A PIV ‘troubleshooting’ of $<uv>$ measurements with hot-wires over 2D rough walls

Lyazid Djenidi¹, Robert A. Antonia², Muriel Amielh³, Fabien Anselmet⁴

¹: Discipline of Mechanical Engineering, University of Newcastle, Newcastle, Australia, lyazid.dhenidi@newcastle.edu.au
²: Discipline of Mechanical Engineering, University of Newcastle, Newcastle, Australia, Robert.Antonia@newcastle.edu.au
³: Institut de Recherche sur les Phénomènes Hors Equilibre, Marseille, France, amielh@irphe.univ-mrs.fr
⁴: Institut de Recherche sur les Phénomènes Hors Equilibre, Marseille, France, anselmet@irphe.univ-mrs.fr

Abstract  Particle image velocimetry (PIV) measurements are carried out in a turbulent boundary layer over a 2D rough surface made of transverse square bars. The aim of this work is to investigate a possible cause of the X-wire near-wall measurements errors observed on similar rough surfaces. The PIV measurements do not show the anomalous near-wall deficit of Reynolds stresses as measured with X-wires over the same surface. An extensive flow visualization analysis of the PIV data for a spacing between the roughness elements of $7k$ ($k$ is the roughness element height) shows the occurrence of large scale inward (sweeps) and outward (ejections) motions with a period of about $10.6\delta/U_0$ ($\delta$ and $U_0$ are the boundary layer thickness and the free stream velocity) observed in the velocity spectra. While these motions dominate the near-wall region and contribute almost equally to the Reynolds shear stress $<uv>$, the mean outward deviation from the main direction is stronger than the inward deviation. Also, when the roughness spacing is reduced to $p = 3k$, the outward deviation reduces significantly more than the inward deviation. The results support the argument that the outward motions, which can have an instantaneous deviation angle of more than $50^\circ$, make the X-wire probe inefficient for detecting the ejection events (associated with the outward motions), particularly if the apex angle of the X-wire is not optimized for capturing the strong flow ejections with large deviations. The results explain in part the disparate information on the effect of the roughness on the Reynolds stresses in the outer region of the turbulent boundary layer over rough walls.

1. Introduction

An impressive number of experimental studies of turbulent flows over rough walls have appeared over the last 20 years. Yet, the data analysis is still stained by the difficulty of estimating with accuracy the wall shear stress and the Reynolds shear stress $<uv>$ (angular brackets denote time averaging, unless otherwise indicated; $u$ and $v$ are the velocity fluctuations in the streamwise and normal-to-the wall directions, respectively). In particular it was found that when the roughness is made up of 2D elements, such as square or circular rods placed transversely to the flow direction, the distributions of $<uv>$ obtained with X-wires tend to decrease abnormally as the wall is approached. (e.g. Smalley et al., 2001). Also the maximum of $<uv>$, found typically near $y/\delta$ of about 0.2 ($y$ and $\delta$ are the distance to the wall and boundary layer thickness, respectively), is significantly smaller, by about 20 to 30%, than correct estimates of the wall shear stress, $\tau_w$. A similar behaviour has also been reported for the wall-normal velocity fluctuation component $v$. Such an abnormal behaviour contributes to the turbulent outer layer “controversy” (Antonia and Djenidi, 2009), i.e. whether the outer layer is affected or not by the rough wall. For example, the available data, mostly at sufficiently large values of the Reynolds number and $\delta k$ ($k$ is the characteristic roughness height), seem to suggest that 3D and transverse 2D rough surfaces may affect the outer layer differently. However, this issue can only be resolved once measurements of $<uv>$ and $<v^2>$ are improved over the 2D rough surface. Antonia and Djenidi (2009) discussed this
issue and the possible resolution of the difficulty of measuring \(<uv>\) and \(<v^2>\) correctly over a 2D transverse roughness. For example, in the absence of a reliable means of testing the validity of the measurement of \(<v^2>\), the measured \(<uv>\) should be compared with an analytical distribution for this quantity, inferred from the mean momentum equation (Li and Perry, 1989; Krogstad et al., 1994).

To date, there is no clear explanation as to why X-wires fail to measure \(<uv>\) and \(<v^2>\) correctly over the 2D transverse roughness elements. Interestingly, the near-wall deficit of \(<uv>\), as measured with X-wires, has also been found over 3D rough surfaces (Mulhearn and Finnigan, 1978; Raupach et al., 1980). Antonia and Djenidi (2009) argue that if the geometry, strength and vertical extent of the regions which contribute strongly to \(<uv>\) depend on the shape and spatial arrangement of the roughness elements, then the near-wall errors associated with the X-wires will differ over different types of rough walls. They also suggest that direct numerical simulation (DNS) databases (e.g. Leonardi et al. 2003; Ikeda and Durbin, 2007; Lee and Sung, 2007) could be used for simulating the effect of the wire lengths and separation between the wires on the measurement of \(<uv>\) in the vicinity of the roughness. However, there are as yet no DNS results of a turbulent boundary layer over a rough surface with sufficiently large values of the ratio \(\delta/k\), clearly a shortcoming that needs to be addressed in the future. From an experimental context, particle image velocimetry (PIV), which can provide reliable information on the instantaneous velocity fields, may arguably be thought to be closest in scope to DNS data.

The present paper reports PIV measurements in a turbulent boundary layer over a 2D rough wall with a view of clarifying why X-wires fail to measure \(<uv>\) correctly on such a surface. In particular, one aim of the study is to verify whether motions away from the wall (or ejections) are responsible for this failure given that the flow angle associated with these motions can exceed the apex angle (or angle between the wires) of the X-wire probe.

2. Experimental facility

2.1 The rough wall

The rough wall consists of a series of stainless steel square bars \((k\text{ (height)} = w\text{ (width)} = 4\text{mm})\). Two particular values (3\(k\) and 7\(k\)) have been used for the distance (or pitch) \(p\) between consecutive elements. The bars are glued onto a flat plate, which is mounted on the water channel floor. The bars cover a longitudinal distance of about 2m. A wedge is placed at the leading edge of the flat plate to ensure that no flow separation occurs.

2.2 PIV setup

The PIV measurements are carried out in a recirculating open water channel (Djenidi et al., 2008). The test section is 8m long, 0.6m wide and 0.6m deep. The 2m long rough wall is located 5m downstream of the contraction. A 200\(mJ\) pulsed Nd:Yag laser is used to illuminate the flow. The laser sheet is shot from the top through a 100\(mm\) diameter Perspex porthole which is flush with the free surface in order not to disturb the flow. A set of cylindrical lenses converts the laser beam into a vertical thin sheet located at the mid-plane \((z = 0, z\text{ is in the spanwise direction})\) of the channel. A digital camera (Kodak ES 1.0) is used with a charge coupled device (CCD) \((1,018 \times 1,008\text{ pixels})\). The PIV images are post-processed using the adaptive correlation method (FlowManager 4.30.27; Dantec) to obtain the instantaneous velocity fields. Each image, which corresponds to an area of about 40 \(x\) 40\(mm^2\) (or 10\(k\) \(x\) 10\(k\)) of the actual flow field, is subdivided into 32 \(x\) 32 pixels with 50\% overlap. Measurements, taken at a streamwise location \(x\) of about 1.5 m from the leading edge of the rough wall, are made across the boundary layer in steps of \(y = 10k\). Initially, about 1,500 velocity fields (the sampling frequency is 10\(Hz\)) were deemed sufficient for computing the mean velocity and the Reynolds stress profiles.
The water is seeded with particles (Optimage Ltd) with an average size of 30µm and a specific gravity of 1.0 ± 0.02. These particles are polycrystalline in structure and have a high light-scattering efficiency. The water depth (h = 0.46m) and flow rate (250m³/h) are kept constant. The free surface is relatively calm (no surface waves are present). The free stream longitudinal and wall-normal turbulence intensities are equal to about 7% of $U_0$ and the boundary layer thickness represents almost half of the water depth. The momentum thickness Reynolds number $R_\theta$ is about 5,500 and 6,500 for $p=3k$ and $7k$, respectively, at the measurement location. This ensures that low Reynolds number effects are negligible, or at least minimized, and should not affect the generality of the results. For $p=3k$, the ratio $\delta/k$ is about 47, which is close to the value above which blockage effects of the roughness elements on the flow may be neglected (Jimenez 2004).

3. Results

Figure 1 shows profiles of $u'$ and $v'$ (the prime denotes the rms) for $p=3k$ and $p=7k$, averaged in the horizontal direction (this includes 2 and 3 roughness elements, respectively). The distributions are normalized with the free stream velocity, $U_0$. The $u'$ profiles display a maximum away from the wall, in contrast to the near-wall peak observed in a turbulent boundary layer over a smooth wall. Also, the decrease in $v'$ occurs closer to the wall than in a smooth wall boundary layer. These features, which have been reported in previous rough wall studies, indicate that turbulence production over this rough wall differs from that over a smooth wall, reflecting a difference in structure, at least near the wall. The DNS data of Leonardi et al. (2003) clearly revealed that, contrary to a smooth wall, there were no quasi-streamwise vortices near the wall when $p$ was larger than 3-4$k$. However, these vortices can be observed when $p=k$ (Djenidi et al., 1999). The fact that $v'$ decreases only close to $y/k = 0$ may indicate that the wall blockage effect is smaller than on a smooth wall. Alternately, it may also suggest that strong ejections take place over this surface near the wall. The moderately high values of $u'$ and $v'$ in the outer part of the boundary layer reflect the relatively high level of background turbulence.
turbulence within the channel.

Figure 1 shows a clear increase in $u'$ and $v'$ when $p$ increases between $3k$ and $7k$, reflecting an increase in the turbulent kinetic energy level. This is consistent with the larger form drag when $p = 7k$ and is well confirmed by the direct numerical simulation results (Leonardi et al., 2003; Lee and Sung, 2007) and, indirectly, by the profiles of $-\langle uv \rangle$ (Figure 2). The $-\langle uv \rangle$ distributions, unlike those obtained with X-wires, do not exhibit the abnormal drop as the wall is approached and are consistent with existing PIV (Lee et al., 2007; Pokrajac et al., 2008), laser Doppler velocimetry (LDV; Kameda et al., 2006) and DNS (Lee and Sung, 2007) results. Using $(-\langle uv \rangle_{\text{max}})^{1/2}$ as a rough estimate for the wall shear stress, the drag coefficient ($C_D$) is equal to about 0.08 for $p = 7k$ and 0.03 for $p = 3k$; these values agree relatively well with experimental (Furuya et al., 1976; Lee et al. 2007) and numerical (Lee and Sung, 2007) values of $C_D$ obtained over similar 2D rough surfaces with $p = 3k$ and $7k$ (see also Antonia and Djenidi, 2009 for other reported values from different studies). This instils reasonable confidence in the present PIV data. However, the $-\langle uv \rangle$ distributions contain features that require some attention before we can use the PIV data to 'troubleshoot' measurements of $-\langle uv \rangle$ from hot wires. Strong variations are visible between the “partitions”, in particular for $p = 7k$. Many checks were carried out to determine the possible sources of these anomalies. For example, several validation criteria and interrogation windows were tested, but no significant differences were obtained from the distributions shown in Figure 2. Even errors associated with peak locking bias were ruled out. The conclusion of these checks suggested that not enough samples were acquired for achieving an adequate convergence for the $-\langle uv \rangle$ statistics. To verify this, we have analyzed the entire time series of the spatially averaged (along $x$ and $y$) velocity components $U_a$ and $V_a$ (e.g. Figure 3; the subscript $a$ denotes spatial averaging with respect to both $x$ and $y$). The averaging is carried out over the whole PIV view field $(40 \times 40mm^2)$ and for the partitions $0 < y/k < 10$ and $10 < y/k < 20$ shown in figures 1 and 2. The signals contain intermittent large amplitude variations with relatively long periods by comparison to
the total sampling duration. The amplitudes are larger for $10 < y/k < 20$ than $0 < y/k < 10$; this is particularly visible on the $V_a$ signals, reflecting the change of the roughness density. Although not shown here, the velocity components averaged along the $x$-direction only exhibited similar trends to those in figure 3 at most $y/k$ positions, indicating that the velocity large variations are related to large scale motions (this is discussed later). Thus, if large scale motions are present, one can expect some pseudo periodicity in the velocity signals. This is indeed observed in the velocity time series for $0 < y/k < 10$. In order to confirm the existence of such patterns, the spectra of the fluctuations $u_a$ and $v_a$ and $u_a v_a$ in Figure 4 (note that the spectrum of $u_a v_a$ is not to be confused with the $u_a v_a$ co-spectrum). Obviously, some caution should be exercised when interpreting these spectra because of the short sampling duration. In view of the relatively large spatial averaging window, it is quite remarkable that both $u_a$ and $v_a$ spectra show

![Figure 3. Time series of the spatially averaged velocity components $U_a$ and $V_a$ for $p = 7k$. Symbols: $0 < y/k < 10$; lines: $10 < y/k < 20$.](image)

a distinct peak at approximately $f k/U_0 = 0.002$ in the region $0 < y/k < 10$. Arguably these peaks indicate the presence of large scale events. Similar peaks were also observed in the spectra of the velocity components averaged along $x$ only at various $y$ positions (not shown here), which confirms the occurrence of large scale events. The spectrum of $u_a v_a$ also has a peak but at a slightly lower frequency ($f k/U_0 = 0.0015$) than that of the $u_a$ and $v_a$ spectra. Quite interestingly, the $u_a v_a$ spectrum for $0 < y/k < 10$ reveals distinct secondary peaks. The latter, which are not as pronounced in the $u_a$ and $v_a$ spectra, suggest that there may be smaller scale events which contribute to the Reynolds shear stresses. In the region $10 < y/k < 20$, the $u_a v_a$ spectrum also displays a dominant peak at about $f k/U_0 = 0.0015$. It is difficult to assess whether or not peaks are present in the $u_a$ and $v_a$ spectra in the region $10 < y/k < 20$; note the seemingly sharp decrease in the $u_a$ spectrum at about $f k/U_0 = 0.002$ preceded by a plateau-like behaviour. This latter feature marks large period “oscillations” in the signals.
In summary, it can be concluded that signals such as those in figure 3 indicate that the number of samples acquired is insufficient to achieve reasonable convergence, at least for $-\langle uv \rangle$, which appears to be more sensitive than $u$ and $v$ to the sampling duration. Clearly, a longer acquisition time is required to ensure that enough large scale events are captured for ensuring a satisfactory convergence for $-\langle uv \rangle$. However, this lack of convergence does not detract from using the PIV results to gain some insight into why X-wires fail to measure $-\langle uv \rangle$ correctly over this rough surface.

The primary peaks ($fk/U_0 = 0.002$) in the spectra correspond to a time period, $T_e$, of about 7.2s or $10.6*\delta U_0$. In Figure 5 the instantaneous velocity fields at $0T_e$, $0.4T_e$ and $T_e$ are shown together with...
the corresponding velocity signal; some (instantaneous) streamlines are included to help visualize the flow direction at these instants. The figure clearly illustrates the periodical pattern observed in the time series. There is a strong correlation between $U_\alpha$ and $V_\alpha$; the signals are overall in (anti-)synchronization, which is an indication of large scale events. The velocity fields at 0 and 7.2s show a large scale inward motion, while the velocity field at 0.4$T_c$ displays a relatively intense outward motion, reflected in the relatively large outward orientation of the streamlines. The large minima (maxima) in $U_\alpha$ ($V_\alpha$) correspond to intense outward motions where the streamlines deviate significantly from the streamwise direction, e.g. Figure 6a where contours of the magnitude of local velocity vector angles (with respect to the x-direction) appear with instantaneous velocity vectors and streamlines. The overall deviation from the streamwise direction can exceed 50° (Figure 6b).

Although not shown here, similar outflows are observed in the region $10 < \gamma/k < 20$ which emanate from the wall region, thus indicating that they can penetrate the outer region of the layer.

These outward motions are reminiscent of fluid outflows from the cavities (space between consecutive roughness elements) observed on the same rough surface but for $p = k$ (Djenidi et al., 1999); the latter are much less intense and have smaller length scales than for the present geometries. The cavities seemed to act as reservoirs of fluid ready to be ejected. The cause of the ejections when $p = k$ was attributed to the passage of near-wall quasi-longitudinal vortices. Clearly, this cannot be the case here since no such vortices are observed. The flow visualization shows that the outward flow is preceded by an inward motion (or sweep): outer region fluid with high velocity moves downward displacing low velocity fluid between the roughness elements, which, on impact with the elements, is ejected outwards with a strong deviation from the streamwise direction. It seems reasonable to infer that X-wires are unlikely to operate correctly in such an environment in view of their limited directional/orientation capacity. Difficulties of using X-wires in the near wall region of a turbulent boundary over a rough surface have been discussed in the literature. For example, Perry et al. (1987) found large differences in $\langle uv \rangle$ over an expanded mesh surface using X-wire probes with 90° and 120° apex angles. Although they reported a strong effect on $v'$, Acharya
and Escudier (1987) found little effect on \( \langle uv \rangle \) using a similar probe and surface as Perry et al. (1987). Krogstad et al. (1992) reported that the apex angle had an effect on \( v' \) over a mesh screen rough wall. These variations imply that the intensity of the fluid ejection depends on the roughness geometry and corroborates the claim (Antonia and Djenidi, 2009) that near-wall measurement errors associated with X-wires will differ over different types of rough walls. The present flow visualization clearly shows that the instantaneous velocity vector can have a very large angular excursion, which would certainly make the X-wire measurements of \( \langle uv \rangle \) unreliable on this particular rough wall surface, at least when \( p/k = 7 \). Interestingly, Lee et al. (2008), who carried out PIV measurements on a similar surface, reported that the effects of the roughness on the Reynolds stresses are felt up to a distance of about 20 to 30\( k \) above the wall.

Figure 5 indicated that the flow deviation during outward motions is stronger than the deviation of

\[
\begin{align*}
\theta \text{ (deg)} & \quad p = 7k \\
\theta \text{ (deg)} & \quad p = 3k
\end{align*}
\]

\[
\begin{align*}
y/k & \quad 0 & 2 & 4 & 6 & 8 & 10
\end{align*}
\]

Figure 7. Time and \( x \) average flow deviation for the inflow (negative \( \theta \)) and outflow (positive \( \theta \)) for \( p = 3k \) and 7k.

the inward motions. This is confirmed by Figure 7 which shows the flow deviation angle across the partition \( 1 < y/k < 10 \) for both inward and outward flows for \( p = 3k \) and 7k. Several observations can be made:

i) The magnitude of the flow deviation is larger for the outward motion than the inward one. Interestingly, Krogstad et al. (1992) showed that the fractional contributions to \( u' \), \( v' \) and \( \langle uv \rangle \) from different flow angles at \( y/\delta = 0.1 \) are skewed towards positive angles implying that outward motions contribute more than inward motions.

ii) The deviation is larger for \( p = 7k \) than \( p = 3k \) (this is consistent with the larger drag for \( p = 7k \)).

iii) The drop in the outward deviation between \( p = 7k \) and \( p = 3k \) is stronger than that for the inward motion; 25% and 5%, respectively.

iv) The variation in the outward deviation between the two roughness spacings is stronger than that for the inward deviation.

Observation (iv) shows that the outward motion, more than the inward one, is controlled by the roughness geometry. These observations clearly show that the (strong) outward motions are the main source of error in the context of X-wire measurements; it also confirms that errors should differ over different types of rough walls. Interestingly, these observations seem to support the suggestion that the decrease of \( v' \) close to \( y/k = 0 \) may be due to the strong ejections, rather than a reduced blockage effect, by comparison to a smooth wall.

Figure 8 shows contours of instantaneous \( uv \) with the corresponding velocity fluctuation field.
The image on the left is at the same instant as that of figure 6 (i.e. $t = 525k/U_0$); the one on the right corresponds to $t = 7242k/U_0$. A comparison between figure 8 (left image) and figure 6 suggests a strong correspondence between $uv$ and $\theta$ contours as well as between $uv$ contours and the fluctuating velocity field; regions of large $uv$ (dark regions) are also regions of large fluctuating velocities. Over most of the field, $u < 0$ and $v > 0$, which, in terms of quadrant analysis events (e.g. Lu and Willmarth, 1973), corresponds to an ejection event. The right image of figure 8 illustrates an instance where $u > 0$ and $v < 0$ (sweep). In both cases, the events take place over a large scale and make the largest contribution to the Reynolds shear stress as can be noted in Figure 9, where the contribution (averaged over time and $x$) of each event to $-<uv>$ is shown across the boundary layer for $p = 7k$. The sweep (Q4) and ejection (Q2) events dominate the process and contribute positively to the Reynolds shear stress while the inward (Q1; $u > 0$ and $v > 0$) and outward (Q3; $u < 0$ and $v < 0$) interaction events contribute negatively; the magnitudes of Q2 and Q4 are significantly larger than those of Q1 and Q3 throughout the entire boundary layer. Similar results were observed in smooth (e.g. Wallace et al., 1972) and rough (e.g. Lee et al. 2009) wall boundary layers. Close to the wall, the sweep events dominate while the ejection events become dominant as the distance from the wall increases.

It is clear that if Q2 (and Q3) events are not well detected by a velocity probe then the Reynolds shear stress would be incorrectly measured. An X-wire probe whose apex angle is not well adapted/optimized for a given rough wall to account for the strong flow deviations, such as those highlighted here, will capture the intermittent ejection events incorrectly, resulting in inadequate measurements of both $v'$ and $-<uv>$. Optical measurement techniques such as LDV and PIV do not suffer from this limitation.
4. Conclusions and discussion

Particle image velocimetry measurements in a turbulent boundary layer developing over a rough wall made of transverse square bars show that \( v' \) and \( \langle uv \rangle \) decrease close to the crest plane \((y/k = 0)\), in contrast with existing X-wire measurements over similar rough walls which indicate a large deficit in these quantities in the near-wall region. The PIV data also reveal that the near-wall region of the flow is dominated by large scale inward and outward motions. It is observed that while these motions contribute nearly equally to the Reynolds shear stress near the wall, the outward flow deviation is significantly stronger than the inward flow deviation; the former can exceed 50\(^\circ\). It is found that the inward deviation is rather not affected by the roughness spacing whereas the outward deviation shows a strong dependence on the spacing; when the latter varies from 7\( k \) to 3\( k \), the outward deviation is reduced by 25\%, while the inward deviation is decreased by only 5\%.

Krogstad et al. (1992) showed that the frequency of occurrence of the inward and outward motions is nearly twice as large on their screen mesh surface than over a smooth wall. They also observed that outward motions with large deflections contributed more significantly to the Reynolds shear stresses than the inward motions. Since it is likely that this frequency and the intensity of the outward motion are even larger for the present 2D rough wall, at least for \( p = 7k \) (which corresponds to a maximum drag), one can expect similar (though more emphatic) effects on \( v' \) and \( \langle uv \rangle \) to those reported for the screen mesh surface. Given the limited directional/orientation sensitivity of X-wires, it seems reasonable to expect that this probe will fail to capture all the events which contribute to \( v' \) and \( \langle uv \rangle \) over 2D rough surfaces and, ultimately, underestimate these quantities in the wall region, where ejections are quite violent. Arguably, the near-wall drop in \( v' \) and \( \langle uv \rangle \) observed in the X-wire is more likely due to a poor angular resolution rather than a possible wall blockage effect.

The PIV analysis explains, at least in part, the disparate information relating to the effect of the roughness on \( v' \) and \( \langle uv \rangle \) in the outer region of the turbulent boundary layer and the apparent differences in the outer layer results between 3D and transverse 2D rough walls. The wall shear stress over a rough wall is commonly estimated as the square root of the maximum of \( \langle uv \rangle \), or its extrapolation to the wall. While this is quite appropriate with DNS, LDV or PIV data, it can result in an important underestimation when the apex angle of the X-wire cannot capture the strong and relatively frequent flow ejections with large deviations. In this case, the wall normalized quantities measured with X-wires would invariably differ from the more reliable DNS, LDV or PIV data.
References
