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Observations of meandering superstructures in the roughness sublayer of a turbulent boundary layer

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ABSTRACT

The existence of meandering superstructures in a turbulent boundary layer overlying irregular roughness is explored with high-frame-rate particle-image velocimetry measurements within the roughness sublayer at moderate Reynolds number. Elongated streamwise fields of view reconstructed from this data using a Taylor's hypothesis approach revealed spanwise-meandering regions of low-streamwise-momentum fluid that extended several boundary-layer thicknesses in the streamwise direction. Such signatures are consistent with previous observations of superstructures in smooth-wall turbulence. Counter-rotating wall-normal vortex cores were found to reside along the spanwise boundaries of these superstructure patterns, consistent with the spatial characteristics of hairpin vortex packets.

1. Introduction

Previous particle-image velocimetry (PIV) measurements in smooth-wall turbulence revealed the occurrence of elongated regions of relatively uniform, low streamwise momentum bounded in the spanwise direction by high-speed fluid within the logarithmic region (Ganapathisubramani et al., 2003; Tomkins and Adrian, 2003). These motions were linked to coherent trains of hairpin-like vortices (Smith et al., 1991; Zhou et al., 1999; Adrian et al., 2000b; Dennis and Nickels, 2011a,b, among others) that collectively induce strong ejections of fluid away from the wall that contribute heavily to the mean Reynolds shear stress (Ganapathisubramani et al., 2003; Wu and Christensen, 2010). In the streamwise–spanwise (x–z) plane, hairpin packets appear as elongated low-momentum regions (LMRs) bounded by wall-normal vortex cores associated with the legs/necks of the vortices and within which intense ejections of low-speed fluid occur (Ganapathisubramani et al., 2003; Tomkins and Adrian, 2003). Other studies have established the importance of these packets in momentum and energy transport (Chong et al., 1998; Kim and Adrian, 1999; Guala et al., 2006; Natrajan and Christensen, 2006).

While previous studies have reported significant turbulent kinetic energy (TKE) content at streamwise scales of several δ (Jimenez, 1998; Kim and Adrian, 1999), recent experiments indicate that the LMRs observed in δ-scale PIV studies are likely sub-regions of much longer, coherent *superstructures* (or very-large-scale motions, VLSMs) that can extend several outer length scales, δ, in the streamwise direction (Ganapathisubramani et al., 2006; Hutchins and Marusic, 2007a,b). Hutchins and Marusic (2007a) used Taylor's hypothesis to reconstruct streamwise-elongated spatial velocity fields using time traces of streamwise velocity from a rake of 10 hot-wire probes spaced in the spanwise direction. These reconstructed fields revealed that log-layer LMRs can actually extend 10—20δ in the streamwise direction and often meander significantly in the spanwise direction. Scales of this streamwise extent are not only energetic but also account for a majority of the Reynolds shear stress within the log layer (Guala et al., 2006; Balakumar and Adrian, 2007). Kim and Adrian (1999) postulated these scales to be the imprint of trains of hairpin packets advecting in a coherent fashion. In fact, Dennis and Nickels (2011b) found experimental support for this hypothesis by applying Taylor's hypothesis to time-resolved stereo-PIV measurements in a cross-stream plane. In addition, they observed that long structures in turbulent boundary layers at moderate Reynolds numbers (Re) are not likely to extend beyond 9δ in the streamwise direction, and attributed the observation of VLSMs longer than 10δ to improper use of thresholding at structure identification.

Mathis et al. (2009) reported that superstructures amplitude modulate the near-wall smaller scales in smooth-wall turbulence, with this modulation growing with increasing Re. This observation

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is consistent with recent evidence indicating the development of an outer-layer peak in the pre-multiplied energy spectra of streamwise velocity fluctuations, centered roughly at the mid-point of the log-layer. This peak is predominantly associated with energy content at streamwise scales of several δ and has been hypothesized as the energetic signature of superstructures (Hutchins and Marusic, 2007b; Mathis et al., 2009). Similar amplitude-modulation observations were reported by Chung and McKeon (2010) in LES of turbulent channel flow at high Re with a long streamwise domain. Finally, Mathis et al. (2011) proposed a simple near-wall model for streamwise velocity in smooth-wall flow based upon this amplitude modulation effect. Thus, understanding the characteristics of these superstructures, particularly outside of the canonical, smooth-wall paradigm, is critical for advancing our understanding of more practical flow scenarios.

In this regard, while most wall-bounded engineering flows suffer from some level of roughness effects, the impact of surface roughness on this structural skeleton of smooth-wall flow is still unresolved. While some efforts indicate that roughness alters the structural and/or statistical attributes of the flow across the boundary layer (Krogstad and Antonia, 1994; Keirsbulck et al., 2002; Tachie et al., 2003, for example), other studies (Ligrani and Moffat, 1986; Raupach et al., 1991; Flack et al., 2005, among others) indicate that the effect of roughness is confined within the roughness sublayer ($\sim 3-5k$, where k is the characteristic roughness height) – even for flows in the presence of significant topographical complexity (Allen et al., 2007; Wu and Christensen, 2007, 2010; Mejia-Alvarez and Christensen, 2010). This latter notion is a reflection of outer-layer similarity (Raupach et al., 1991) wherein at high Re, surface conditions set the wall shear stress and δ, while the outer-layer turbulence adjusts itself to these conditions in a universal manner. Jimenez (2004) suggested $\delta/k > 40$ as a necessary condition for outer-layer similarity to exist. While some studies seem to contradict this condition (Antonia and Krogstad, 2001; Krogstad et al., 1992), this is not the case when one uses the equivalent sand roughness height k_s to assess this scale separation as δ/k_s (Schultz and Flack, 2005; Flack et al., 2005). In this regard, k_s is a well-established method for comparing bulk roughness effects in wall turbulence from geometrically dissimilar roughness patterns, and Flack et al. (2005) proposed $0 < y \lesssim 3-5k_s$ as a more robust bound for the roughness sublayer.

The PIV measurements of Nakagawa and Hanratty (2001) in the streamwise-wall-normal (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. Volino et al. (2007) observed the spatial signatures of hairpin vortex packets in instantaneous PIV velocity fields in both x–y and x–z planes for flow over woven wire mesh. Two-point correlations indicated a slight reduction in the streamwise spatial coherence close to the wall, compared to smooth-wall flow, that diminished with increasing wall-normal position. Other studies have also reported little impact of roughness on the outer-layer structure based on two-point velocity correlations (Raupach et al., 1991; Volino et al., 2007; Flores et al., 2007; Wu and Christensen, 2007; Mejia-Alvarez and Christensen, 2010), though Hong et al. (2011) reported a roughness signature in u' spectra that persisted in the outer layer. Finally, Wu and Christensen (2010) reported that while irregular roughness altered the streamwise coherence of the large scales, elongated LMRs bounded by wall-normal vortex cores, consistent with hairpin packets, still populated this flow at the outer edge of the roughness sublayer.

To the date, few studies have considered the effect of roughness on the coherence of superstructures, particularly within the roughness sublayer for scenarios with only moderate scale separation between k (or k_s) and δ. For example, Hutchins et al. (2012) utilized a spanwise array of sonic anemometers to measure velocity time series in the atmospheric surface layer over mildly-rough terrain (transitionally rough given $k_s^+ \sim 21$) and used Taylor's hypothesis to reconstruct streamwise-elongated spatial velocity fields as in their previous lower-Re laboratory studies (Hutchins and Marusic, 2007a). These reconstructed fields revealed meandering superstructures in the logarithmic region of this high Re flow [$\mathrm{Re}_\tau \sim O(10^6)$], remarkably consistent with their previous smooth-wall laboratory observations. These results lend further support to the notion that the outer-layer structure of rough-wall flow is relatively immune to the direct influence of roughness. However, it must be noted that significant scale separation existed between k_s and δ in this flow ($\delta/k_s \sim 30{,}000$) and these observations were made well outside of the roughness sublayer – the region where the direct impact of roughness is strongest (while $3-5k_s$ demarcates the roughness sublayer, these measurements occurred at $y \approx 1070k_s$). Thus, while these measurements support that the outer-layer structure of the flow is relatively immune to roughness effects in the scenario of significant scale separation between k_s and δ, there are many practical flows for which this scale separation is more moderate, resulting in direct perturbation of the log-layer structure by roughness.

Of relevance, Birch and Morrison (2011, 2012) conducted hot-wire measurements in turbulent channel flow over grit-type roughness at $4800 \lesssim \mathrm{Re}_\tau \lesssim 5500$. This roughness pattern presented a non-Gaussian distribution of scales, with the larger roughness elements randomly arranged in a sparse and isotropic manner. Roughness effects were observed to extend up to $y/h \approx 0.04$ (where h is the channel half-height), meaning that the roughness sublayer extended to $y^+ \approx 220$ at most. Assuming a logarithmic region in channel flow over the wall-normal extent $30 \lesssim y^+ \lesssim 0.3h^+$ (with $y^+ = 0.3h^+ \approx 1650$ at most for this study), one can infer that the roughness sublayer and the logarithmic region of the flow overlapped by about 12% of the logarithmic region at most. The authors observed that large-scale motions within the logarithmic region (at $y/h = 0.15$, but outside of the roughness sublayer) exhibited longer streamwise autocorrelations than their smooth-wall counterparts. This result suggests that perturbations in the logarithmic region introduced by a mild overlap with the roughness sublayer might alter the large-scale organization of the flow.

Finally, Mejia-Alvarez and Christensen (2013) recently conducted wall-parallel stereo-PIV measurements deep within the roughness sublayer of a turbulent boundary layer over a highly irregular surface, with moderate scale separation ($\delta/k_s \sim 49$ and $\delta/k \sim 24$, where k is taken as the average peak-to-valley roughness height). They observed δ-scale, streamwise elongated low- and high-momentum pathways in the mean streamwise velocity, fixed at well-defined spanwise locations. As a result, turbulence statistics that would exhibit a homogeneous distribution in smooth-wall flows, presented strong spanwise heterogeneity. Mejia-Alvarez and Christensen (2013) hypothesized that these low-momentum pathways could be the imprint of trains of hairpin vortex packets channeled through preferential paths owing to the roughness below. Building on this work, the present contribution explores the persistence of meandering superstructures in the roughness sublayer of a turbulent boundary layer with moderate scale separation between the roughness and the flow: $\delta/k_s \sim 49$ and $\delta/k \sim 24$, with the logarithmic region of this flow residing at $100 < y^+ < 0.15\delta^+ \approx 784$ (Mejia-Alvarez and Christensen, 2013). With these measures, the logarithmic layer is either 62% or fully contained within the roughness sublayer (depending on whether the latter is defined by $y^+ < 5k_s^+ \approx 523$ or $y^+ < 5k^+ \approx 1097$, respectively). Therefore, the effect of roughness in the present experiment could directly interact with log-layer motions. In addition, as will be reported later, $k_s^+ \approx 107$ for the present study which confirms that the flow under study is in the fully-rough regime. High-frame-rate PIV measurements in a wall-parallel plane within the roughness