DNS OF CHANNEL FLOW WITH TWO-SCALE SURFACE ROUGHNESS ON ONE WALL

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Abstract We numerically investigate the influence of two-scale surface roughness on turbulent flow with roughness on one wall. The friction Reynolds number is 400. The two-scale surface roughness influences the rms transverse velocity fluctuation over the smooth wall, which is opposite to the rough wall. The intensity of this fluctuation is a key component in producing the Reynolds stress.

Turbulent flow over a rough wall has been extensively studied, experimentally, theoretically and numerically over the last 100 years and is still the subject of current research [1, 2]. Much of this work has been focussed on surfaces that are either composed of random roughness, or of a periodic distribution of identical roughness elements. But there are many practical situations in which the roughness consists of elements of two distinctly different scales, and experimental studies (e.g. [3]) have shown that the addition of a second small scale roughness can alter the turbulent fluxes in the boundary layer. In this study, the influence is examined using Direct Numerical Simulation (DNS).

The computational domain and the roughness configurations are illustrated in Figures 1 and 2 respectively, and the simulation parameters are provided in Table 1. The computational domain consists of a rough lower wall and a smooth upper wall, and the origin of the coordinate system is located at the centre of the lower wall. Fully developed turbulent flow is driven by a constant streamwise mean pressure gradient, at a friction Reynolds number of 400. The dimensions of the computational domain, normalized by the friction length, are almost identical to those used in previous DNS studies [1, 2], as are the large scale roughness elements. The small scale roughness is created by adding small bars to the top of the large roughness elements as shown in Figure 2(b).

The governing equations are the continuity and the Navier-Stokes equations, solved using the fractional-step method with the RK3/CN scheme for time-integration. The domain was discretized using a fully-staggered grid and conservative finite difference schemes [4] – second order central difference schemes for the x and y directions and a fourth order scheme for the z direction [4]. The spanwise bars were simulated using an immersed boundary method, as in previous studies [1, 2].

The surprising influence of the small scale roughness can be seen by comparing the instantaneous normalized pressure fields ($p^+ = p/\rho u_*^2$) for the flow with and without small scale roughness (Runs 1a and 2a, Figure 3). In general, the small scale roughness increases the pressure around the bars, but the influence extends almost all the way across the channel. Transverse profiles of the mean streamwise velocity U^+ (Figure 4) for different values of the roughness spacing show that the influence of the small scale roughness increases with the spacing of the large scale roughness, but that the influence is most noticeable in the upper half of the channel, far from the roughness elements, where the streamwise velocity increases. Since the imposed mean pressure gradient is the same in all cases, this implies a reduction in surface drag. The small scale roughness also modifies the distribution of the transverse velocity fluctuations v^+_{rms} (Figure 5), but in a way that is almost independent of the spacing of the large scale roughness elements; the small scale roughness consistently enhances v^+_{rms} close to the rough wall and reduces it close to the smooth wall. This is likely to have a significant effect on the structure of the turbulence in the near wall region, through its contribution to the production of Reynolds stress, and this will be described further in the final paper.

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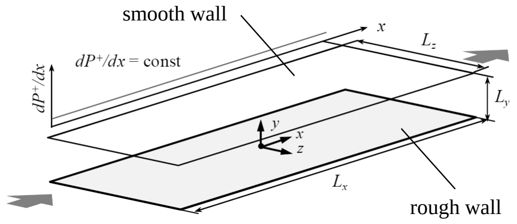

Figure 1. Schematic diagram of the computational domain and the coordinate system ($P^+ = P/\rho u_*^2$ is the mean dimensionless pressure.)

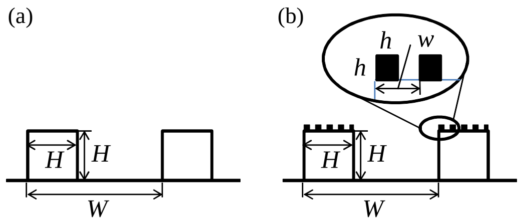

Figure 2. Schematic diagram of the roughness configurations. (a) Large scale roughness (b) Large and small scale roughness

Table 1. Simulation parameters. $N_x \times N_y \times N_z$ is the number of grid points in the x, y and z directions respectively; $\delta = L_y/2$

Run	Symbol	Scale of the roughness	H/δ	H^+	W/H	h/δ	h^+	$L_x \times L_y \times L_z$	$N_x \times N_y \times N_z$
Run 1a	○				2				
Run 1b	△	one-scale roughness	0.1	40	4	-	-	$3.2\delta \times 2\delta \times 1.6\delta$	$512 \times 168 \times 128$
Run 1c	□				8				
Run 2a	●				2				
Run 2b	▲	two-scale roughness	0.1	40	4	0.0125	5	$3.2\delta \times 2\delta \times 1.6\delta$	$1024 \times 168 \times 128$
Run 2c	■				8				

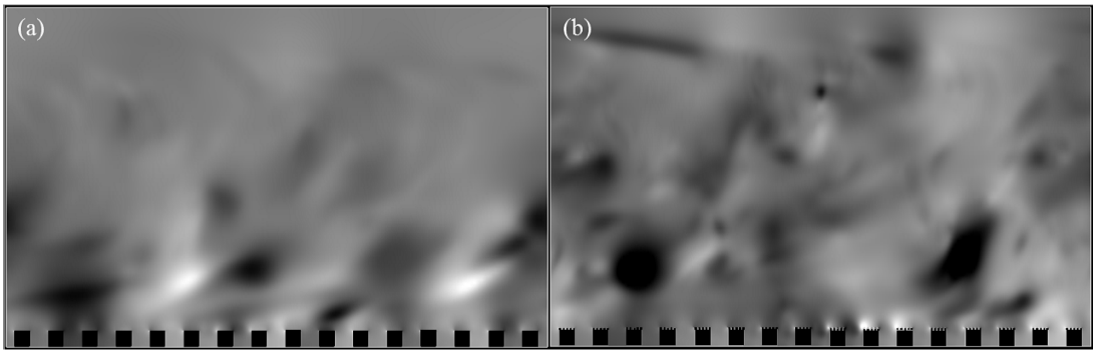

Figure 3. Instantaneous static pressure field $p^+ = p/\rho u_*^2$ in the x-y plane. (a) Run 1a; (b) Run 2a. Black: $p^+ = -0.5$; White: $p^+ = +0.5$

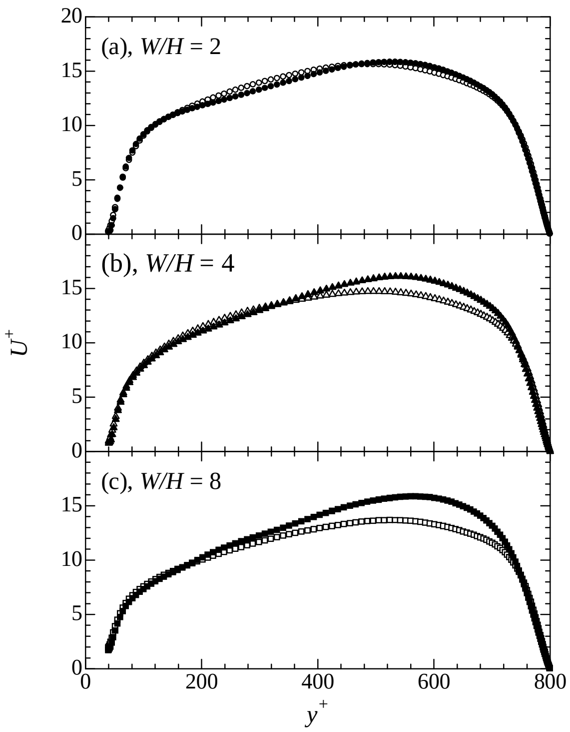

Figure 4. Profiles of mean streamwise velocity U^+

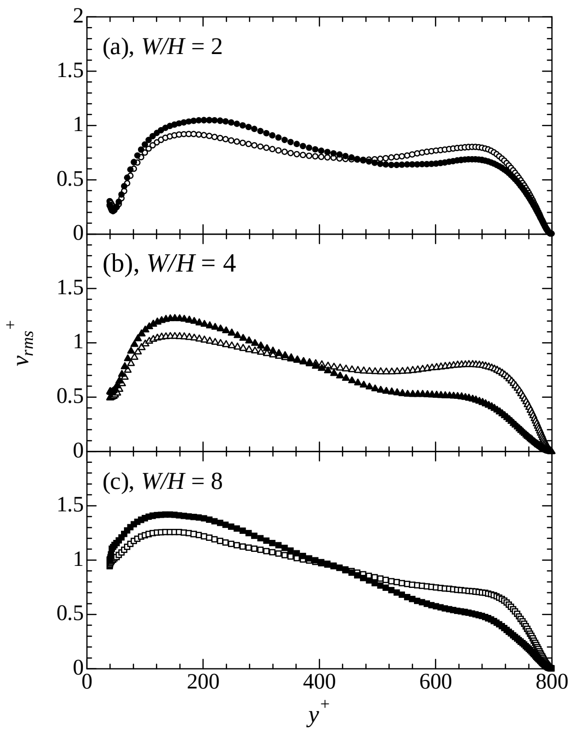

Figure 5. Profiles of rms transverse velocity v^+_{rms}