

FULLY ROUGH BEHAVIOUR OF RIBLETS AND RIDGES WITH DIFFERENT CROSS-SECTIONAL SHAPES

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INTRODUCTION

Many turbulent flows are exposed to surfaces with heterogeneous properties. The effect of such surfaces on turbulent properties and drag is of great interest, especially for technical applications.

The influence of a structured surface on the flow can be evaluated by the shift ΔU^+ it induces in the logarithmic region of the viscous-scaled mean velocity profile

$$U^+ = \frac{1}{\kappa} \ln y^+ + B - \Delta U^+, \quad (1)$$

where the von Kármán constant κ and the empirically determined constant B are the same as for a smooth surface. The quantity ΔU^+ is known as the roughness function.

In case of k-type roughness, a fully rough regime in which the roughness function can be described as a logarithmic function of the roughness characteristic length scale is reached.

$$\Delta U^+ = \frac{1}{\kappa} \ln l_g^+ + B \quad (2)$$

In this work, the characteristic length scale l_g^+ is the square root of the groove cross section [1] scaled in viscous units (see Figure 1 for reference).

The fully rough regime of k-type roughness is known to be due to the predominance of pressure drag over viscous drag. However, also trapezoidal riblets and ridges have been found to follow the fully rough curve in their drag increasing regime, even though the structures which are aligned with the streamwise direction do not induce pressure drag.

This project investigates the emergence of the fully-rough regime for streamwise-aligned ridge geometries, comparing sharp-edged and smoother cross-sectional shapes. Additionally, characteristic features in the flow statistics are analysed with the final aim of predicting the onset and the extent of this regime at different viscous ridge sizes.

METHODOLOGY

In this work, we complement data for trapezoidal riblets and ridges from the work by von Deyn *et al.* [2] with data for ridges with rectangular and half-circular cross-section. Sketches of all surfaces are depicted in figure 1, the geometrical dimensions can be found in table 1. All ridges are elongated in the streamwise direction.

In the experimental campaign, the roughness function is obtained indirectly based on pressure drop measurements along the surfaces which are used to calculate the friction coefficient. Based on the work of Gatti and Quadrio (2016) [3], the

roughness function can be calculated as

$$\Delta U^+ = \frac{1}{\kappa} \ln \sqrt{\frac{C_f}{C_{f,0}}} + \sqrt{\frac{2}{C_{f,0}}} - \sqrt{\frac{2}{C_f}} \quad (3)$$

being C_f and $C_{f,0}$ the friction coefficients of the ribbed and smooth surfaces, respectively, evaluated at the same bulk Reynolds number.

Hot-wire anemometry (HWA) data were also collected for two selected viscous sizes of the rectangular ridge geometry, enabling a more detailed characterization of the flow field above these structured surfaces.

The experimental dataset is complemented by a numerical one, obtained through DNS [4], for ridges of trapezoidal and semi-circular cross section. DNS data allows easier access to statistics in the near wall region, and to evaluate ΔU^+ values directly from the mean velocity profiles.

RESULTS AND DISCUSSION

The experimental and numerical results are shown by means of ΔU^+ over l_g^+ in figure 2. In addition, reference curves representing the fully rough asymptote are shown as dashed lines.

In the experiments, drag reduction is observed for the trapezoidal riblets only. For all other surfaces, the ΔU^+ values fall in the drag-increasing regime, as the l_g^+ -values are always above 20 wall-units. The data from the trapezoidal riblets/ridges follow the fully rough asymptote in the range $10 < l_g^+ < 40$ before starting to deviate from it. For the other surface types, the minimum reached l_g^+ values from the experiments are too high to determine whether a fully rough regime is taking place. However, the DNS data for the half-circular cross section suggests that a fully-rough regime is present also for such cross-section shape, proving that such regime is not related to the presence of sharp corners in the wall geometry.

The behaviour of the rectangular ridge geometry differs slightly from that of the other cross-sectional shapes. For low l_g^+ , the increase in ΔU^+ appears less steep, and the pronounced peak at $l_g^+ \approx 50$ observed for the other geometries is not evident for RR. Nevertheless, the curve still seems to approach the fully rough asymptote with decreasing l_g^+ . As numerical data for this surface type are not yet available, the behaviour at lower l_g^+ remains an open question and requires further investigation.

Hot-wire measurements enable a look into the flow field above the rectangular ridge surface. The measurements are taken at two different Reynolds numbers, corresponding to

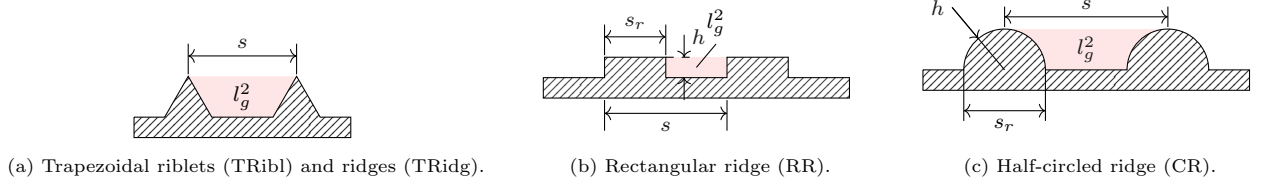


Figure 1: Sketches of the investigated surfaces. The red area between two ridges marks l_g^2 . All geometrical parameters are specified in Table 1.

	h/s	s_r/s	Experiments		DNS	
			s/δ	l_g^+	s/δ	l_g^+
TRibl	0.48	0.48	0.05	$6 \div 70$	-	-
TRidg	0.38	0.43	0.44	$28 \div 540$	[0.10 0.22 0.44]	$20 \div 200$
RR	0.17	0.50	0.47	$21 \div 290$	-	-
CR	0.25	0.50	0.63	$40 \div 525$	[0.10 0.15]	$10 \div 40$

Table 1: Geometrical parameters and l_g^+ range for the experimental and DNS investigations.

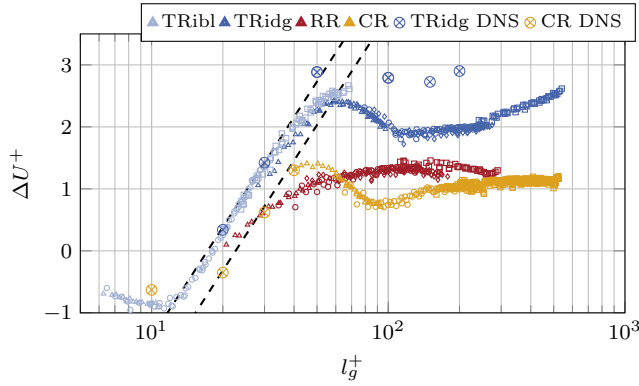


Figure 2: ΔU^+ over l_g^+ for the structured surfaces. Black dashed lines represents the slope for the fully rough asymptote with $\kappa = 0.39$ (as in Ref.[2]). Crossed circles represent DNS results.

$l_g^+ \approx \{73, 137\}$ and $\Delta U^+ \approx \{1.19, 1.31\}$, respectively. The results are shown in figure 3 by means of mean streamwise velocity, normalized by the global bulk velocity in the test section. The black lines depict lines of constant velocity, in the following referred to as isovels. It can be seen that the influence of the surface structures is restricted to the vicinity of the wall (up to $y/\delta \approx 0.2$) as the isovels start to bulge around the ridge with increasing Reynolds number and thus increasing l_g^+ , whilst the flow in the channel centre is unaffected. In investigations on drag and corresponding flow fields above heterogeneous rough surfaces, a correlation of increasing flow field heterogeneity and increasing drag has been found [5]. Such a correlation is also observed in the existing data set. However, it remains to be investigated whether an increase in heterogeneity of the flow field is also observed for the fully rough range.

Further analysis of the HWA and DNS datasets will enable a more detailed characterization of the mean flow and Reynolds stress distributions in the near-wall region, as well as a quantitative assessment of the relationship between wall-normal extent of the flow heterogeneity along z and the resulting ΔU^+ values.

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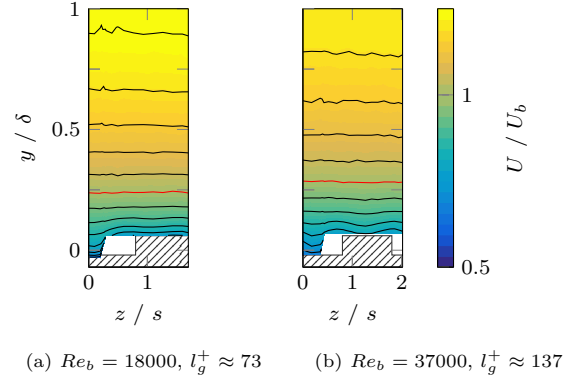


Figure 3: Mean streamwise velocity field normalized with the bulk velocity (U_b) over the rectangular ridge surface.

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