COOPERATIVE DRAG REDUCING EFFECT OF LONGITUDINAL RIBLETS AND SPANWISE WALL OSCILLATIONS.

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Abstract Turbulent flow over a ribbed wall oscillating in a spanwise direction is investigated numerically via DNS. It is shown that cooperative drag reducing effect of longitudinal riblets and spanwise wall oscillations exceeds significantly the performance of each method of flow manipulation. Limited amount of optimization simulations is performed. In the optimal case 13% net drag reduction is attained (with the loses associated with ribbed wall oscillations taking in account).

FORMULATION

Longitudinal ribs (riblets) and spanwise surface oscillations are two well known techniques of turbulent drag reduction. Riblets reduce turbulent spanwise velocity fluctuations in the near-wall region of turbulent flow. At appropriate riblets height and spanwise separation this results in a significant reduction of turbulent wall friction. However, additional friction on the riblets surface makes the resultant effect not very appreciable. Experimentally approved turbulent drag reduction on a ribbed surface ranges from 6 to 8% [1].

The mechanism of turbulent drag reduction by spanwise wall oscillations is less understandable. Numerical simulations indicate that the structures responsible for turbulence generation are damped noticeably in the near-wall fluid layer entrained by the oscillating wall. The decrease in wall friction may reach a value of several tens percents. However, the energetic losses connected with a spanwise friction on the oscillating wall should be taken in account when evaluating the net performance of the method. According to DNS results the net power saving does not exceed a value of a few percent [2] even at optimal oscillation parameters.

In the current work the capability of joint application of riblets and surface oscillations is investigated for the first time. The problem is solved numerically for the open plane channel model (a plane channel with one rigid and one shear-free wall) at Re_τ = 180. The incompressible Navier-Stokes equations are solved using finite-difference discretization scheme in space and a semi-implicit Runge-Cutta method in time [3]. Periodic boundary conditions are employed in homogeneous streamwise direction x and in spanwise direction z. The lower rigid wall ($y = 0$) is equiped with a set of blade-shape riblets of height h_r and separation s_r (see figure 1). This wall is subjected to harmonic spanwie oscillations with velocity $W_w \sin \omega t$. It is suitable to consider the flow in a moving frame oscillating with the lower wall which makes the geometry of the flow steady. No-slip boundary conditions are applied on the surface $y = 0$ as well as on the surface of riblets which are considered to be infinitely thin. The Navier-Stokes equations in moving frame are solved in rectangular domain without riblets, while the no-slip conditions on the riblet surfaces are satisfied by using an immersed boundary method of [4]. Up to 64 riblets per spanwise flow period were considered in simulations on the grid with up to $256 \times 120 \times 512$ meshes. Computational grid was stretched in the y and z directions to make smaller mesh size in normal direction in the vicinity of all rigid surfaces (see figure 1(b)). The pressure-Poisson equation is solved using Fourier method in homogeneous direction x and cyclic reduction method of [5] in $(y - z)$ plane.

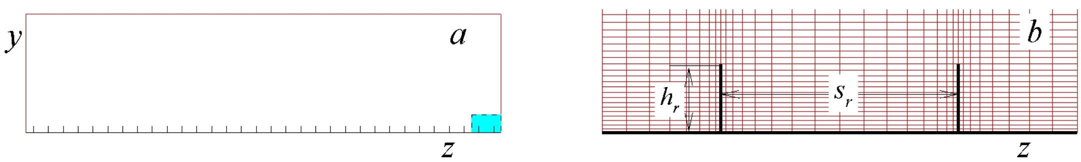

Figure 1. a) Cross sectional view of the computational domain with riblets on the lower wall; b) close-up of computational domain fragment (shaded on the left figure) with riblets and computational grid lines.

RESULTS

Computational algorithm was verified by simulations of turbulent flows over steady ribbed wall and over smooth oscillating wall. In the first set of simulations it was found that longitudinal blade-shaped riblets can really produce net drag reduction. The maximum performance of 8% is produced by riblets with height $h_r^+ = 5 - 7$ and spanwise separation

$s_r^+ = 20$. This finding is in good agreement with existing numerical and experimental results. Results of the second set of simulations of the flow over smooth oscillating wall agree very well with those, obtained in simulations of [2]. In particular, the maximum net energy saving of about 8% was found at oscillation parameters $T_w^+ = 2\pi/\omega^+ = 125,\ W_w^+ = 4.5$ which is close to 7.3% reported in [2].

When evaluating drag reducing performance of ribbed oscillating wall the energy losses connected with wall oscillations should be taken in account. In addition to those in the case of smooth wall oscillations, which were specified in [2] the power required to overcome aerodynamic resistance of moving riblets

$$P_p = \frac{1}{t_f - t_i} \int_{t_i}^{t_f} W(t) \int_{S_r} (p_- - p_+)\, \mathrm{d}S_r \mathrm{d}t \tag{1}$$

must be taken into account. Here, $W(t)$ is the wall velocity, p_+ and p_- are the pressures on two opposite sides of riblets, S_r is the one-side riblets surface. The power in eq-n (1) is averaged over time interval (t_i, t_f).

When searching the optimal riblets and oscillation parameters it looks reasonable to start from oscillation parameters optimal in smooth wall case: $T_w^+ = 125,\ W_w^+ = 4.5$. In simulations with these T_w, W_w and varied riblets parameters h_r, s_r it was found that cooperative drag reducing effect of riblets and wall oscillations can exceed significantly the effect of each method of flow manipulation. For each riblet height net energy saving of oscillating ribbed wall as a function of spanwise separation shows a clear maximum in the vicinity of $s_r^+ = 12 - 13$ (see figure 2). Maximum performance of 13.6% compared with uncontrolled flow is attained at $h_r^+ = 4.3$. Limited number of simulations with oscillation parameters variation did not give higher value of net energy saving.

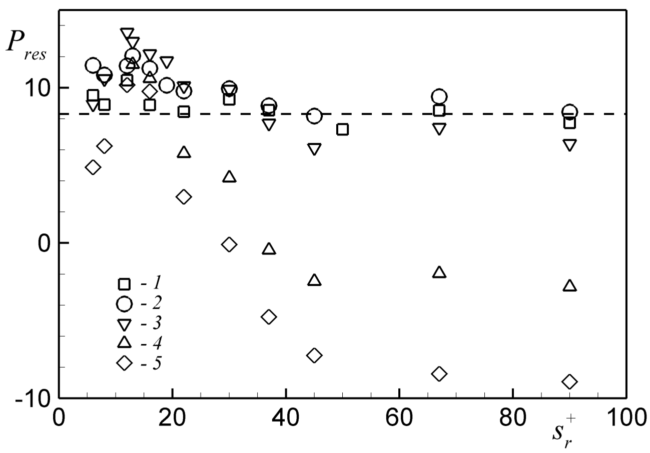

Figure 2. Net energy saving of oscillating ribbed wall as a percentage of the friction power spent in the uncontrolled (smooth, steady wall) case. Symbols: 1, $h_r^+ = 0.7$; 2, $h_r^+ = 1.9$; 3, $h_r^+ = 4.3$; 4, $h_r^+ = 5.9$; 5, $h_r^+ = 6.5$. Oscillation parameters: $2\pi/\omega^+ = 125,\ W_w^+ = 4.5$. Dashed line corresponds to smooth wall oscillations.

References

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