THE NEAR WALL REGION IN TURBULENT FLOW PAST STEADY AND UNSTEADY ROUGH SURFACES

F. Fabiani
Avio S.p.A.
email fabrizio.fabiani@aviogroup.com

P. Orlandi
Dipartimento di Ingegneria Meccanica e Aerospaziale
Università La Sapienza
Via Eudosiana 16, I-00184, Roma
email orlandi@dma.ing.uniroma1.it

ABSTRACT

In the present study the interest is in the analysis of the friction of the flow past transverse sinusoidal surfaces with the number of waves $\lambda = 5$, $\lambda = 10$ and $\lambda = 20$ moving with a phase velocity $c/U_0 = 0, 0.2$ and 0.4. The turbulent flow develops in a channel of length $L_1 = 8h$ with one wall smooth, and the other with the the surface given by $y = A\cos(k(x_1 - ct))$, where $k = 2\pi\lambda/L_1$ and the amplitude is $A = 0.2h$. The simulations have been performed at $Re = U_0h/\nu = 4200$, which for the smooth channel give a $R_\tau = u_\tau h/\nu = 180$.

INTRODUCTION

The DNS of turbulent flows past rough surfaces has been successful to understand better the complex flow physics and its dependence on the kind of surfaces. The group in Roma produced several papers on this subject, starting with Leonardi *et al.*(2003) ending with Orlandi (2009); in these studies steady rough surfaces of two- and three-dimensional shape were considered. Orlandi *et al.*(2006) validated the numerical simulations by a comparison of the pressure distribution on two-dimensional rods, with that measured by Furuya *et al.*(1976). Regarding the flow physics, Leonardi *et al.*(2003) explained why maximum drag is achieved for square bars at $w/k = 7$ (w is the separation between the square bars and k is the height of the elements). Moreover, Orlandi *et al.*(2003) demonstrated that, the normal velocity distribution on the plane of the crests is the driving mechanism for the modifications of the near wall structures. The results suggested that a new parametrisation for rough flows can be obtained by $\widetilde{u}'_2|_w$, with $\widetilde{u}'_i = \langle u'^2_i \rangle^{1/2}$ (the index $i = 1$ indicates streamwise, $i = 2$ normal and $i = 3$ spanwise directions, angular brackets $\langle\rangle$ averages in the homogeneous directions, and the subscript w values at the plane of the crests). A continuous transition between smooth ($\widetilde{u}'_2|_w = 0$) and rough walls ($\widetilde{u}'_2|_w \neq 0$) was observed. To be effective the parametrisation should lead to an expression for $U^+ = \langle u_1 \rangle^+$ (+ indicates dimensionless wall units obtained with the friction velocity u_{τ_R} of the rough wall) similar to the equation (Schlichting (1976) Pg.582)

$$U^+ = 8.48 + 5.75\log_{10}(y/K_S) = 8.48 + \frac{1}{\kappa}\log(y^+/K_S^+) \quad (1)$$

with K_S, a quantity without direct physical meaning, but allowing to fit the experimental data. This equation can be recast as $U^+ = \kappa^{-1}\log(y^+) + B - \Delta U^+$, where ΔU^+ is the roughness function, accounting for the downwards shift of the log-law for smooth wall canonical channel flow caused by the roughness, B is a constant equal to 5.5, and $\kappa = 0.41$ is the von Karman constant. Orlandi & Leonardi (2008) obtained a simple relationship for the logarithmic velocity profile, in wall units. In their expression, the mean velocity at the plane of the crests U_w, was subtracted to estimate the differences in U between smooth and rough walls, within the viscous and buffer layers. The expression for fully rough flows, with y the distance from the plane of the crests, is

$$U^+ - U_w^+ = \kappa^{-1}\log(y^+) + B(1 - \frac{\widetilde{u}'_2|_w^+}{\kappa}) \quad (2)$$

Orlandi (2009) has also observed in transitional rough channels that only when $\widetilde{u}'^+_2|_w$ is greater than the threshold value of 0.6 there is a transition from a laminar to a turbulent regime. This was demonstrated by changing the shape, the density and the distribution of solid obstacles. The threshold value for $\widetilde{u}'_2|_w^+$ is reached only if the height k^+ of the protuberance is greater than 15, which is a size comparable to that of the near wall streamwise vortices and that was obtained in several transitional experiments.

In the present study the interest is in the analysis of the friction of the flow past transverse sinusoidal surfaces with the number of waves $\lambda = 5$, $\lambda = 10$ and $\lambda = 20$ moving with a phase velocity $c/U_0 = 0, 0.2$ and 0.4. As in the previous simulations the turbulent flow develops in a channel of length $L_1 = 8h$ with one wall smooth, and the other with the thickness of the surface given by $y = A\cos(k(x_1 - ct))$, where $k = 2\pi\lambda/L_1$ and the amplitude is $A = 0.2h$. The comparison between the steady wavy wall and the two dimensional square bars lead to a higher resistance for the former due to the increased oscillations of the recirculating flow in the cavities of the roughness surface.

NUMERICAL METHOD

The numerical methodology was described in several previous papers, but it is worth to shortly summarise the main features of the method consisting in the resolution of the non-dimensional Navier-Stokes and continuity equations for incompressible flows

$$\frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{1}{Re}\frac{\partial^2 u_i}{\partial x_j \partial x_j} + \Pi\delta_{1i}, \qquad \frac{\partial u_j}{\partial x_j} = 0, \tag{3}$$

where Π is the pressure gradient required to maintain a constant flow rate, u_i is the component of the velocity vector in the i direction and p is the pressure. The reference velocity is the centerline laminar Poiseuille velocity profile U_P, and the reference length is the half channel width h. These equations have been discretized in an orthogonal coordinate system through a staggered central second-order finite-difference approximation. The discretization scheme of the equations is reported in chapter 9 of Orlandi (2000). To treat complex boundaries, Leonardi & Orlandi (2006) developed an immersed boundary technique, whereby the mean pressure gradient to maintain a constant flow rate in channels with rough surfaces of any shape is enforced. In the presence of rough walls, after the discrete integration of RHS_1 (right-hand-side in the $i = 1$ direction) in the whole computational domain, a correction is necessary to account for the metrics variations near the body. This Immersed Boundary technique, previously used for steady boundary, has been opportunely modified to impose to the flow a normal velocity equal to the wall velocity $v = \partial y/\partial t = kAc\sin(k(x_1 - ct))$. The evaluation of the metric coefficients at $n + 1/2$ simplify the wall treatment. The method has been tested by reproducing the Mittal *et al.*(2008) results for the flow past an impulsive accelerated cylinder.

On the smooth wall there is only the viscous friction, while on the rough surfaces it is given by several contribution, which have been evaluated and analysed. All the simulations have been performed at $Re = U_0 h/\nu = 4200$, which for the smooth channel give a $R_\tau = u_\tau h/\nu = 180$.

RESULTS

Fig.1a shows the time history, in a short period of time, of the total friction, normalised with the mean friction of the smooth channel Π_0. From this figure the large differences with the smooth channel appear; for the stationary surface with $\lambda = 5$ the friction is large, for the greater unsteadiness of the separation bubble in the cavity, with respect to that in the small cavity with $\lambda = 10$. This result corroborates the results of Leonardi *et al.*(2003) for rectangular cavities with different values of w/k. In addition, Fig.1b shows that the sinusoidal shape with $\lambda = 20$ produces a higher friction than that for square bars with $w/k = 1$, due to the generation of higher fluctuations of the normal velocity component, which, in the previous studies was demonstrated to be the key parameter in flows past rough surfaces (Orlandi & Leonardi 2008). When the $\lambda = 5$ wave travels at a certain speed there is a reduction in resistance, depending on the value of c, and the reduction is even greater for $\lambda = 10$ being also less than that for the smooth channel when $c = 0.4$ (Fig.1a). The large fluctuations of the friction for $\lambda = 20$ travelling at $c = 0.4$ in Fig.1b are related to the high fluctuations of u'_2 emanating from the interior of the cavity and in part also to numerical reasons due to the fact that the pressure has not been corrected, therefore when the distance between the first grid point and the wavy wall becomes very small large gradients occur.

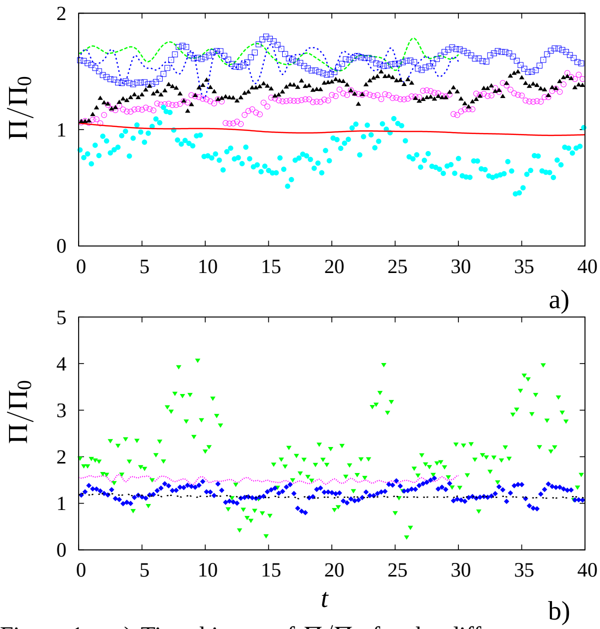

Figure 1. a) Time history of Π/Π_0 for the different cases solid red channel, $\lambda = 5$ dashed green $c = 0$, open squares $c = 0.2$, open circles $c = 0.4$, $\lambda = 10$ dotted blue $c = 0$, solid triangles $c = 0.2$, solid circles $c = 0.4$. b) $\lambda = 20$ dash-dotted blue $c = 0$, solid diamond $c = 0.2$, solid nabla $c = 0.4$, black dot dashed square bars.

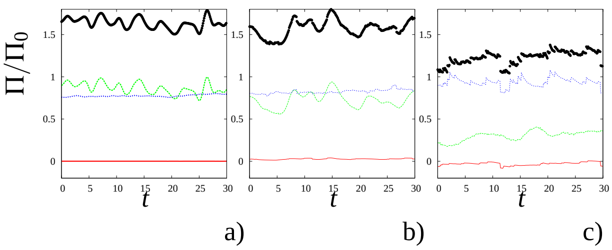

Figure 2. Time history of Π/Π_0 for $\lambda = 5$ a) $c = 0$, b) $c = 0.2$, c) $c = 0.4$ black dot total, red solid non-linear, green dashed pressure, blue dotted viscous.

To understand why the friction decreases by increasing the speed, the different contribution to the drag have been analysed in Fig.2. It has been observed that there is a small reduction of the viscous drag when $c = 0.2$ and that this is mainly related to the reduction of the form drag (Fig.2b). When $c = 0.4$ Fig.2c shows that the reduction of the form drag is much greater leading to a resistance comparable to that of a smooth channel. To understand the effect of the variations of c on shorter waves the analysis is shown in Fig.3 for $\lambda = 10$. It can be observed that the frequencies and the amplitude of the oscillations in Fig.3 are higher than those in Fig.2. Fig.3c shows that for $c = 0.4$ the resistance in several instants can be smaller than that for the smooth channel. Also in this case the reduction is due to the form drag.

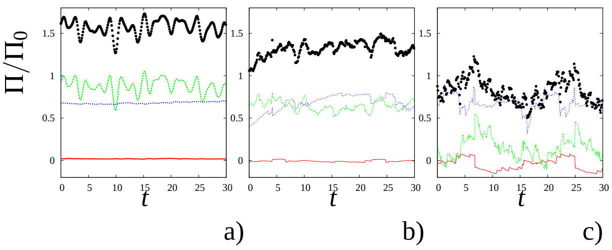

Figure 3. Time history of Π/Π_0 for $\lambda = 10$ a) $c = 0$, b) $c = 0.2$, c) $c = 0.4$ black dot total, red solid non-linear, green dashed pressure, blue dotted viscous.

To have an idea on the changes of the turbulent stresses in the whole channel, the profiles have been evaluated, above the plane of the crests, by averaging a large number of fields in time and in the homogeneous directions x_1 and x_3. These profiles can be of relevance to some engineering applications, for instance in wind energy production the towers are located offshore in the North Sea, where the surface of the sea can be considered as a travelling wave, which, depending on the day can have different phase velocities and wave length. Fig.4 shows the profiles of $\langle u_2'^2 \rangle$ and to emphasize the near wall region a semi-log scale is used. The profiles show that very intense values can be achieved implying that the bursts of u_2' can be so strong to produce damages on the blades. The comparison with the profile for the smooth channel depicts large differences in presence of the rough surface, and that the u_2 fluctuations near wall the plane of the crests, for steady surfaces are smaller than for travelling waves. The greatest values are found for the short wave moving with $c = 0.4$

To understand in more detail the physics of the normal stress in Fig.5 the energy spectra in the streamwise direction has been evaluated just above the plane of the crest. This figure shows peaks in correspondence of the wave number of the surface and that, in accordance with the previous observations, the energy content at these wave number is higher as greater is the propagation velocity c.

Flow visualizations of the u_2 fluctuations at a certain time at the same distance from the plane of the crests where the spectra in Fig.5 have been calculated are of help to understand the distribution of the high peak. To investigate the dependence on the wave length the three flows with $c = 0.4$ have been considered, because of the highest penetration depth of the disturbances for this velocity. In all cases, Fig.6 shows that the strong ejections are in the side of the wave that moves upwards and as it should be expected these affect the central region of the channel in a different measure. This can be appreciated by contour plots, for instance at $x_3 = 2$, in a $x_1 - x_2$ section. The three Fig.7 show that indeed for $\lambda = 20$ the ejections are stronger than for waves with smaller λ. Animations

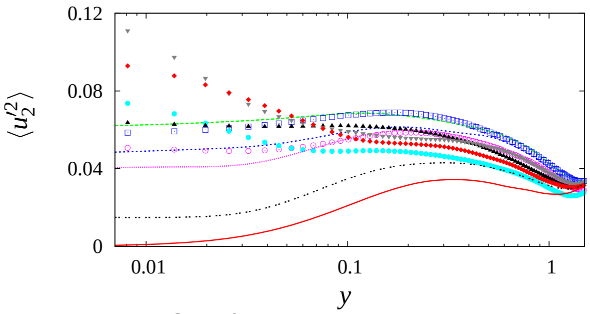

Figure 4. Profiles of the normal stress legend as Fig.1

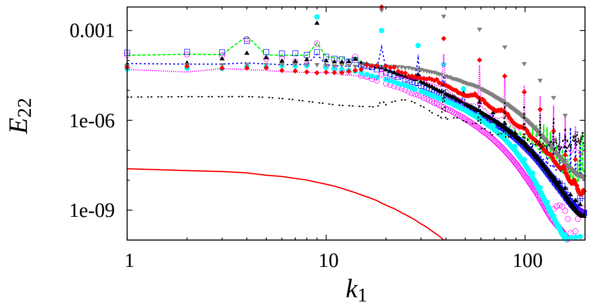

Figure 5. One-dimensional energy spectra at the plane of the crests for u_2 in the streamwise direction, legend as Fig.1

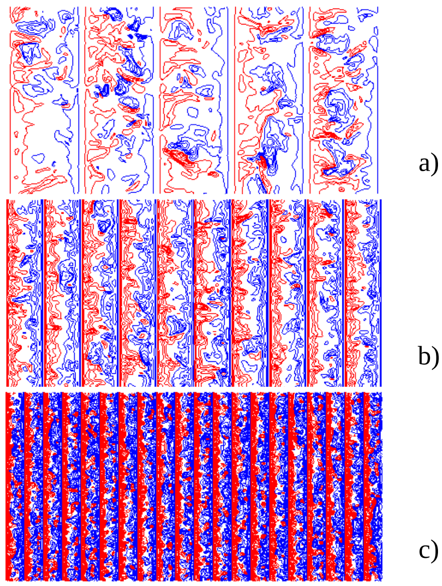

Figure 6. Contour plots of the u_2 fluctuations in a $x_1 - x_3$ section near the plane of the crests for $c = 0.4$ with $\Delta u_2 = 0.4$: a) $\lambda = 5$, b) $\lambda = 10$, c) $\lambda = 20$.

show better than visualizations at one instant the flow complexity near the travelling waves.

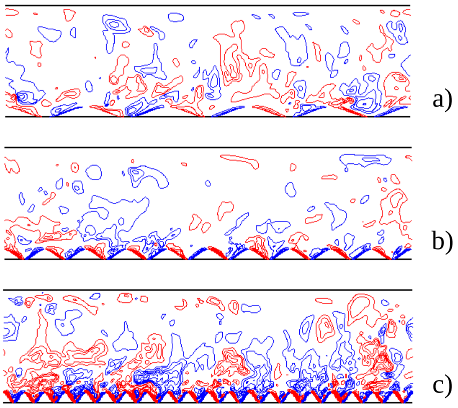

Figure 7. Contour plots of the u_2 fluctuations near the plane of the crests for $c = 0.4$ with $\Delta u_2 = 0.4$: a) $\lambda = 5$, b) $\lambda = 10$, c) $\lambda = 20$.

The profiles of the turbulent stress $\langle u_1' u_2' \rangle$ in the whole channel are given in Fig.8a, where, it is interesting to notice the absence of the expected specularity in the two side of the channel with two small walls. The reason is that this simulation, as all the others, has been initiated from a field obtained with square bars with $w/k = 1$. From this result it can be deduced that the large asymmetric scales do not adjust rapidly, while the near wall structures, in a short transient, form and produce the right amount of turbulence. This stress at the plane of the crests, accounting for the form drag, corroborates the previous observations, that is, that, for $c = 0$, the form drag decreases by increasing the value of λ, and that there is a large dependence on the phase velocity c. It has been checked that the total drag increases linearly with x_2 from the value at the smooth wall (almost the same for any roughness) to that at the plane of the crests. The viscous friction at the plane of the crest is strongly related to the value of U_W, that depends on the shape of the rough surface. Fig.8b shows that the viscous friction is large for the smooth and for the square bars, it decreases by reducing λ, and does not change when the waves are travelling. The experimentalists, in taking measurements in flows past rough walls, can benefit from the constant behaviour predicted by these DNS at low Reynolds number.

In the DNS flow visualizations of the vorticity components allow to show that a certain degree of isotropization is generated near the rough surfaces, and its level is higher as higher is the friction. The large amount of results, in literature, obtained by the DNS in different conditions, allow to draw the conclusion, that to have a low drag the near wall vortical structures should have, as much as possible, a large coherence in the streamwise direction. On the contrary a tendency towards isotropic turbulence implies incoherent structures leading to drag increase. This has been demonstrated by flow visualizations and by two-point correlations. Less emphasis, has been directed to analyse the dependence of the spectra on the roughness and the differences with the spec-

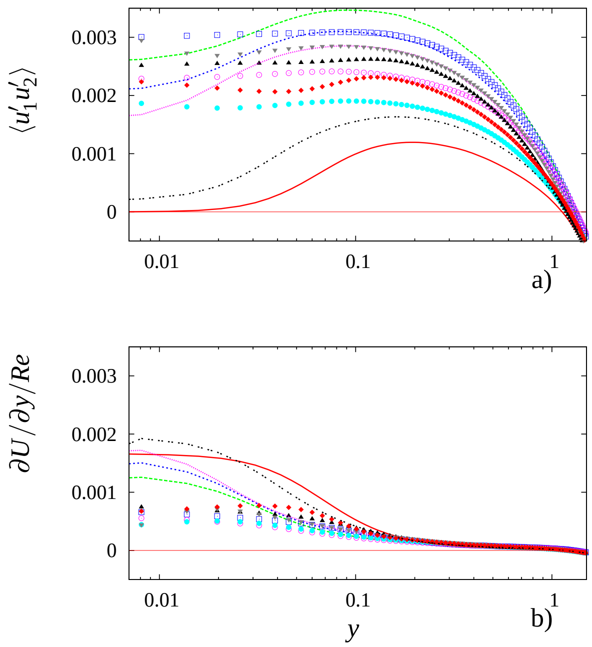

Figure 8. Profiles of a) the turbulent stress and b) the viscous stress, legend as Fig.1

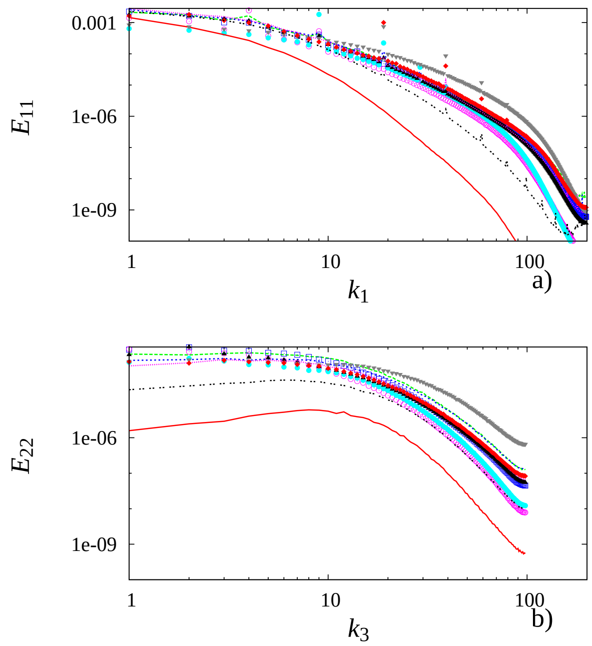

Figure 9. One-dimensional energy spectra at a distance from the plane of the crests $y = 0.05$; a) for u_1 in the streamwise direction, b) for u_2 in the spanwise direction; legend as Fig.1

tra in smooth channel, which were deeply investigated by del' Alamo & Jimenez (2003). Fig.9 shows the one dimensional spectra of u_1' in x_1 and of u_2' in x_3 which give an idea of the shape of the near wall structures. The first peak in Fig.9a is related to the forcing by the wave length of the surface, and the higher harmonics are generated by the flow non-linearity. The common feature in the streamwise and spanwise spectra is given by the higher energy content at the small scales with respect to that in smooth channels. In agreement with the previous arguments the highest energy at the small scales is for the surfaces generating the highest resistance. In Fig.9b when the friction increases the peaks move to low *k*, implying wide near wall structures.

CONCLUSIONS

In this paper are described the preliminary results of DNS of flows past unsteady rough surfaces, constituted by travelling waves. The effects of the phase velocity c and of the wave length λ on the flow resistance have been described and the increase or reduction of the friction has been related to the change of the flow physics near the plane of the crests. To perform the DNS of this kind of flows the Immersed Boundary Technique requires modifications with respect to that used for steady surfaces. The reason why we claim that these are preliminary results is due the difficulty to have an exact mass conservation for unsteady surfaces, which is related to the values of λ and of c. The loss of mass can be related to the fact that regions that, at a certain time, are in the solid at the successive instant are in the fluid, and therefore the results depend at which instant the metric entering in the discretization at the first grid point close to the surface are evaluated. However, despite these difficulties, we think that the main physics has been captured explaining which component contributes to the increase or to the reduction of the total resistance.

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