WALL-BOUNDED TURBULENCE OVER HIGHLY POSITIVELY AND NEGATIVELY SKEWED ROUGHNESS

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Summary While most engineering rough surfaces have only moderately skewed height distributions, examples of irregular rough surfaces with very high positive or negative skewness are not unusual. In the current study, the fluid dynamic properties of a set of seven irregular rough surfaces with skewness varying from -2.3 to $+2.3$ are investigated using direct numerical simulations of turbulent channel flow. We observe that the roughness function saturates both for very high positive and very high negative skewness, showing that extrapolation of existing empirical correlations for moderate skewness will overpredict the roughness effect for extremely skewed cases.

INTRODUCTION

The fluid dynamic effects of a rough surface are known to increase with the roughness height but are also influenced by a number of other topographical parameters. Amongst these, the skewness of the height distribution Ssk has been identified as a key topographical parameter [1]. The effect of surface skewness on wall-bounded turbulence has been the subject of both experimental [2] and numerical [3] investigations. However, the skewness values covered in these studies encompass only a relatively narrow range for this parameter not exceeding $Ssk \approx \pm 1$. When surveying the skewness and kurtosis Sku values of typical engineering rough surfaces (see map shown in figure 1(a)), we observe that while many rough surfaces have only moderately skewed height distributions, cases with $Ssk \gg 1$ or $Ssk \ll -1$ commonly occur. For example, surfaces affected by light calcareaous tubeworm-fouling display high skewness and kurtosis [4], as the sparse tubeworm features cause sharp local deviations relative to surrounding smaller-scale roughness features. The aim of the current study is a systematic investigation of rough surfaces with extreme skewness values, and to test existing empirical correlations developed in the context of previous studies for more moderately skewed roughness [1, 2].

NUMERICAL METHOD

The fluid dynamic properties of seven different rough surfaces with Ssk ranging from -2.3 to $+2.3$ have been investigated using direct numerical simulations of turbulent channel flow.

All rough surfaces have been generated using the surface generation algorithm of Patir [5, 6]. The heightmaps are then passed through a low-pass Fourier filter to generate smoothly-varying rough surfaces [7]. Two representative examples of the resulting rough surfaces are illustrated in figure 1(b). All surfaces have been scaled to the same mean-peak to valley height and have closely matched values in effective slope ($ES \approx 0.2$) to allow the current study to focus on the effects of the higher moments of the height distribution. The skewness and kurtosis values of the investigated cases are representative of values typically found for engineering rough surfaces (see figure 1(a)).

For each surface, a direct numerical simulation of turbulent channel flow at $Re_\tau = 395$ with constant mean streamwise pressure gradient has been conducted. Uniform grid spacing ($\Delta x^+ = \Delta y^+ = 4.94$) and periodic boundary conditions were applied in the streamwise and spanwise directions. In the wall-normal direction, uniform grid spacing was used within the roughness layer ($\Delta z^+_{\text{min}} = 0.67$). Above the highest roughness peak, the wall-normal grid spacing was gradually increased reaching $\Delta z^+_{\text{max}} \approx 5$ at the channel centre.

RESULTS

The roughness function, ΔU^+, and mean streamwise velocity profiles (see figure 2) show that the roughness effect increases with Ssk for moderate values of Ssk consistent with trends observed in previous studies. Outer-layer similarity of the mean streamwise velocity profile is recovered in all cases. However, for very highly positively and negatively skewed cases, the roughness effect saturates - no significant further increase in ΔU^+ is observed as Ssk is increased above 1; similarly, ΔU^+ stays constant for high negative values of $Ssk \leq -1.5$. The observed behaviour can be approximately fitted by a tanh-function. Extrapolation of existing empirical correlations for positively and negatively skewed surfaces [2] to $Ssk > 1$ or $Ssk < -1$ would predict an increase in the roughness function for both high positive and high negative skewness. This difference in behaviour between moderately and extremely skewed surfaces could be attributed to the fact that very highly skewed surfaces are typically characterised by a sparse distribution of extreme roughness peaks or very deep roughness pits embedded into a 'background roughness' composed of smaller roughness features. In contrast, moderately skewed surfaces typically display a much more dense distribution of pits ($Ssk < 0$) or peaks ($Ssk > 0$).

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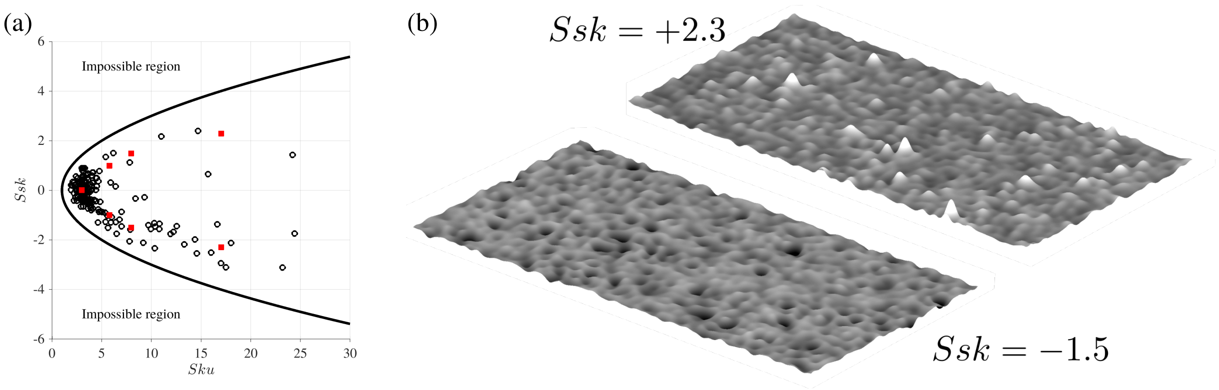

Figure 1: (a) Map of skewness and kurtosis values (black circles) reported for engineering surfaces (for details refer to [8]); the filled red squares indicate the configurations investigated in the current study. (b) Two representative examples of the generated surfaces: case $Ssk = +2.3$ and case $Ssk = -1.5$.

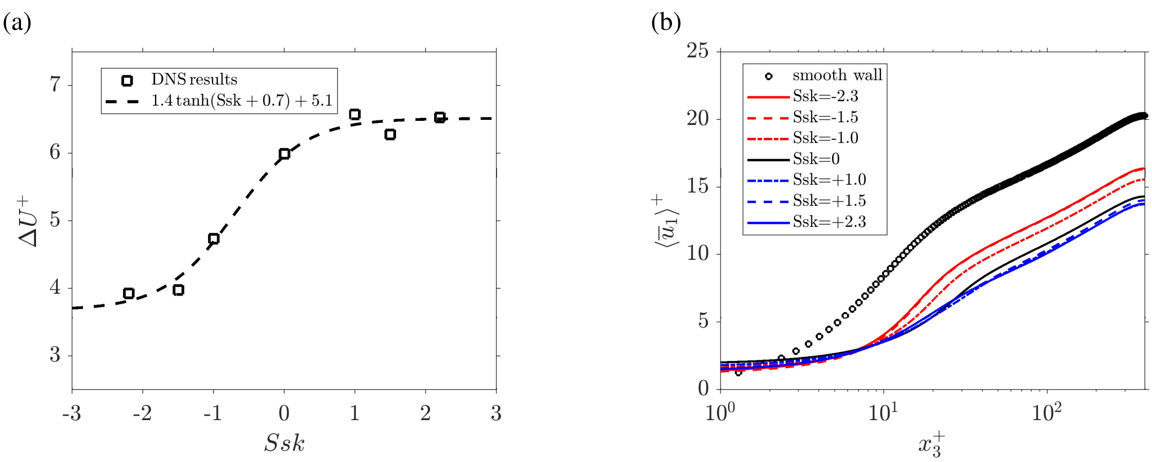

Figure 2: (a) Roughness function ΔU^+ versus skewness Ssk. (b) Mean streamwise velocity profiles.

CONCLUSIONS

Direct numerical simulations of turbulent channel flow over highly positively and negatively skewed surfaces were performed at a friction Reynolds number of 395. The highly skewed surfaces show a saturation in the roughness function for both very high positive and negative values of Ssk (see figure 2). This demonstrates that the fluid dynamic behaviour of highly skewed surfaces cannot be extrapolated from results obtained for more moderately skewed surfaces [1, 2]. A detailed analysis of the turbulent velocity fluctuations, the surface pressure statistics, and their dependence on surface skewness is currently ongoing.

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