23rd Australasian Fluid Mechanics Conference - 23AFMC
Sydney, Australia
4 – 8 December 2022

Paper No: AFMC2022-137

# Towards the characterisation of multi-scale roughness for turbulent boundary-layer measurements

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## 1 Introduction - Drag Prediction from Effective Slope

Surface roughness incurs a drag penalty in many engineering flows (Chung *et al.* 2021). Predicting this drag penalty purely from the measurable properties of the roughness topography such as root-mean-square height ($S_q$), skewness ($S_{sk}$) or streamwise effective slope ($ES$) is therefore highly desirable. Amongst these properties, $ES$, which is the mean absolute streamwise gradient of the surface topography, has been shown to be a useful property for predicting the increased drag from the transitionally rough to fully rough regime (Napoli *et al.* 2008). However, whilst both $S_q$ and $S_{sk}$ converge for adequate sample sizes and intervals, $ES$ shows a different behaviour. This is illustrated through an example of a power-law surface (exponent -1.8), shown in figure 1(a). The profile is generated at a spatial resolution of $O(10^{-5}\text{mm})$. In figure 1(b), the roughness properties for this profile are shown as a function of the sampling interval ($\Delta x$). For this range of sampling intervals, convergence is achieved for all other properties except $ES$. This is because for real, multi-scale rough surfaces, as the sampling interval is refined, the integrated effect of small-scale, high-slope roughness features will increase $ES$. Since practical roughness is, in theory at least, resolvable to microscopic levels, the value of $ES$ can essentially be unbounded, leading to erroneous drag prediction.

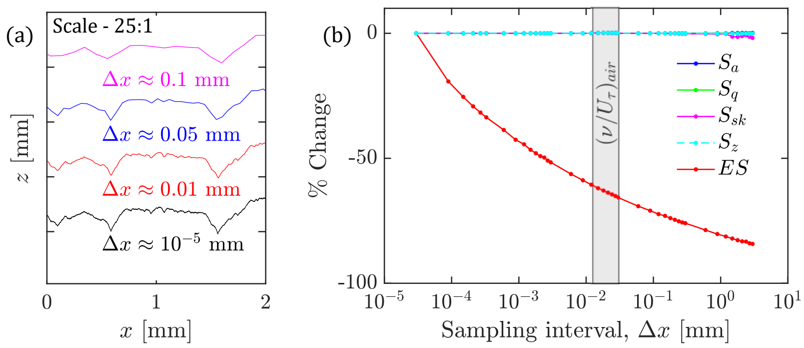


**Figure 1.** (a) Sample of a generated rough surface, $z(x)$, for various sampling intervals $\Delta x$ (shown with an offset to enable comparison). (b) Percentage change in the values of various roughness properties from the value computed at the smallest $\Delta x$. The gray region in (b) indicates the extents of the viscous length scale for air at the typical Reynolds numbers of experiments.

To show this, a realistic, multi-scale rough surface is generated using the MARS algorithm (Jelly & Busse 2019) which was then machined from acetaldehyde co-polymer sheets using an in-house CNC router. The tool, a 2mm diameter ball-nosed cutter, is passed along the $y$-direction with a step-over distance of 0.6mm in the $x$-direction. This introduces small ridge-like features on the finished surface, known as scallops, which have a maximum height of ~0.04mm. The heightmap of the physical surface is obtained directly from the machining toolpath and has a spatial resolution of ~10μm. A sample

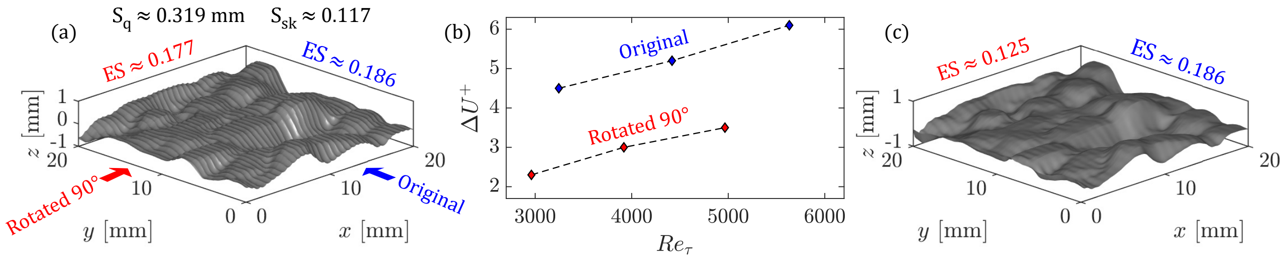


**Figure 2.** (a) Sample of the rough surface used for the measurements, reconstructed from the machining toolpath (tool is passed in the $y$-direction). The flow direction for the two measurement cases are indicated by the arrows with corresponding $ES$ shown by matched colours. (b) Drag penalty, $\Delta U^+$, plotted as a function of $Re_\tau = U_\tau \delta / \nu$. (c) The same heightmap reconstructed with a spectral low-pass filter to smooth the scallops.

of this heightmap is shown in figure 2(a). The roughness properties computed from this heightmap suggest that the rough surface has a nearly matched value of $ES$ for either direction of its orientation with respect to the flow. Therefore, the drag penalty for the Rotated 90° case is expected to be nearly equal to the Original case. To test this, flow measurements were acquired using hot-wire anemometry for the two orientations of the rough surface for $3000 \lessapprox Re_\tau \lessapprox 6000$, where $Re_\tau = U_\tau \delta / \nu$. Here $\nu$ is the kinematic viscosity, $U_\tau$ is the friction velocity and $\delta$ is the boundary-layer thickness. The drag penalty, quantified as $\Delta U^+$, is clearly lower for the Rotated 90° case, as shown in 2(b). This is the case in which the scallops are normal to the flow direction. Our hypothesis here is that the flow does not perceive the increased slope due to the scallops as they are small relative to the viscous length scale, $\nu / U_\tau$. Surfaces are considered to be hydrodynamically smooth if their equivalent sandgrain roughness, $k_s \lessapprox 4\nu / U_\tau$ (Chung *et al.* 2021). For the present case, the maximum height of the scallops $\sim 3\nu / U_\tau$ at the highest $Re_\tau$. Thus, if we apply a filter to smooth out the scallops from the heightmap we obtain a surface, shown in figure 2(c), with a lower slope $ES \approx 0.125$ for the Rotated 90° case, which is consistent with the lower measure of $\Delta U^+$ from the experiment. However, as $Re_\tau$ is increased, the contribution from these scallops may require consideration. To determine this, experiments are currently being undertaken with a set of rough surfaces derived from a single roughness heightmap (a multi-scale, Gaussian surface with $ES \approx 0.13$) but manufactured with a systematically increased step-over distance of the machining tool. The benchmark case is one for which the maximum scallop height is $\sim 0.3\nu / U_\tau$, i.e. it is nearly identical to the numerically generated surface. The maximum scallop height is varied from this benchmark to $\sim 12\nu / U_\tau$, increasing the measured $ES$, while keeping other parameters matched. The flow based characterisation of the rough surface can thus be determined.

## 2 Conclusions

Steep gradients of small features on real, multi-scale rough surfaces can lead to artificially high values of $ES$ that do not accurately predict their drag penalty. To accurately characterise such surfaces for drag prediction, flow dependant filtering may be required. This is crucial not only for drag prediction, but also for scanning, replicating and meshing (for CFD) of rough surfaces.

## References

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