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Non-equilibrium effects on rough-wall turbulent boundary layers

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Rough-wall boundary layers over bio fouled ship hulls experience non-equilibrium conditions due to a variety of reasons related to operating environment and/or design choices. This non-equilibrium could be due to the spatially varying pressure gradients that is typically experienced due to surface contours of the ship hull or due to the spatially heterogeneous roughness due to clustering of marine fouling. Both these conditions lead to challenges in predictions as most of our current design/prediction tools cannot account for non-equilibrium. In this work, we explore both these cases of non-equilibrium through wind tunnel experiments. First, we examine the history effects of different pressure gradients on rough-wall boundary layers and compare that to that of a smooth wall as well as a rough wall operating in zero-pressure-gradient. Second, we examine the response of the flow to finite streamwise patches of roughness, and we attempt to characterize the skin-friction drag and flow phenomena for increasing streamwise length of roughness fetch. Measurements are carried out at University of Southampton's wind tunnel that has a cross-section of 1.2m x 1m and is 12m long. Spatially varying pressure gradients are established by mounting a large airfoil in the freestream and altering its angle of attack. The heterogeneous roughness setup is realized by installing streamwise strips of P24 sandpaper of different lengths and it captures the entire range from homogeneous roughness to impulsive roughness (where the fetch length is comparable to boundary layer thickness).

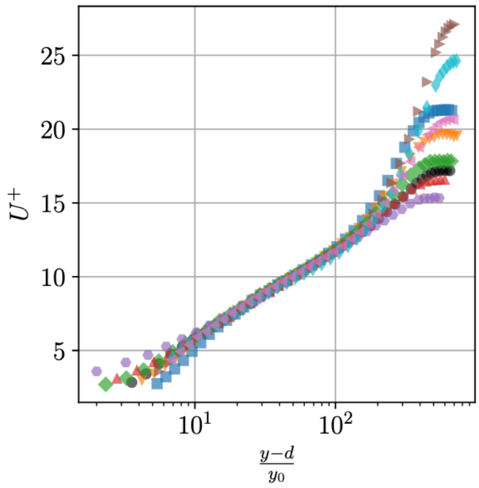

Figure 1: Mean velocity profile of a rough surface for different pressure gradient histories.

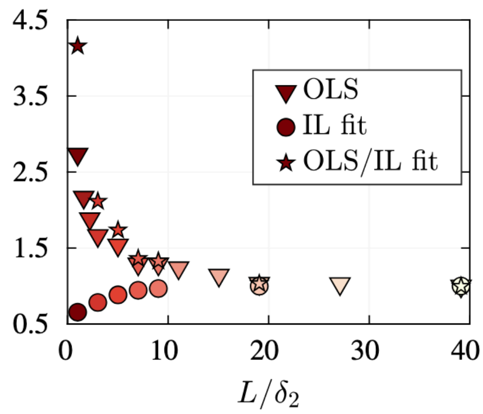

Figure 2: Variation of ks with fetch length. Both log law based ks and Cf based ks are shown.

In both cases, measurements include Particle Image Velocimetry over the entire flow field as well as drag balance measurements to get an accurate estimate of equivalent sandgrain roughness (k_s). For the pressure gradient case, data indicates that k_s is independent of pressure gradient history at high Reynolds numbers as shown in figure 1 where the same k_s value (from ZPG) is used to scale the flows with different pressure gradient histories. Therefore, we only need to account for the effects of pressure gradient to determine the excess skin-friction drag. The flow itself responds to the pressure gradient with a lag and this lag appears to be dependent on the roughness condition. Therefore, any predictive model must capture this lag effect accurately. For the heterogeneous roughness case, the value of k_s depends on the streamwise fetch of the roughness (as seen in figure 2) and this dependence varies based on our needs. For example, the if we fit k_s to the log region, we get one trend while matching the value of Cf (assuming outer layer similarity) provides an opposite trend. However, these two values converge to that of homogeneous rough surface for large streamwise fetch. The final talk will also present other results from further data analysis related to both types of non-equilibrium.