High Reynolds number wall turbulence over smooth and rough surfaces

Ivan Marusic*
*Melbourne School of Engineering
University of Melbourne
Victoria 3010, Australia
Email: imarusic@unimelb.edu.au, Web page: http://people.eng.unimelb.edu.au/imarusic/index.html

ABSTRACT

Turbulent boundary layer flows have been studied for many decades, and indeed this is fully justified given the importance of these flows in a vast array of applications. Invariably, in marine applications these wall-bounded turbulent flows evolve over hydrodynamically rough walls, and to date there have been little high-fidelity data for rough wall flows under high Reynolds number conditions. Here we present measurements of turbulent boundary layers above smooth walls and sandpaper roughness across a wide range of friction Reynolds numbers, and equivalent-sandgrain-roughess Reynolds numbers. For the laboratory rough-wall measurements, the mean wall shear stress is determined using a floating element drag balance. Detailed comparisons are made between the smooth and rough-wall cases, including measurements made using multi-component hot-wires and large and small-field PIV.

The measurements cover nearly an order of magnitude in friction Reynolds number (Re_τ) while spanning the transitionally to fully rough regimes (equivalent sand-grain-roughness range, $k_s^+ = 37{-}98$), and in doing so also maintain very good spatial resolution. Distinct from previous studies, the inner-normalized wall-normal velocity variances, exhibit clear dependencies on both k_s^+ and Re_τ well into the wake region of the boundary layer, and only for fully rough flows does the outer portion of the profile agree with that in a comparable Re_τ smooth-wall flow. Consistent with the mean dynamical constraints, the inner-normalized Reynolds shear stress profiles in the rough-wall flows are qualitatively similar to their smooth-wall counterparts. Quantitatively, however, at matched Reynolds numbers the peaks in the rough-wall Reynolds shear stress profiles are uniformly located at greater inner-normalized wall-normal positions. Comparison of the normalized contributions to the Reynolds stress from the second quadrant (Q2) and fourth quadrant (Q4) exhibit noticeable differences between the smooth- and rough-wall flows. The overall time fraction spent in each quadrant is, however, shown to be nearly fixed for all of the flow conditions investigated. The data indicate that at fixed Re_τ both Q2 and Q4 events exhibit a sensitivity to k_s^+. The present results are discussed relative to the combined influences of roughness and Reynolds number on the scaling behaviours of boundary layers.

A detailed comparison of spectra is also presented between the smooth and rough-wall flows. Temporal and true spatial descriptions of the same flow are available from hot-wire anemometry and high-spatial-range particle image velocimetry, respectively. The results show that over the resolved flow domain, true spatial spectra of smooth-wall streamwise and wall-normal velocity fluctuations agree, to within experimental uncertainty, with those obtained from time series using Taylor's frozen turbulence hypothesis. The same applies for the streamwise velocity spectra on rough walls. For the wall-normal velocity spectra, however, clear differences are observed between the true spatial and temporally convected spectra. For the rough-wall spectra, a correction is derived to enable accurate prediction of wall-normal velocity length scales from measurements of their time scales. Potential violations to Taylor's hypothesis in flows above perturbed walls may help to explain conflicting conclusions in the literature regarding the effect of near-wall modifications on outer-region flow. In this regard, all true spatial and corrected spectra presented here indicate structural similarity in the outer region of smooth- and rough-wall flows, providing evidence for Townsend's wall-similarity hypothesis.