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# REGULAR AND IRREGULAR SURFACES IN TURBULENT CHANNEL FLOWS

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Rough surfaces are often encountered in many practical applications, and have been studied by laboratory and numerical experiments. Nikuradse (1933) [4] investigated in a laboratory experiment the Reynolds number dependency of the friction coefficient in round pipes roughened by sand grains. These surfaces can not be classified by the statistics of their surface thickness, and are therefore difficult to reproduce. Other experiments analyzed the flow past two and three-dimensional regular surfaces. Until now, numerical experiments considered regular surfaces (Orlandi (2013) [5]), that leads to a decrease or an increase of the drag depending on the shape of the surface. It was observed that the drag reducing geometries generate ordered and more anisotropic structures than those near smooth walls. The size of the grooves is an important parameter: when it is small, the coherent near wall structures do not penetrate inside the grooves (Choi et al. (1993) [2]).

In the present simulations, a turbulent channel at $Re = 4200$ ($Re_{bulk} = 2800$) in presence of several rough surfaces is investigated. Some of the simulations are repeated at $Re = 12600$ to study the influence of the Reynolds number on the drag, and to verify the Townsend similarity hypothesis (Townsend (1976) [7]). The roughness is located only on the bottom wall. The interaction between the flow and the surface is reproduced by the immersed boundary technique, described in Orlandi and Leonardi (2006) [6]. The regular surfaces consist of square and triangular bars and staggered rows of cubes of height $k_{max} = 0.2h$. The irregular surfaces are generated from the flow in a turbulent smooth channel in a plane parallel to the wall at a distance $y^+ = 12$. Two surfaces are considered, one with thickness proportional to the streamwise fluctuating velocity component, and the other to the pressure. The maximum peak to valley depth is set equal to $0.2h$. The surfaces thus obtained have well defined values of any order statistics, but the large fluctuations associated require a huge number of grid points. An iterative smoothing procedure has been applied to reduce the number of grid points in $x$ and $z$, yet maintaining the irregularity of the surfaces shown in figure 1. The smoothing, applied to the staggered cubes, produces a regular wave-like surface.

Table 1 reports the total drag $T_D = \tau_R/\tau_S$ defined as the total stress at the plane of the crests $\tau_R$, scaled with $\tau_S$ at the smooth wall. The viscous drag $V_D = \nu(\frac{\partial U}{\partial y})_R/\tau_S$ and the form drag $F_D = \langle uv\rangle_R/\tau_S$ are the two contributions to $T_D$. The triangular riblets (TS) yield the highest drag reduction, of about 8.5%, which is not achieved at a higher Reynolds number (TSR). This occurs because the roughness height in this case is $k^+ = 105$ plus units ($k^+ = 31$ in TS), therefore the vortices penetrate between the roughness elements and the drag reduction effect is lost. The irregular surface proportional to $U_1$ gives a drag reduction lower than for TS. The contributions to $T_D$ show that $F_D$ is larger and $V_D$ is smaller

(a)

(b)

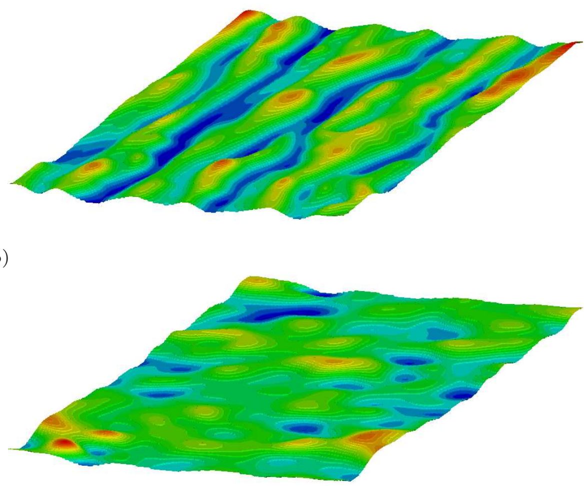

Figure 1: Irregular surfaces obtained from streamwise velocity U1 (a) and pressure PR (b) at $y^+ = 12$, coloured by the height

than those for TS. This is due to the smaller solid area for U1 at the plane of the crests, allowing a greater $\langle U\rangle_R$, implying a lower mean shear $(\partial U/\partial y)_R$.

Orlandi (2013) [5] identified the vertical stress at the plane of the crests $\tilde{v}_R^+ = \langle v'^2\rangle_R^{0.5}$ as the scaling parameter for the roughness function: $\Delta U^+ = B\kappa^{-1}\tilde{v}_R^+$ (figure 2a). The present simulations together with those in Orlandi (2013) [5] show that the turbulent viscosity normalized with the molecular viscosity $\nu_T/\nu = F_D/V_D$ is related to $\tilde{v}_R^+$, in particular $\nu_T/\nu = 9.4(\tilde{v}_R^+)^4$ (figure 2b). These relationships support the idea that $\tilde{v}_R^+$ is linked to the shape of the rough surfaces and, acting as a boundary condition, affects the overlying turbulent flow. The relationship for $\nu_T/\nu$ may be of help in RANS simulations, particularly for the Spalart-Allmaras model. Aupoix and Spalart (2003) [1] rely on the imposition of the turbulent viscosity at the interface as a boundary condition to reproduce the roughness. What at the moment is missing is a connection between $\tilde{v}_R^+$ and the geometrical parameters of the surface. A parametrization of the surface, by means of the effective slope introduced by Napoli et al. (2008) [3] will be investigated.

## REFERENCES

[1] B. Aupoix and P. R. Spalart. Extensions of the spalart-allmaras turbulence model to account for wall roughness. *Int. J. Heat Flow*, 24:454–462, 2003.

[2] H. Choi, P. Moin, and J. Kim. Direct numerical simulation

| Surface | $Re_{\tau,R}$ | $Re_{\tau,S}$ | $T_D$ | $V_D$ | $F_D$ | $h_R$ | $\tilde{v}_R^+$ |
|---|---|---|---|---|---|---|---|
| CH | 177 | 178 | 1.000 | 1.000 | 0.000 | 1.000 | 0.000 |
| SC | 356 | 126 | 2.000 | 0.614 | 1.380 | 1.346 | 0.817 |
| SL | 199 | 170 | 1.150 | 0.818 | 0.330 | 1.042 | 0.515 |
| ST | 216 | 160 | 1.250 | 1.150 | 0.103 | 1.109 | 0.283 |
| TR | 186 | 162 | 1.100 | 0.305 | 0.798 | 1.041 | 0.701 |
| TS | 155 | 182 | 0.915 | 0.650 | 0.265 | 0.942 | 0.365 |
| U1 | 165 | 172 | 0.954 | 0.343 | 0.611 | 0.992 | 0.585 |
| PR | 188 | 165 | 1.090 | 0.287 | 0.807 | 1.042 | 0.721 |
| CS | 394 | 123 | 2.260 | 0.358 | 1.900 | 1.361 | 0.920 |
| SCR | 1027 | 332 | 2.090 | 0.291 | 1.800 | 1.361 | 1.020 |
| TSR | 525 | 435 | 1.120 | 0.165 | 0.957 | 1.058 | 0.918 |

Table 1: Roughness parameters; Subscripts R and S indicate respectively the rough and smooth wall; $T_D = F_D + V_D$ is the total drag, with $V_D$ and $F_D$ being the viscous and form drag components, normalized with the friction of the smooth wall; $h_R$ is the distance from the rough wall of the maximum of velocity, used as reference length for $Re_{\tau,R}$. The reference length for $Re_{\tau,S}$ is $h_S = 2 - h_R$

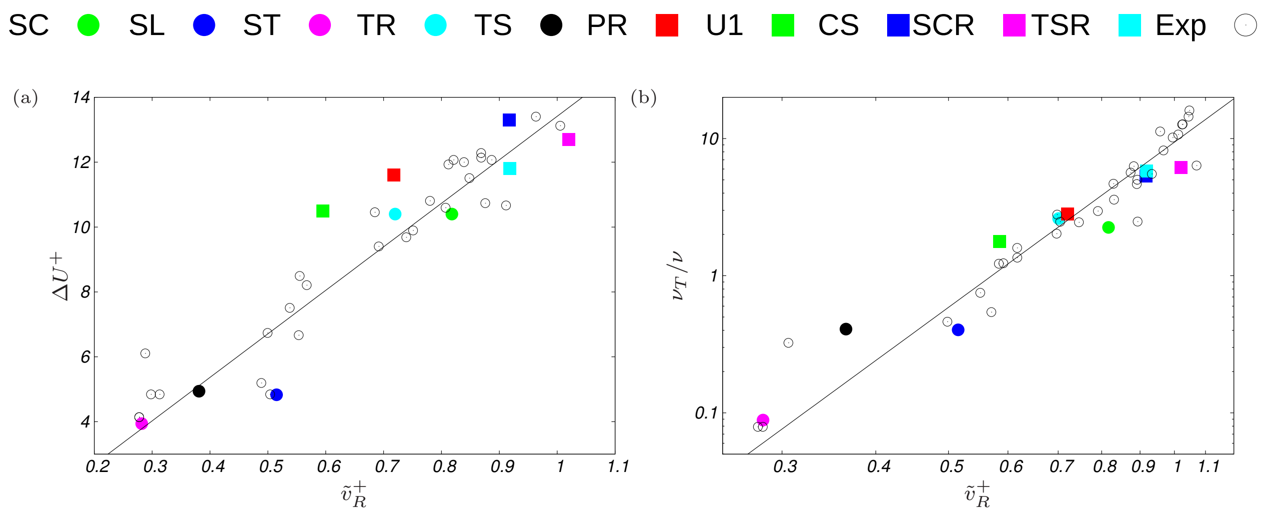


Figure 2: (a) Roughness function $\Delta U^+$ as a function of $\tilde{v}_R^+$. The solid line is $\Delta U^+ = B\kappa^{-}1\tilde{v}_R^+$; (b) Normalized turbulent viscosity versus $\tilde{v}_R^+$. The solid line is $\nu_T/\nu = 9.4(\tilde{v}_R^+)^4$. ● and ■ are the present simulations, ○ are the data in Orlandi (2013) [5]

of turbulent flow over riblets. *J. Fluid Mech.*, 255:503–539, 1993.

[3] E. Napoli, V. Armenio, and M. De Marchis. The effect of the slope of irregularly distributed roughness elements on turbulent wall-bounded flows. *J. Fluid Mech.*, 613:385–394, 2008.

[4] J. Nikuradse. Stromungsgesetze in rauhen rohren (english translation 1950: Laws of flow in rough pipes). NACA Tech. Memorandum 1292, 1933.

[5] P. Orlandi. The importance of wall-normal reynolds stress in turbulent rough channel flows. *Phys. Fluids*, 25:110813, 2013.

[6] P. Orlandi and S. Leonardi. Dns of turbulent channel flows with two- and three-dimensional roughness. *J. Turbul.*, 7:N53, 2006.

[7] A. A. Townsend. *The Structure of Turbulent Shear Flows.* Cambridge University Press, 2nd Edition, 1976.