CROSS-PLANE STEREO-PIV MEASUREMENTS OF A TURBULENT BOUNDARY LAYER OVER HIGHLY IRREGULAR ROUGHNESS

BY

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DISSERTATION

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Abstract

The characteristics of a turbulent boundary layer overlying a complex roughness topography were explored with stereo particle-image velocimetry measurements in the wall-normal–spanwise plane. The roughness under consideration was replicated from a turbine blade damaged by deposition of foreign materials containing a broad range of topographical scales arranged in a highly irregular manner. Such roughness is representative of that encountered in a broad range of practical flow systems, such as turbine-blade arrays, heat exchangers and marine vehicle surfaces, for example. Thus, understanding its impact on flow in a controlled laboratory environment is meant to provide a bridge to more fully understanding roughness effects in these practical scenarios.

Low-frame-rate stereo particle image velocimetry (PIV) measurements were conducted in the cross-flow, spanwise-wall-normal, plane at moderate Reynolds number. The single-point turbulence statistics in this plane displayed strong spanwise heterogeneity, in particular spanwise-alternating low- and high-momentum flow pathways in the mean flow marked by enhanced Reynolds stresses and turbulent kinetic energy. The spanwise regions between high- and low-momentum flow pathways were occupied by swirling motions, suggesting the generation and sustainment of turbulent secondary flows due to the spanwise heterogeneity of the complex roughness under consideration.
High-frame-rate stereo PIV measurements were then conducted in the same spanwise-wall-normal plane and at the same Reynolds number to study the turbulent kinetic energy and Reynolds shear stress content of the flow as a function of scale in the presence of this complex roughness. Similar to that observed for the mean and turbulence quantities noted above, frequency spectra of streamwise velocity at fixed wall-normal location also display strong dependence on spanwise position. In particular, the roughness promotes enhanced turbulent kinetic energy content of the large-scale motions and smaller-scale motions. Depending on spanwise location, pre-multiplied spectra highlight significant modification of the energy content of the very large-scale motions due to roughness when compared to smooth-wall flow. Interestingly, spanwise locations where high-momentum pathways reside in the mean flow embody higher turbulent kinetic energy and Reynolds shear stress content at streamwise scales of the very-large-scale motions compared to that observed at spanwise locations of low-momentum pathways.
To my beloved wife, Bianca

To my parents, Maria Laura and Julio Barros
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<th>Description</th>
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<tr>
<td>AM</td>
<td>Amplitude Modulation</td>
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<tr>
<td>FOV</td>
<td>Field-Of-View</td>
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<td>HMP</td>
<td>High-Momentum Pathway</td>
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<tr>
<td>HMR</td>
<td>High-Momentum Region</td>
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<tr>
<td>LMP</td>
<td>Low-Momentum Pathway</td>
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<td>LMR</td>
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<td>LSM</td>
<td>Large-Scale Motions</td>
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<td>PIV</td>
<td>Particle Image Velocimetry</td>
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<td>RMS</td>
<td>Root-Mean Square</td>
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<td>RSS</td>
<td>Reynolds Shear Stress</td>
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<td>SVD</td>
<td>Singular Value Decomposition</td>
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<tr>
<td>TBL</td>
<td>Turbulent Boundary Layer</td>
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<td>TKE</td>
<td>Turbulent Kinetic Energy</td>
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<td>VLSM</td>
<td>Very-Large-Scale Motions</td>
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<td>ZPG</td>
<td>Zero Pressure Gradient</td>
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List of Symbols

Latin symbols

B  Smooth-wall log law intercept
h  Half-height of the channel
k  Characteristic roughness height
ks  Equivalent sand-grain roughness height
kx  Streamwise wavenumber
Re  Reynolds number
Reδ*  Reynolds number based on the displacement thickness
Reθ  Reynolds number based on the momentum thickness
Reτ  Reynolds number based on the friction velocity
Reχ  Reynolds number based on the streamwise distance
t  Time coordinate
u  Streamwise instantaneous velocity component
ur  Friction velocity
Ub  Bulk velocity
Ue  Free-stream velocity
ΔU+  Roughness function
v  Wall-normal instantaneous velocity component
\( w \) Spanwise instantaneous velocity component
\( x \) Streamwise coordinate
\( y \) Wall-normal coordinate
\( y^* \) Viscous length scale
\( z \) Spanwise coordinate

**Greek symbols**

\( \delta(\cdot) \) Uncertainty in the estimation of \( \cdot \)
\( \delta \) Boundary layer thickness
\( \delta^* \) Displacement thickness
\( \eta \) Roughness elevation
\( \epsilon(\cdot) \) Percentage error in \( \cdot \)
\( \kappa \) Von Krmn constant
\( \lambda_{ci} \) Swirling strength
\( \Lambda_{ci} \) Signed swirling strength
\( \lambda_x \) Streamwise wavelength
\( \nu \) Kinematic viscosity
\( \omega_x \) Streamwise vorticity
\( \omega_y \) Wall-normal vorticity
\( \omega_z \) Spanwise vorticity
\( \Pi \) Wake parameter
\( \rho \) Density of the fluid
\( \tau_w \) Wall-shear stress
Mathematical operators

⟨·⟩ Ensemble average

Superscripts

′ Fluctuation
+
Normalization with inner scaling
Chapter 1

Introduction

Boundary layers form when an unbounded flow, usually uniform and unidirectional, encounters a solid interface, reducing its momentum near the wall due to viscous effects, that propagate outward in the wall-normal direction. Upon initial interaction of the flow with the surface, the boundary layer will be laminar in nature until it has advected a sufficient streamwise distance for transition to turbulence to occur. In an idealized, yet convenient way, when the free-stream flow hits a flat smooth wall plate, a laminar boundary-layer is form, that continues to grow as it travel downstream. The streamwise location of transition is typically demarcated in terms of a unit Reynolds number (Re), defined as \( \text{Re}_x = U_e x / \nu \), where \( U_e \) is the free-stream velocity, \( \nu \) is the kinematic viscosity and \( x \) the streamwise flow development length along the flat plate. Under nominal smooth-wall, zero-pressure-gradient conditions, this transition will occur at \( \text{Re}_x \sim \times 10^6 \). In fact, most flow systems are influenced by turbulent boundary layers, both in industrial applications as well as in many environmental flow scenarios. The flow behavior of the boundary layer can play a defining role in these applications, from setting the drag and heat transfer characteristics at a surface to sculpting landscape in geophysical flows. While smooth-wall flows have been extensively studied owing to their relative simplicity for detailed experimental and numerical characterization, most practical flow surfaces exhibit some degree of roughness that oftentimes will evolve over time. Thus, the impact of roughness on
wall turbulence must be characterized to ensure that it impact is accurately accounted for in predictions of practical flow systems.

1.1 Mean-flow characteristics of rough-wall flow

Roughness can dramatically alter the behavior of the flow compared to smooth-wall conditions. When the upcoming boundary layer suffers an abrupt change in surface conditions, an internal layer is formed within the existing boundary layer within which roughness effects are directly felt (Smits & Wood, 1985). If roughness conditions persist downstream, this internal layer will adapt to the new surface condition and eventually engulf the entire boundary layer. Under such a scenario, in the immediate vicinity of the rough surface, the well-known roughness sublayer is formed, which, as stated in Raupach et al. (1991), is the layer directly affected by the associated length scales of the roughness elements. This roughness sublayer usually extends $2 - 5k$ from the wall in the wall-normal direction, where $k$ is a measure of the roughness height (Raupach et al., 1991).

In the overlap and outer region, the main effect of roughness on the mean velocity is a downward shift in the profile (Clauser, 1956; Hama, 1954). This downward shift, $\Delta U^+$, is called the roughness function and reflects the increased drag induced by roughness compared to smooth-wall flow. Thus, the mean velocity profile in the logarithmic region of a rough-wall turbulent boundary layer is given by

$$U^+ = \frac{1}{\kappa} \ln(y^+) + B - \Delta U^+ + \frac{\Pi}{\kappa} W\left(\frac{y}{\delta}\right)$$

(1.1)

where, $\kappa$ is the von-Karman constant, $B$ is the smooth-wall log law intercept, $\Pi$ is the wake parameter, and $\delta$ is the boundary layer thickness. When the rough-wall
mean velocity profile (eq. 1.1) is evaluated at \( y = \delta \), \( \Delta U^+ \) can be determined as the difference between the smooth- and rough-wall log law for the same \( Re_\delta^* \) – the Reynolds number based on the displacement thickness, \( \delta^* \) (Hama, 1954; Flack et al., 2005). Therefore, the roughness function can be expressed as

\[
\Delta U^+ = \left( \frac{U_e}{u_\tau} \right)_{\text{smooth}} - \left( \frac{U_e}{u_\tau} \right)_{\text{rough}} \tag{1.2}
\]

where \( u_\tau \) is the friction velocity. The roughness function depends on the Reynolds number and some characteristic scale of the roughness, either a geometric measure \( (k) \) or the equivalent sand-grain roughness height \( (k_s) \) that represents the equivalent sand-grain size from the Nikuradse (1950) pipe flow experiments that produces the same drag as an arbitrary roughness topography in the full-rough regime (Schlichting, 1979).

When the roughness Reynolds number, \( k^+ \equiv k/y_* \) (where \( y_* = \nu/u_\tau \) and \( u_\tau \) is the friction velocity), is sufficiently small \( (k^+ \lesssim 5) \), the flow is considered hydraulically smooth, which implies that \( \Delta U^+ = 0 \), and any perturbations created by the rough surface are damped by viscous forces within the laminar sublayer. The flow becomes transitionally rough as \( k^+ \) increases \( (5 \lesssim k^+ \lesssim 70) \), where the additional turbulence created by the roughness elements surpasses the ability of the flow’s viscosity to damp these perturbations, leading to an overall increase in drag, or skin friction. Consequently, this also promotes an increase in \( \Delta U^+ \) that is a function of both Re and \( k \). Further increase in \( k^+ \) leads to a linear dependence between \( \Delta U^+ \) and \( k^+ \), which characterizes the flow as fully rough and independent of Re as form drag drives the surface drag. As noted earlier, a common scale to characterize roughness is the equivalent sand grain roughness height, \( k_s \) from the Nikuradse (1950) experiments. Using the parameter \( k_s \) to characterize the roughness height, Nikuradse (1950) found
that the mean velocity profile still obeys the log law and the intercept constant was \( \approx 8.5 \). Thus, the roughness function \( \Delta U^+ \) for the fully regime can be determined by

\[
\Delta U^+ = \frac{1}{\kappa} \ln(k_s^+) + B - 8.5.
\] (1.3)

1.2 Motivation

As already mentioned, the surface conditions encountered in many technologically-relevant flow systems, from internal flow such as oil and gas pipelines to external flows such as turbine blades, ship hulls, wind turbines and heat exchanger, for instance, can deteriorate over time due to multiple damage mechanisms that generate irregular topographies embodying a broad range of scales. Roughness directly degrades the performance of these practical systems, leading to an increase in drag and heat transfer loads at the surface. Many efforts have studied the impact of surface roughness on wall turbulence, with most of these efforts employing simplified idealized roughness, such as sand grain, woven mesh and 2D roughness elements ordered in a regular fashion. Figure 1.1(a) illustrate such simplified roughness that is often characterized by a single roughness scale arranged in an ordered manner.

Although these idealized roughness characterizations are relatively easy to implement in laboratory experiments, they do not reflect the full topographical richness of practical roughness. In fact, roughness in practical flow systems is highly irregular, containing a multitude of topographical scales. For instance, surfaces of turbine blades suffer cumulative damage over their lifetime due to different damage mechanisms, such as deposition of foreign materials, pitting and spallation of the thermal barrier coating (Bons et al., 2001), all of which are marked by a broad range of topographical scales. One example of realistic roughness is depict in figure 1.1(b),
which shows the topographical complexity that marks realistic roughness. Figure 1.2 presents a few examples of damaged turbine blades, such as erosion, fuel deposition, spallation of the thermal barrier coating and deposition of foreign materials. Given this complexity that is not necessarily reflected in idealized roughness models often used in laboratory studies, it is crucial to establish a deeper understanding of the impact of more realistic roughness on the turbulent characteristics of wall-bounded flows. By doing so, this could lead to maximizing performance, viability, longevity and efficiency in these technologically-relevant applications.

1.3 Structural organization of smooth-wall turbulent boundary layers

Over the past few decades, many studies have been conducted to better understand the structures of turbulence in wall-bounded flows. After the groundbreaking observations of Theodorsen (1952), with his conceptual model of the horseshoe vortex, and the Kline et al. (1967) observations of near-wall streaks with spacing of $100 y_*$, an appreciation for and concomitant focus on understanding the role of coherent structures
in wall turbulence processes has grown immensely.

Recent advances in flow diagnostics that can measure spatial distributions of flow, such as particle image velocimetry (PIV), have led to seminal advances in understanding the structural attributes wall turbulence. The streamwise–wall-normal ($x - y$) plane two-dimensional PIV measurements of Adrian et al. (2000b) provided a direct visualization of the coherent ordering of hairpin-like structures, consistent in spirit with the horseshoe vortex conceptual model of Theodorsen (1952), into larger-scale structural entities termed hairpin vortex packets. Figure 1.3 provides an illustration of a PIV laser lightsheet measuring a hairpin vortex packet in this plane. In particular, the streamwise alignment of individual hairpin-like structures into larger-scale packets observed by Adrian et al. (2000b) across the boundary layer in a hierarchy
of scales is marked by an inclined interface formed by the spanwise-oriented heads of each structure beneath which a region of streamwise momentum deficit is apparent due to the collectively-induced ejection events generated by each of the vortices in a packet. Thus, these large-scale packets induce low-momentum regions (LMRs) previously identified in streamwise–spanwise \((x-z)\) plane PIV measurements that are bounded by wall-normal vortex cores likely associated with the legs/necks of the individual vortices of hairpin packets (Ganapathisubramani et al., 2003; Tomkins & Adrian, 2003; Wu & Christensen, 2010) and within which intense ejections of low-speed fluid are generated (Ganapathisubramani et al., 2003; Wu & Christensen, 2010).

Instantaneous PIV fields in the \(x-z\) plane within the log layer also reveal the
existence of high-momentum regions (HMRs) adjacent to LMRs within which strong sweep events are observed. Figure 1.4 provides an Illustration of a PIV laser lightsheet dissecting through a hairpin vortex packet in this wall-parallel plane. This spanwise-alternating behavior of LMRs and HMRs is consistent with the spanwise-alternating sign of the two-point correlation of streamwise velocity in the $x - z$ plane (Ganapathisubramani et al., 2005; Wu & Christensen, 2010). More recently, hot-wire measurements indicate that the LMRs observed in $\delta$-scale PIV studies can actually extend several $\delta$ in the streamwise direction (Hutchins & Marusic, 2007). These ‘super-structures’ can meander significantly in the spanwise direction Hutchins & Marusic (2007) and can embody a significant fraction of the turbulent kinetic energy and Reynolds shear stress (Kim & Adrian, 1999). It is these motions that appear to amplitude modulate the smaller scales in the near-wall region of the flow (Mathis et al., 2009a). Leveraging these amplitude-modulation observations, Marusic et al.
Figure 1.5: Illustration of a PIV laser lightsheet measuring a hairpin vortex packet in the wall–normal-spanwise ($y-z$) plane. Hairpin vortex packet cartoon extracted from Adrian et al. (2000b) and Mathis et al. Mathis et al. (2011) proposed a predictive inner–outer model for the streamwise turbulence statistics in smooth-wall turbulence at high Re. While providing significant information about the structural characteristics of the flow, measurements at fixed wall-normal locations (i.e., fixed $x-z$ PIV planes) unfortunately do not provide details as to the wall-normal dependence of the dominant spanwise scales of the flow.

Measurements in the wall-normal–spanwise ($y-z$) plane overcome such limitations; however, PIV measurements in this cross-flow plane are extremely challenging, as the bulk flow direction is normal to the lasersheet. Figure 1.5 provides an illustration of a PIV laser lightsheet traversing through a hairpin vortex packet in this cross-flow plane wherein one would expect to see the momentum deficit induced by the collective induction of the vortices in the packet extend far from the wall, bounded by
streamwise vortex cores representing slices through the legs/necks of the individual vortices. Despite the measurement challenges, a few studies have successfully employed PIV to study wall turbulence in the cross-stream plane (Ganapathisubramani et al., 2005; Hutchins et al., 2005; Carlier & Stanislas, 2005). In particular, Hutchins et al. (2005) and Ganapathisubramani et al. (2005) used stereo PIV in cross-stream planes inclined at 45° and 135° to the streamwise direction in a replication of the original flow-visualization imaging planes of Head & Bandyopadhyay (1981). These measurements revealed inclined vortical structures bounding LMRs that are consistent with the hairpin vortex packet model of wall turbulence. Spanwise-adjacent HMRs were also observed in the instantaneous fields, with both LMR and HMR events extending well into the outer layer of the flow. Analysis of spatial correlations of velocity in these inclined cross-stream planes also uncovered imprints consistent with hairpin vortex packets. Hutchins & Marusic (2007) used channel flow DNS fields to compute the conditionally-averaged velocity field associated with an LMR in the wall-normal–spanwise plane at low Re. This field was characterized by an LMR bounded on either spanwise side by an HMR, between which streamwise vortices resided. Similar conditional average results for the large scales were reported by Chung & McKeon (2010) from large-eddy simulations (LES) of turbulent channel flow at friction Reynolds numbers (Re) of 2,000 and 200,000.

With the appreciation that individual, smaller-scale vortices actually contribute to transport processes at the larger scales owing to their coherent ordering into larger-scale packets, the features of the large-scale motions (LSMs; 1 – 3δ in streamwise extent) and very-large-scale motions (VLSMs or superstructures; 5 – 8δ in streamwise extent) of the flow have received considerable renewed attention recently. The existence of such scales in the flow was first reported by Townsend (1958) and Grant
(1958), where the presence of large-scale motions (LSM) inferred from the long tails of time-delayed streamwise, $u$, velocity auto-correlations that could extended to $1.4\delta$. These works also concluded that these LSMs carry a significant fraction of turbulent kinetic energy (TKE). It is now thought that these LSMs first identified several decades ago in two-time correlations are in fact the statistical imprint of the hairpin packets reported by Adrian et al. (2000b). More recently, Kim & Adrian (1999) investigated the existence of VLSMs in the outer layer of a fully-developed turbulent pipe flow. They showed that the premultiplied streamwise velocity spectrum captured in the lower portion of the logarithm layer has a bimodal distribution, embodying a peak at a relatively “low” wavenumber (associated with streamwise scales of 12–14 pipe radii; presumably VLSMs) and a secondary peak at a slightly higher wavenumber (associated with streetwise scales of 1–3 pipe radii; presumably LSMs), with this bimodal distribution present over a range of Re. They were the first to conjecture that the VLSMs are the result of a coherent streamwise alignment of LSMs. Guala et al. (2006) extended this understanding by showing that the VLSMs in pipe flow are energetic, containing approximately 50% of the TKE of the streamwise velocity component, as well as more than half of the Reynolds shear stress (RSS).

Given the fact that internal and external flows can show marked differences, particularly in the outer layer (Wu & Christensen, 2006; Monty et al., 2009), recent efforts have focused on whether scales comparable to VLSMs in internal flows exist in turbulent boundary layers. Balakumar & Adrian (2007) performed hot-wire measurements on both channel and TBL flows for a wide spectrum of Reynolds number. They found that the VLSMs on these flows carry a significant fraction of the streamwise content of the TKE (40-65%) and Reynolds shear stress (30-50%), similar to the pipe-flow results reported by Guala et al. (2006) in turbulent pipe flows.
These VLSMs, also often called ‘superstructures’, persist under realistic scenarios, such TBL atmospheric flow, whose Re can be three orders of magnitude higher than laboratory conditions (Kunkel & Marusic, 2006; Hutchins & Marusic, 2007). In particular, Kunkel & Marusic (2006) compared the streamwise and wall-normal velocity spectra from the atmospheric boundary layer with laboratory data showing similar behavior. However, in the premultiplied form, the authors reported some noticeable quantitative differences from the laboratory data, mainly due to measurement difficulties and also due to possible roughness effects on properly identifying convection velocities when using Taylor’s hypothesis. Hutchins & Marusic (2007) used a spanwise rake of hot-wire sensors to reconstruct streamwise-elongated fields of view from time-traces of $u'$ which revealed what they report as the spatial signatures of superstructures, or VLSMs. These fields showed regions of streamwise momentum deficit ($u' < 0$) that extended several $\delta$ in the streamwise direction, with a characteristic spanwise width of approximately $0.4\delta$. Interestingly, these elongated regions of $u' < 0$ were not straight but instead displayed significant spanwise meandering.

The most recent studies of VLSMs, or superstructures, report evidence suggesting that these scales modulate the smaller-scale motions in the near-wall region (Mathis et al., 2009a,b). In particular, Mathis et al. (2009a) applied a scale-decomposition on the zero-pressure gradient turbulent boundary layer streamwise velocity fluctuations using the Hilbert transform. This analysis revealed that the large-scale motions in the log region amplitude modulate the the smaller scales in the near-wall region. This modulation behavior is also seen in the inner region of both channel and pipe flows, regardless of the modal differences of the largest energetic scales when compared with boundary layers. However, some variations are noted in the outer region (Mathis et al., 2009b).
1.4 Impact of roughness on the smooth-wall structural paradigm

The impact of roughness on this structural skeleton of smooth-wall flow is not yet fully understood. While some efforts indicate that roughness alters the structural and/or statistical attributes of the flow throughout the entire boundary layer (Krogstad & Antonia, 1994; Keirsbulck et al., 2002; Tachie et al., 2000, 2003), other studies (Ligrani & Moffat, 1986; Raupach et al., 1991; Volino et al., 2007; Wu & Christensen, 2007, 2010; Mejia-Alvarez & Christensen, 2010) indicate that the effect of roughness is confined within the immediate vicinity of the roughness—the so-called roughness sublayer (3-5\(k\), where \(k\) is a measure of the characteristic roughness height). This latter notion is consistent with Townsend’s wall similarity hypothesis Townsend (1976), extended to rough-wall turbulence by Raupach et al. (1991), which states that at high Re, surface conditions set the wall shear stress and the boundary-layer thickness, \(\delta\), while the turbulence outside the roughness sublayer adjusts itself to these conditions in an universal manner. A necessary condition for this similarity to exist is a broad scale separation between \(k\) and the outer length scale of the flow (typically taken as \(\delta\)). Previous efforts indicate \(\delta/k\) must exceed 40–50 for this similarity to exist (Jimenez, 2004; Flack et al., 2005). The geometrical details of the roughness can also play a critical role as to the existence of outer-layer similarity, with flow over three-dimensional (3D) roughness topographies often displaying such similarity in contrast to flow over two-dimensional (2D) topographies wherein the large spanwise extent of the roughness generates large-scale flow structures that grow well into the outer layer (Krogstad & Antonia, 1999; Lee & Sung, 2007; Volino et al., 2009).

From a structural viewpoint, the PIV measurements of Nakagawa & Hanratty
(2001) in the $x - y$ plane of turbulent channel flow with a wavy bottom wall revealed the spatial coherence of this flow to be quite similar to that of smooth-wall flow in the outer region. This observation is interesting given that the wavy wall under consideration was 2D in nature. Volino et al. (2007) observed the spatial signatures of hairpin vortex packets in instantaneous PIV velocity fields in $x - y$ and $x - z$ measurement planes for a turbulent boundary layer (TBL) over woven wire mesh (3D roughness). Two-point correlations indicated a slight reduction in the streamwise spatial coherence close to the wall, compared to smooth-wall flow, that quickly diminished with increasing wall-normal position. Finally, Wu & Christensen (2007) reported outer-layer similarity for flow over highly-irregular roughness replicated from a turbine blade damaged by deposition of foreign materials based on PIV measurements in the $x - y$ plane. In a follow-up effort, Wu & Christensen (2010) reported that this irregular roughness altered the characteristic streamwise and, to a lesser extent, the spanwise length scales of the flow based on stereo PIV measurements in a streamwise–spanwise plane near the outer edge of the roughness sublayer ($y \approx 0.2\delta$ relative to the mean elevation of the roughness). Nevertheless, the rough-wall flow was still found to embody many of the structural attributes of hairpin vortex packets, including elongated LMRs bounded by wall-normal vortex cores interpreted as slices through the legs/necks of hairpin vortices.

Very little work has been perform to fully address the impact of roughness in the LSMs and VLSMs that are known to drive many aspects of smooth-wall turbulence, including the potential impact of roughness on the TKE and RSS content of these scales. Related to this is the possibility that the outer-layer of rough-wall flow is not directly impacted by roughness but rather equilibrates to the $\delta$ and wall shear stress set by the roughness. Known as Townsend’s outer-layer similarity hypothesis,
it is not known whether this notion holds at the scales of the LSMs and VLSMs. Krogstad et al. (1992) performed hot-wire measurements in TBL over wire mesh (k-type roughness; $\delta/k = 50$). The authors reported small differences between the smooth and rough-wall flows in the both streamwise velocity spectra, $\phi_{uu}$, and the co-spectra, $\phi_{uv}$, but significant differences in the wall-normal velocity spectra, $\phi_{vv}$. This latter difference was found to exist at all wavenumbers for two wall-normal positions in the outer layer ($y/\delta = 0.1$ and 0.4). Krogstad & Antonia (1999) then investigated differences between two type of roughness (wolves mesh, $\delta/k = 50$, and 2D rods, $\delta/k = 47$) as compared to smooth-wall flow, and they identified similar trends for the velocity spectra in the outer layer as reported by Krogstad et al. (1992). Although the aforementioned works identified alterations (small, but present) in the streamwise velocity spectra, their results also showed a distinctive peak in the premultiplied form of spectra at $k_x \delta \approx 2$ ($\lambda_x / \delta \approx 3$), which indicates the presence of LSMs in the outer layer, similar to the smooth-wall counterpart (Kim & Adrian, 1999; Guala et al., 2006; Balakumar & Adrian, 2007) However, up to this point, it cannot be concluded the impact of roughness on these larger-scale motions inside the log region (and subsequently inside the roughness sublayer).

The structural attributes of a TBL flow over woven wire mesh (3D roughness) were investigated by Volino et al. (2007). They observed spatial signatures of hairpin vortex packets in instantaneous PIV velocity fields in the $x-y$ and $x-z$ measurement planes. The two-point correlations indicated a slight reduction in the streamwise spatial coherence close to the wall, compared to smooth-wall flow, that quickly diminished with increasing wall-normal position. Similar trends were observed by Wu & Christensen (2007), where they reported outer-layer similarity for flow over the same complex roughness employed herein based on PIV measurements in the $x-y$
plane. In a followup work, Wu & Christensen (2010) reported that this roughness altered the characteristic streamwise and, to a lesser extent, the spanwise length scales of the flow based on stereo PIV measurements in a streamwise-spanwise plane near the outer edge of the roughness sublayer \((y \approx 0.2\delta\) relative to the mean elevation of the roughness). Nevertheless, the 3D rough-wall flow was still found to embody many of the structural attributes of hairpin vortex packets, including elongated LMRs bounded by wall-normal vortex cores interpreted as slices through the legs/necks of hairpin vortices. Interestingly, Volino et al. (2009) found that 2D, \(k\)-type roughness (transverse square bars; \(\delta/k = 32\)) has a significant impact on the spatial scales of the flow in both near-wall region and in the outer layer. Two-point correlation of the streamwise velocity shows on average an increase of 42\% of the streamwise extent, 39\% increase of the wall-normal extent and 10-15\% increase of the spanwise extent when compared with both smooth- and 3D rough-wall.

More recently, Allen et al. (2007) reported streamwise velocity spectra measured deep within the log layer of a transitionally-rough turbulent pipe flow. The streamwise premultiplied spectra show fairly good agreement with smooth-wall flow, indicating little modification of the underlying turbulence structure. Monty et al. (2011) measured the impact of regular roughness composed by braille dots on a TBL. Streamwise velocity spectra tended to collapse at smaller scales in the outer region with smooth-wall data, in accordance with Townsend’s similarity hypothesis. They did, however, identify reductions in the energy content of the larger scales \((\lambda/\delta \approx 6)\) at higher Re in the log region, suggesting potential manipulation of LSMs and VLSMs in the presence of regular roughness. Similar modification of the energy content of the larger scales was reported by Jacobi & McKeon (2011), but for a vastly different roughness scenario: a single impulse of 2D roughness in a TBL. Discrepancy maps of streamwise
velocity spectra (Perturbed minus Smooth) a few roughness heights downstream of the roughness impulse showed significant LSM and VLSM suppression up to the wall-normal height of the roughness perturbation. Similar modifications of the larger-scale energy content was achieved using a single circular cylinder element immersed into the log layer of turbulent channel flow (Pathikonda, 2013). While these studies only considered spatially-compact roughness perturbations, they clearly suggest the possibility of modifying the energy content of flow scales far larger than the roughness itself.

It has been reported that some 3D roughness can lead to preferential paths of the instantaneous structures, creating local regions of momentum deficit and surplus in the streamwise mean velocity. In a more recent effort, Mejia-Alvarez & Christensen (2013) conducted stereo PIV measurements in the streamwise–spanwise plane deep within the roughness sublayer ($y = 0.047\delta$) of a TBL overlying the same highly irregular roughness as Wu & Christensen (2007, 2010). The results revealed that roughness introduces a high degree of spanwise heterogeneity in the form of low- and high-momentum pathways in the ensemble-averaged velocity, perhaps promoting the “channeling” of the instantaneous structures at preferential regions over the roughness. Other works have also identified mean-flow heterogeneity for flow over ordered roughness that displays spanwise heterogeneity. Nugroho et al. (2013) identified spanwise periodicity in the mean flow overlying well-ordered converging-diverging riblet roughness similar to the observations of Mejia-Alvarez & Christensen (2013), specifically spanwise-alternating regions of enhanced streamwise momentum deficit and surplus. Vermaas et al. (2011) identified similar spanwise heterogeneity in flow overlying spanwise-alternating regions of high and low roughness that induced significant lateral exchange of momentum. Finally, Willingham et al. (2014) reported
significant spanwise heterogeneity in the mean flow for ordered, spanwise-alternating regions of high and low roughness in large-eddy simulations (LES) of a turbulent boundary layer and ascribed this heterogeneity to turbulent secondary flows induced by the spanwise roughness transitions.

1.5 Objectives

The intent of the present contribution is to further explore the structural attributes of a turbulent boundary layer in the presence of the highly-irregular roughness topography employed in previous efforts Wu & Christensen (2007, 2010); Mejia-Alvarez & Christensen (2010). The focus of the present measurements and analysis is on the structural attributes of this flow in the wall-normal–spanwise plane as well as on the impact of complex roughness on the characteristics of LSMs and VLSMs known to carry a significant fraction of the TKE and RSS in smooth-wall flow. To this end, stereo PIV measurements in the wall-normal–spanwise ($y - z$) plane were conducted at both low and high frame rates. The low-frame-rate measurements were meant to provide a simultaneous assessment of the flow’s spanwise spatial characteristics as well as their coherence in the wall-normal direction. The high-frame-rate measurements were conducted in a narrow wall-normal strip in the cross-flow ($y - z$) plane, allowing the calculation of velocity spectra and co-spectra, with a particular focus on the characteristics of the LSMs and VLSMs as a function of wall-normal and spanwise position.

Chapter 2 provides details of the conducted experiments as well as a discussion about the challenges of stereo-PIV measurements in cross-flow. Chapter 3 presents the results of the stereo-PIV validation experiments in the turbulent channel flow. The results from the TBL experiments are discussed in chapter 4 for the low-frame-
rate experiments, which focuses on the impact of the roughness in the mean turbulent quantities, and in chapter 5 for the high-frame-rate experiments, where spectral analysis is conducted to assess the impact of roughness on the larger-scales motions of the flow inside the roughness sublayer.
Chapter 2
Experiments

The present contribution utilizes stereo particle image velocimetry (PIV) measurements in the wall-normal-spanwise ($y-z$) (cross-flow plane) for all of the experiments discussed herein. Stereo PIV is a quantitative visualization technique in which all the three velocity components are measured simultaneously over a large planar field-of-view, providing instantaneous snapshots of the flow under consideration. However, the measurement plane studied herein for which the mean flow is normal to the lightsheet, and hence the field of view, presents unique challenges and difficulties of implementation to ensure acquisition of accurate data sets.

This chapter describes the experimental facilities utilized in this work along with the experimental methodology employed. Initial channel-flow measurements were undertaken to provide validation of the cross-flow plane stereo PIV implementation in a wall turbulence environment for which DNS data is readily available for comparison. Initial rough-wall measurements with hemispheres were also undertaken in the turbulent channel flow to identify challenges and solutions to utilizing the cross-plane stereo PIV methodology in the presence of complex topography. Following these validation experiments, turbulent boundary layer experiments were conducted in the cross plane in a wind tunnel facility. As the main objective of this work is to investigate the spatial and temporal signatures of the turbulent structures over both smooth-rough-wall flow in the spanwise-wall-normal ($y-z$), two stereo-PIV systems
were employed; (i) a low-frame-rate, high spatial resolution stereo PIV system to study the impact of the complex, multi-scale roughness used herein on the statistical quantities of the flow, and (ii) a high-frame-rate stereo PIV system to capture time series of all three velocity components at approximately 1000 points across the planar field of view to investigate the impact of roughness on the large and very large scales of motion in the flow. In both cases, smooth-wall measurements were also conducted to provide a baseline of comparison for the rough-wall measurements.

2.1 Experimental facilities

2.1.1 Channel flow facility

The channel-flow facility used in this work is a closed-loop circuit system, where the working fluid is air. The facility is firstly composed by a blower, which provides the driving force to pump the fluid through the facility. The flow speed is adjusted by a frequency inverter that allows precise control of the flow rate. A conditioning section, positioned downstream to the blower, is composed of a series of screens, honeycomb and a contraction, with the goal of minimizing large disturbances from the blower and damping the turbulence before entering the test section. The test section, made of transparent acrylic, has a development length of $216h$, where $h = 25.4 \text{ mm}$ is the half-height of the channel. The aspect ratio of flow cross-section is 10.125:1, yielding nominally two-dimensional flow along the channel’s spanwise centerline. At the channel entrance, the flow on the top and bottom walls is tripped by 36-grid sandpaper, ensuring fully-developed flow conditions at the measurement section. Lastly, the flow is returned to the blower from the return section that is constructed from aluminum air ducts. Figure 2.1 presents a detailed schematics of
Figure 2.1: Schematic of the channel-flow facility (source: Christensen (2001)).
the channel flow facility, and figure 2.2 shows a photo of the facility. For more information about the facility and its construction, see Christensen (2001).

In order to evaluate the wall shear stress, $\tau_w$, static pressure readings were taken along the streamwise length of the channel in the fully-developed region where the streamwise pressure gradient is constant. Density and viscosity were assessed by measuring the fluid temperature and atmospheric pressure in concert with an ideal gas relation in addition to Sutherland’s correlation for kinematic viscosity. Using these fluid properties, the friction velocity, $u_f \equiv (\tau_w/\rho)^{1/2}$ and the viscous length scale, $y_* \equiv \nu/u_f$, were determined.

To perform the PIV experiments, the flow was seeded with olive oil droplets generated by a Laskin nozzle. The olive oil was injected into the facility from a inlet...
located at the return section. The particles were fed into the facility until the desired concentration was achieved.

2.1.2 Wind tunnel facility

The turbulent boundary layer experiments were conducted in an open-circuit Eiffel-type, boundary-layer wind tunnel. The wind tunnel facility is 20.0m long, 3.4m wide and 2.5m tall, and it is composed by three main sections: the conditioning section, the test section and the exhaust section. Figure 2.3 shows a schematic of the flow facility [figure 2.3(a)] and two photos of the actually wind tunnel [figure 2.3(b) and 2.3(c), respectively].

The air enters the conditioning section and travels through a series of meshes and a honeycomb to damp any external large flow disturbances, achieving a nearly isotropic turbulence condition. Then, the air flow through the contraction section with an area ration of 10, reducing the turbulence intensity levels to roughly 0.16% (Meinhart, 1994). After the conditioning section the air enters the test section, where the boundary layer is formed. The air exits the wind tunnel through the exhausting section, which is composed by a long, low-angle diffuser that transitions in cross section, from the rectangular shape of the test section to the circular shape of the fan. To damp most of the aerodynamic noise generated by the flow and fan, an acoustic diffuser is positioned at the end of the wind tunnel.

The test section of the tunnel is 6m long, 45.7 cm tall and 91.4 cm wide, and all boundary layers were formed on a smooth boundary layer plate suspended above the bottom wall of the tunnel. The test section was designed to facilitate optical assess. The bottom of the test section is constructed of glass, and the left and right sides are composed of 4 accessible plexiglas windows at each side. The test-section
ceiling is adjustable along the streamwise length to achieve zero-pressure gradient conditions. In order to achieve this condition, pressure taps are located along the streamwise length of the boundary layer with a streamwise separation of 30.5 cm.

The boundary layer plate consists of two, 3-m long and 91.4-cm wide smooth-wall sections smoothly joined at the streamwise center of the test section. To minimize the possible formation of corners vortices, wooden fillets with 25.4 mm radius were fitted on both sides of the boundary-layer plate covering the entire streamwise length of the test section. The boundary layer plate has an elliptical shape leading edge to smoothly receive the incoming flow and avoid flow separation. In addition, the flow was tripped with a 4.7 mm rod placed 25 cm downstream of the boundary-layer plate’s leading edge. The boundary layer thickness at the end of the boundary layer plate is about 100 mm, ensuring two-dimensionality as this thickness is approximately
nine times smaller than the width of the test section.

To perform the PIV experiments, the flow was seeded with olive oil droplets generated by eight Laskin nozzles. Each Laskin nozzle can operate individually, having its own olive oil container. All eight self-contained nozzles were placed about 2 m upstream of the inlet of the wind tunnel, enabling precise control of the olive oil mist allowing a perfectly uniform distribution of oil mist before being pulled into the tunnel. While running the experiments, a continuous feed of particles was maintained to achieve the desired PIV concentration, thus maximizing not only accuracy but most importantly high spatial resolution in the measurements.

2.2 Validation of stereo PIV cross-plane implementation: Turbulent channel flow experiments

As mentioned previously, the channel-flow experiments provided well-control conditions to validate the stereo-PIV measurements in the wall-normal-spanwise ($y-z$) plane. Measurements were conducted for fully-developed smooth-wall turbulent channel flow at $Re_T = 600$ to facilitate direct comparison of the single-point statistics with DNS data at comparable $Re$ (Moser et al., 1999). Measurements were also conducted at the same $Re$ for flow 2 mm downstream of a $8h$-long region of roughness consisting of a staggered array of 4-mm diameter hemispheres placed along the bottom wall of the channel (see figure 2.4). This pattern was adhered to a floating plate within the channel-flow test section (Wu & Christensen, 2006) that allowed the base of the hemisphere pattern to be carefully aligned to be coincident with upstream smooth-wall conditions. Therefore, the lower wall in the measurement plane contained roughness
Table 2.1: Experimental parameters.

<table>
<thead>
<tr>
<th>Surface</th>
<th>$Re_\tau$</th>
<th>$h$</th>
<th>$u_\tau$</th>
<th>$y_*$</th>
<th>$k$</th>
<th>Field of View</th>
<th>No. of Realizations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth</td>
<td>600</td>
<td>25.4</td>
<td>0.370</td>
<td>42.3</td>
<td>–</td>
<td>$4h \times h$</td>
<td>2500</td>
</tr>
<tr>
<td>Rough†</td>
<td>613</td>
<td>25.4</td>
<td>0.374</td>
<td>41.4</td>
<td>2</td>
<td>$4h \times 2h$†</td>
<td>2500</td>
</tr>
</tbody>
</table>

†Smooth-wall flow on upper half of channel simultaneously resolved.

while the upper wall remained smooth. Thus, the rough-wall measurements presented herein simultaneously captured the interaction of fully-developed smooth-wall turbulent channel flow with a short length of roughness along the bottom wall and fully-developed smooth-wall flow along the top wall. Flow parameters for the smooth- and rough-wall experiments are summarized in table 2.1.

Stereo particle-image velocimetry was used to measure all the three velocity components in the wall-normal–spanwise ($y-z$) plane of the flow. The system employed consisted of two 4k×2.7k pixel, 12-bit, frame-straddle CCD cameras (TSI 11MP) and a 190 mJ/pulse dual-cavity pulsed Nd:YAG laser (Big Sky). A 1.0 mm thick laser lightsheet was formed by three cylindrical lenses and directed into the channel test section in the $y-z$ plane from above with the spanwise center of the lightsheet coincident with the spanwise center of the channel. Figure 2.4 presents a schematic of the stereo PIV arrangement. The cameras viewed the $y-z$-oriented lightsheet from downstream through optical-grade glass side-walls of the channel at angles of $\pm 35^\circ$ from the streamwise ($x$) direction. Lenses with a focal length of 180 mm were utilized to image a field of view of approximately $4h \times h$ (spanwise by wall-normal) for the initial smooth-wall measurements and $4h \times 2h$ for the rough-wall measurements with an $f$-number of 8. The angle between each lens and camera CCD array
Figure 2.4: Schematic of the stereo PIV arrangement as well as the roughness under consideration.

was adjusted to satisfy the Scheimpflug condition which ensured uniform focus across each image but results in a variable magnification. The flow was seeded with 1 μm olive-oil droplets generated by a Laskin nozzle and timing of the cameras, lasers and image acquisition was controlled with a timing unit with 1 ns resolution.

Two-thousand and five hundred statistically-independent planar, three-component velocity fields were acquired per surface condition. The final velocity fields has a grid spacing of 237 μm in the wall-normal and spanwise directions. This grid spacing translates into a spatial resolution of $11.2y_*$. The resulting field-of-view yielded a $406 \times 107$ vector grid of instantaneous velocity vectors on the $4h \times h$ field of view.
for the initial smooth-wall measurements and a $413 \times 200$ vector grid on the $4h \times 2h$ field of view for the rough-wall measurements.

### 2.3 Turbulent boundary layer experiments

#### 2.3.1 Complex roughness topography

The rough surface used was the same as that originally fabricated and studied by Wu & Christensen (2007, 2010); Mejia-Alvarez & Christensen (2010, 2013). This surface is a scaled version of a profilometric surface scan of a turbine blade damaged...
by deposition of foreign materials, which was first reported by Bons et al. (2001).
Figure 2.5(a) presents a topographical map of the rough surface, which is marked by a broad range of topographical scales occurring in an irregular arrangement. The average peak-to-valley roughness height of this surface is \( k = 4.25 \text{mm} \) while the root-mean square (RMS) roughness height, \( k_{rms} \), is 1.0 mm, while the skewness and kurtosis are 0.16 and 2.27, respectively. Mejia-Alvarez & Christensen (2010) explored the spectrum of topographical scales embodied in this topography and found singular value decomposition (SVD) to provide the most appropriate basis for describing this irregular topography. They found that 95% of the full-surface content was captured with the first 16 SVD modes (4.2% of the total modes) and that this level of topographical reconstruction accurately reproduced the flow physics over the original topography. As described in Wu & Christensen (2007, 2010), a 3-m long replica of this topography was achieved by mirroring it in both the streamwise and spanwise directions and fabricated with a powder-deposition printer. This roughness was mounted on cast aluminum plates and placed along the downstream half of the boundary-layer plate by adjusting its height above the bottom wall of the tunnel such that the mean elevation of the roughness was coincident with the upstream smooth-wall conditions. Thus, the boundary layers under study were allowed to initially develop over the first 3 m of the smooth boundary-layer plate followed by an additional 3 m of development over the roughness. In all cases the flow was tripped with a cylindrical rod near the upstream end of the boundary-layer plate and all measurements were conducted approximately 2.3 m downstream of the leading edge of the roughness. Wu & Christensen (2007) previously reported this rough-wall flow to have achieved self-similar conditions at this measurement location. Figure 2.5(c) presents a zoomed-in photo of a portion of the roughness replica in the wind tunnel. This photo highlights the
The complex, multi-scale nature of the topography whose elements, in the present experiments, protrude into the outer (logarithmic) region of the flow but are an order of magnitude smaller than the characteristic flow depth ($\delta$).

### 2.3.2 Low-frame-rate experiments

Figure 2.6(a) presents a schematic of the stereo PIV arrangement for the low-frame-rate cross-plane ($y-z$) experiments. The system employed consisted of two 4k × 2.75k pixel, 12-bit, frame-straddle CCD cameras (TSI 11MP) and a 190 mJ/pulse, dual-cavity pulsed Nd:YAG laser (Quantel). A 1.0 mm thick laser lightsheet was formed by three cylindrical lenses and directed into the tunnel’s test section in the $y-z$ plane. The cameras viewed the $y-z$-oriented lightsheet from upstream through optical-grade glass side-walls of the wind tunnel at angles of $\pm 45^\circ$ from the streamwise ($x$) direction. In the measurement plane, the angle between each lens and camera CCD array was adjusted to satisfy the Scheimpflug condition ensuring uniform focus across the field of view. The flow was seeded with 1 $\mu$m olive-oil droplets generated by a Laskin nozzle and timing of the cameras, lasers and image acquisition was controlled with a timing unit with 1 ns resolution.

The field of view for the smooth-wall case was $1.2\delta \times 2.4\delta$ (wall-normal by span-

---

<table>
<thead>
<tr>
<th>Surface</th>
<th>$U_e$ (m/s)</th>
<th>$Re_\theta$</th>
<th>$\delta$ (mm)</th>
<th>$y_*$ (µm)</th>
<th>$k$ (mm)</th>
<th>$\delta/k$</th>
<th>Field of View ($y \times z$)</th>
<th>No. of Fields</th>
</tr>
</thead>
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<td>Smooth</td>
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<td>85.3</td>
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<td>-</td>
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<tr>
<td>Rough</td>
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<td>22.1</td>
<td>$1.5\delta \times 3.0\delta$</td>
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</tr>
</tbody>
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Table 2.2: Summary of the experimental parameters for the low-frame-rate stereo PIV measurements in the $y-z$ plane.
Figure 2.6: (a) The cross-plane stereo PIV arrangement for the low-frame-rate measurements. (b) Topographical map of the rough surface illustrating the locations of the cross-flow measurement plane (red line) and the Mejia-Alvarez & Christensen (2013) wall-parallel field of view (blue box).

wise), resulting in a vector grid spacing of $470 \mu m (18y_*)$ in both spatial directions. For the rough-wall case the field of view was $1.5\delta \times 3.0\delta$, which resulted in a vector grid spacing of $520 \mu m (30y_*)$ in both spatial directions. For the smooth-wall experiments, two-thousand, six hundred statistically independent planar, three-component velocity fields were acquired in the cross-flow measurement plane at $Re_\theta \simeq 10300$. In addition, for the rough-wall experiments, ten thousand statistically independent planar, three-component velocity fields were acquired in the same cross-flow measurement plane at $Re_\theta \simeq 14000$. These fields were considered statistically independent since the vector-field acquisition rate of 0.5 Hz translated to a roughly $35 m (~350\delta)$ streamwise separation between consecutive fields at the Re studied. Table 2.2 provides a summary of the low-frame-rate measurements conducted in addition to the important flow parameters.
Table 2.3: Summary of the experimental parameters for the high-frame-rate stereo PIV measurements in the $y-z$ plane of the rough-wall flow.

<table>
<thead>
<tr>
<th>Surface</th>
<th>$U_e$ (m/s)</th>
<th>$Re_\theta$</th>
<th>$\delta$ (mm)</th>
<th>$k$</th>
<th>$\delta/k$</th>
<th>Field of View ($y \times z$)</th>
<th>Acq. Freq. (kHz)</th>
<th>No. of Fields</th>
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</thead>
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<td>80.0</td>
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<td>-</td>
<td>$0.8 \delta \times 1.3 \delta$</td>
<td>1.5</td>
<td>3000</td>
</tr>
<tr>
<td>Rough</td>
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<td>4500</td>
<td>90.0</td>
<td>4.25</td>
<td>21.2</td>
<td>$0.8 \delta \times 1.3 \delta$</td>
<td>1.5</td>
<td>3000</td>
</tr>
<tr>
<td>Smooth</td>
<td>17.3</td>
<td>10000</td>
<td>85.3</td>
<td>-</td>
<td>-</td>
<td>$0.1 \delta \times 1.3 \delta$</td>
<td>10</td>
<td>21845</td>
</tr>
<tr>
<td>Rough</td>
<td>17.5</td>
<td>13700</td>
<td>94.9</td>
<td>4.25</td>
<td>22.1</td>
<td>$0.1 \delta \times 1.3 \delta$</td>
<td>10</td>
<td>21845</td>
</tr>
</tbody>
</table>

2.3.3 High-frame-rate experiments

Figure 2.7 presents a schematic of the stereo PIV arrangement for the high-frame-rate experiments. The system consisted of two 1k $\times$ 1k pixel, 10-bit, CMOS cameras (Fastcam APX-RS Photron) and a 30 mJ/pulse at 1 kHz, dual-cavity pulsed Nd:YLF laser (Litron). A 1.0 mm thick laser lightsheet was formed by three cylindrical lenses and directed into the tunnel’s test section in the $y-z$ plane. The cameras viewed the $y-z$-oriented lightsheet from a forward-scattering perspective to maximize the intensity of the scattered light imaged by the cameras given the reduced energy output of the high-repetition laser utilized for these measurements, with one camera upstream to the laser lightsheet and the other downstream of it, through optical-grade glass side-walls of the wind tunnel at angles of $\pm45^\circ$ from the streamwise ($x$) direction. In the measurement plane, the angle between each lens and camera CMOS array was adjusted to satisfy the Scheimpflug condition which ensured uniform focus across the field of view. The flow was again seeded with 1 $\mu$m olive-oil droplets generated by a Laskin nozzle and timing of the cameras, lasers and image acquisition was controlled with a timing unit with 1 ns resolution.

Table 2.3 summarizes the high-frame-rate stereo PIV experiments conducted at
two different acquisition rates. In order to study the overall dynamics of the flow in both the roughness sublayer and the outer layer of the rough-wall flow simultaneously, an acquisition rate of 1.5 kHz was utilized. Doing so allowed the full 1k × 1k camera array size to be active and also maximized the laser energy output over this relatively wide (δ-scale) field of view. To maintain sufficient time resolution in these measurements so that the evolution of all but the smallest scales of motion (y∗) could be captured, the Re of these 1.5 kHz measurements was somewhat lower than those of the previously described low-frame-rate PIV measurements in this cross-flow plane. Reducing Re ensured that the streamwise displacement of the flow through the lightsheet between consecutively acquired PIV velocity fields was comparable to the in-plane grid spacing so that the evolution of the smallest resolved in-plane motions were also resolved in an out-of-plane sense. These experiments provided a basis for reconstructing the qualitative features of the larger-scale motions across both
the roughness sublayer as well as the outer layer of the flow. Under this scenario, Taylor’s hypothesis can be utilized to convert the temporal dimension to equivalent streamwise position assuming that the turbulence is frozen with respect to the advection in the streamwise direction. A single advection velocity was utilized when reconstructing the instantaneous structures based on the bulk velocity of the flow, giving $x \simeq (t_0 - t) \bar{U}$ (Dennis & Nickels, 2008, 2011; Van Doorne & Westerweel, 2007) in a manner consistent with previous hot-wire reconstructions reported by Marusic and co-workers that first revealed the spatial imprints of superstructure events in smooth-wall flow.

Data was also acquired with the high-frame-rate stereo PIV arrangement in the same cross-flow plane at 10 kHz over a narrow (in wall-normal) but wide (in spanwise) field of view just above the crests of the roughness ($\sim 0.1\delta \times 1.3\delta; y \times z$). These measurements were performed at the higher Re of the low-frame-rate cross-plane stereo PIV measurements and are unique because they resolve all three components of velocity at 10 kHz at roughly 1000 grid points in the narrow spanwise strip in a simultaneous manner. Such a measurement cannot be achieved with hot-wire sensors (recall that Marusic and co-workers utilized ten hot-wire sensors in a spanwise array in their initial smooth-wall measurements that captured the spatial imprints of superstructures) nor has such a measurement been achieved by PIV. Thus, the frequency spectrum of each velocity component can be fully documented at multiple spanwise and wall-normal positions so that the energy content as a function of scale as well as spanwise and wall-normal position can be documented. Furthermore, since all three velocity components were acquired simultaneously, the full TKE frequency spectrum can be reconstructed at each grid point as can the various co-spectra combinations (particularly that of the Reynolds shear stress, $u'v'$, which can be utilized to study
RSS content as a function of scale as well as spanwise and wall-normal position). Of particular interest will be documenting how the roughness studied herein alters the scale distribution of TKE and RSS energy content, and how it might drive spanwise dependence of TKE and RSS energy content across different scales of the flow.

2.4 Challenges of cross-plane stereo-PIV measurements

The challenge of the present measurements lies in the strong out-of-plane motion that must be imaged as the mean flow in the streamwise direction is oriented normal to the measurement plane. Thus, finding a balance between the desire to achieve a high dynamic ranges to well resolve all the three velocity components and the need to maintain the particles inside the laser lightsheet in the presence of such strong out-of-plane motion is critical. As such, a strong out-of-plane motion must be accurately captured simultaneously with quite weak in-plane motions. Thus, the lightsheet thickness and the time delay, $\Delta t$ between images must be carefully adjusted to provide adequate dynamic range in the velocity measurements.

Figure 2.8 presents a schematic of a top view of the laser lightsheet illuminating the tracers particles in a cross-flow measurements and further demonstrate such challenges. The left half of figure 2.8 illustrates a conventional lightsheet thickness of a 2D PIV setup, which usually lies between $250\mu m$ and $500\mu m$. One could use such a lightsheet thickness for cross-plane measurements; however, the dynamic range of the particle displacements will be heavy compromised, particularly for the in-plane components. To overcome this problem, the bulk displacement must be maximized, say, for example, $\Delta x \approx 10\, px$. With this bulk displacement, the particles captured
by the first exposure of a conventional 2D PIV lightsheet, represented by the dash circles, will be mostly lost in the second exposure, represented by the blue circles, due to this large displacement. By increasing the laser lightsheet thickness to about 1 mm, most of the particles exposed in the first frame will be present in the second exposure as well, as demonstrated on the right half of figure 2.8. In wall turbulence, this measurement is particularly challenging as the out-of-plane motion will vary across the lightsheet: small near the wall and large in the outer region of the flow. Thus, cross-plane measurement is a coupled problem between the time delay, $\Delta t$, which will dictate the dynamic range of the particle displacements and how thick the lightsheet is which will allow this dynamic range to be achieved by minimizing the loss of particles pairs due to the out-of-plane motion. Clearly, there is a limit on how thick the lightsheet can be which will eventually limit the dynamic range. Luckily, for a recommended cross-plane lightsheet thickness of 1 mm the dynamic range for wall-bounded flows are high enough to accurately capture the flow. Table 2.4 summarizes the time delay and the range of displacements achieved for all

Figure 2.8: Schematic illustrating a top view comparing a traditional 2D PIV laser lightsheet versus a thicker, cross-plane stereo-PIV lightsheet in the presence of strong a mean flow normal to the lightsheet.
Table 2.4: Summary of the time delay, $\Delta t$, and the particles displacement, $\Delta x$ and $\Delta y$, in the individual 2D for all the experiments conducted.

<table>
<thead>
<tr>
<th>Experiments</th>
<th>$\Delta t$ (µs)</th>
<th>$\Delta x_{\text{min}}$ (px)</th>
<th>$\Delta x_{\text{max}}$ (px)</th>
<th>$\Delta x_{\text{mean}}$ (px)</th>
<th>$\Delta y_{\text{min}}$ (px)</th>
<th>$\Delta y_{\text{max}}$ (px)</th>
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<td>Channel</td>
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<td>5</td>
<td>16</td>
<td>11</td>
<td>-4</td>
<td>4</td>
</tr>
<tr>
<td>Low-frame TBL</td>
<td>45</td>
<td>2</td>
<td>12</td>
<td>7</td>
<td>-3</td>
<td>3</td>
</tr>
<tr>
<td>1.5kHz TBL</td>
<td>240</td>
<td>3</td>
<td>12</td>
<td>7.5</td>
<td>-3</td>
<td>3</td>
</tr>
<tr>
<td>10kHz TBL</td>
<td>20</td>
<td>1</td>
<td>4</td>
<td>2.5</td>
<td>-1</td>
<td>1</td>
</tr>
</tbody>
</table>

The experiments conducted herein. It should be noted that the values shown in this table represent the displacement of the particles in the cameras’ coordinate system. Figure 2.9 presents schematics of the two-camera coordinate system relative to the tunnel’s coordinate system for the two stereo-PIV setups employed in this work. It can be clearly seen from these schematics that, for the low-frame-rate experiments, from the Camera 1 perspective, the particles’ bulk motion is translated to a positive motion in the camera’s $x_{c1}$ direction (from left to right in the CCD sensor). The opposite is seen for Camera 2, where, from its perspective, the particles’ bulk motion is translated to a negative motion in the camera’s $x_{c2}$ direction (right to left in the CCD sensor). For the high-frame-rate stereo-PIV experiments, as both cameras were mounted on the same side of the wind tunnel, the particles’ bulk motion is translated into a negative motion in the camera’s $x$ direction (from right to left in the CMOS sensor). The particles’ motion captured from each of the cameras coupled with the calibration (which will be discussed later in the text) and the time delay are the basis for reconstructing all 3 components of the velocity.

As mentioned previously, one of the challenges of a cross-plane stereo-PIV measurements in a TBL is the desire to achieve a high dynamic range so the much weaker
Figure 2.9: Schematic showing the cameras’ coordinate system relative to the tunnel’s coordinate system for both stereo PIV setups employed.
Figure 2.10: Histogram of the displacement of the particles after the stereo reconstruction for one instantaneous snapshot of the channel flow.
in-plane velocity components can be accurately resolved. The displacements from
the instantaneous 2D PIV fields that are reconstructed into three-component velocity
fields have a direct influence on the final stereo reconstructed field. This means that
if high dynamic range is achieved when correlating and inspecting the displacement
of the two 2D fields will result in a high dynamic range for the stereo reconstruction,
enabling one to accurately reconstruct the in-plane velocities. Figure 2.10 shows the
histograms of particle displacements from a single instantaneous snapshot in chan-
nel flow after the stereo reconstruction. From the 2D displacements presented in
table 2.4 for the channel flow, $\Delta x \approx 5–16$ and $\Delta y \approx -4–4$, it can be seen how this mo-
tion reflects to the true particle displacement histogram displayed in figure 2.10. The
streamwise displacement, $U$, ranges from around 7 px to 23 px, peaking at around
20 px. The wall-normal and spanwise displacements, $V$ and $W$, respectively, have
almost a Gaussian distribution, ranging from $-3$ to 3 px for the wall-normal displace-
ment and $-4$ to 3.5 px for the spanwise displacement. This result, together with the
information provided on table 2.4, confirm that a high dynamic range was achieved to
accurately resolve all three component of the velocity in the present implementations.

2.4.1 Calibration

Accurate stereo PIV measurements required careful calibration of the angular-offset
imaging system to accurately assess the image magnification that varies considerably
across each camera’s image due to the angular offset arrangement employed. In
addition, image distortion can introduce significant, even debilitating, errors in stereo
PIV measurements but careful calibration can provide a means of negating such
distortion effects. Calibration targets are commercially sold by PIV companies, and
they work well in many PIV applications. However, for specialized applications such
as that undertaken herein, it is recommended that a custom target is designed as most commercial targets will not cover the entire field-of-view (FOV) with calibration dots, or there may not be enough calibration dots in the FOV to accurately reconstruct the mapping function (depending of which commercial package or the calibration method used). To this end, custom calibration targets were designed for the majority of the experiments conducted in this work. The major drawback of a custom target is the necessity of translating the target in the out-of-plane direction to discern the motion of the particles when they move through the laser lightsheet.

For the channel-flow experiments, a target consisting of dots spaced at 2 mm in both the horizontal and vertical directions was carefully aligned to be coincident with the laser lightsheet. Figure 2.11 presents sample images of the calibration target acquired by the two cameras. This target was printed on specialized high-resolution paper and glued on a flat aluminum plate (3/16-in thick). A translation system was built to accurately move the target in the out-of-plane direction. This system was comprised of aluminum frames (80-20) that perfectly sat inside the channel’s
Figure 2.12: (a) Images of the calibration target used for the channel-flow experiments (b) the resulting mapping function. Green lines represent the in-plane polynomial fit. Similar target and calibration procedures were used for the low-framer-rate turbulent boundary layer experiments.
Figure 2.13: (a) Image of the target used in the 1.5 kHz high-frame-rate experiments viewed from each of the cameras with the detected calibration dots in green. (b) Corrected target image using the calibration mapping function to assess its quality.
Figure 2.14: (a) Image of the target used in the 10 kHz high-frame-rate experiments viewed from each of the cameras. (b) Same target images with the detected calibration dots in green. (c) Corrected target image using the calibration mapping function to assess its quality.
test section and a micrometer translation stage with 1 µm resolution. The target plate was mounted on the translation stage by means of a 1/4-in aluminum bracket. In addition, the whole system was securely fastened onto the test section floor to avoid any movement while translating the target plate. Images of this target were then acquired by both cameras at this position as well as with the target translated ±500 µm upstream and downstream of lightsheet center.

A similar system was employed for the low-frame-rate turbulent boundary layer calibration. A single-plane target consisting of dots spaced at 2.5 mm in both the horizontal and vertical directions was utilized in the wind-tunnel cross-plane experiments. The front face of this target was carefully aligned with the center of the lightsheet. Images of this target were then acquired by both cameras at this position as well as with the target translated ±250 µm upstream and downstream of lightsheet center. Once the calibration target images were acquired, the next step involved detecting the calibration dots and determining the mapping functions from the two image coordinate systems of the cameras to the single, object (flow) coordinate system. For both the channel flow and low-frame-rate turbulent boundary layer experiments, the TSI Insight software package was used to perform the calibration. This software uses image thresholding and centroid detection to identify and locate the calibration dots and then employs the least-squares mapping methodology proposed by Soloff et al. (1997) to generate the mapping functions. This method consisted of generating calibration mapping functions to map the two, 2-D image planes to the 3-D space defined by the laser lightsheet using a least-squares fit. A polynomial function of 3rd-order was used for the in-plane fit and a 1st-order polynomial was used for the out-of-plane motion. Figure 2.12(b) provides the resulting mapping function, where the green lines represent the in-plane polynomial fit. A detailed discussion about the accuracy
of this calibration method can be found in Scarano et al. (2005).

The high-frame-rate turbulent boundary layer measurements were captured and processed using a different software package (Lavison DaVis). This software uses a different calibration method based on a pinhole camera model proposed by Tsai (1986). This method brings the advantage of requiring a single target image from each of the cameras, without the need for translating the target in the out-of-plane direction (although this method allows the use of multiple target images at different positions or the use of 3D targets as well). This procedure is based on solving projection equations for each of the two cameras to account for the out-of-plane motion (Willert, 1997). Two calibration target were used for the high-frame-rate experiments. For the 1.5 kHz measurements, a commercial 3D target was used (TSI; 300 mm × 300 mm) consisting of equally spaced dots at 10 mm in both horizontal and vertical directions on both sides of the target, where every dot is 1 mm apart from each other in a diagonal fashion. Figure 2.13(a) provides the target image seen from both cameras. As mentioned previously, the cameras were set on the same side of the wind tunnel. Thus, in this configuration each camera captures a different side of the target. Figure 2.13 presents images of the 3D target captured by the two cameras with the detected dots in addition to the target image corrected using the mapping function. Since the FOV of the 10 kHz experiments consisted of a narrow wall-normal but wide spanwise strip, a custom target was designed to fit these unique geometrical conditions. This target consisted of equally spaced dots at 2.5 mm in both the horizontal and vertical directions that was printed on high quality transparency paper, as the cameras had to view both sides of the target. The target was placed between two pieces of very thin optical grade glass. In order for the target to stand perfectly vertical, two steel brackets were attached to both pieces of glass to provide
for a stable vertical orientation. The target was then carefully aligned with the cen-
ter of the lightsheet. As mentioned previously, the calibration method used in these
10 kHz experiments did not require translation of the target using the aforementioned
projection-equation approach. Figure 2.14 shows the calibration target viewed from
each of the cameras, together with the detected dots and the corrected target image
to illustrate the quality of the calibration.

2.4.2 Processing of the PIV images

Following successful calibration, the PIV images acquired by each camera in the three
already mentioned configurations (channel flow, low- and high-frame-rate measure-
ments) must be interrogated to facilitate reconstruction of each pair of 2D vector fields
into a single, three-component velocity field using the mapping functions determined
during calibration. Thus, each three-component velocity field was derived from two,
2-D displacement fields generated from the time-delayed pairs of images acquired by
each camera. In all flow cases, these pairs of time-delayed images were interrogated
using a recursive, two-frame cross-correlation methodology. The first-pass interro-
gation was performed with a bulk window offset to minimize loss of particle pairs,
while the final-pass interrogation was performed with square interrogation spots of
size 16 × 16 pixel² with 50% overlap to satisfy the Nyquist sampling criterion, and the
second window was locally offset by an integer pixel displacement determined during
the first-pass interrogation. Statistical validation tools were employed between passes
to identify and replace erroneous vectors as well as after the final interrogation pass
was completed. This included a median filter with 3 × 3 kernel and 2px threshold
limit to remove erroneous vectors that were large in magnitude and also erroneous
vectors that did not fit consistently with the neighboring vector field. To substitute
<table>
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<th>$y$-offset (px)</th>
<th>$z$-offset (px)</th>
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<th>Spot A (px$^2$)</th>
<th>Spot B (px$^2$)</th>
<th>Weight</th>
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<td>0</td>
<td>-</td>
<td>rect.</td>
<td>$22 \times 24$</td>
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<td>0</td>
<td>5</td>
<td>rect.</td>
<td>$32 \times 32$</td>
<td>$32 \times 32$</td>
<td>round</td>
<td>$16 \times 16$</td>
<td>$16 \times 16$</td>
</tr>
<tr>
<td>rate TBL</td>
<td>Rough</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>rect.</td>
<td>$32 \times 32$</td>
<td>$32 \times 32$</td>
<td>round</td>
<td>$16 \times 16$</td>
<td>$16 \times 16$</td>
</tr>
</tbody>
</table>

Table 2.5: Summary of the important PIV processing parameters for all the experiments conducted herein.
Figure 2.15: Example of the same instantaneous velocity field processed with different interrogation spot sizes.
the identified wrong vectors a procedure consisted of replacing the wrong vector with displacements assessed from alternate correlation peaks (secondary peaks) identified during the interrogation process (Rohaly et al., 2002). Any remaining holes were filled using a $3 \times 3$ interpolation scheme. It should be noted that the high particle seeding density meant that only 1-2% of the total number of vectors were interpolated following validation. All fields were then low-pass filtered with a narrow Gaussian filter, whose radius was set to be $80\%$ of the vector grid spacing, to remove high-frequency noise. Each pair of 2D displacement fields was then recombined using the aforementioned mapping function to reconcile all three instantaneous velocity components on the measurement plane defined by the laser lightsheet. Table 2.5 summarizes the processing parameters for all the experiments conducted herein.

To illustrate how the final PIV interrogation spot size plays a role in determine the three velocity components, figure 2.15 presents a instantaneous velocity field processed using a final spot size of $64 \times 64 \text{ px}^2$ (figure 2.15a), $32 \times 32 \text{ px}^2$ (figure 2.15b) and finally $16 \times 16 \text{ px}^2$ (figure 2.15c). As the final interrogation spot size is decreased, both the in-plane ($v$ and $w$; represented by vectors) and out-of-plane ($u$; represented by contours) velocity components become better resolved, revealing more information about the flow under study. This can be clearly seen at $z \approx -15 \text{ mm}$ and $y \approx 6 \text{ mm}$. For the $64 \times 64 \text{ px}^2$ spot size, the in-plane velocity reveals only a single vortex, whereas for $16 \times 16 \text{ px}^2$, a counter-rotating vortex pair is seen to sit at this position. Another example can be seen at $z \approx -27 \text{ mm}$ and $y \approx 4 \text{ mm}$, where the result from a spot size of $64 \times 64 \text{ px}^2$ displays nearly zero in-plane velocities, but for a final spot of $16 \times 16 \text{ px}^2$, another counter-rotating vortex pair is clearly resolved.
2.5 Uncertainty of the statistical quantities

This section summarizes the uncertainties present in the statistical quantities of the low- and high-frame-rate measurements over the rough-wall flow. Mejia-Alvarez (2010) provides a comprehensive discussion of the errors involved in stereo-PIV measurements and how they propagate through various turbulence statistics. Following his analysis, the total random error on the velocities is defined as

\[
\delta(U) = \sqrt{[\delta_s(U)]^2 + [\delta_{sp}(U)]^2},
\]

(2.1)

where

\[
\delta_s(U) = \frac{\langle u'^2 \rangle^{1/2}}{\sqrt{n-1}},
\]

(2.2)

is the sampling error (or the standard error of the mean) of the turbulent velocity signal, and

\[
\delta_{sp}(U) = \frac{\delta_{sp}(u)_{max}}{\sqrt{n}},
\]

(2.3)

is the sub-pixel accuracy in PIV measurements, and \( n \) is the number of samples recorded. There are two primary sources of error in PIV measurements: peak-locking error and the aforementioned uncertainty in the estimation of the sub-pixel particle displacement. These uncertainties are directly related with to the particle-image diameter (Westerweel, 1997; Christensen, 2004). As discussed in Christensen (2004), errors associated with peak-locking will only be relevant for particle-image diameters less than 2 pixels. Since the particle-image diameter of the present measurements lie within 2-3 pixels, the errors associated with peak-locking are therefore rendered negligible and the pdfs of particle displacement presented in figure 2.10 confirm a lack of peak locking in the present measurements. Consequently, the primary un-
Table 2.6: Total random error on an ensemble basis.

<table>
<thead>
<tr>
<th>Exp.</th>
<th>n</th>
<th>$\delta_s(U)$ (m/s)</th>
<th>$\delta_s(V)$ (m/s)</th>
<th>$\delta_s(W)$ (m/s)</th>
<th>$\delta_{sp}(U)$ (m/s)</th>
<th>$\delta_{sp}(V)$ (m/s)</th>
<th>$\delta_{sp}(W)$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-frame rate (rough)</td>
<td>10000</td>
<td>0.019</td>
<td>0.009</td>
<td>0.012</td>
<td>0.002</td>
<td>0.002</td>
<td>0.002</td>
</tr>
</tbody>
</table>

Uncertainty in the PIV measurements is due to the random nature of the sub-pixel displacement estimation. This error is approximately $\delta_{sp}(\Delta \xi)_{max} \approx 0.15$ pixels based on the particle-image diameter. Note that equation 2.3 is expressed in velocity terms. To translate the sub-pixel uncertainty from pixel to velocity, the magnification, $M$, and the time-delay, $\Delta t$, between image pairs must be known. This translation from pixel-to-velocity is given as

$$\delta_{sp}(u)_{max} = M \frac{\delta_{sp}(\Delta \xi)_{max}}{\Delta t}.$$  

Table 2.6 summarizes the total random error of the ensemble velocity components.

Progressive averaging of the mean turbulent quantities was performed to illustrate the convergence of these quantities as a function of the number of samples. The results in figure 2.16 illustrate clear convergence of the turbulence quantities under consideration, from which the normalized uncertainties of the turbulence quantities using a 95% confidence level can be garnered as reported in table 2.7. In the rough-wall low-frame-rate experiments, the uncertainties will vary with position in the wall-normal–spanwise measurement plane. Thus, values reported for these uncertainties correspond to locations were they show strong non-zero values in the ensemble averages.

Uncertainties on the estimation of the friction velocity, $u_\tau$, vary slightly upon the
Figure 2.16: Example showing the turbulent quantities convergence as a function of the number of samples.

\[
\frac{\langle U \rangle}{\langle \rangle}
\]

\[
\frac{\langle V \rangle}{\langle \rangle}
\]

\[
\frac{\langle W \rangle}{\langle \rangle}
\]

\[
\frac{\langle u' \rangle}{\langle \rangle}
\]

\[
\frac{\langle v' \rangle}{\langle \rangle}
\]

\[
\frac{\langle w' \rangle}{\langle \rangle}
\]
\[
\epsilon(\langle U \rangle) \quad \epsilon(\langle V \rangle) \quad \epsilon(\langle W \rangle) \quad \epsilon(\langle u'^2 \rangle) \quad \epsilon(\langle v'^2 \rangle) \quad \epsilon(\langle w'^2 \rangle) \quad \epsilon(\langle u'v' \rangle) \quad \epsilon(\langle u'w' \rangle) \quad \epsilon(\langle v'w' \rangle)
\]

<table>
<thead>
<tr>
<th>Experiment</th>
<th>(\epsilon(\langle U \rangle)) (%)</th>
<th>(\epsilon(\langle V \rangle)) (%)</th>
<th>(\epsilon(\langle W \rangle)) (%)</th>
<th>(\epsilon(\langle u'^2 \rangle)) (%)</th>
<th>(\epsilon(\langle v'^2 \rangle)) (%)</th>
<th>(\epsilon(\langle w'^2 \rangle)) (%)</th>
<th>(\epsilon(\langle u'v' \rangle)) (%)</th>
<th>(\epsilon(\langle u'w' \rangle)) (%)</th>
<th>(\epsilon(\langle v'w' \rangle)) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-frame rate (rough)</td>
<td>0.61</td>
<td>3.85</td>
<td>3.74</td>
<td>2.50</td>
<td>2.64</td>
<td>3.70</td>
<td>4.10</td>
<td>8.42</td>
<td>13.60</td>
</tr>
</tbody>
</table>

Table 2.7: Percentage uncertainty of the mean turbulence quantities with 95% confidence interval.
method used. Volino et al. (2011) reported an uncertainty of ±3–5% on the friction velocity using the Clauser chart method. They also verified that the constant stress method produces similar results, within 2% difference between these methods. In the present work, the friction velocity was estimated using the constant stress method.

Finally, the uncertainty of the spectral analysis presented herein is demonstrated for the high-frame-rate experiments, following the procedure reported in Bendat & Piersol (2011). The spectra calculations performed in this work were accomplished using a fast Fourier transform (FFT) algorithm. The estimation of the autospectral density function for a time signal \( x(t) \) is given by

\[
G_{xx}(f) = \frac{2}{T} |X(f, T)|^2,
\]

where \( X(f, T) \) is the finite Fourier transform of \( x(t) \). It can be shown that the normalized random error is

\[
\epsilon[G_{xx}(f)] = \sqrt{\frac{2}{n}}
\]

Unfortunately, this produces unacceptable random error for most applications. Alternatively, one can compute the autospectral density functions by ensemble averaging different sub-records to obtain a final smoothed estimate, defined as

\[
\hat{G}_{xx}(f) = \frac{2}{n_d T} \sum_{i=1}^{n_d} |X(f, T)|^2,
\]

where \( n_d \) is the number of sub-records. Therefore, as discussed in Bendat & Piersol (2011), it can be demonstrated that the random error is

\[
\epsilon[\hat{G}_{xx}(f)] = \frac{1}{\sqrt{n_d}}
\]
Table 2.8: Summary of the uncertainty in the autospectral density function.

<table>
<thead>
<tr>
<th>Case</th>
<th>$n_d$</th>
<th>$\varepsilon[\hat{G}_{xx}(f)]$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth</td>
<td>1200</td>
<td>2.89</td>
</tr>
<tr>
<td>Rough</td>
<td>280</td>
<td>5.98</td>
</tr>
</tbody>
</table>

As a result, the uncertainty in the autospectral density estimation is only dependent on the number of ensembles used. Table 2.8 summarizes these uncertainties.

In the present work, the Welch method (similar to equation 2.7) was employed to calculate the auto- and co-spectral densities. The velocity signal was divided into sub-records, each having a length of $T/4$ with 50% overlap between samples, resulting in an effective 8 ensembles. In addition to the Welch average, ensemble average of each spectrum at multiple spanwise positions was performed to help the convergence. For the smooth-wall case, the full width of the domain ($N_w = 150$) was used, and for the rough-wall cases, a small spanwise width ($N_w = 7$) was employed. This spanwise width in the rough-wall case corresponds to the characteristic spanwise width of the roughness elements under consideration. To help further convergence, and thus reduce the error of the spectral densities, ensemble average over the 5 captured runs was performed for the rough-wall cases.
Chapter 3

Cross-Plane Stereo PIV Validation in Turbulent Channel Flow

Given the challenges of conducting stereo PIV measurements in the cross-flow plane as described in the previous chapter, principally the fact that the mean flow is normal to the lightsheet, preliminary experiments were conducted in turbulent channel flow to validate the experimental methodology to be employed in the wind-tunnel experiments. Turbulent channel flow was selected for this validation owing to availability of direct numerical simulation (DNS) data for comparison coupled with the relative simplicity of experimental setup compared to the larger wind tunnel. In addition to validation of the experimental methodology through comparison with DNS data, the spatial characteristics of the flow in this plane were also explored to better understand the underlying imprints of the larger flow scales in this cross-flow plane. Finally, initial rough-wall measurements were conducted in turbulent channel flow with a short streamwise fetch of hemispheres in order to troubleshoot challenges that may be faced with deploying the cross-flow stereo PIV method in the presence of complex topography.

As described in detail in the previous chapter, smooth-wall measurements were first conducted at a friction Reynolds number of $\text{Re}_\tau \equiv u_\tau h/\nu = 600$, where $h$ is the channel half-height, and comparison of the single-point statistics is made to direct numerical simulation data at similar Re (Moser et al., 1999) to validate the experimental protocol employed. Preliminary measurements were then conducted just downstream
of a $8h$-long patch of roughness consisting of a staggered array of 4-mm diameter hemispheres.

### 3.1 Smooth-wall flow

#### 3.1.1 Instantaneous structure

Figure 3.1(a) presents a representative instantaneous fluctuating velocity field in the wall-normal–spanwise ($y - z$) plane of smooth-wall turbulent channel flow at $Re_\tau = 600$. The in-plane wall-normal and spanwise velocity fluctuations are shown as vectors while the out-of-plane streamwise velocity fluctuations are presented as background contours. The streamwise velocity fluctuations are marked by large-scale ($h$-scale) regions of low streamwise momentum and high streamwise momentum that appear to alternate in the spanwise direction. These regions, which can extend to, or even beyond, the channel centerline represent the cross-plane signatures of LMRs and HMRs that have been previously identified in wall-parallel PIV measurements (Ganapathisubramani et al., 2003; Tomkins & Adrian, 2003) and most recently linked to superstructures that can extend several outer length scales in the streamwise direction while meandering in the spanwise direction (Hutchins & Marusic, 2007). Figure 3.1(b) presents a zoomed-in view of a portion of the full field in figure 3.1(a) [demarcated by the red box] in which a large-scale LMR and a large-scale HMR are notable and separated in the spanwise direction by $\sim 0.5h$. Both of these large-scale events extend well into the outer layer ($y \approx 0.5 - 0.75h$). Focusing upon the visualized LMR in figure 3.1(b), which have been previously linked to the low-momentum regions collective induced by the vortices within hairpin vortex packets, streamwise vortices are notable along its left and right boundaries. In addition, this
Figure 3.1: Representative instantaneous fluctuating velocity field for smooth-wall flow. (a) Full field; (b) Zoomed-in view coincident with red-bordered box in (a); Contours of (c) instantaneous Reynolds shear stress, $u'u'$, and (d) signed swirling strength, $\lambda_{ci}$, for zoomed-in view in (b). Solid and dashed line contours in (c) and (d) demarcate boundaries of HMRs and LMRs, respectively.
LMR embodies significant instantaneous contributions of Reynolds shear stress as is observed in figure 3.1(c) which presents contours of instantaneous $u'v'$ overlaid with line contours of $u'^+ = \pm 2$ meant to outline the boundaries of the various LMRs and HMRs present in this realization. In particular, the positive $v'$ noted within this LMR coupled with the negative $u'$, characteristic of an LMR, together yield a large-scale region of negative $u'v'$ associated with ejection of low-speed fluid away from the wall. This observation is again consistent with the hairpin packet model. Likewise, the negative $v'$ noted within the visualized HMR in figure 3.1(b) coupled with the positive $u'$, characteristic of an HMR, yields a region of negative $u'v'$ that is due to the sweeping of high-speed fluid from the outer region toward the wall. Apart from these $h$-scale events, smaller LMRs and HMRs are visualized in the near-wall region that are often bounded by vortical structures. These smaller-scale regions can co-exist beneath the larger-scale LMRs and HMRs, supporting the notion that such structures occur in a hierarchy of scales across the flow. As proposed by Adrian et al. (2000b), packets of varying size would be expected throughout the wall-normal extent of the flow, with smaller, younger, slower packets residing close to the wall where they are likely formed and successively larger, older packets populating the outer region of the flow while maintaining a near-wall footprint. Finally, figure 3.1(d) presents contours of swirling strength, a local vortex identifier (Adrian et al., 2000a), marked with the sign of the instantaneous streamwise vorticity to distinguish between clockwise- and counter-clockwise-rotating vortices in the $y – z$ plane (line contours demarcating the boundaries of the LMRs and HMRs are also included). A few counter-rotating pairs of streamwise vortex cores are notable outboard of the LMRs and HMRs, with the former consistent with slices through the legs/necks of hairpin-like structures that collectively induce ejections of low-speed fluid away from the wall. However, most of
the streamwise vortex cores visualized in figure 3.1(d) seem to occur in isolation, consistent with previous observations that many hairpin-like structures either have only one leg or have one leg that is much stronger than the other, yielding an asymmetric hairpin or ‘cane’ vortex (Zhou et al., 1999).

3.1.2 Single-point statistics

Single-point statistics were computed from the ensemble of 2500 smooth-wall velocity fields by ensemble averaging followed by line-averaging in the statistically-homogeneous spanwise direction. Thus, each data point represents an average over 812,000 velocity samples. The sampling error is estimated to be less than 1%, though the uncertainty of these statistics when scaled in inner units (i.e., by \(u_r\) and \(\nu\)) is approximately 4% due to the uncertainty in estimating the friction velocity via measurements of the streamwise pressure gradient and fluid properties. Thus, symbol size embodies the uncertainty bounds for each statistic presented.

Figure 3.2(a) presents the inner-scaled mean velocity profile (\(U^+\) versus \(y^+\)) for the smooth-wall case compared with the result from DNS at \(Re_r = 590\) (Moser et al., 1999). While the experimental data does not resolve the viscous sublayer nor most of the buffer layer, as the first grid-point resides at \(y^+ = 17.6\) \((y = 0.0293h)\), the expected log-layer behavior is observed as the experimental result is in good agreement with the DNS profile. Similar consistency is noted in outer units (\(U/U_{CL}\) versus \(y/h\)) as well [figure 3.2(b)].

Figure 3.3 presents profiles of all three Reynolds normal stresses (\(\langle u'^2 \rangle\), \(\langle v'^2 \rangle\) and \(\langle w'^2 \rangle\)) as well as the Reynolds shear stress (\(\langle u'v' \rangle\)) computed from the smooth-wall stereo PIV data compared to the same profiles garnered from DNS at similar Re (Moser et al., 1999). This comparison reveals a reasonable level of agreement.
Figure 3.2: Mean profile for smooth-wall turbulent channel flow (symbols) compared with the DNS result Moser et al. (1999) at $Re_{\tau} = 590$ (line) in (a) inner and (b) outer units.
Figure 3.3: Profiles of Reynolds normal and shear stresses for smooth-wall flow (symbols) compared with DNS results Moser et al. (1999) at $Re_\tau = 590$ (lines).

between the experimental and computational results, including in the Reynolds shear stress where both profiles exhibit the characteristic linear behavior in the outer region due to the dominance of turbulent stresses over viscous stresses. Some differences are noted in the near-wall region where all three Reynolds normal stresses are slightly under-estimated compared to their DNS counterparts. These differences are partially due to the finite size of the interrogation windows employed when interrogating the PIV images (the final window size was approximately $11.2y_* \times 11.2y_*$) which necessarily yields averaging over structures smaller than this dimension. In addition, as the wall is approached the relative error in the velocity fluctuations increases owing to a fixed resolvable particle displacement ($\sim 0.1$ pixels) coupled with a reduction in the
mean streamwise velocity compared to the outer region of the flow. This effect is particularly apparent when the mean flow is normal to the measurement plane because one must be diligent to minimize the possibility of appreciative particle loss out of the plane in the outer region where the out-of-plane velocity is strongest. Thus, the dynamic range of the out-of-plane particle displacements in the near-wall region is unfortunately reduced. As such, resolving small-scale velocity fluctuations, particularly $v'$ and $w'$, becomes more challenging when a large field of view like that employed herein is desired. Nevertheless, the consistency of these turbulent stresses with the DNS result to within roughly 10% ($\pm 4\%$ due to uncertainty in $u_\tau$) is encouraging, particularly since the interest herein is in the behavior of the larger spatial scales of the flow.

### 3.1.3 Short streamwise fetch of roughness

Cross-plane stereo PIV measurements were then conducted for flow over a short streamwise fetch of roughness to ascertain and resolve issues associated with such measurements in the presence of complex topography. Figure 3.4 presents fields of ensemble-averaged streamwise and wall-normal velocity in the $y - z$ measurement plane for the rough-wall experiment. For reference, the bottom wall in this view was rough while the top wall remained smooth. In addition, the roughness pattern, appropriately scaled, is shown along the bottom wall and all fields are normalized by the upstream smooth-wall friction velocity as the local $u_\tau$ over the roughness was not accessible in this experiment owing to the developing internal layer over the short roughness fetch. The $8h$-long fetch of roughness along the bottom wall generates a region of notable streamwise momentum deficit compared to the flow along the upper smooth wall of the channel that is strongest close to the roughness and decreases with
Figure 3.4: Ensemble-averaged, inner-scaled (a) streamwise, $U^+$, and (b) wall-normal, $V^+$, velocity in the $y - z$ measurement plane. The lower wall is rough (roughness pattern shown for reference) while the upper wall is smooth.
increasing wall-normal position. This reduction in $U^+$ is consistent with increased drag incurred when the flow encountered the roughness and its wall-normal extent provides a measure of how far these roughness effects have grown away from the wall in the form of an internal layer formed at the abrupt transition from smooth-to-rough wall conditions. The effect of roughness is also notable in figure 3.4(b) which presents the ensemble-averaged wall-normal velocity, $V^+$. While this mean velocity component is essentially zero in the smooth-wall region of the flow, as one would expect for fully-developed smooth-wall turbulent channel flow, the current roughness creates significant mean wall-normal velocity—approximately 10% of the mean streamwise velocity in the immediate vicinity of the roughness. While $V^+$ decreases with increasing wall-normal position, it is still 3–5% of $U^+$ for $y \sim 0.5h$. Again, the propagation of these roughness effects into the outer region represents the growth in the wall-normal extent of the internal layer as the flow advects downstream.

The results in figure 3.4 also serve to highlight the challenges of cross-plane stereo PIV measurements in the presence of roughness, specifically the inaccessibility to data in the immediate vicinity of the roughness. As is evident in the contour plots of both $U^+$ and $V^+$, the flow within $\sim 2.5$ mm of the hemispheres was not captured in this measurement. As the hemispheres were opaque, the laser light interactions with the surface resulted in reflections that overwhelmed the scattered light of the tracer particles within this near-wall region. Even if the hemispheres had been manufactured in a transparent medium, the curvature of the surface would still induce significant reflections in this region. In addition, viewing the flow in this near-wall region was partially occluded by the hemispheres themselves, further impeding the imaging of the scattered light from the tracer particles.

Similar roughness-induced modifications are notable in the Reynolds normal stresses,
\( \langle u'^2 \rangle^+ \), \( \langle v'^2 \rangle^+ \) and \( \langle w'^2 \rangle^+ \), which are presented in figure 3.5. While \( \langle u'^2 \rangle^+ \) displays a characteristic maximum very close to the smooth wall [figure 3.5(a)], the roughness induces a significant enhancement in \( \langle u'^2 \rangle^+ \) that extends well into the outer layer. Closer inspection of \( \langle u'^2 \rangle^+ \) along the rough wall of the channel reveals localized peaks in \( \langle u'^2 \rangle^+ \) just above the spanwise center of each hemispherical element. Similarly, while \( \langle v'^2 \rangle^+ \) displays its characteristic peak near \( y = 0.1h \) along the smooth upper wall [figure 3.5(b)], the roughness significantly enhances \( \langle v'^2 \rangle^+ \) in the immediate vicinity of the roughness with localized peaks again roughly centered just above the individual elements. A similar enhancement in \( \langle w'^2 \rangle^+ \) by the roughness compared to the smooth-wall flow along the upper half of the channel is apparent in figure 3.5(c). Since the sum of these three Reynolds normal stresses are proportional to the turbulent kinetic energy, the present observations can be interpreted as a roughness-induced enhancement of the turbulent kinetic energy (roughness-induced turbulence production), particularly in localized regions near the peaks of the individual roughness elements.

Finally, figure 3.6 presents the ensemble-averaged Reynolds shear stresses, \( \langle u'v' \rangle^+ \), \( \langle u'w' \rangle^+ \) and \( \langle v'w' \rangle^+ \). As with the Reynolds normal stresses, the dominant Reynolds shear stress, \( \langle u'v' \rangle^+ \) [figure 3.6(a)], is greatly enhanced by the roughness along the bottom wall compared to the smooth-wall result along the top wall. Interestingly, while both \( \langle u'w' \rangle^+ \) and \( \langle v'w' \rangle^+ \) are at least an order of magnitude smaller than \( \langle u'v' \rangle^+ \) for the case of fully-developed smooth-wall turbulent channel flow (the weak non-zero values of both components for the present smooth-wall flow are roughly within the statistical sampling errors for these ensemble averages), the present results suggest a roughness-induced generation of these two Reynolds shear stresses in the presence of roughness, particularly in the case of \( \langle v'w' \rangle^+ \) [figure 3.6(c)].
Figure 3.5: Ensemble-averaged, inner-scaled Reynolds normal stresses in the $y-z$ measurement plane. (a) $\langle u'^2 \rangle^+; \ (b) \langle v'^2 \rangle^+; \ (c) \langle w'^2 \rangle^+$. The lower wall is rough (roughness pattern shown for reference) while the upper wall is smooth.
Figure 3.6: Ensemble-averaged, inner-scaled Reynolds shear stresses in the $y - z$ measurement plane. (a) $\langle u'v' \rangle^+$; (b) $\langle u'w' \rangle^+$; (c) $\langle v'w' \rangle^+$. The lower wall is rough (roughness pattern shown for reference) while the upper wall is smooth.
Chapter 4

Low-Frame-Rate Measurements in a Turbulent Boundary layer

This chapter\(^1\) presents results garnered from the low-frame-rate, high-resolution stereo PIV measurements conducted in the cross-flow plane for smooth-wall flow, against which the rough-wall results are compared, and flow over complex roughness. While these measurements do not capture the dynamics of the flow owing to the 0.5 Hz acquisition rate, the relatively wide spanwise field of view (2.4\(\delta\)) and high spatial resolution (18\(\gamma_*\)) provide unique simultaneous views of both the smaller and larger scales of the flow.

4.1 Smooth-wall flow

The spanwise-wall–normal (\(y - z\)) smooth-wall experiments were conducted for a Reynolds number based on the momentum thickness of 10400. The ensemble-averaged statistics presented were computed by averaging 2600 statistically independent velocity realizations in this measurement plane.

Figure 4.1 presents the outer-scaled ensemble-averaged velocity fields in the spanwise-wall–normal (\(y - z\)) measurement plane. More specifically, figure 4.1(a) shows the mean streamwise velocity (\(\langle u \rangle / U_e\)). The expected homogeneity of \(U\) in the spanwise direction under smooth-wall conditions is readily apparent in this field. The ensemble-averaged wall-normal, (\(\langle v \rangle / U_e\)), and spanwise, (\(\langle w \rangle / U_e\)), velocities are shown in fig-

\(^1\)Portions of this chapter are reported in Barros & Christensen (2014).
ure 4.1(b) and figure 4.1(c), respectively. At first glance, spatial heterogeneities are noted in these two mean velocity components. However, the magnitude of these heterogeneities are two to three orders of magnitude smaller than the free-stream velocity and are of the same order as the uncertainty in the PIV measurements themselves. Thus, they in fact do not compromise the quality and validity of the results presented herein but do provide a baseline for evaluating levels of differences between the smooth- and rough-wall results.

The Reynolds normal stresses together with the $TKE$ are presented in figure 4.2, where figure 4.2(a) presents the outer-scaled streamwise stress, $\langle u'^2 \rangle / U_e^2$, figure 4.2(b) the outer-scaled wall-normal stress, $\langle v'^2 \rangle / U_e^2$, figure 4.2(c) the outer-scaled spanwise stress, $\langle w'^2 \rangle / U_e^2$, and finally, figure 4.2(d) the outer-scaled $TKE$, $TKE \equiv 1/2(u'^2 + v'^2 + w'^2)$; $TKE / U_e^2$). The contour level were set to be the same as the rough-wall results that will be shown in section 4.2. Therefore, a direct comparison between smooth- and rough-wall results can be assessed. These results display the expected spanwise heterogeneity and their magnitudes are consistent with those previously reported in the literature for measurable components ($u'^2$ and $v'^2$) to within the measurement uncertainty.

Finally, the Reynolds shear stresses are presented in figure 4.3. Again, the contour levels were adjusted to match the ones for the rough-wall case in section 4.2, allowing a direct comparison between these results. Outer-scaled $\langle u'v' \rangle$ is shown in figure 4.3(a) and displays expected spanwise homogeneity and magnitudes consistent with previous studies. The other two outer-scaled Reynolds shear stresses, $\langle u'w' \rangle / U_e^2$ and $\langle v'w' \rangle / U_e^2$ are shown in figure 4.3(b) and figure 4.3(c). These two shear-stress components display weak values that are within the uncertainty of the PIV measurements themselves. Thus, the visualized spatial variability is attributed to measurement uncertainty and
Figure 4.1: Ensemble-averaged velocities scaled with outer units in the $y - z$ plane for the smooth-wall flow. (a) Streamwise velocity, $\langle u \rangle / U_e$; (b) Wall-normal velocity, $\langle v \rangle / U_e$ and (c) Spanwise velocity, $\langle w \rangle / U_e$. 

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Figure 4.2: Ensemble-averaged Reynolds normal stresses scaled with outer units in the $y-z$ plane for the smooth-wall flow. (a) Streamwise, $\langle u'^2 \rangle / U_e^2$; (b) Wall-normal, $\langle v'^2 \rangle / U_e^2$; (c) Spanwise, $\langle w'^2 \rangle / U_e^2$. (d) Outer-scaled TKE.
Figure 4.3: Ensemble-averaged Reynolds shear stresses scaled with outer units in the $y-z$ plane for the smooth-wall flow. (a) $\langle u'v' \rangle / U_e^2$; (b) $\langle u'w' \rangle / U_e^2$; (c) $\langle v'w' \rangle / U_e^2$. 
not underlying physical processes (nor sampling error). Given this, these smooth-wall results provide a baseline of comparison with the rough-wall results, particularly in identifying differences associated with true modifications of the flow by roughness in contrast to differences owing to variability in the measurements due to underlying uncertainties.

4.2 Rough-wall flow

4.2.1 Single-point statistics

Figure 4.4 presents the outer-scaled mean streamwise velocity \(\langle u \rangle / U_e\) with the roughness topography upstream of the measurement plane presented as well. The mean streamwise velocity is marked by strong heterogeneity in the form of spanwise-localized low-momentum pathways (LMPs) bounded by high-momentum pathways (HMPs) that alternate in the spanwise direction. The LMPs are identified as regions of enhanced local mean streamwise momentum deficit, whereas, the HMPs are identified as regions of local mean streamwise momentum surplus (their spanwise positions are labelled in figure 4.4). These LMPs and HMPs differ from the LMRs and HMRs previously identified in instantaneous velocity fields of both smooth- (Ganapathisubramani et al., 2003; Tomkins & Adrian, 2003) and rough-wall flow (Volino et al., 2007; Wu & Christensen, 2010) as they appear in the ensemble-averaged streamwise velocity (figure 4.4). As noted in Chapter 1, Mejia-Alvarez & Christensen (2013) identified similar mean-flow heterogeneities in a \(x - z\) plane deep within the roughness sublayer for flow over this same topography, revealing that these LMP and HMP features can extend at least \(\delta\) in the streamwise direction. The streamwise mean velocity field in figure 4.4 indicates that such mean-flow heterogeneities can extend to over half
Figure 4.4: Ensemble-averaged streamwise velocity, $\langle u \rangle / U_e$, in the $y-z$ plane for the rough-wall flow.
of the boundary-layer thickness in addition to being $\delta$-scale in the streamwise direction (Mejia-Alvarez & Christensen, 2013). These patterns are highly reminiscent of the spanwise heterogeneity in the mean streamwise velocity reported by Nugroho et al. (2013) surmised from single hot-wire measurements in flow overlying ordered herringbone roughness that embodied distinct spanwise periodicity. Mejia-Alvarez & Christensen (2013) conjectured that the LMPs and HMPs could be preferential pathways for instantaneous, large-scale motions (LMRs and HMRs) or persistent wakes generated by dominant roughness features in the case of the LMP. Of interest, the magnitude of this noted spanwise variation in $U$ is an order of magnitude larger than the variability noted in the mean velocity of the smooth-wall flow, indicating that it represents a modification of the underlying flow processes by roughness rather than the imprint of inherent variability associated with the measurements themselves.

Figure 4.5 and 4.6 show the mean wall-normal ($\langle v \rangle/U_e$) and spanwise ($\langle w \rangle/U_e$) velocities, respectively, normalized using outer-scale units. Likewise to the mean streamwise velocity (figure 4.4), both $\langle v \rangle/U_e$ and $\langle w \rangle/U_e$ show significant spanwise heterogeneities. Focusing upon the mean wall-normal velocity in figure 4.5, it can be observed that regions where LMPs reside are characterized by positive values of $\langle v \rangle/U_e$, while, in contrast, HMPs regions are characterized by negative values of $\langle v \rangle/U_e$. For the mean spanwise velocity (figure 4.6), the bounds of the LMPs and HMPs are marked by alternating positive and negative values of $\langle w \rangle/U_e$, specially close the rough surface. These results are consistent with the presence of secondary flow (which will be better developed further in the text). It should be pointed out that these results are an order on magnitude larger than the variability noted in the smooth-wall results [figure 4.1(b) and 4.1(c)], indicating that it is in fact a consequence of the impact of the roughness on these mean quantities.
Figure 4.5: Ensemble-averaged wall-normal velocity, $\langle v \rangle/U_e$, in the $y - z$ plane for the rough-wall flow.
Figure 4.6: Ensemble-averaged spanwise velocity, $\langle w \rangle / U_e$, in the $y - z$ plane for the rough-wall flow.
Figure 4.7: Ensemble-averaged turbulent kinetic energy, $TKE/U_e^2$, in the $y-z$ plane for the rough-wall flow.
Figure 4.8: Ensemble-averaged Reynolds shear stress, \( \langle u'v' \rangle / U_e^2 \), in the \( y - z \) plane for the rough-wall flow.
Figures 4.7 and 4.8 present the outer-scaled mean turbulent kinetic energy ($TKE \equiv 1/2(u'^2 + v'^2 + w'^2)$) and mean RSS ($\langle u'v' \rangle / U_e^2$), respectively, in the $y-z$ plane. Both of these single-point turbulence statistics display significant spanwise heterogeneity, with variability an order of magnitude larger than that noted in their smooth-wall counterparts, particularly enhanced regions of both $TKE$ and RSS spatially coincident with the identified LMPs in the mean streamwise velocity (figure 4.4). Similar signatures of enhanced behavior are also notable in the other RSS components ($\langle u'w' \rangle$ and $\langle v'w' \rangle$), which are quite weak in smooth-wall flow; not shown for brevity) spatially coincident with the identified LMPs. These cross-plane signatures are entirely consistent with the wall-parallel plane measurements of Mejia-Alvarez & Christensen (2013) which revealed $TKE$ and RSS enhancement within the regions occupied by LMPs, with this enhancement extending at least $\delta$ in the streamwise direction. Since the Reynolds shear stresses play a defining role in the production of $TKE$ from the mean flow, these results suggest that the roughness under consideration may promote generation of $TKE$ in preferential regions within the roughness sublayer. In addition, the unique view afforded in the $y-z$ plane highlights enhancement of $TKE$ and RSS quite far from the wall ($y \approx 0.6\delta$).

Finally, figure 4.9 presents contours of outer-scaled, ensemble-averaged signed swirling strength, $\langle \Lambda_{ci} \rangle (\delta/U_e)$. Here, $\Lambda_{ci} = \omega_x |\lambda_{ci}|$, where $\lambda_{ci}$ is the imaginary portion of the complex-conjugate eigenvalues of the velocity gradient tensor and is a frame-independent measure of local rotation (Adrian et al., 2000a). Thus, $\lambda_{ci} \neq 0$ indicates the presence of local vortical motion and is marked with the sign of the in-plane streamwise vorticity ($\omega_x$) to retain the sense of rotation in $\Lambda_{ci}$. Interestingly, $\langle \Lambda_{ci} \rangle$ is quite heterogeneous in space, with regions of $\langle \Lambda_{ci} \rangle < 0$ at the left spanwise boundaries of the LMPs identified in figure 4.4 and regions of $\langle \Lambda_{ci} \rangle > 0$ at the right
Figure 4.9: Ensemble-averaged signed swirling strength, $\langle \Lambda_{ci} \rangle (\delta/U_e)$, in the $y-z$ plane.
spanwise boundaries of the LMPs. A region of $\langle \Lambda_{ci} \rangle \approx 0$ is noted coincident with the LMPs. This pattern is consistent with counter-rotating swirling motions residing at the left and right boundaries of each LMP whose rotational sense is consistent with the ejection of low-speed fluid from the near-wall region into the outer region of the boundary layer, thus provide a mechanism for the generation and maintenance of the identified LMPs. Furthermore, the identified swirling motions are also likely responsible for the $TKE$ [figure 4.7] and RSS [figure 4.8] enhancements noted within the roughness sublayer and coincident with the identified LMP patterns. The occurrence of these counter-rotating swirling motions bounding the LMPs is entirely consistent with similar patterns noted in LES of turbulent boundary layers overlying ordered spanwise roughness transitions (alternating, streamwise-elongated patches of low and high roughness) by Willingham et al. (2014) who surmised these patterns to be the imprint of turbulent secondary flows owing to the ordered spanwise heterogeneity in roughness height.

To further assess the impact of roughness on the formation of mean-flow heterogeneity, figure 4.10(a) presents the ensemble-averaged mean velocity components from figures 4.5 and 4.6 in a slightly different manner, with the in-plane mean velocity components shown as vectors to complement the mean streamwise velocity shown as contours. A spanwise roughness profile, $\eta(z)$, is shown below the mean velocity field and represents the streamwise-averaged topographical height over a $\delta$-long streamwise fetch immediately upstream of the measurement location. The strong spanwise variation of this streamwise-averaged roughness profile highlights the spanwise heterogeneity of the roughness. Focusing upon the in-plane mean velocity components, $\langle v \rangle$ and $\langle w \rangle$, whose magnitude are roughly 5% of $U_e$ (about one order of magnitude weaker than $\langle u \rangle$), there exist clear imprints of swirling motions in the mean flow.
bounding the LMPs identifiable in the mean streamwise velocity contours, consistent
with the $\langle \Lambda_{ci} \rangle$ field shown in figure 4.9. These swirling motions serve to separate the
LMPs and HMPs in the spanwise direction. Comparing the spanwise positions of the
LMP and HMP features with the spanwise variation in roughness height, $\eta(z)$, [shown
beneath the mean velocity field in figure 4.10(a)], it appears that the HMPs tend to
sit at spanwise positions of relatively elevated topography while the LMPs tend to
reside at spanwise positions of relatively recessed topography. The swirling motions
in the mean velocity field, which sit between adjacent LMP and HMP patterns, thus
tend to sit at spanwise locations where a spanwise gradient in the roughness height
occurs owing to a transition from elevated to recessed topography, and vice-versa.

To clarify these spatial relationships between the spanwise variation in the rough-
ness height and the occurrence of LMPs, HMPs and swirling motions, figure 4.10(b)
presents a low-pass-filtered version of the streamwise-averaged roughness profile (black
line; Fourier cut-off filter at $0.125\delta$) meant to highlight the larger-scale topographical
features and variations of the roughness in the spanwise direction. The noted spanwise
variation of this streamwise-averaged, smoothed roughness profile further highlights
the spanwise heterogeneity of the roughness, particularly at the larger topographical
scales. In addition, figure 4.10(b) shows the spanwise gradient in roughness height
($\partial\eta/\partial z$; red line) computed from the smoothed spanwise profile of roughness height.
It is readily apparent that regions of locally high roughness elevation, at $z/\delta \approx -1.00$
and -0.20 in figure 4.10(b), coincide with the spanwise positions of HMPs in fig-
ure 4.10(a) [An additional HMP resides at $z/\delta \approx 0.5$ where the smoothed roughness
profile is locally elevated in figure 4.10(b) but has less pronounced valleys at its span-
wise boundaries]. On the other hand, regions of more recessed topography, near
$z/\delta \approx -1.25, -0.60, 0.15$ and 1, align well with the spanwise positions of LMPs.
Figure 4.10: (a) Mean velocity field (contours: 〈u〉; vectors: 〈v〉 and 〈w〉) with the spanwise roughness profile averaged over a δ-long fetch upstream of the measurement plane shown below the field (Scaled by a factor of five). Flow is into the page. (b) Low-pass-filtered spanwise roughness profile (black line) and its spanwise gradient (red line).

Focusing on the LMP that resides at z/δ ≈ 0.15, a counterclockwise swirling motion in the mean velocity field bounds this LMP near z/δ ≈ 0, coincident with a transition in topography from elevated to recessed in the positive spanwise direction (i.e., ∂η/∂z < 0). Likewise, a clockwise swirling motion bounds this LMP near z/δ ≈ 0.35 coincident with a transition in roughness from recessed to elevated (i.e., ∂η/∂z > 0).

The opposite pattern is noted for the HMP that resides at z/δ ≈ −0.2, wherein a clockwise swirling motion coincides with a transition from recessed to elevated topography near z/δ ≈ −0.4 (∂η/∂z > 0), and a counterclockwise swirling motion coincides
with a transition from elevated to recessed topography near $z/\delta \approx 0$ ($\partial \eta / \partial z < 0$).

These mean-flow patterns are remarkably consistent with those identified by Willingham et al. (2014) from LES of turbulent boundary-layer flow overlying periodic spanwise transitions in ordered roughness from elevated to recessed, despite the roughness presented herein being significantly more complex than that considered in this LES study. In particular, Willingham et al. (2014) observed the formation of persistent LMPs over the recessed roughness and HMPs over the regions of elevated roughness, bounded by streamwise-oriented, counterclockwise-rotating swirling motions in the $y - z$-plane mean velocity field at spanwise locations coincident with transitions from elevated to recessed roughness ($\partial \eta / \partial z < 0$) and clockwise-rotating swirling motions at spanwise locations coincident with transitions from recessed to elevated roughness ($\partial \eta / \partial z > 0$). These patterns are entirely consistent with the heterogeneity identified herein despite the significant complexity of the present roughness compared to the well-ordered spanwise roughness transitions studied by Willingham et al. (2014). Thus, we interpret these spatial patterns in the cross-plane mean velocity field as the imprint of turbulent secondary flows in the form of streamwise-elongated roll cells excited by spanwise gradients in topographical height which then induce spanwise-alternating regions of enhanced turbulent kinetic energy and Reynolds shear stress. Again, it must be stressed that these mean-flow patterns are distinct from low- and high-momentum regions identified in instantaneous flow fields of wall turbulence which occur randomly in the spanwise direction.

Unfortunately, cross-plane stereo PIV measurements at additional streamwise locations in the self-similar region of the rough-wall boundary layer were not possible owing to imaging limitations in the wind tunnel. However, the streamwise persistence of these motions is highlighted by comparing the present cross-plane data with the
Figure 4.11: Ensemble-averaged streamwise velocity, $\langle u \rangle$, in the $y-z$ plane plotted with $\langle u \rangle$ from the $x-z$ measurements of Mejia-Alvarez & Christensen (2013) at $y = 0.1\delta$ (relative to the mean elevation) and at comparable Re.
wall-parallel stereo PIV measurements at $y = 0.1\delta$ (relative to the mean elevation of the roughness) by Mejia-Alvarez & Christensen (2013) over the same roughness and at comparable Re. As illustrated in figure 2.6(b), the wall-parallel plane measurements were conducted over an $x - z$ region that overlapped well with the current cross-plane data and a composite figure illustrating the mean streamwise velocity from both measurements is presented in figure 4.11. While the wall-parallel plane data of Mejia-Alvarez & Christensen (2013) has a much narrower spanwise field of view, it overlaps and extends approximately $1.2\delta$ downstream of the current cross-plane measurement location and highlights the streamwise persistence of both an LMP and HMP that are clearly captured in both planes. Consistency between the two measurement planes is also noted in the $TKE$ and the Reynolds shear stress (not shown for brevity), similarly illustrating the $\delta$-scale streamwise persistence of these mean-flow motions. Thus, the turbulent secondary flows reported herein at a single streamwise position in fact have $\delta$-scale persistence in the streamwise direction when complemented by the results of Mejia-Alvarez & Christensen (2013).

### 4.2.2 Mean vorticity components

Figure 4.12 presents contours of components of the vorticity vector for flow over the complex roughness. The same low-pass filtered of the streamwise-averaged roughness profile, shown in figure 4.10(b) (black line), together with its spanwise gradient (blue line) are plotted to help highlight the locations of LMPs, HMPs and the secondary motions. Streamwise gradients have been neglected in the calculation of the vorticity as homogeneity at fixed spanwise position in the mean flow for this roughness condition has been previously reported (Mejia-Alvarez & Christensen, 2013) and partially presented in figure 4.11. The presence of mean streamwise vorticity in the form of
Figure 4.12: Contours of mean vorticity components for the rough-wall flow. (a) $\langle \omega_x \rangle$; (b) $\langle \omega_z \rangle$; (c) $\langle \omega_y \rangle$. 

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δ-scale roll cells is clearly evident in figure 4.12(a) and is entirely consistent with that noted in figure 4.9 where swirl strength with the sign of $\langle \omega_z \rangle$ was used to demonstrate the presence of mean-flow swirling motions. The large values of $\langle \omega_z \rangle$ close to the surface are due to the strong lateral outflow at the base of the HMPs and associated large vertical gradient of $\langle w \rangle$ in this region. Figure 4.12(b) shows mean spanwise vorticity, which is equivalent to the wall-normal gradient of the mean streamwise velocity. From this figure, it is evident that the largest $\langle \omega_z \rangle = \partial \langle u \rangle / \partial y$ occurs at the base of the HMPs, thus confirming that the highest drag occurs coincident with the HMPs and thus coincident with regions of relatively elevated roughness. Finally, figure 4.12(c) presents mean wall-normal vorticity, $\langle \omega_y \rangle$, which reflects the spanwise mean flow gradient (since the $\partial/\partial x_1$ term is negligible) and exhibits extreme values (positive and negative) in a localized region precisely above the roughness heterogeneity (i.e., high spanwise roughness gradients). Further, we emphasize consistency in the sign of $\langle \omega_y \rangle$ positive(negative) on the left(right) side of the HMPs, due to spanwise decrease(increase) of the mean streamwise velocity component $\langle u \rangle$.

4.2.3 Reynolds stress components

Figure 4.13 presents all the components of the Reynolds stress tensor to further explore spatial heterogeneity in the individual stress components. The same low-pass filtered of the streamwise-averaged roughness profile, shown in figure 4.10(b) (black line), together with its spanwise gradient (blue line) are plotted to help highlight the locations of LMPs, HMPs and the secondary motions. It is clear from these figures that spatial heterogeneity exists in the turbulent stress distributions that are far different to what would otherwise be present for flow over a homogeneous roughness or a smooth wall (see figures 4.2 and 4.3). The normal stresses
Figure 4.13: Contours of Reynolds stress tensor components normalized in outer scales. (a) $\langle u'^2 \rangle / U_e^2$; (b) $\langle u'v' \rangle / U_e^2$; (c) $\langle v'^2 \rangle / U_e^2$; (d) $\langle u'w' \rangle / U_e^2$; (e) $\langle w'^2 \rangle / U_e^2$; (f) $\langle v'w' \rangle / U_e^2$. 
(figure 4.13a, 4.13c, and 4.13e) exhibit maximum values immediately above regions of high roughness, where HMPs reside, leading to enhanced TKE in the very near-wall region over high roughness. Elevated values of the normal stresses are also noted above regions of relatively recessed roughness where LMPs reside, but further away from the wall which yields the enhanced TKE noted earlier coincident with LMPs. Figures 4.13(b), 4.13(d), and 4.13(f) show the shearing stress components where important spanwise variations of these stresses is noted. Figure 4.13(b) illustrates that large values of $\langle u'v' \rangle$ occur at the base of the HMP. Likewise with the normal stresses, the wall-normal attenuation of $\langle u'v' \rangle$ within the HMPs is considerable larger than in the adjacent LMPs, with enhanced $u'v'$ readily apparent further from the wall at spanwise positions coincident with LMPs. Figure 4.13(f) shows the $\langle u'w' \rangle$ shearing stress, which Willingham et al. (2014) previously studied for its role in sustaining lateral momentum exchange in close proximity to the roughness heterogeneity inferred from LES simulation of streamwise aligned patches of “high” and “low” roughness. The patterns in this stress component are also reflective of the swirling motions noted in the mean velocity field, interpreted as the imprint of mean secondary motions in this rough-wall flow. Finally, figure 4.13(f) illustrates the $\langle v'w' \rangle$ shearing stress which also embodies spatial heterogeneity at levels that exceed the variability noted in its smooth-wall counterpart(figures 4.2 and 4.3).

The strong spatial heterogeneities noted in all components of the Reynolds stress tensor necessarily lead to strong spatial gradients in these quantities. In a collaboration between our group and that of Prof. William Anderson at the University of Texas at Dallas, Anderson et al. (2014) recently reported these strong spatial gradients in the Reynolds stress components to be the driver of the turbulent secondary flows reported herein. In particular, Anderson et al. (2014) has shown these motions to be
associated with Prandtl's secondary flow of a second kind as detailed in Bradshaw (1987). While the author and his advisor have been deeply involved in arriving at these secondary-flow observations and the data presented herein was analyzed and interpreted in this context, this complex, intertwined analysis and interpretation with the LES results of Prof. Anderson precluded precise identification of the scientific contributions of each researcher involved. Thus, erring on the side of caution, this portion of the research has not been included in this thesis.

4.2.4 Quadrant analysis of $\langle u'v' \rangle$

To further explore the overall RSS behavior of the LMPs and HMPs, quadrant analysis was employed. The instantaneous $u'v'$ events that generate the RSS field shown in figure 4.8 are formed by different combinations of $u'$ and $v'$ instantaneous events. More specifically, depending upon the combination, these events will lie in one of the four quadrant of the $u' - v'$ plane. It is well known, and has also become an important nomenclature in wall-bounded flows, that negative contributions to the $\langle u'v' \rangle$ are termed ejection, $Q_2 : u' < 0, v' > 0$, and sweep, $Q_4 : u' > 0, v' < 0$, events. Positive contributions to the $\langle u'v' \rangle$ are known as inward, $Q_3 : u' < 0, v' < 0$, and outward, $Q_1 : u' > 0, v' > 0$ interactions. It is well-appreciated that ejection and sweep events dominate, in a mean sense, over inward and outward interactions as reflected in the negative sign of $\langle u'v' \rangle$ throughout the boundary layer.

The quadrant decomposition of instantaneous $u'v'$ events is given by

$$\langle u'v' \rangle_{Q}(y, z; H) = \sum_{n=1}^{N} u'(y, z)v'(y, z)I_{Q}(y, z; H),$$  \hspace{1cm} (4.1)

where $H$ is the hyperbolic hole size and $N$ is the total number of samples. It should
be noted that the averaging reflected in the summation of eqn. (4.1) is only through the ensemble of velocity fields (hence, \( N = 10000 \)) so as to maintain the wall-normal and spanwise dependence of the decomposition and thus facilitate identification of spatial heterogeneity in the various quadrant contributions. The indication function, \( I_Q(y, z) \) in eqn. (4.1) is defined as

\[
I_Q(y, z; H) = \begin{cases} 
1, & \text{when } |u'(y, z)v'(y, z)|_Q \geq T(y, z) \\
0, & \text{otherwise},
\end{cases}
\]

(4.2)

where \( T(y, z) \) is a threshold allowing one to consider different strengths of the instantaneous RSS events that contribute to the mean RSS. This threshold is defined as

\[
T(y, z) = H\sigma_u(y, z)\sigma_v(y, z),
\]

(4.3)

where \( \sigma_u(y, z) = \sqrt{\langle u'^2 \rangle} \) and \( \sigma_v(y, z) = \sqrt{\langle v'^2 \rangle} \) are the root-mean-square (RMS) streamwise and wall–normal velocities, respectively, which vary in both \( y \) and \( z \) (thus justifying the spatial dependence of \( T \)).

A hyperbolic hole size of \( H = 0 \) is considered first, meaning all \( u'v' \) events contributing to the mean RSS in figure 4.8 are considered in the analysis. Of particular interest is determining which RSS contribution(s) are responsible for the spatial heterogeneity noted in the mean RSS of figure 4.8. Figure 4.14 presents \( Q_1 \) and \( Q_3 \), outward and inwards interactions, respectively, for smooth- and rough-wall flow at \( H = 0 \). The weak spatial variability noted in the smooth-wall results represents a measure of the sampling error associated with the reduced number of samples owing to decomposition of the \( u'v' \) events into four possible contributions. Thus, this level of variability provides a baseline for determining whether trends noted in the rough-wall results are due to underlying physical processes or simply statistical vari-
Figure 4.14: Contour maps of outward, $Q_1; \langle u'v' \rangle_1/U_e^2$, and inward, $Q_3; \langle u'v' \rangle_3/U_e^2$, interactions for (a,c) smooth- and (b,d) rough-wall flow for $H = 0$. 
ability. Indeed, strong spatial heterogeneity and elevated levels of both $Q_1$ and $Q_3$ are readily apparent in the rough-wall results. Despite these observations, the values of the $Q_1$ and $Q_3$ contributions in the rough-wall flow represent only a small fraction of the overall mean RSS of figure 4.8, meaning they play little role in the overall development of the rough-wall flow.

Figure 4.15 presents the quadrant contribution for ejections ($Q_2$), $\langle u'v' \rangle_2/U_c^2$, and sweeps ($Q_4$), $\langle u'v' \rangle_4/U_c^2$, for both smooth- and rough-wall flow at $H = 0$. In contrast to the inward- and outward-interactions [figure 4.14], the contributions of ejections and sweeps for $H = 0$ are intense and display a high degree of spatial heterogeneity in the spanwise direction of the rough-wall flow. The smooth-wall results show clear homogeneity in the spanwise direction within the sampling error of these statistics. Of interest, the events noted in the $Q_2$ and $Q_4$ contributions appear to be the main contributors to the heterogeneities seen in the mean RSS (figure 4.8). In both smooth- and rough-wall flow, nearly equal contributions of ejection and sweeps are observed. In addition, regardless of the spatial heterogeneity in the rough-wall case, $Q_2$ events penetrate further from the wall than their $Q_4$ counterparts. In fact, this is also seen for the smooth-wall flow. It should be noted that, for both flow cases, ejections and sweeps are nearly one order of magnitude larger (in absolute value) compared to inward and outward interactions.

In order to assess the role of the more intense RSS events to these trends, quadrant analysis with a hyperbolic hole size of $H = 4$ is presented in figures 4.16 and 4.17. It is clear that the inward and outward interactions (figure 4.16) are nearly zero throughout the entire field for both smooth- and rough-wall flow. In contrast, ejection and sweeps events, depicted in figure 4.17, clearly show spanwise spatial heterogeneities for the rough-wall flow. In contract, the smooth-wall results shows a good degree
Figure 4.15: Contour maps of ejections, $Q_2; \langle u'v' \rangle_2/U_e^2$, and sweeps, $Q_4; \langle u'v' \rangle_4/U_e^2$, for (a,c) smooth- and (b,d) rough-wall flow for $H = 0$. 
Figure 4.16: Contour maps of outward, $Q_1; \langle u'v' \rangle / U_e^2$, and inward, $Q_3; \langle u'v' \rangle / U_e^2$, interactions for (a,c) smooth- and (b,d) rough-wall flow for $H = 4$. 
Figure 4.17: Contour maps of ejections, $Q_2; \langle u'v' \rangle_2 / U_e^2$, and sweeps, $Q_4; \langle u'v' \rangle_4 / U_e^2$, for (a,c) smooth- and (b,d) rough-wall flow for $H = 4$. 
of homogeneity in the spanwise direction as expected. Focusing upon the roughness sublayer \((y/\delta < 0.3)\) of the rough-wall flow, spanwise positions where HMPs reside \((z/\delta \approx -1.00; z/\delta \approx -0.40; z/\delta \approx 0.60)\) are characterized by stronger ejections, occurring deeper towards the rough surface, when compared with regions where LMPs reside \((z/\delta \approx -1.25; z/\delta \approx -0.65; z/\delta \approx 0.15; z/\delta \approx 1.00)\). The opposite is seen for the sweeps events, where inside the roughness sublayer regions where LMPs reside show stronger \(Q_4\) events and regions where HMPs reside show weaker \(Q_4\) events. In the outer layer, ejection events show some degree of spanwise heterogeneities, with more enhanced regions coinciding with spanwise positions where LMPs reside. Thus, these results indicate that both HMPs and LMPs are characterized by stronger sweeps and ejections events.

### 4.2.5 Spatial coherence

The low- and high-momentum pathways identified in the ensemble-averaged streamwise velocity of figure 4.4 could perhaps reflect that the roughness studied herein somehow promotes preferential alignment of large-scale motions along these pathways. However, it is not known whether these pathways represent spatially-correlated turbulent events or simple concatenations of uncorrelated events that are advecting along the same streamwise path. In order to assess the spatial coherence of these large-scale motions, two-point inhomogeneous velocity correlation coefficients were computed. These correlations are computed as

\[
\rho_{u_iu_j}(y, z; x, y_{ref}, z_{ref}) = \frac{\langle u_i'(y_{ref}, z_{ref})u_j'(x, y, z) \rangle}{\sigma_{u_i}(x, y_{ref}, z_{ref})\sigma_{u_j}(x, y, z)},
\]  

\[\tag{4.4}\]
in the $y-z$ plane at fixed $x$ where $(y_{ref}, z_{ref})$ defines the spatial location of the reference point in this measurement plane.

Figure 4.18 presents two-point velocity correlation coefficients in the $y-z$ measurement plane for a reference point situated within the LMP identified in Figure 4.11 at $(y_{ref}, z_{ref}) = (0.15\delta, 0.15\delta)$. In figure 4.18(a), $\rho_{uu}$ is characterized by a primary peak (local maximum) at $(y_{ref}, z_{ref}) = (0.15\delta, 0.15\delta)$ that is bounded in the spanwise direction by correlation minima. This maximum correlation at the reference location indicates that the large-scale motions that travel along the identified LMP have significant wall-normal coherence on the order of $\delta$. The alternating positive/negative nature of $\rho_{uu}$ in this $y-z$ plane is again consistent with the occurrence of spanwise-alternating LMRs and HMRs in instantaneous velocity fields (Wu & Christensen, 2010) and indicates that the LMP identified in figure 4.11 are often bounded in the spanwise direction by an HMP. The spanwise coherence of these $\delta$-scale motions is $z/\delta \approx 0.3$ and they have a spanwise spacing of roughly $0.35\delta$. In contrast, $\rho_{vv}$ [Figure 4.18(b)] has much more compact spanwise coherence, though it is still characterized by a primary correlation peak at $(y_{ref}, z_{ref}) = (0.15\delta, 0.15\delta)$ that is bounded by correlation minima in the spanwise direction. Similar behavior is noted in $\rho_{uw}$ [Figure 4.18(d)].

The characteristics of $\rho_{uu}$, $\rho_{vv}$ and $\rho_{uw}$ in the $y-z$ plane are consistent with the imprint of streamwise-aligned motions, or a larger-scale collection of such structures, that pump low-speed fluid away from the wall and draw high-speed fluid towards the wall. Such motions result in the generation of intense RSS-producing events. Finally, $\rho_{ww}$ [Figure 4.18(c)] displays a V-shaped region of positive correlation above which a wall-normal-elongated region of strong negative correlation resides. The symmetry of this correlation with respect to the location of the LMP suggests consistency with the occurrence of spanwise pairs of counter-rotating streamwise vortex cores. In other
Figure 4.18: Two-point velocity correlation coefficients in the wall-normal–spanwise ($y-z$) plane for a reference point positioned within the LMP identified in the figure 4.11 at $(y_{ref}, z_{ref}) = (0.15\delta, 0.15\delta)$ that is demarcated with an 'X':

(a) Autocorrelation of streamwise velocity, $\rho_{uu}$; (b) Autocorrelation of wall-normal velocity, $\rho_{vv}$; (c) Autocorrelation of spanwise velocity, $\rho_{ww}$; (d) Cross-correlation of streamwise and wall-normal velocities, $\rho_{uv}$.  

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words, the configuration of $\rho_{ww}$, particularly its persistence into the outer region of the boundary layer, is consistent with the combined action of the legs of hairpin-like, or similarly oriented, vortical structures.

Figure 4.19 presents velocity correlation coefficients for a reference location within an identified HMP. Figure 4.19(a) shows the streamwise two-point velocity correlation coefficient, $\rho_{uu}$, computed at $(y_{\text{ref}}, z_{\text{ref}}) = (0.15\delta, -0.25\delta)$, where an HMP resides. The behavior of $\rho_{uu}$ at the HMP, similar to the same correlation on the previously identified LMP, also shows a primary peak (local maximum) at $(y_{\text{ref}}, z_{\text{ref}}) = (0.15\delta, -0.25\delta)$ that is bounded in the spanwise by correlation minima, and the spanwise alternating nature of LMRs and HMRs, showing $\delta$-scale spatial coherence in both the spanwise and wall-normal directions. Both wall-normal, $\rho_{vv}$ and streamwise–wall-normal, $\rho_{uv}$, correlations shown in figures 4.19(b) and 4.19(d), respectively, have qualitatively similar spatial coherence to those computed at the LMP. Interestingly, the biggest difference between the correlations computed at the HMP and LMP locations is in the spanwise autocorrelation, $\rho_{ww}$. As described above, $\rho_{ww}$ at the identified LMP [figure 4.18(c)] shows a V-shape region of positive correlation and a region of strong wall-normal-elongated negative correlation above the positive correlation core. In contrast, the $\rho_{ww}$ computed at a HMP displays a somewhat inverse behavior, showing a inverted V-shape region of negative correlation lying above a region of positive correlation.
Figure 4.19: Two-point velocity correlation coefficients in the wall-normal–spanwise \((y,z)\) plane for a reference point positioned within the HMP identified in the figure 4.11 at \((y_{\text{ref}}, z_{\text{ref}}) = (0.15\delta, -0.25\delta)\) that is demarcated with an ‘X’.

(a) Autocorrelation of streamwise velocity, \(\rho_{uu}\); (b) Autocorrelation of wall-normal velocity, \(\rho_{vv}\); (c) Autocorrelation of spanwise velocity, \(\rho_{ww}\); (d) Cross-correlation of streamwise and wall-normal velocities, \(\rho_{uv}\).
Chapter 5

High-Frame-Rate Measurements in a Turbulent Boundary layer

Following on the previously shown results focused on the impact of complex roughness on wall turbulence, particularly with observations of turbulent secondary flows induced by such roughness, this chapter seeks to identify the impact of complex roughness on the TKE and RSS content of LSMs and VLSMs, particularly differences from their well-documented behavior in smooth-wall flow. In light of the existence of turbulent secondary flows for this complex roughness, we also seek to understand the behavior of LSMs and VLSMs as a function of spanwise position, particularly their characteristics at spanwise locations coincident with LMPs and HMPs. In particular, are the spectral characteristics of these superstructures, known to amplitude modulate the near-wall flow, significantly different at spanwise locations of LMPs and HMPs? If so, do these differences alter their influence on the near-wall flow? To address these fundamental questions about the larger-scale motions of the flow, high-frame-rate stereo PIV data in the cross-flow plane was employed to assess the localized impact of highly irregular roughness within the roughness sublayer on these structures in a TBL. Two set of experiments were performed: a large field-of-view, 1.5k field/s that provides a view of the overall spatial structure across the boundary layer; and a narrow wall-normal measurement strip at 10k fields/s, which would equate to having a rake of roughly 1000 triple-wire sensors simultaneously acquiring all three velocity components. These 10k fields/s measurements reported herein were performed at the
same Re as the low-frame-rate cross-plane stereo PIV measurements from section 4.2, ensuring the same flow scenario/conditions under which the aforementioned turbulent secondary flows were observed.

5.1 Results

5.1.1 Instantaneous fields

Figure 5.1(a) presents a representative instantaneous fluctuating velocity field in the \( y - z \) measurement plane for the rough-wall case acquired at 1.5 kHz, providing a wall-normal view that engulfs nearly the entire boundary-layer thickness. The in-plane wall-normal \( (v') \) and spanwise \( (w') \) velocity fluctuations are shown as vectors and the out-of-plane streamwise velocity fluctuations \( (u') \) are presented as background contours. Note that the positive streamwise \( (x) \) direction, and hence the mean flow, is into figure 5.1(a). The streamwise velocity fluctuations are marked by large \((\delta\text{-scale})\) regions of low and high instantaneous streamwise momentum that appear to alternate in the spanwise direction with a spacing of \( \sim 0.5\delta \). These patterns are interpreted as the cross-plane signatures of the LMRs and HMRs and can often extent to the edge of the boundary layer. Focusing upon the large-scale LMR near \( z = -0.2\delta \) in figure 5.1(c), its left boundary is populated by counter-clockwise-rotating vortex cores identified with signed swirling strength \( (\Lambda_{ci} < 0; \text{blue}) \) while its right boundary is populated by vortex cores with clockwise rotation \( (\Lambda_{ci} > 0; \text{red}) \). Furthermore, rather intense, positive wall-normal velocity fluctuations \( (v') \) are observed within this LMR, resulting in a large-scale region of low-speed fluid ejected away from the wall which contributes heavily to the mean RSS (Figure 5.1b). This LMR is flanked on its spanwise boundaries by HMRs within which intense, negative \( v' \) create a large-scale
Figure 5.1: (a) Representative instantaneous fluctuating velocity field in the $y-z$ plane from the 1.5 kHz rough-wall data (contours: $u'$; vectors: $v', w'$). Contours of (b) instantaneous contributions to the RSS, $u'v'$, and (c) signed swirling strength, $\Lambda_{ci}$ for field in (a). Solid and dashed line contours in (b) and (c) demarcate boundaries of HMRs and LMRs, respectively.
sweep of high-speed fluid towards the wall which also contributes heavily to the mean RSS (Figure 5.1b). Apart from these $\delta$-scale events, smaller LMRs and HMRs are visualized in the near-wall region that are often bounded by streamwise vortex cores. These smaller-scale regions appear to co-exist beneath the larger-scale LMRs and HMRs, supporting the contention that such structures occur in a hierarchy of scales across the flow. As proposed by Adrian et al. (2000b) for smooth-wall turbulence, packets of varying size would be expected throughout the wall-normal extent of the flow, with smaller, younger, slower packets residing closer to the wall where they are likely formed and successively larger, older packets populating the outer region of the flow while maintaining a near-wall footprint. It was shown that many of the structural attributes of the hairpin packet persist in the presence of 3D roughness (Volino et al., 2007; Wu & Christensen, 2007, 2010; Mejia-Alvarez et al., 2013). However, their characteristic spatial scales are modified as Wu & Christensen (2010) and Mejia-Alvarez & Christensen (2010) both found that the roughness employed herein alters the streamwise length scales of the flow. Nevertheless, despite the presence of a rough boundary, the overall structural attributes of the flow are quite consistent, at least qualitatively, with those of smooth-wall turbulence. This observation is in accordance with Townsend’s wall similarity hypothesis (Townsend, 1976) whereby the roughness sets the wall shear stress and the boundary-layer thickness and the turbulence in the outer region simply adjusts itself to these constraints in a universal manner.

5.1.2 Imprints of large- and very-large scale motions in rough-wall flow

Figure 5.1 clearly highlights the existence of $\delta$-scale attributes in the cross-flow consistent with signatures of LSMs and VLSMs in smooth-wall flow. The cross-plane
high-frame-rate stereo PIV data affords one the opportunity to also explore the presumed streamwise elongation of these motions in a manner consistent with that often utilized to convert hot-wire time traces to equivalent spatial extent. This exact methodology allowed Hutchins & Marusic (2007) to reconstruct spanwise and elongated streamwise fields of view from time series acquired simultaneously from a spanwise rake of 10 hot-wire sensors that led to their observations of spanwise meandering regions of $u' < 0$ that extended multiple $\delta$ in the streamwise direction which they termed superstructures (consistent with attributes of VLSMs). As the streamwise displacement of the bulk flow between consecutive instantaneous vector fields herein was maintained at half of the lightsheet thickness, consistent with the in-plane spatial resolution, Taylor’s hypothesis was utilized to convert the temporal dimension to equivalent streamwise position assuming that the turbulence is frozen with respect to mean advection in the streamwise direction. Here a single wall-parallel ($x \times z$) plane was reconstructed in the spirit of that reported in Hutchins & Marusic (2007) for smooth-wall flow based on the mean streamwise velocity at this wall normal position, giving $x \simeq (t_0 - t)\bar{U}$ (Dennis & Nickels, 2008, 2011; Van Doorne & Westerweel, 2007).

Figure 5.2 presents the result of this Taylor’s-hypothesis reconstruction in the wall-parallel $x - z$ plane at $y/\delta = 0.15$ highlighting the presence of an instantaneous LMR demarcated with contours of $u' < 0$. Here several multiple-$\delta$ regions of connected $u' < 0$ that have significant spanwise meander are readily apparent in a manner quite reminiscent of that observed by Hutchins & Marusic (2007) for smooth-wall flow. A zoomed-in region is also presented with color contours of in-plane signed swirling strength demarcating the locations of wall-normal vortex cores. Focusing upon the zoomed-in region in Figure 5.2, it is apparent that the streamwise-elongated LMRs are bounded on the spanwise edges by counter-rotating vortex cores in a manner
Figure 5.2: Wall-parallel $x - z$ view of an LMR at $y/\delta = 0.15$ demarcated with contours of negative streamwise velocity fluctuation from Taylor’s hypothesis reconstruction. A zoomed-in region is also presented with color contours of signed swirling strength demarcating the locations of wall-normal vortex cores.
consistent with hairpin vortex packets. In addition, this figure highlights the elongated streamwise extent of these superstructures, which appear to extend $5 - 6\delta$ in the streamwise direction, again entirely reminiscent of similar patterns reported by Hutchins & Marusic (2007) from measurements using a spanwise array of hot-wire sensors in conjunction with Taylor’s hypothesis to reconstruct streamwise-elongated, wall-parallel fields of view in a smooth-wall TBL. As already mentioned previously and also shown in the recent work of Wu & Christensen (2010), albeit for much shorter streamwise extents ($\delta$), these LMRs are qualitatively similar to the structures found in smooth-wall flow. The present reconstructions, however, show that these LMRs have streamwise extents of multiple $\delta$ and could be the imprint of superstructures previously identified in smooth-wall flow which embody a significant fraction of TKE and RSS. Mejia-Alvarez et al. (2014) previously reported the existence of such superstructures in this same rough-wall flow in elongated wall-parallel fields of view constructed by stitching together time-delayed PIV velocity fields acquired in the wall-parallel plane. Despite the limited temporal resolution (1.5k fields/s) and a narrower spanwise domain (only $0.5\delta$) the present observations confirm those initially reported by Mejia-Alvarez et al. (2014), particularly the existence of streamwise-elongated regions of $u' < 0$ that spanwise meander.

Figure 5.3 presents a time history of the streamwise velocity fluctuations as a function of wall-normal position for three scenarios: smooth-wall flow (figure 5.3a) and rough-wall flow at two different spanwise positions: coincident with an LMP (figure 5.3b) and coincident with an HMP (figure 5.3c). The time axis is normalized by the cross-plane bulk velocity and $\delta$, allowing the streamwise length scale of flow events to be qualitatively inferred from these time histories, while the wall-normal position is normalized by $\delta$. Here, only a portion of the high-frame-rate data acquired
Figure 5.3: Time-history *versus* wall-normal position for (a) smooth-wall and rough-wall flow along and (b) LMP and (c) HMP. The time axis was normalized by the bulk velocity and the boundary layer thickness to give a qualitatively sense of the length-scale of the different structures presented on these flows.
is presented for clarity. Focussing on the smooth-wall result in figure 5.3a), many \( \delta \)-scale events of LMRs (blue contours; \( u' < 0 \)) and HMRs (red contours; \( u' > 0 \)) alternate along the time axis, all with different wall-normal extents ranging from \( y \approx 0.2\delta \) to \( 0.8\delta \). In addition, the inclined nature of these structures away from the wall is readily apparent in this presentation of the time histories, with a characteristic angle of 12-17 degrees. This inclination is consistent with previous studies of smooth-wall turbulence, particularly the typical inclination of hairpin vortex packets (Adrian et al., 2000b; Christensen & Adrian, 2001). The structural character of the flow as inferred from the time history of \( u' \) is quite different in the presence of roughness. Figure 5.3b) shows the time series of the flow at a spanwise position coincident with an LMP and figure 5.3c) at an HMP. For both locations, the flow is qualitatively distinct from the smooth-wall case, particularly the flow closer to the rough surface (\( y/\delta < 0.1 \)) where distinct small-scale features are present at scales consistent with that of the roughness. In addition, the flow within the roughness sublayer shows significant differences when compare with the smooth-wall case. The structures present along an LMP, depicted in figure 5.3b), appear smaller in streamwise extent when compared with the smooth-wall structures. Although these features still resemble packet-like structures, some LMRs have rather steep inclination angles compared to the smooth-wall flow, such as those located at \( tU_b/\delta \approx -8 \) and \( \approx -17 \), with both extending to \( y/\delta \approx 0.4 \). The structures present along the HMP, shown in figure 5.3c), appear to have longer streamwise extent than those situated along the LMP and appear to be more consistent with the character of the smooth-wall flow.

To better visualize the modification that multi-scale complex roughness introduces on the instantaneous structure of the flow, figure 5.4 provides a zoomed-in version of figure 5.3 with the addition of the other two fluctuating velocity components, \( v'/U_e \).
Figure 5.4: Time-history versus wall-normal position for (a) smooth-wall and rough-wall flow along and (b) LMP and (c) HMP. The time axis was normalized by the bulk velocity and the boundary layer thickness to give a qualitatively sense of the length-scale of the different structures presented on these flows.
and $w'/U_e$ together with the instantaneous RSS events, $u'v'/U_e^2$. Focusing on the streamwise instantaneous events (first row in figure 5.4), significant structural modifications can be seen for the LMP and HMP cases, particularly for $y/\delta \leq 0.1$ where enhanced small-scale activity is noted in the two roughness cases compared to the smooth-wall flow. As mentioned previously, these events have a length scale consistent with that of the roughness and likely represent flow structures directly generated at the wall by the roughness. Furthermore, the larger-scale events depicted for the LMP case appear distinctly shorter in streamwise extent compared to those identified at the location of an HMP. As mentioned previously, a more significant alteration of the VLSM is seen for the LMP and highlighted in the zoomed-in figure. Significant structural modification can also been seen for the wall-normal fluctuating velocity, $v'$, shown in the second row of figure 5.4. While the smooth-wall case reflects high degree in variability in $v'$, the two rough-wall cases show more ordered occurrences of $v'$ events in time as well as larger-scale extent in the wall-normal direction. Similar behavior is identified in the spanwise fluctuating velocity, $w'$, depicted in the third row of figure 5.4. Perhaps the most notable structural modifications by roughness are apparent in the instantaneous RSS events, shown in the fourth row of figure 5.4. Similar to all the velocity components, roughness seems to introduce smaller-scale RSS events close to the rough surface, particularly along the LMP. In fact, for the structures visualized in this zoomed-in plot, the events along the LMP appear to be more significantly modified compared to the smooth-wall flow than those of the HMP. This could indicate that at an LMP the roughness impact on the structural skeleton of smooth-wall flow penetrates deeper into the boundary layer, where at an HMP it is more confined to a region closer to the rough surface.

In order to quantitatively assess the impact of roughness on the LSMs and VLSMs
present in the flow, specifically their TKE and RSS distribution across scales deep within the roughness sublayer, premultiplied energy spectra were computed from the 10k fields/s experiments. These spectra were computed from time series extracted from the PIV fields. The total number of samples were 21845, corresponding to a total time of $\approx 2.2s$ which corresponds to $406\delta/U_e$. The individual power spectral density (PSD) of the velocity was computed using the Welch method, where the time-series signal was divided into 5 segments with 50% overlap to reduce the variance in the PSD. A Hanning window function was applied to each of the segmenta to suppress the Gibb’s phenomenon at high frequencies (Guala et al., 2006). Although great care was taken when performing the experiments, PIV data suffers from some degree of noise that can degrade the velocity spectra calculation. Vétel et al. (2011) showed that the PIV noise is uncorrelated in time which significantly improves the efficiency of temporal denoising methods. In order to minimize this effect, all of the velocity time-series signals were denoised by a convolution of a narrow Gaussian filter with a standard deviation of $0.7\Delta t$. To assist in the convergence of the spectra, localized spanwise averaging was performed. For the smooth case (figure 5.5a) a spanwise average was perform over the full width of the domain, while for the spectra at the LMPs and HMPs a localized spanwise average over 4 mm intervals was performed (this corresponded to approximately the spanwise width of the larger roughness elements of the topography). To help further convergence, the rough-wall spectra were averaged over 5 independent runs.

To estimate the wavenumber spectra, Taylor’s frozen field hypothesis was use to convert frequency to streamwise wavenumber. Although the validity of the Taylor’s hypothesis to accurately determine the true spatial spectra is still a subject of debate (Dennis & Nickels, 2008; Del Alamo & Jiménez, 2009; Kim & Adrian, 1999), it
has little impact on the observations reported herein since, as point out by Guala et al. (2006), the time-delayed correlations decay faster than the two-point correlations due to the evolution of the turbulent structures as they advect through the PIV measurement plane. Thus, the streamwise wavenumber determined as \( k_x = 2\pi f / U(y) \), where \( U(y) \) is the local mean velocity at the wall-normal location, and the streamwise wavelength was computed as \( \lambda_x = 2\pi / k_x \), will reveal less energy at low wavenumbers compared to the true spatial spectrum. Since the main goal of the present effort is to determine the fractional content of both TKE and RSS that reside at low wavenumbers and are associated with LSMs and VLSMs, the errors involved with Taylor’s hypothesis and convection velocities are not large enough to impact these observations.

Premultiplied spectral plots for the streamwise velocity, \( k_x \phi_{uu} \) for all of the examined cases (smooth, LMP and HMP) are displayed in figure 5.5. As stated in Balakumar & Adrian (2007), premultiplied spectra are useful to clearly present the contribution of the different wavelengths to the spectra and to locate peaks in the spectral densities. All of the spectra shown herein were normalized using ensemble-averaged followed by a spanwise average velocity profiles, where \( \delta \) was determined 99% of the free stream velocity and \( u_\tau \) from the plateau value from \( u_\tau = \sqrt{\nu \partial \langle U \rangle / \partial y - \langle u'v' \rangle} \).

The smooth-wall premultiplied spectra with outer-flow scaling, illustrated in figure 5.5(a), show the expected double-peak structure that was reported in many previous works (Kim & Adrian, 1999; Balakumar & Adrian, 2007; Mathis et al., 2009a). These peaks correspond to the energy of the VLSM (\( \approx 6\delta \)) and LSM (\( \approx 1\delta \)) structures. Here, we follow the same convention as Guala et al. (2006); Balakumar & Adrian (2007) to distinguish the VLSMs from the LSMs, specifically utilizing a dividing line at \( k_x \delta = 2 \), which is demarcated by the vertical dashed line in figure 5.5.
Figure 5.5: Premultiplied streamwise velocity spectra, $k_x\phi_{uu}^+$, for (a) smooth-wall flow and rough-wall flow along an (b) LMP and an (c) HMP. Dash vertical line demarcates the VLSM boundary ($k_x\delta < 2$). (---)$y/\delta = 0.032$; (-----)$y/\delta = 0.045$; (-----)$y/\delta = 0.052$; (-----)$y/\delta = 0.060$; (-----)$y/\delta = 0.068$; (-----)$y/\delta = 0.075$; (-----)$y/\delta = 0.082$. 
Of interest, Kim & Adrian (1999) interpreted this double-peak structure as the organization of hairpin-like vortices into large- and very large scale motions, with the peak at $\lambda \approx 1\delta$ corresponding to individual hairpin vortex packets and the peak at $\lambda_x \approx 6\delta$ to the alignment of these packets into streamwise-elongated trains of packets. In this outer-unit representation, the spectra show an increase of energy of the VLSM as a function of wall-normal position, consistent with previous studies (Kim & Adrian, 1999; Balakumar & Adrian, 2007). These smooth-wall results are utilized as a baseline against which the rough-wall results are compared.

Figure 5.5(b) presents pre-multiplied streamwise velocity spectra at a spanwise location coincident with an LMP in the mean velocity field. Significant structural alteration can be seen coincident with the LMP, where the results suggest a shift in energy away from VLSM scales to smaller scales. In particular, there is a distinct peak at $k_x\delta \approx 2$, suggesting a concentration of $u'$ energy in structures of scale $\lambda_x \approx 3\delta$. Moreover, in this outer scale plot, the results suggest that further way from the wall the energy of the high-wavenumber streamwise scales, $k_x\delta > 2$ diminishes. On the other hand, the opposite behavior is seen for the low-wavenumber scales, $k_x\delta < 2$, where the energy content of these scales increases as a function of wall-normal position. It is worth mentioning once more that these measurements were taken deep within the roughness sublayer and they reflect the behavior of the flow in the vicinity of the rough surface.

The premultiplied streamwise velocity spectra coincident with an HMP, shown in figure 5.5(c) show quite different trends than those along the LMP. These spectra show a bimodal distribution, reminiscent of the smooth-wall spectra, with distinct concentrations of energy at $\lambda_x \approx 6\delta$ and $\approx 1.5\delta$, which is similar to the smooth-wall spectra shown in figure 5.5(a). This behavior suggests the presence of both VLSM
and LSM along HMPs, whereas the VLSM energy appeared suppressed along the LMP which only embodies a peak at $\lambda_x \approx 3\delta$. Similar behavior regarding the energy of the low- and high-wavenumber scales as a function of wall-normal position is found at the HMP. The energy at scales higher that $k_x\delta > 2$ decreases with the wall-normal distance, and for scales less than $k_x\delta$ their energy increases with wall-normal distance.

Figure 5.6 shows the premultiplied wall-normal velocity spectra for the smooth, LMP and HMP cases. In contrast to the premultiplied streamwise velocity spectra
where a significant fraction of the energy resides at large scales, the wall-normal contributions to TKE reside predominantly at small scales as noted in the smooth-wall spectra (figure 5.6a). In particular, a distinct peak is noted for all wall-normal positions, with the peak position varying from \( \approx 35k_x\delta \) near the wall to \( \approx 20k_x\delta \) further from the wall. In addition, the energy of the low-wavenumber wall-normal scales increases as a function of wall-normal position. Both the LMP and HMP cases (figures 5.6b and c, respectively) display similar behavior as the smooth-wall flow; however, for these cases, the roughness introduces a greater wall-normal dependency. In addition, the position of the peak for close to the roughness occurs at higher wavenumbers – \( \approx 40k_x\delta \) for the LMP and \( \approx 50k_x\delta \) for the HMP. Thus, roughness enhances the \( v' \) contributions to TKE close to the wall, particularly at the small scales. Further from the wall, both roughness cases show the peak in the spectrum moving to a wavenumber closer to the smooth-wall result.

Additionally, figure 5.7 presents premultiplied spanwise velocity spectra, \( k_x\phi_{ww}^+ \), for the smooth-wall, LMP and HMP cases. The spectra for all 3 cases seems to display peaks at \( \approx 10k_x\delta \) consistently for all wall-normal positions. However, in the vicinity of the peak, the smooth-wall spectra display a higher degree of wall-normal dependence than is observed in the LMP and HMP cases. Interestingly, an opposite behavior is seen for lower wavenumbers for both the LMP and HMP cases when compared with the smooth-wall result. For the smooth-wall case, although small but apparent, the energy of the lower wavenumber scales is proportional to the wall-normal position. However, the opposite is seen for both the HMP and LMP cases, where the energy content of the lower wavenumbers is inversely proportional to wall-normal position.

Finally, figure 5.8 shows the premultiplied co-spectra, \( k_x\phi_{uv}^+ \). The smooth-wall co-spectra, figure 5.8(a), show significant \( u'v' \) content at larger scales (lower wavenum-
Figure 5.7: Premultiplied spanwise velocity spectra, $k_x \phi_{ww}^+$, for (a) smooth-wall flow and rough-wall flow along an (b) LMP and an (c) HMP. Dash vertical line demarcates the VLSM boundary ($k_x \delta < 2$). For line legend, see figure 5.5.
Figure 5.8: Premultiplied co-spectra, $k_x \phi_{uv}^+$, for (a) smooth-wall flow and rough-wall flow along an (b) LMP and an (c) HMP. Dash vertical line demarcates the VLSM boundary ($k_x \delta < 2$). For line legend, see figure 5.5.
bers) as previously reported by Guala et al. (2006); Balakumar & Adrian (2007) The LMP and HMP cases, depicted in figure 5.8(b) and (c), respectively, display a very different behavior when compared with the smooth-wall co-spectra. While significant $u'v'$ content is still noted at larger scales, the HMP and LMP cases show drastically enhanced wall-normal dependence. Close to the wall, the peak in the co-spectra for both the LMP and HMP cases resides at smaller scales ($\approx 8k_x\delta$ for the LMP case; $\approx 5k_x\delta$ for the HMP case), and this peak location shifts towards lower wavenumber with increasing wall-normal location until a peak location comparable to the smooth-wall result is noted. This result highlights the drastic influence of roughness on the smaller scales of the flow and perhaps also its influence in suppressing aspects of the larger-scale motions (VLSMs and LSMs).

To determine the TKE and RSS content as a function of scale (i.e., for the different streamwise wavelengths) for the three cases investigated herein [smooth, LMP and HMP], cumulative distributions of TKE and RSS from all wavenumber were calculated as

$$
\gamma_{ij}(\lambda_x) = 1 - \frac{\sum_{k_0}^{k_{max}} \phi_{ij}(k_x) \Delta k_x}{\sum_{0}^{k_{max}} \phi_{ij}(k_x) \Delta k_x}
$$

(5.1)

Figure 5.9 presents the cumulative TKE distribution as a function of streamwise wavelength, $\lambda_x$, for various wall-normal locations. Here, the cumulative TKE is computed using the velocity spectra from all three fluctuating velocity components and thus embodies the full TKE contribution. For the smooth-wall case, shown in figure 5.9(a), the VLSMs (scales larger than $3\delta$) carry about 45% of the TKE. This result is consistent with Balakumar & Adrian (2007). Roughness reduces the overall TKE content of the VLSMs and also introduces a more apparent wall-normal dependence when compared to the smooth-wall case, as can be seen for both the LMP and HMP cases (figures 5.9b) and c). Similarly to the streamwise velocity spectra
Figure 5.9: Cumulative TKE distribution as a function of streamwise scale for (a) smooth-wall flow and rough-wall flow at an (b) LMP and an (c) HMP. Dash line demarcates the VLSM ($\lambda/\delta > 3$). For line legend, see figure 5.5.
behavior, the cumulative TKE distribution at an LMP shows significant alterations when compared with the smooth-wall and HMP results, with a significant reduction of the TKE content of the VLSMs to 35-40\% compared to the 45-50\% TKE content noted in the smooth-wall and HMP cases. Additionally, both rough-wall cases show stronger wall-normal dependence of the TKE content, which introduces a variation of the TKE content of the VLSMs as a function of wall-normal distance.

Figure 5.10 presents the cumulative RSS distribution as a function of streamwise wavelength. For the smooth-wall case, shown in figure 5.10(a), trends very similar to those of Balakumar & Adrian (2007) are noted, with the RSS fraction content at the scales of the VLSMs having strong wall-normal dependence, varying from 35\% (closer to the wall) to 45\% (further from the wall). As expected from the premultiplied co-spectra presented in figure 5.8, the RSS content of the VLSMs is smaller for rough-wall flow. At an LMP, the RSS content of the VLSMs, depicted in figure 5.10(b), ranges from less than 20\% close to the wall to 40\% further from the wall. Similar trends are noted for the HMP results, with RSS residing principally at smaller scales, particularly close to the wall, with an increase in VLSM RSS content with increasing wall-normal position.
Figure 5.10: Cumulative RSS distribution as a function of streamwise scale for (a) smooth-wall flow and rough-wall flow at an (b) LMP and an (c) HMP. Dash line demarcates the VLSM ($\lambda_x/\delta > 3$). For line legend, see figure 5.5.
Chapter 6
Conclusions and Future Work

6.1 Conclusions

A turbulent boundary layer overlying complex roughness was investigated using stereo PIV measurements in the wall–normal-spanwise ($y-z$) cross-flow plane. The roughness studied herein was characterized by a multitude of topographical scales distributed in a highly-irregular manner – reminiscent of surface roughness encountered in many technological applications. The measurements conducted in the present work present a significant challenge as the bulk of the flow advected through the measurement plane. The focus of the present effort was on the structure of the roughness sublayer, including turbulence modifications imposed by the roughness as well as the impact of this complex roughness on the characteristics of the large- and very-large-scale motions known to drive transport processes in smooth-wall turbulence.

Before conducting the turbulent boundary layer experiments, stereo PIV measurements were made in the wall-normal–spanwise plane of turbulent channel flow for fully-developed smooth-wall conditions to validate the cross-plane stereo PIV experimental methodology at a Re for which DNS data was available. Measurements were then conducted for fully-developed channel flow interacting with a $8h$-long streamwise fetch of staggered 4-mm diameter hemispheres along the bottom wall of the channel (the upper wall remained smooth) to identify and solve any challenges associated with
deploying the cross-plane stereo PIV method in the presence of complex topography. The smooth-wall turbulent channel flow measurements revealed excellent agreement with DNS results at a similar Re_{τ}, both in the mean streamwise velocity as well as the Reynolds normal and shear stresses. Inspection of instantaneous velocity fields in this cross plane revealed the spatial signatures of LMRs and HMRs, the former of which have been previously linked to the occurrence of hairpin vortex packets in the outer layer of wall turbulence. The simultaneous measurements of flow over the roughened bottom wall and smooth top wall revealed a strong streamwise momentum deficit induced by roughness associated with the increased local flow drag upon encountering the short patch of roughness. The formation of an internal layer at the abrupt transition from smooth-to-rough conditions was readily apparent for flow along the bottom (rough) wall where this momentum deficit extended approximately 0.5h in the wall normal direction. Enhancement of the Reynolds normal and shear stresses by roughness is also observed along the bottom wall of the channel. Data within approximately 2.5 mm of the hemispheres was not accessible owing to laser reflections from the hemispheres and optical path blockage by the roughness. Nevertheless, both the smooth and rough wall measurements highlight the fidelity of the cross-plane stereo PIV methodology in documenting the flow characteristics of wall turbulence in the presence of complex topography, particularly the larger-scale motions of the flow that reside a few millimeters away from the wall.

Cross-plane stereo PIV experiments were then conducted in a turbulent boundary layer overlying a complex roughness topography. Strong mean-flow heterogeneities in the form of spanwise‐alternating low- and high-momentum pathways separated by streamwise-oriented swirling motions were identified, with the LMPs embodying intense regions of enhanced TKE and Reynolds shear stress. Interestingly, the iden-
tified LMP and HMP patterns tend to occur at spanwise locations of recessed and elevated roughness (relative to the mean elevation), respectively, with the swirling motions residing at spanwise locations of intense spanwise gradients in topographical height (clockwise-rotating when $\partial \eta / \partial z > 0$ and vice-versa). Further, comparison of the present cross-plane observations with those of Mejia-Alvarex & Christensen (2013) in a wall-parallel plane of the same rough-wall flow highlights the $\delta$-scale persistence of these mean-flow motions in the streamwise direction. All of these patterns are remarkably consistent with other recent observations of spanwise flow heterogeneities in the presence of well-controlled spanwise transitions in roughness, from the ordered herringbone patterns studied by Nugroho et al. (2013) to the ordered, spanwise-alternating regions of high and low roughness considered by Willingham et al. (2014). Thus, the spanwise heterogeneities identified herein, which extend well into the outer layer of the flow and extend at least $\delta$ in the streamwise direction, are interpreted as turbulent secondary flows induced by the spanwise heterogeneity of the roughness under consideration akin to that observed previously by both Nugroho et al. (2013) and Willingham et al. (2014) for more ordered roughness arrangements.

Furthermore, it is conceivable that the LMP and HMP patterns identified herein, and by others for more structured roughness, represent preferential spanwise alignments of instantaneous LMRs and HMRs along streamwise paths owing to regions of recessed and elevated roughness, respectively, in contrast to their propensity to meander in the spanwise direction in smooth-wall flow (Hutchins & Marusic, 2007). Regardless of their origin, the existence of such secondary motions in the mean flow could promote preferred regions of enhanced/diminished transport, drag and heat transfer and must therefore be accounted for in flow systems influenced by topography with spanwise heterogeneity. To evaluate whether these regions represent spatially-
correlated turbulent events, two-point correlations were computed at the spatial location of an identified LMP. The results show a high degree of spatial coherence along what appears to be perhaps preferential flow paths for larger, $\delta$-scale motions.

Finally, high-frame-rate stereo PIV was employed to capture the tim-dependent flow in the spanwise–wall-normal $(y,z)$ plane deep within the roughness sublayer of a turbulent boundary layer overlying the same complex roughness. As noted above, this roughness topography introduces spanwise heterogeneities in the mean flow in the form of low- and high-momentum pathways that are flanked by counter-rotating swirling motions–interpreted as the imprint of roughness-induced turbulent secondary flows. The present data was utilized to study the impact of roughness on the $TKE$ and RSS content of the larger scales of the flow, principally LSMs and VLSMs. Taylor’s hypothesis reconstructions of streamwise elongated fields of view highlight the presence of long, meandering motions consistent with that previously identified in smooth-wall flow by Hutchins & Marusic (2007) which are known to embody a significant fraction of the $TKE$ and RSS in smooth-wall flow. In the case of roughness, time-history plots as a function of wall-normal position coincident with the aforementioned LMP and HMP patterns associated with the roughness-induced secondary flows revealed significant modification of the $TKE$ and RSS content of these motions. In particular, premultiplied spectra of streamwise velocity at an LMP display a peak at $\lambda_x \approx 3\delta$, whereas the spectra at an HMP show a bimodal distribution reminiscent of smooth-wall flow, with peaks at $\lambda_x \approx 1.5$ and $\lambda_x \approx 6$. This result suggests the presence of both VLSMs and LSMs at HMPs, but a noted reduction in VLSM energy along an LMP. Cumulative $TKE$ distribution as a function of scale confirms this noted reduction of VLSM energy content at an LMP, in contrast to the $TKE$ content of VLSMs at an HMP which revealed similar fraction of $TKE$ content as the
smooth-wall flow. Finally, roughness significantly alters the distribution of RSS as a function of scale. Very close to the rough wall, most RSS content resides at scales comparable to the roughness. This peak in RSS content shifts to larger scales with increasing wall-normal location, though the RSS content of VLSMs at an HMP and an LMP are still reduced when compared with the smooth-wall flow.

6.2 Future Work

In the light of the alterations that the complex roughness seems to introduce in both the $TKE$ and RSS content as a function of scale at specific spanwise locations, particularly along LMPs, it is suggested that amplitude modulation effects be investigated in the rough-wall flow. In particular, it is known that the larger scales of the flow amplitude modulate the smaller-scales in the near-wall region of smooth-wall flow (Mathis et al., 2009a) and, given that the present roughness introduces spanwise dependence of the $TKE$ and RSS content as a function of scale that significantly alters the energy content of the LMS and VLSM, the notion of amplitude modulation in the rough-wall flow should be documented. It is possible, given the observations presented herein, that the amplitude modulation effect is reduced along paths of LMPs owing to a reduction in the influence of VLSMs at these spanwise positions and perhaps an enhancement in modulation effects along HMPs where VLSMs appear less impacted by roughness. The implications of amplitude modulation in rough-wall flow are critical to near-wall modeling efforts. For example, Mathis et al. (2011) proposed a predictive inner–outer model for the streamwise turbulent statistics for smooth-wall based on correlations founded in amplitude modulation effects. If amplitude modulation is still present in rough-wall flow, wherein the near-wall region is significantly perturbed by individual roughness elements, then such a model may provide a frame-
work for improved near-wall modeling of more practical flow scenarios impacted by roughness. However, the results presented herein indicate that amplitude modulation effects may vary significantly with position in the flow owing to the identified turbulent secondary flows that appear to impact the large- and very-large-scale motions. Further study of these issues is warranted to further advance modeling of rough-wall turbulence, particularly for more accurate large-eddy simulations of such flows at Re inaccessible to DNS.

Finally, the origin and robustness of the identified turbulent secondary flows must be understood. How are these secondary flows linked to the features of the topography? Do they represent an “ordering” of existing structures along preferential paths? Are these secondary motions self-sustaining should the roughness abruptly end? All of these questions must be addressed in order to more fully understand how such motions might be born and persist since the existence of these secondary flows can have substantial impact on a number of flow scenarios. For example, biofouling of surfaces is tremendous issue in sea-borne transportation. The existence of secondary flows may lead to streamwise-elongated pathways of nutrient-rich and nutrient-starved regions at the wall that perhaps would promote or inhibit growth of biofouling and thus effectively “sculpt” the way roughness grows on such surfaces. Many other technological and environmental examples of this kind can be envisaged owing to these secondary flows, so their origin, characteristics and persistence must be better understood. One simple experiment might be to perturb the flow prior to the present complex roughness with another roughness of significantly different characteristic scale. If the spanwise positions of the secondary flows remain unchanged, then this observations would speak to their relative robustness to perturbation. If their position and/or characteristics were to change under this perturbation, then per-
haps these secondary flows have a history prior to complex roughness or are perhaps preferential flow paths of existing large-scale motions.
References


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