Suboptimal Control of Wall Turbulence with Moving Dimples

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Effective control of wall-bounded turbulent flows for skin-friction drag reduction is of significance in scientific research as well as in engineering problems. During the past several decades, there is a rapid progress in understanding the self-sustenance or regeneration mechanism of near-wall turbulence. Hence, various control strategies have been presented, aiming at reducing the skin friction drag, by intervening in the regeneration cycle of near-wall turbulence. For instance, the opposition control scheme proposed by Choi et al. (1994) used the blowing/suction through the wall to counteract the sweep and ejection motions induced by streamwise vortices in buffer layer. Inspired by this intuitive but successful idea, more practical control laws were then found by employing information measurable at the wall, e.g. the neural network (Lee et al. 1997) and the suboptimal control (Lee et al. 1998). On the other hand, instead of the blowing/suction through the wall, the deformable wall was then adopted in the opposition control (Kang & Choi 2000). From the practical point of view, the real wall surface cannot be deformed continuously. Endo et al. (2000) presented a new design consisting of arrays of sensors and actuators of finite dimensions at the wall. The actuators are deformable and elongated in the streamwise direction, while the sensors capture the wall information as input of actuators. An explicit control scheme was proposed, based on the spanwise gradient of wall shear stress due to its correlation with the near-wall coherent structures, and about 10% drag reduction was obtained for $Re_\tau = 150$. Noteworthily, development of MEMS technology in recent years increased the feasibility and potential of such active control strategy in real applications.

In the present study, we apply the suboptimal control on the turbulent channel flow for drag reduction by moving dimple actuators via direct numerical simulation. The incompressible Navier-Stokes equations are solved in the curvilinear coordinates by the pseudo-spectral method. Periodic boundary conditions are used in the streamwise and spanwise directions, and no-slip boundary conditions are applied at the top and bottom walls. A coordinate transformation is introduced to map the irregular physical domain into a rectangular computational domain, and a third-order time-splitting scheme is adopted for time advancement (Ge et al. 2010). The Reynolds number based on the mean bulk velocity and the channel half-height is 2850. The domain size is $2\pi \times 2 \times \pi$ in the streamwise, normal and spanwise directions respectively, and the corresponding grid numbers are $128 \times 65 \times 128$. At the bottom wall, total $32 \times 32 \times 2$ sensors and dimple actuators are distributed in an interlaced pattern, as shown in Fig.1. The diameter of the dimple is about 10 viscous wall units. The center velocity of the dimple is determined according to the suboptimal control strategy. A cost functional based on the spanwise gradient of the spanwise wall shear stress is adopted, as proposed by Lee et al. (1998). By a linear simplification of the governing equation, a simple relationship between the normal velocity of the moving wall and the spanwise wall shear stress is obtained in the spectral space. In the present study, the control law is transformed into the physical space, i.e.

$$v\left(x_j, z_k\right) = C_0 \sum_{j'}^{J_0} \sum_{k'}^{K_0} W^{w}_{j'k'} \left.\frac{\partial w}{\partial y}\right|_w \left(x_{j+j'}, z_{k+k'}\right), \tag{1}$$

where W denotes the weighting function and C_0 denotes the control strength. The exact form of the weighting function extends into the whole wall. For practical purposes, a truncation of the weighting function has to be made, and in the present simulations a spanwise elongated rectangular truncation box of 3×17 grid numbers containing two sensors is adopted, which is effective by considering both the drag reduction rate and the computational cost. In computing Eq.(1), wall information outside of the sensors is reconstructed by averaging or linear interpolation, and the two ways are found to yield similar drag reduction rate. In simulation, we observed that the dimples become static gradually using the suboptimal control, which increases the pressure drag. The reason is that the spanwise wall shear stress is contaminated due to the presence of dimples, and thus the wall information cannot effectively reflect the influence of near-wall coherent structures. To solve this problem, we use a low-pass filter to eliminate the high-frequency fluctuations of the spanwise wall shear stress, and the filtered stress is used as the control input. Time histories of total drag and pressure drag of the bottom wall are displayed in Fig.2, where the suboptimal, opposition and no control cases are included for comparison. We can see that there is about 3% reduction in the total drag for the filtered suboptimal control, similar with the opposition control case, while no drag reduction is obtained for the original suboptimal control, due to the increase of the pressure drag.

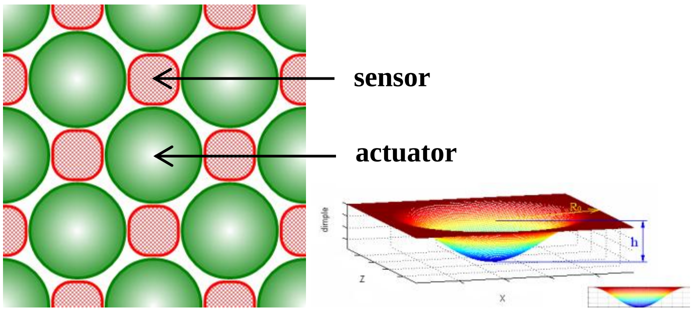

Figure 1. Arrangement of sensors and actuators for suboptimal control

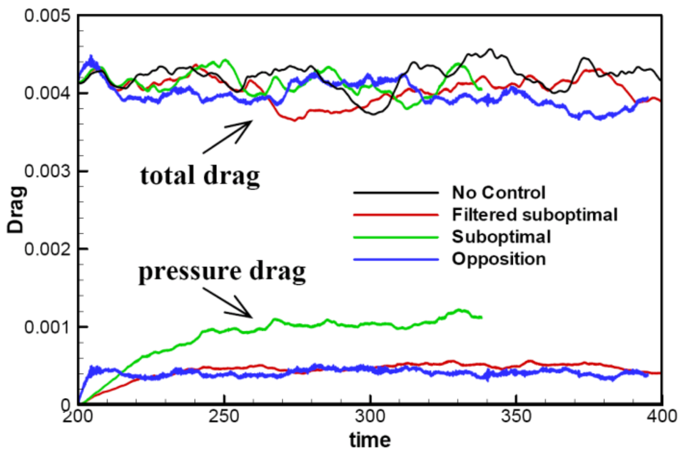

Figure 2. Time histories of the skin friction drag

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