Placidi, M. & Ganapathisubramani, B. (2016). On the effects of surface morphology on the structure of wall-turbulence. Springer Proceedings in Physics, 165, pp. 149-154. doi: 10.1007/978-3-319-29130-7_27

Original citation: Placidi, M. & Ganapathisubramani, B. (2016). On the effects of surface morphology on the structure of wall-turbulence. Springer Proceedings in Physics, 165, pp. 149-154. doi: 10.1007/978-3-319-29130-7_27

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Chapter 1
On the effects of surface morphology on the structure of wall-turbulence

Marco Placidi and Bharathram Ganapathisubramani

1.1 Abstract

Experiments were conducted in the fully-rough regime on surfaces with large relative roughness ($h/\delta \approx 0.1$) generated by regularly distributed LEGO$^{\text{TM}}$ bricks of uniform height, arranged in different configurations. Measurements were made with high resolution PIV on six different frontal solidities, λ_F, at fixed plan solidity, λ_P. Results indicate that the spatial underlying structure of the turbulence across the different surface morphologies is universal in both its shape and orientation in relation to the flow velocity. Harpin packets inclination with respect of the wall is also found to be consistent not only across the different wall surfaces but also when compared to previous studies on smooth walls. Slices of two-point correlations for both streamwise and wall-normal velocity fluctuations and Reynolds shear stresses present a good collapse across the entire y/δ range for all wall morphologies.

1.2 Motivations and background

Surface roughness is commonly encountered in nature and it represents a challenge in numerous engineering applications. Nevertheless, very little is understood about rough walls compared to their smooth wall counterpart [10]. Luckily, smooth and rough walls present similarities which are commonly employed in the study of boundary layers [16]. Among these, it is well documented that hairpin-like vortical structures populate smooth wall turbulent boundary layers at low and moderate Reynolds numbers and tend to align coherently to form larger-scale structures termed hairpin vortex packets [1, 7]. Therefore, given that vortex organisation in the outer region is commonly observed in instantaneous snapshots of wall turbulence, these structures are bound to leave their imprint upon the statistics of the flow [5]. The main feature ascribed to harpin packets is a series of vortices aligned in the streamwise direction forming a large-scale forward-leaning alternation of high and low momentum regions. Few studies have also supported the presence of similar harpin-like structures in the outer layer of rough wall boundary layers, providing that the roughness is small compared to the boundary layer thickness ($h/\delta < 0.05$). The morphology of these rough surfaces were either irregular, based on damaged turbine blades [19], or regular woven mesh [17]. However, it is still unclear if and to what extent the same vortical structure signature would persist in flows over large surface roughness. PIV measurements were therefore acquired in the (x, y) plane of fully turbulent flows over different high relative roughness morphologies ($h/\delta \approx 0.1$). The aim was to explore the effect of these severe wall conditions on the different types of structures in the outer region of turbulent boundary layers.

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1.3 Experimental facility and details

Experiments were carried out in the suction wind tunnel at the University of Southampton. The tunnel has a working section of 4.5 m in length, with a 0.9 $m \times 0.6$ m cross section. The free-stream turbulence intensity is homogenous and less than 0.3%. The same facility has been used for previous studies on rough walls [4, 3, 14, 2, amongst others]. The streamwise, wall-normal and spanwise directions are here given along the $x-y-z$ directions and $u-v-w$ are the corresponding velocities. Fluctuating velocities are denoted with a $'$. Experiments were conducted in nominally zero-pressure-gradient ($K = (\nu/U_e^2)[dU_e/dx] \approx 5 \times 10^{-8}$) at 11.5 m/s. For rough surfaces, this study used a LEGO$^{\text{TM}}$ baseboard onto which rectangular LEGO$^{\text{TM}}$ bricks (or blocks), uniformly distributed in staggered array, were securely fixed. These bricks presented a uniform height ($h = 11.4$ mm). Six different patterns at fixed plan coverage were adopted to examine the effects of frontal solidity on the structure of the turbulence ($\lambda_F = 0.09, 0.12, 0.15, 0.18, 0.21, 0.24$). The different cases were designed on the basis of previous studies' predictions for the peak in drag, $D = D(\lambda_F)$ [10]. A fetch length of about 20δ was covered with brick elements to guarantee the fully rough regime [3]. Measurements were acquired using planar Particle Image Velocimetry (PIV). Some of the main parameters characterising the different surfaces are given in table 1.1. The reader is referred to [13] for further details on the surface morphology and the experimental setup.

Table 1.1 Relevant experimental parameters.

Dataset	λ_F	λ_P	$\delta (mm)$	h/δ	$U_\tau (m/s)$	Re_τ	$\delta^* (mm)$	h^+	$\alpha_{u'u'}$ (0.4)	$\alpha_{u'u'}$ (0.5)
LF1	0.09	0.27	111	0.102	0.60	4600	17	463	13°	12°
LF2	0.12	0.27	122	0.090	0.66	5500	22	518	11°	10°
LF3	0.15	0.27	121	0.093	0.69	5700	22	541	13°	13°
LF4	0.18	0.27	122	0.093	0.75	6300	24	588	11°	10°
LF5	0.21	0.27	129	0.088	0.81	7200	27	635	14°	11°
LF6	0.24	0.27	127	0.090	0.80	7000	27	628	13°	11°

1.4 Results

As [1] and [15] pointed out, one looks at the streamwise velocity correlations to infer information about the structure of the turbulence (i.e. vortex packets). Figure 1.1 (a) shows contours of the two-point correlations of the streamwise fluctuating velocity, $R_{u'u'}$. A forward-leading structure of positive correlation is shown revealing a large-scale structure coherency consistent with imprint of packets [1]. The correlations are inclined toward the flow direction. Here an example is shown for the LF4 case with the correlation centred at $y_{ref} = 0.4\delta$. However, this is representative of all the other cases and similar conclusions can be drawn when alternative wall-normal locations are considered. The inclination angle of these structures can be inferred, following [6], by a least-square fit procedure along the points further away from the auto-correlation peak at $y = y_{ref}$, along different contour lines. The results of this procedure are reported in table 1.1. Inclination angles were found in the range of $10-13°$ and a slight sensitivity to the change in surface morphology was noticed, although a clear trend is difficult to infer. The current results are in line with previous findings on both smooth and rough walls investigations, which suggested similar values for the characteristic inclination of the packets [17, 18, 8, 6, 9, 5, 1, 15, 12]. On the contrary, the current results do not seem to suggest that the surface morphology can have a significant influence on the vortex packets inclination, certainly not to the extend some researchers have previously documented [11].

Also reported in figure 1.1 (b) are correlations of the wall-normal fluctuations, $R_{v'v'}$. These correlation structures are found to be compact in both streamwise and wall-normal directions with an extent that is much lower than for $R_{u'u'}$. This is consistent with previous findings [17, 18, 8, amongst others]. Finally, two-point correlations of the Reynolds shear fluctuations, $R_{u'v'}$, are presented in figure 1.1 (c). These are characterised by a backward leaning structure of strong negative correlation, the extent of which is larger than the wall-normal correlation but considerably smaller than the streamwise coherency, as previously reported [17].

The effect of the considered surface morphologies on the turbulent structure can be further explored taking a slice through the auto-correlation points of $R_{u'u'}$ $R_{v'v'}$ and $R_{u'v'}$ in both streamwise and wall-normal directions, as highlighted by the dashed and solid lines in figure 1.1 respectively. These are presented in figure 1.2 (a) to (e). A very good collapse in both the streamwise and wall-normal cuts is found across all the different cases although this becomes poorer in $R_{u'v'}$ due to the higher experimental uncertainty in the determination of this quantity. To conclude, both the consistency in the inclination of the vortex packets and the collapse of all the main correlation cuts across different roughness topologies seem to offer a clear indication that the underlying spatial structures of the turbulence (i.e. vortex packets and their characteristics) are largely unaffected by changes in surface morphology - hence universal. This universality also extend to the smooth wall cases.

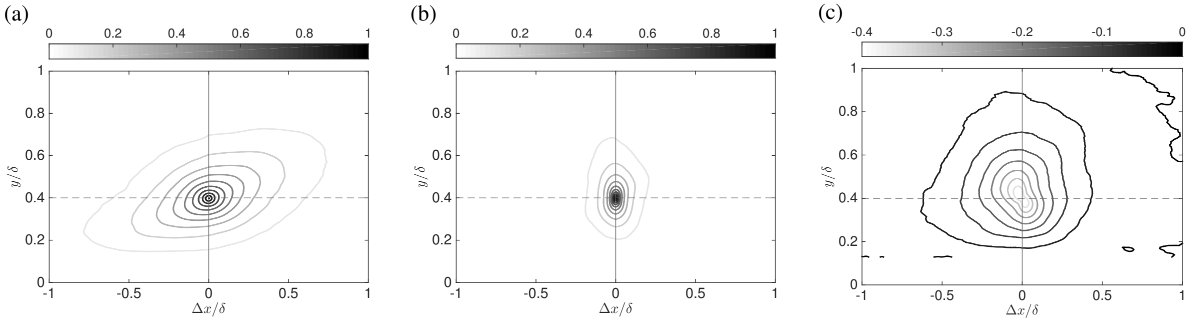

Fig. 1.1 Two-point correlation of (a) streamwise, (b) wall-normal and (c) Reynolds shear stress fluctuations. Colorbar represents the normalised correlation coefficient, $R_{u'u'}$, $R_{v'v'}$ and $R_{u'v'}$. Flow is left to right. Example for LF4.

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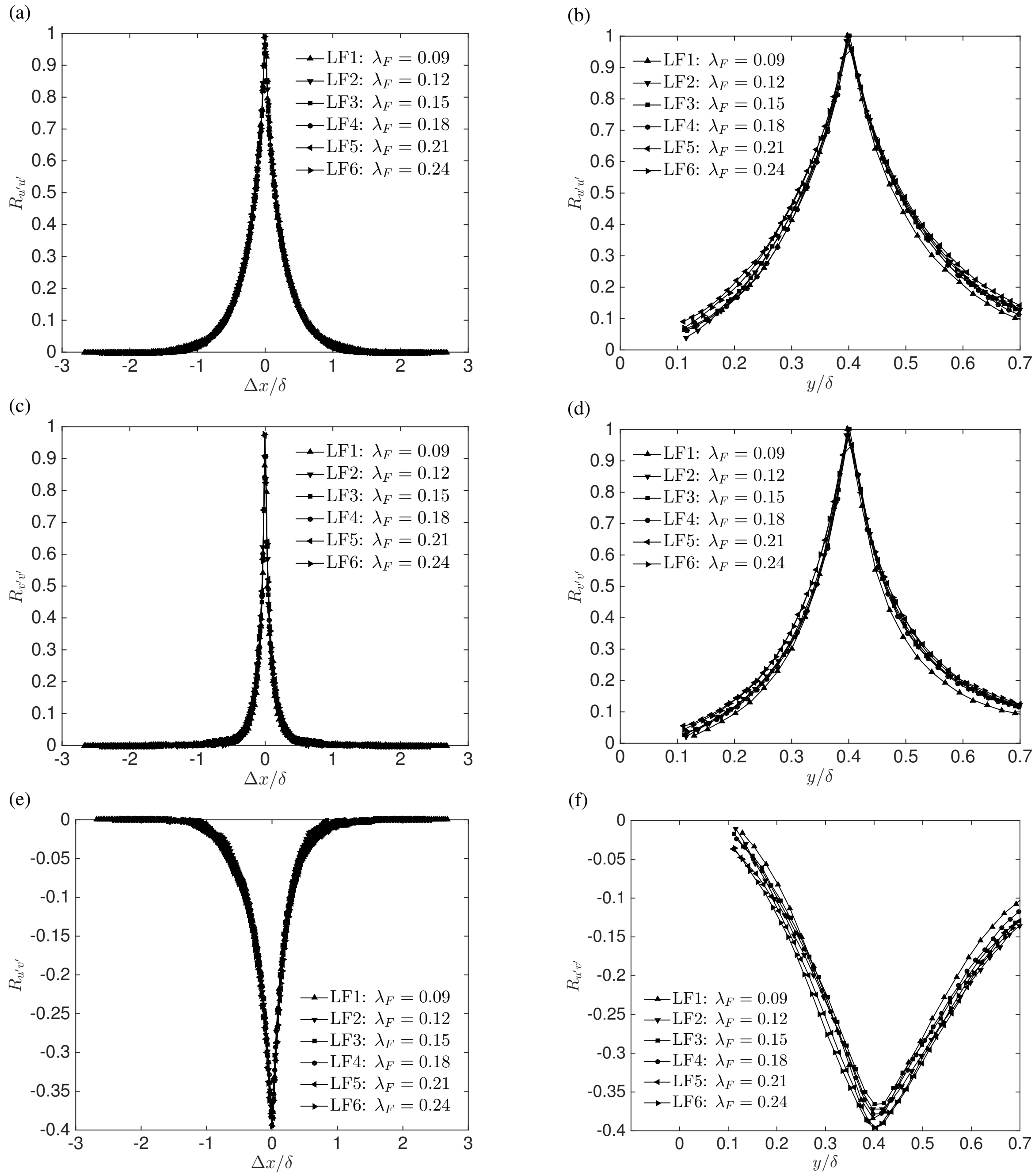

Fig. 1.2 (Left) Streamwise and (right) wall-normal slices through auto-correlation points of (top) $R_{u'u'}$, (centre) $R_{v'v'}$ and (bottom) $R_{u'v'}$ contours as a function of λ_F ($\lambda_P = const = 0.27$). Solid lines represent the real data resolution whist markers are spaced every five vectors for clarity.

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