the roughness strip modified the boundary layer structure albeit to some certain degree. This is not surprising, Pearson *et al.* [4] found that relative to smooth wall data, $-\langle uv\rangle$, $\langle u^2\rangle$, and $\langle v^2\rangle$ are slightly increased in the region near the wall, and these changes in the Reynolds stress contributes to change observed in $R_{\rm uv}$. However, the decreases of $R_{\rm uv}$ in the outer regions of the boundary layer may likely suggest an interfering of the roughness strip with the large-scale structure of the boundary layer. The reduction of $R_{\rm uv}$ is closely related to the decrease of $\langle u'v'\rangle$ (see [4]) and emphasizes the strong decorrelation between u and v fluctuations.

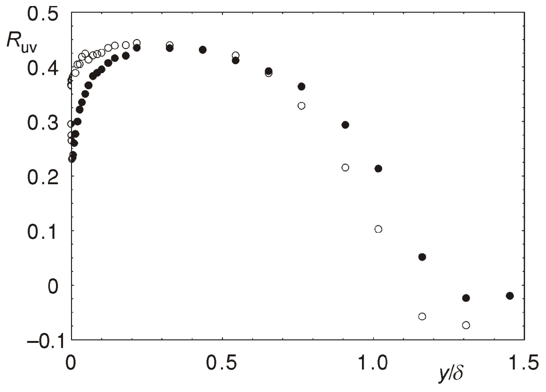

Figure 2. Variations of the correlation coefficient $R_{\rm uv}$ at $x/\delta = 3$
– smooth wall; ○ – roughness strip

Third-order velocity moments

The previous result suggests a modification in the boundary layer structure due to the presence of roughness strip. Figure 3, which, show the distributions of the turbulent energy transport of the Reynolds stresses ($\langle u^3\rangle$, $u^2v\rangle$, $uv^2\rangle$, $\langle v^3\rangle$) would shed more light in the changes that occurs in the boundary layer structure. Relative to undisturbed smooth wall data, the intensities of $u^3\rangle$, $u^2v\rangle$, and $uv^2\rangle$ were decreased in the region $y/\delta < 0.1$ and increased in the range $0.1 < y/\delta < 0.5$. The magnitudes of $u^3\rangle$, $u^2v\rangle$, and uv^2 relaxes to the smooth wall data in the remaining part of the boundary layer. Unlike u^3 , u^2v and uv^2 , v^3 is increased in the region $y/\delta < 0.75$ and returns to the undisturbed smooth wall value at the other part of the boundary layer.

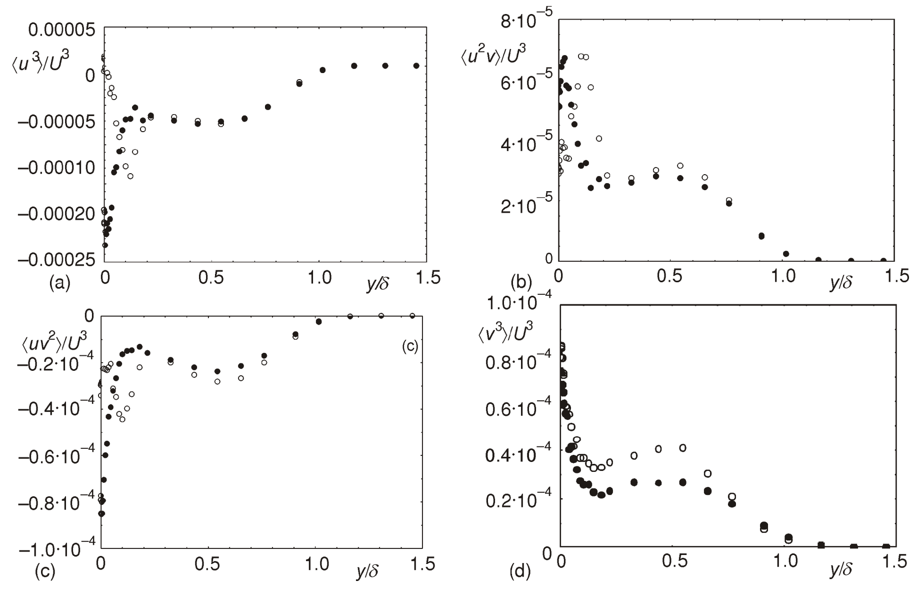

Figure 3. Distributions of the turbulent energy transports at $x/\delta = 3$ (symbols are as in fig. 2)

The result may suggest a modification in the boundary layer structure, which, would lead to a change in the organized motion of the boundary layer. This is not surprising, since a change in boundary condition would possibly influence both the large and small motions of the boundary layer. The change is consistent with the effect of short roughness strip observed on the normal-stresses, and shear stress by Pearson *et al.* [4]. The change observed in u^2v and v^3 may suggest an alteration in the transport of u'^2 and v'^2, respectively, by v' velocity fluctuation. This further indicates that the wall-normal transport of the sub-layer fluid has been interfered with by the roughness element due to the modification of the near-wall coherent structures. More importantly, the change in

v^3 may provide strong indication of the alteration of the active based motion. Further, the modification in uv^2 suggests an alteration in the momentum transport of $-\langle uv \rangle$ by v' velocity fluctuation. Interestingly, especially for u^3, u^2v, and uv^2 there exist two peaks in the region $y/\delta < 0.3$ as compared to the undisturbed smooth wall, which, consist of a peak value in the same region. The location of the second peak may likely suggest the region between the two internal layers, which, do occur in a flow such as this Pearson *et al.* [4]. This observation is consistent with the result of Andreopoulos and Wood [6]. Andreopoulos and Wood [6] found that the maxima in the Reynolds stresses u^2, v^2 and $-$ uv, occur in the region between the two internal layers.

Turbulent kinetic energy diffusion

Because the term vw^2 cannot be measured using conventional X-wire techniques, it is estimated as $k(u^2v + v^3)$, where $k = w^2 /(u^2 + v^2)$. In that respect, the turbulent kincetic energy (TKE) diffusion is calculated from $(u^2v + v^3 + uw^2)/ \ y$. Figure 4 shows the distribution of TKE diffusion for flow over the smooth wall and roughness strip. Relative to the smooth wall data, roughness strip data shows considerable greater diffusion for y/δ 0.2. This is due to the increased gradients which result from the large maxima and minima occurring in the distributions of v^3 and u^2v. However, for the remaining part of the boundary layer, the smooth wall data shows noticeable increase over the roughness strip data. For smooth wall, a gain of TKE by diffusion occurs below y/δ 0.2 and a loss of TKE by diffusion occurs for $0.2 < < y/\delta < 0.5$. In the case of flow over short roughness strip, a gain in TKE by diffusion occurs nearly throughout the boundary layer. Nevertheless, the magnitude of the gain in TKE by diffusion is considerably greater for the smooth wall than for the roughness strip in region y/δ 0.2. This indicates that the roughness strip modified the turbulent energy by interfering with the near-wall structures.

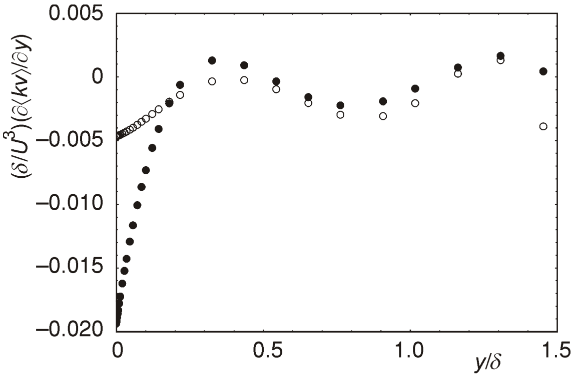

Figure 4. TKE diffusion for flow over the smooth and roughness strip (symbols are as in fig. 2)

Skewness and flatness factor

The skewness ($S_\alpha = \langle \alpha^3 \rangle / \langle \alpha^2 \rangle^{3/2}$) and flatness factor ($F_\alpha = \langle \alpha^4 \ / \ \alpha^2 \ ^2)$ of u and v are shown in fig. 5 for flow over the smooth and roughness strip. In the region y/δ 0.5,

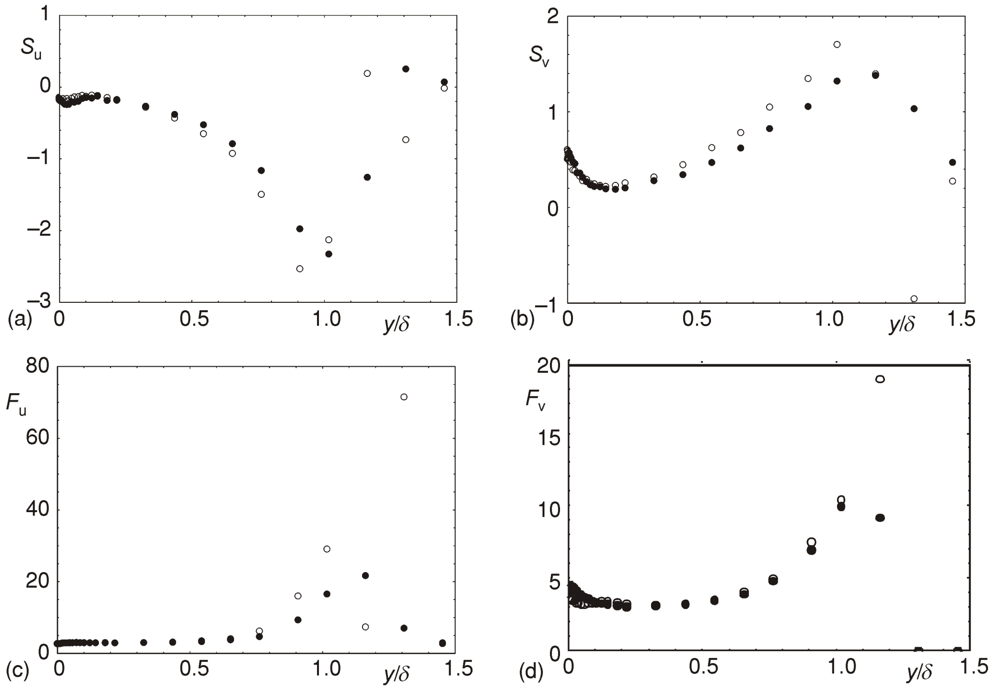

Figure 5. Variations of skewness and flatness factors at $x/\delta = 3$
(a) skewness of u fluctuation, (b) skewness of v fluctuation, (c) flatness of u fluctuation, (d) flatness of v fluctuation (symbols are as in fig. 2)

there is little noticeable effect of roughness strip on the skewness of *u* and *v* as observe in the mild variation of the smooth and roughness strip data sets. However, beyond this region, the effect of roughness strip begins to be enhanced as reflect in the departures of the disturb profile from the smooth wall. In contrast to skewness of *u* and *v*, the flatness factor of *u* and *v* are practically unaffected by the roughness strip, with the exemption of the flatness factor of *v*, which, show considerable decrease below the smooth wall data in the region near the wall. There are nevertheless some differences in the flatness of *u* between smooth and disturbed flows as the edge of the turbulent/non-turbulent interface is approached. Interestingly, while there are no sign changes in skewness and flatness factor of *u* and *v* for flow over the smooth and roughness strip, the effect of roughness is stronger on the skewness than flatness factor.

Conclusions

The effect of short roughness strip on the turbulent boundary layer has been quantified. The results indicate that short roughness strip modified the structure of the boundary layer as reflected in the changes in R_{uv}, third-order moments, skewness and flatness factor. The roughness strip modulates the behavior of the turbulent transport of the Reynolds stresses especially in the region between the two internal layers. The effect of short roughness strip is more pronounced on the skewness than flatness factor albeit as the edge of the turbulent/non-turbulent interface is approached. There is a gain in turbulent kinetic energy by diffusion through out the boundary layer of the short roughness strip, contrary to results obtained for flow over the smooth wall.

Nomenclature

F_α – flatness factor, [–]
R_θ – momentum thickness Reynolds number (= $U_1\theta/\nu$), [–]
R_{uv} – correlation coefficient, [–]
S_α – skewness, [–]
U_1 – free stream velocity, [ms^{-1}]
u – velocity in streamwise direction, [ms^{-1}]
u' – velocity fluctuation in the streamwise direction, [ms^{-1}]
v – velocity in transverse direction, [ms^{-1}]
v' – velocity fluctuation in the transverse direction, [ms^{-1}]
w – velocity fluctuation in spanwise direction, [ms^{-1}]
x – streamwise distance, [m]
y – transverse distance, [m]

Greek letters

α – u or v
δ – boundary layer thickness, [m]
θ – boundary layer momentum thickness, [m]
ν – kinematics viscosity of the fluid, [m^{2}s^{-1}]
– small change

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Paper submitted: August 10, 2006
Paper revised: July 10, 2007
Paper accepted: October 30, 2007