Assessment of Large-Scale Motion in Turbulent Boundary Layer Subjected to a Short Roughness Strip[†]

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Measurements have been made in a turbulent boundary layer which is subjected to a short roughness strip, with the view to examine the influence of short roughness strip on the large scale motion. This is quantified through the analysis of autocorrelation of the fluctuating velocities in the streamwise and wall-normal downstream of a roughness strip. Also, distributions of cross correlation functions are presented. The results indicate that, reference to the smooth wall, there are noticeable changes in the distributions of autocorrelation and cross correlation functions, suggesting that the large scale motion is altered as a result of the modification of the structure near the wall in the presence of the roughness element. This change extends to significant portion of the boundary layer.

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Introduction

It has been well established the technological importance of wall-bounded turbulent flows. A turbulent flow is characterized by three-dimensional chaotic motions often caused by coherent structures of various magnitudes and orientations. However, the study of how turbulent shear flow responds to different perturbations present interests from both fundamental and engineering points of view. For example, turbulent boundary layers over rough surfaces have considerable engineering interest due to the increased transport of heat and mass, usually associated with an increase in momentum transport Krogstad and Antonia [1]. The study of turbulent boundary layer to sudden perturbation in form of short roughness strip can lead to an improvement in the effectiveness of the flow control strategies Bushnell and McGinley [2] and also advance our knowledge in the context of turbulence modelling for wall-bounded flows. Pearson et al. [3] used laser Doppler velocimetry (LDV) to quantify the effect of a short roughness strip on a boundary layer through the measure-

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ments 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 change in the skin friction and Reynolds stresses distributions. This was later confirmed by their flow visualizations results. Oyewola [4] measured higher-order turbulent statistics in a boundary layer subjected to a short roughness strip. He found that the third-order moments were increased in the region between the two internal layers (Pearson et al. [3], Andreopoulos and Wood [5])). Oyewola et al. [6] extends the work of Oyewola [4] and carried out the statistical analysis of the turbulence structure downstream of a short roughness strip. Their results indicated that the energy distributions among eddies are altered in the presence of the roughness strip and the change was stronger near the wall ($y/\delta < 0.2$) of the boundary layer. In this present study, which extend the work of Oyewola et al. [6], further examining the effect of short roughness strip on the near-wall turbulence structure. This is necessary in order to gain more insight into the dynamics of the layer. The quantification is implemented through the analysis of autocorrelation of fluctuating velocities in the streamwise (u) and wall-normal (v) over the smooth and roughness strip for some region near the wall. The cross correlation functions of u and v are also presented.

1. Experimental Details and Conditions

Experiments were made in a 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-dimensional 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

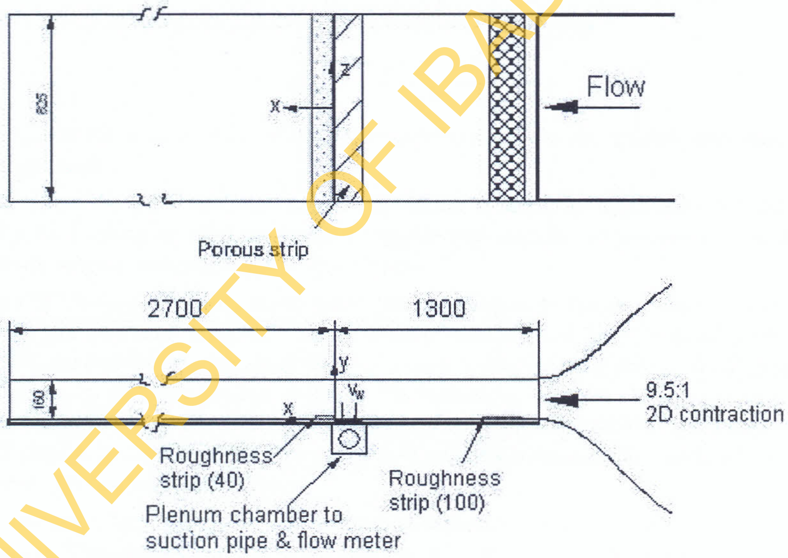

Fig. 1. Schematic arrangement of the working section.

fully turbulent state to be reached. The two-dimensionality 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 $\pm 4\ \%$ of the centerline velocity). Because the working section was designed initially for suction measurements, a dummy plate was mounted flush 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.

The free-stream velocity U_1 is 7 m/s and the corresponding momentum thickness Reynolds number $\mathrm{R}_\theta (U_1\theta/\nu$, 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 to 5000 Hz, offset and amplified to within ± 5 V, then sampled and digitized at 6000 to 10000 Hz. A 40 s data record was used at each measurement station to ensure the convergence (to within $\pm 0.5\ \%$) of mean velocity and velocity fluctuation. The experiments were repeated 5 times and the experimental uncertainty is within $\pm 5\ \%$. It should be noted that this uncertainty would definitely be translated into the analysis of auto and cross correlation coefficients. However, using the descriptive statistics and Student t-test, the distributions of auto and cross correlation coefficients of smooth wall (without roughness) were not significantly different ($p < 0.05$) from published results in literature.

2. Autocorrelation Coefficients

In order to gain insight into the effect of roughness strip on the structure of the turbulence, the autocorrelation coefficients of streamwise (u) and wall-normal velocity fluctuations for flow over the smooth wall and roughness strip are shown in Fig. 2 and 3 at $x/\delta = 3$ and for $y/\delta = 0.050$, 0.065 and 0.140. The two-point autocorrelation coefficient defined as

$$R_\alpha = \frac{\alpha(x)\alpha(x+r)}{\alpha^2},$$

(where α stands for u or v and r is the separation between the two points) was obtained using Taylor's hypothesis.

Fig. 2 shows the autocorrelation coefficients of the streamwise (u) velocity fluctuation. Note that in all plots hereinafter solid lines depict experimental data for the smooth wall, while dashed ones serve for cases when roughness strip is present.

From Fig. 2a ($y/\delta = 0.05$), the distributions lies marginally below those of smooth wall for $r < 0.0025$ and increases marginally above those of smooth wall for $r > 0.0025$. Whereas for $y/\delta = 0.065$, the distribution rise above those of smooth wall especially for $r > 0.001$ and increases as y/δ increases as evidence for $y/\delta = 0.140$. The behaviour suggests a change in the streamwise size of the initial structure due to the modification of the structure near the wall by the roughness strip. This change in the size of the structure would reflect a change in the organized motion of the layer, specifically the large scale motion.

This change in the streamwise size extends to significant portion of the layer as observed in Figs. 2b and c. This is not surprising, [3] found that relative to smooth wall data, $\langle u^2 \rangle$ and $\langle v^2 \rangle$ are slightly increased in the region near the wall, and these changes in the Reynolds stress is a result of inactive and active motions which are candidature of large scale motion.

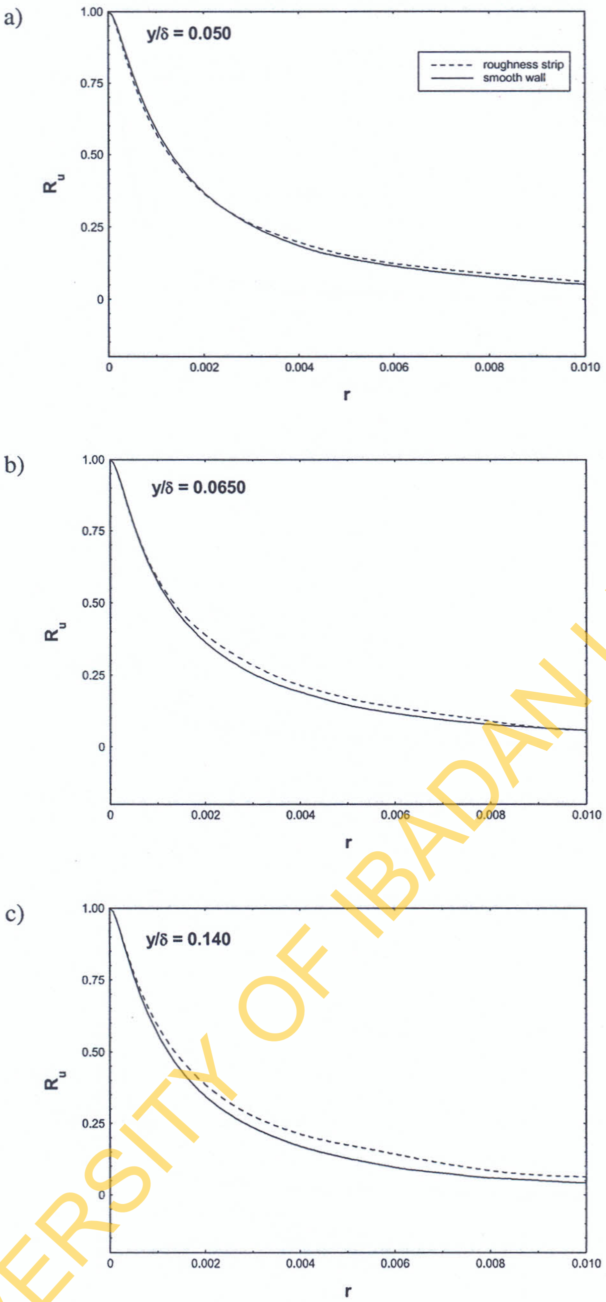

Fig. 2. Variations of the autocorrelation coefficient of u at $x/\delta = 3$ for smooth wall and roughness strip: a) $y/\delta = 0.050$; b) $y/\delta = 0.065$; c) $y/\delta = 0.140$.

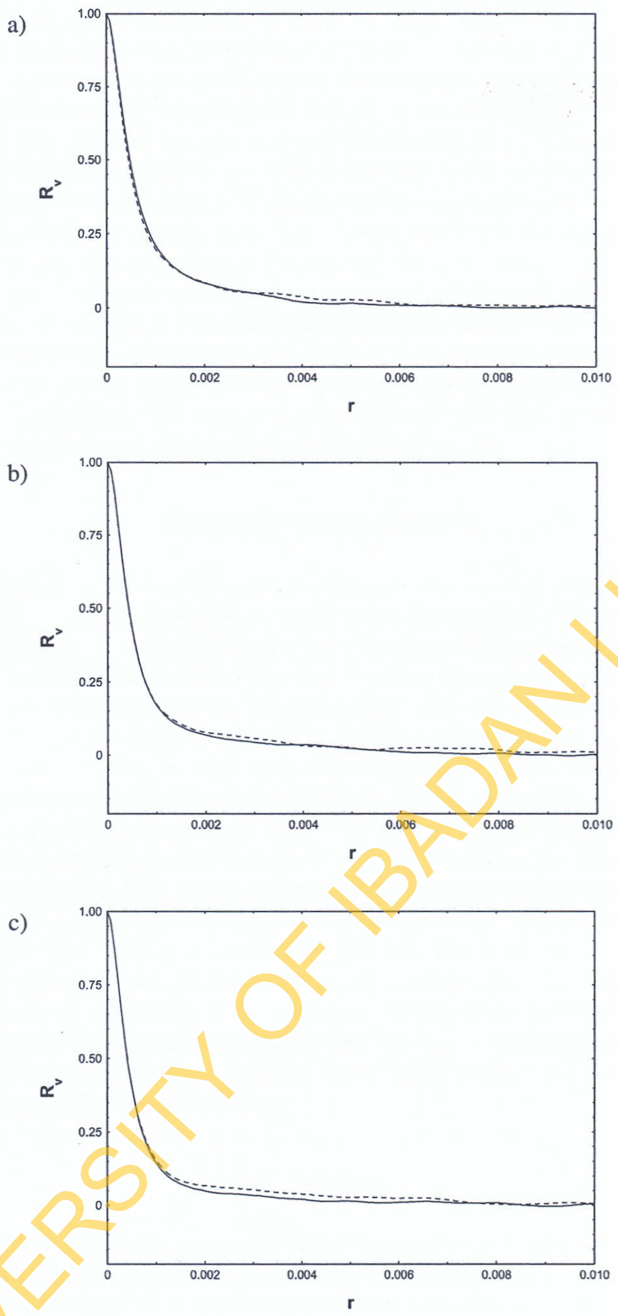

Fig. 3. Variations of the autocorrelation coefficient of v at $x/\delta = 3$ for smooth wall and roughness strip: a) $y/\delta = 0.050$; b) $y/\delta = 0.065$; c) $y/\delta = 0.140$.

The previous result of autocorrelation coefficient of u fluctuation suggests a modification in the structure near the wall due to the presence of roughness strip. Fig. 3, which, show the variations of the autocorrelation coefficient of the wall-normal velocity (v) at $x/\delta = 3$ and for $y/\delta = 0.050$, 0.065 and 0.140. In contrast to the autocorrelation coefficients of u, the changes observed are not too significant. However, there are noticeable changes in the distributions with reference to the undisturbed layer. For instance, for $y/\delta = 0.050$, the distribution of roughness strip lies a little bit below those of the smooth wall for $r < 0.0015$ and rises a little bit over those of smooth wall for $r > 0.0015$. Meanwhile, for other y/δ, the distributions collapse perfectly for $r < 0.001$ and rises a little bit over those of smooth wall. The changes however would suggest a change in the length scales in that direction as a result of the modification in the structure near the wall. This is not surprising, since a change in boundary condition would possibly influence both the large and small scale motions of the layer. In summary, the present shows that the effect of roughness strip is stronger on autocorrelation coefficient of u than those of v. It should be noted that u and v receives contribution from inactive and active motions, respectively, and these might reflects on the changes observed in their correlations. The change is consistent with the effect of short roughness strip observed on the normal-stresses, and shear stress (Pearson et al. [3]).

3. Cross-Correlation Functions

The previous results of the autocorrelation coefficients of u and v showed that the short roughness strip modified the large-scale motion of the structure near the wall of the boundary layer. The distributions of cross correlation functions of u and v are shown in Fig. 4 in order to vividly assess the differences in the large scale motion of the flow over the smooth and roughness strip. The cross correlation functions of the flow over the roughness strip show more of the negative values. The reason for this is not yet clear but is likely to be associated with the large scale streamwise vortical motions, which occur one after the other with opposite signs of rotation. There is a considerable change in the distributions with reference to the smooth wall. If the distributions of the roughness strip are transpose, the results shows that, for $\tau < 0$, (where τ is the time delay) the roughness strip rises above the smooth wall, overshoot for $\tau = 0$ and lies below the smooth wall for $\tau > 0$ in all the regions considered. This would indicate that the near-wall vortical structures downstream of the roughness strip have been altered significantly. The alteration suggests a change in the large-scale motion of the layer. This is not surprising, the flow visualizations of [3] showed that the quasi-streamwise vortices are modified downstream of the roughness strip. They also showed that the apparent break-up, or weakening, of the vortices in the immediate neighborhood of the strip is consistent with the overshoot in their skin friction distributions. A similar overshoot is observed in the present cross correlation functions. This may further suggests that the flow is more intermittent over the roughness strip than the smooth wall.

Conclusions

The effect of short roughness strip on the large scale motion in a turbulent boundary layer has been investigated through the analysis of autocorrelation coefficients and cross correlation functions. There are noticeable changes in the distributions of the autocorrelation coefficients as compared to the smooth wall, suggesting a change in the size of the structure near the wall. This change reflects a change in the large scale motion of the layer. This is further confirmed in the distributions of the cross correlation functions. The effect of roughness strip is stronger on the autocorrelation of u than those of v.

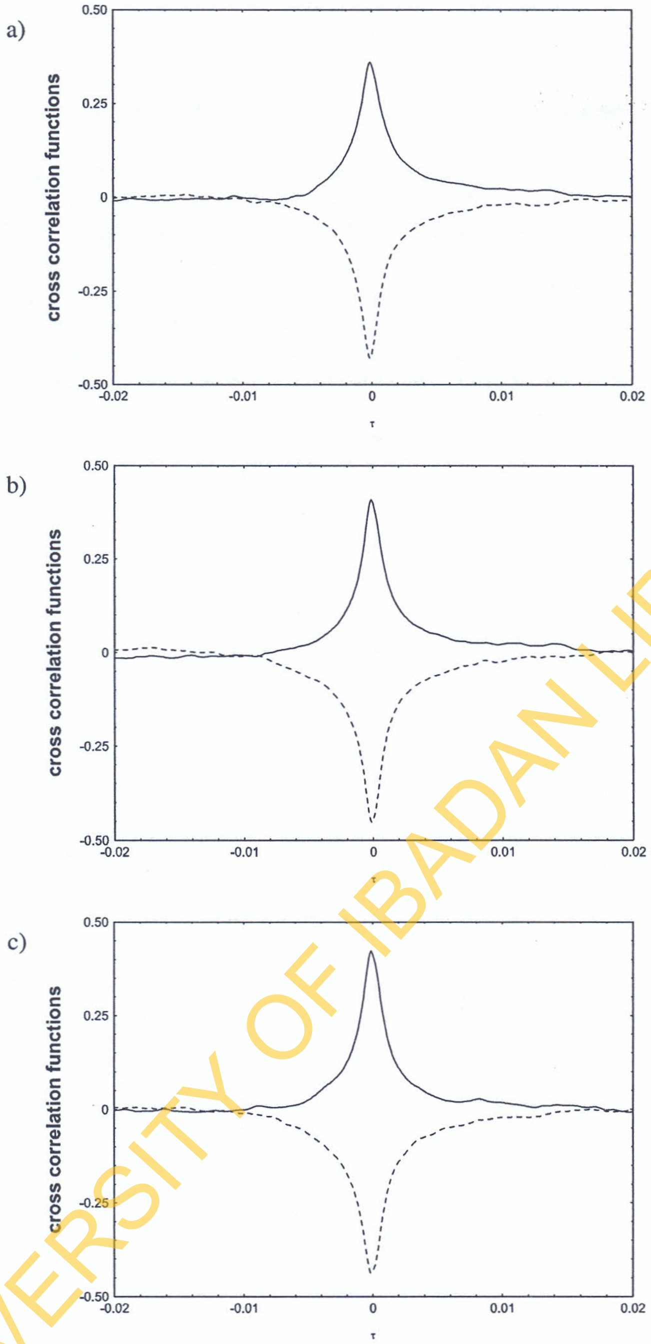

Fig. 4. Distributions of the cross-correlation functions at $x/\delta = 3$ for smooth wall and roughness strip: a) $y/\delta = 0.050$; b) $y/\delta = 0.065$; c) $y/\delta = 0.140$.

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