Turbulent Flow Over Urban-Type Roughness Using PIV

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Abstract Wind tunnel measurements of turbulent boundary layers over rough and smooth surfaces have been carried out using PIV. The roughness elements used were an urban-type surface with 5-mm square, random-height elements and the ratio of the mean roughness height to the boundary thickness was $h/\delta = 0.042$. The Reynolds number based on the momentum thickness was about $Re_\theta = 12{,}500$. By using PIV measurements, the effects of surface roughness on the mean flow and Reynolds stresses across the entire boundary layer were examined and compared with that of a smooth wall. Spatial correlation data, extracted from the PIV images were used to provide information about eddy structures and comparisons have been made with previous data for the uniform cube surface.

1 Introduction

The structure of the smooth wall turbulent boundary layer has been the object of enormous research effort over several decades. However, much less has been done to identify eddy structure over rough walls, particularly very rough walls as in the present case where the roughness height is not a very small fraction of the total boundary layer depth. Castro et al. [1] performed an experimental study on an urban type roughness which comprised uniform height cubes. Their results showed that the surface roughness leads to near-surface eddy structure behaviour that is significantly different from that in smooth-wall flows. In their work, point measurement techniques (HWA and LDA) were employed. Whilst these techniques are ideal for determining the statistical properties of the turbulence, they are less useful for identifying the three-dimensional dynamics of the various individual structures. The most appropriate experimental approach to reveal the existence and kind of organised

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T.B. Nickels (ed.), *IUTAM Symposium on The Physics of Wall-Bounded Turbulent Flows on Rough Walls*, IUTAM Bookseries 22, DOI 10.1007/978-90-481-9631-9_9,

structures is to obtain instantaneous pictures of the flow field using PIV techniques. Recently, Reynolds and Castro [2] carried out PIV measurements of the boundary layer flow over an array of cubes of uniform height. Their study mainly involved the flow just above the canopy within the roughness sublayer. The current experiments formed a natural extension to the earlier work reported by [1, 2] but with random height roughness elements. The main objectives are therefore to (i) examine the effects of non-uniform roughness throughout the entire boundary layer, (ii) deduce the detailed structural features of the flow at a number of streamwise locations (i.e. for various h/δ), (iii) identify to what extent these are different in both the near-wall region and the outer flow from those typical of classical smooth-wall flows and (iv) make comparisons with previous PIV results obtained for uniform roughness cases.

2 Experimental Facility and Setup

The experiments were undertaken in a wind tunnel and the roughness comprised a staggered array of 5 mm square random-height elements. The data presented here were obtained at a location 3.0 m from the start of the roughness and with a freestream velocity of 10 m/s. We used a PIV system consisting of a CCD camera (1024 × 1024 pixel CCD array size) with LaVision Davis 7.2 software. The flow plane of interest was illuminated with a Nd:YLF laser. To maximise resolution, the field of view was kept at about 60 mm square. The interrogation window size was 16 × 16 pixels with a 50% overlap, giving a special resolution of about 1 mm. All measurements presented were obtained with the double pulse laser set at 50 Hz. The hotwire data were also obtained partly as a check on the PIV accuracy in determining the statistical properties of the turbulence. The probes were gold plated tungsten wires with a length of about 1 mm and the X-wires were nominally ±60° to the mean flow direction. Sampling frequency was 10 kHz, with sampling times of 60–100 s.

3 Results and Discussions

3.1 Mean Flow and Turbulence

Figure 1a shows the mean velocity profiles in defect form. These are plotted using standard Rotta [3] scaling (i.e. normalising y by h/Δ, the Clauser thickness). Also shown for comparison are the results from the smooth wall, also obtained using PIV. A fairly good collapse is seen in the overlap and the outer regions supporting the notion of a universal defect profile for rough and smooth walls. Comparison of normalized Reynolds stresses between smooth and rough wall was also examined.

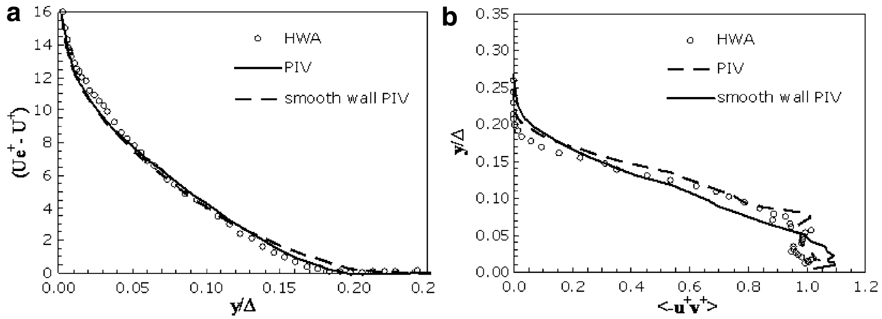

Fig. 1 (**a**) Deficit velocity profiles. (**b**) Effects of roughness on normalised Reynolds shear stress

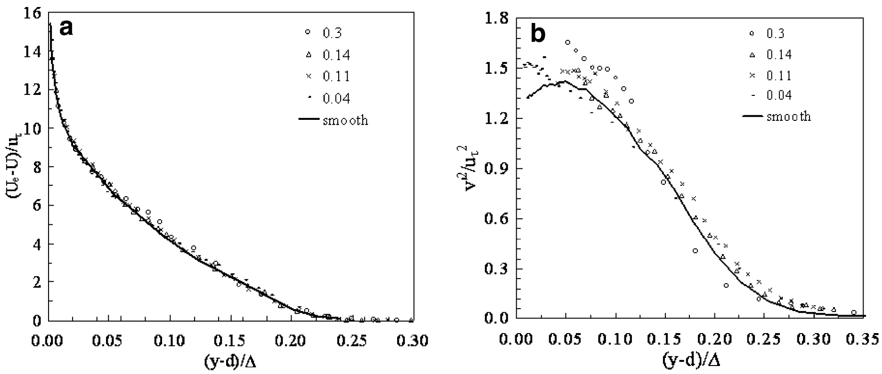

Fig. 2 (**a**) Mean velocity profiles. (**b**) Wall-normal Reynolds stresses, with the legend giving values of h/δ

It was found that the Reynolds streamwise stress remains unaffected while marginal differences in both wall normal and shear stress profiles were observed up to about half way within the boundary layer. Figure 1b shows the normalised Reynolds shear stress profiles for both the smooth and rough surfaces. The relative roughness height at this measurement location was $h/\delta = 0.042$ which is still higher than the height generally accepted to be the limit for acceptance of Townsend's [4] hypothesis. As a result, some differences in the shear stress are evident in Fig. 1b. Figure 1 also shows the profile data from HWA and within the expected accuracy of both the techniques, the data collapse reasonably well. Therefore, the general agreement between the data obtained using different techniques is satisfying.The HWA data at smaller fetches, Fig. 2a, shows the universality of the mean velocity profile up to relatively large values of h/δ. This gives further evidence of the robustness of mean flow profiles. As expected, Fig. 2b shows that normalised wall-normal stress increases with decreasing fetch, at least in the inner region. In the outer region, however, noticeable differences from the smooth wall are still evident at higher values of h/δ, with stresses here falling somewhat below smooth wall values.

3.2 Two-Point Correlation Functions

Figure 3 shows contours of the two point spatial correlation of the streamwise (Fig. 3a) and normal (Fig. 3b) fluctuating velocities obtained over the random roughness at $y/\delta = 0.255$. A number of important features can be observed from the R_{uu} data. First, the contours of constant correlation magnitude are roughly elliptical in shape with the major axis tilted at an angle to the streamwise direction. The correlation length in the streamwise direction is large. Similar features have been observed in a number of previous studies. For example, the tilt in the contours of constant correlation magnitude were reported in the space–time correlation of Kovasznay et al. [5], and later observed without the use of Taylor's hypothesis using PIV measurements in Ganapathisubramani et al. [6], Christensen and Wu [7] and very recently in Reynolds and Castro [2]. All of these measured correlations reported in the literature are in very good qualitative agreement with Fig. 3. The vertical velocity correlation, R_{vv}, is shown in Fig. 2b. These contours are quite different from the streamwise velocity correlations in that the length scales, observed by the extent of the non-zero correlation values in the both x and y directions, are more limited. Also the correlations are slightly elongated in the vertical direction. These features were also observed in the channel data of Liu et al. [8]. Figure 4a shows an example of a streamwise velocity spatial correlation for a point over the center of a roughness element. These data correspond to a constant y-slice at $y/\delta = 0.255$ through the contour plot in Fig. 3. The results show clear evidence of two scale behaviour within the roughness sublayer. There is an initial fall close to an exponential with a length scale of $L_x/\delta = 0.22$, followed at larger separations by a fall that follows $L_x/\delta = 0.46$; the two trends are shown in Fig. 4. Streamwise velocity correlation plots throughout the boundary layer were studied and it was found that the two scale behaviour gradually disappears with increasing wall normal distance. These observations suggest that the flow around the canopy top is dominated by the canopy produced turbulence. Similar behaviour was also observed by Reynolds and Castro [2] near the canopy top of uniform 10 mm cubes. The two scale behaviour is not typical for smooth wall flows, however, in the present case, the smooth surface

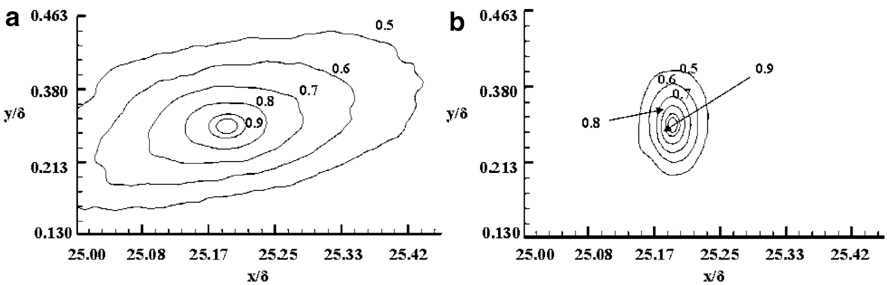

Fig. 3 Contours of two point spatial correlation of (**a**) streamwise, R_{uu} and (**b**) normal fluctuating velocity, (**b**) R_{vv} over random roughness at $y/\delta = 0.255$. The contour levels are labelled on the plots

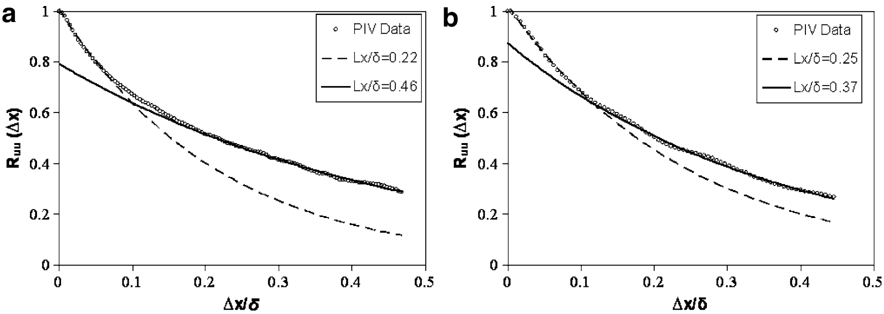

Fig. 4 Two-point streamwise velocity spatial correlation variation with streamwise separations. (**a**) Rough surface; (**b**) smooth surface. Line show curves following $e^{-\frac{\Delta x}{L_x}}$ trends

exhibited similar two scale behaviour near the wall which also diminishes in the outer layer of the boundary layer. However, the apparent differences between the two scales for the smooth surface is much smaller than the rough surface (Fig. 4b). The PIV correlation data was also used to determine integral length scales. These length scales are defined as the separations at which the appropriate spatial correlation has fallen to 0.368. Figure 4a shows the ratio of the length scales with vertical and streamwise separations for the streamwise velocity components (L_{xuu}/L_{yuu}). It can be seen that the ratio of the length scales lies within the range 2.0-2.6 for both the rough and smooth surfaces. This confirms that the eddy structures have large correlation lengths in the streamwise direction as seen in Fig. 3a. Also, there is an increase in (L_{xuu}/L_{yuu}) with height within the inner region of the flow, which is indicative of more elongated eddies up to a distance of $y/\delta = 0.255$. Above this distance, (L_{xuu}/L_{yuu}) decreases and the eddies in the outer region become less elongated. The same trend is also seen for the smooth surface. However, it is important to note that in the inner region, the ratio (L_{xuu}/L_{yuu}) is higher over the smooth surface indicating that the eddies are more elongated than those over the rough surface.

The average structure angle of R_{uu}, which represents an estimate of the average inclination angle of outer-layer vortex packets, is assessed by extracting the line of maximum correlation at each y_{ref}. Christensen and Wu [7] attempted to quantify the tilt angle of the iso-contours of the correlation magnitude by identifying the points on each iso-contour that are furthest from the reference location. The variation of structure angle with height is shown in Fig. 5. It can be seen that the average eddy structure angle decreases with height for the rough surface. The data agree well with those obtained by Reynolds and Castro [2] over uniform 10 mm cubes, also shown in Fig. 5. The mean value was found to be 11°, which is identical to the mean angle found by Christensen and Wu [7]. Similar contour plots were also derived for the smooth-surface at various points and the resulting variation in structure angle is shown in Fig. 5. It can be seen, that except close to the near-wall region, where the trend is opposite from that of the rough surface, the average inclination angle is roughly constant at around 11°. There is some scatter

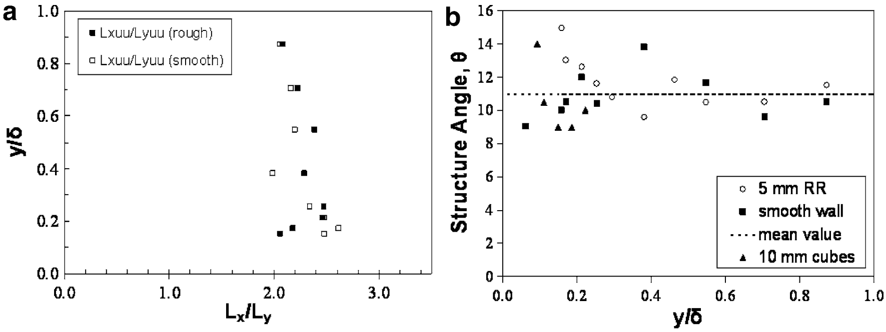

Fig. 5 (**a**) Ratios of streamwise to vertical length scales for the streamwise velocity components. (**b**) Average inclination angle of R_{uu} as a function of wall-normal position

in θ, owing to small inaccuracies in deducing the structure angle. Neverthless, the average values of θ presented in Fig. 5 are certainly consistent with the angles noted in [2, 7].

4 Conclusions

The PIV results on smooth and rough wall turbulent boundary layers show that the mean velocity profiles collapse well in velocity defect form. Both the Reynolds wall normal and shear stress profiles show marginal differences whereas, the Reynolds streamwise stresses remain unaffected. The spatial correlation data shows evidence of two scale behaviour in the near wall region which gradually disappears with increasing wall normal distance. Beyond the near-wall region, the mean value of the average structure angle was measured and found to be 11°. This value is the same for both the rough and smooth surfaces. We conclude, therefore, that at this low value of $h/\delta = 0.042$, the overall averaged structure is quite similar for both the smooth and rough surfaces. At large values of h/δ, HWA data shows evidence for the robustness of the mean flow velocity profiles, whereas the wall-normal stresses increase with increasing h/δ in the inner region of the flow. More experiments using PIV are being undertaken to examine turbulence structures at higher values of h/δ.

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