Effects of Spanwise Wall Disturbance on Heat and Momentum Transfer in Turbulent Channel Flow

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Abstract: We propose a new predetermined control scheme for turbulent skin friction reduction by extending the concept of the conventional spanwise wall-oscillation control. The present scheme employs stationary, but longitudinally-varying spanwise velocity at the wall as a control input. It is found that the present scheme achieves a higher drag reduction rate with less power input compared to the spanwise oscillation control. The net energy saving is significantly improved from 7 % to 32 %, while the heat transfer rate is also depressed in a similar manner.

Turbulent skin friction is one of the key factors for energy penalty in various fluid machineries such as aircrafts, marine vessels and pipe transport. Although intensive research on turbulence control has been conducted over the last few decades, its application to real engineering flows remains to be a difficult task mainly due to lack of understanding of turbulence, difficulties in developing control theory for such complex phenomena, and fabrication/maintenance costs of hardware such as actuators and sensors.

Among various control schemes, active control has a high potential to manipulate turbulent flow flexibly and robustly. Generally, active control is further classified into the feedback and predetermined controls. Recently, the predetermined control draws much attention, since it does not require sensors to obtain flow information and the spatial scale of control input is not constrained by that of inherent turbulent structures close to a wall. So far, various types of predetermined control input have been proposed such as spanwise wall oscillation (Quadrio & Ricco (2005)), streamwise/spanwise traveling waves (Min et al. (2008), Du et al. (2007)) and steady transpiration (Ricco et al. (2007)). Although they achieve considerable drag reduction, they commonly suffer from a penalty of large power consumption. For example, Quadrio & Ricco (2005) showed that the spanwise oscillation control leads to net energy saving only when the amplitude of control input is small, and ideally the net energy saving rate is 7 % at most.

In the present study, we propose a new predetermined control scheme to achieve a higher drag reduction rate with less power input. We consider a fully developed turbulent channel flow under a constant bulk Reynolds number, i.e., $Re_B = U_B\delta / \nu = 2293$, where U_B, δ and ν are the bulk mean velocity, channel depth and kinematic viscosity of fluid, respectively. The streamwise, wall-normal and spanwise directions are denoted by x, y and z, respectively. The Navier-Stokes, continuity and energy equations are solved by a pseudo-spectral method. The computational domain size is $5\pi\delta$ and $\pi\delta$ in the x- and z- directions, respectively.

Taking a clue from the conventional spanwise wall oscillation control, we consider a more general form of control input at the wall as:

$$w(x, y=\pm 1, z, t) = w_0 \exp\left\{ i\left(k_x x + k_z z + \omega t\right)\right\}. \qquad (1)$$

Here, $y = \pm 1$ corresponds to the top and bottom walls, while w is the velocity component in the z-directions. The variable parameters of the control input in Eq. (1) are the amplitude w_0, streamwise and spanwise wavenumber k_x and k_z, and the frequency ω.

In this manuscript, we focus on the stationary but longitudinally-varying control ($\omega = k_z = 0$, $k_x \neq 0$) as shown in Fig. 1. Specifically, w_0^+ is set to be 2 and 5, while the streanwise wavelength L_x is changed as $L_x^+ = 2\pi / k_x^+ =$ 294, 589, 1178, 1766 and 2355. They correspond to $L_x = L_x^* / \delta^* =$ 0.625π, 1.25π, 2.5π, 3.75π and 5π, respectively. Here, the values with an asterisk denote dimensional quantities.

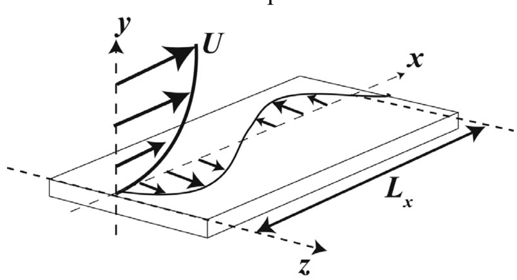

Figure 1: Schematic figure of stationary, but longitudinally-varing control input.

Figure 2 shows time traces of spatially-averaged wall shear stress at the two walls. When w_0^+ = 2, the drag reduction rate is about 15 %, and its dependency on the streamwise wavelength L_x is relatively weak. In contrast, when w_0^+ = 5, the effect of L_x is more pronounced, and the largest drag reduction rate of 43 % is obtained at $L_x^+ =$ 1178. Assuming that the typical convective velocity of the quasi-streamwise vortices close to the wall is around u^+ = 10, the optimal wavelength L_x^+ of 1178 approximately corresponds to a temporal periodicity of $T^+ = 2\pi / \omega^+ \sim$ 120. This agrees well with the optimal period of the conventional spanwise wall oscillation control (Ricco et al., (2005)). Indeed, the phase-averaged spanwise mean velocities in the stationary and oscillatory controls show quite similar behavior near the wall as shown in Fig. 2. These facts suggest that the drag reduction mechanism in the stationary control is essentially the same as that in the oscillatory control.

Figure 3 shows a comparison between the time traces of flow pumping power and control power input under the stationary control at $L_x^+ =$ 1178 and the oscillatory control at $T^+ =$ 125. In both cases, w_0^+ is set to be 5.0. It is found that the stationary control achieves a higher drag reduction rate than the oscillatory control with smaller power input. As a result, 32 % net energy saving is obtained in the stationary control, while only 7 % in the oscillatory control. In addition, the energy gain G, which is defined by the ratio of the pumping power saved and the control power input, is G = 6.0 in the stationary control, while G = 1.6 in the oscillatory control. These results indicate that the stationary control is more effective in reducing turbulent friction drag than the oscillatory control.

Control of turbulent heat transfer is also an important issue in practical applications. In the present study, the temperature field is calculated as a passive scalar, and two boundary conditions are considered, i.e., the constant, but two different wall temperatures (CWT), and the constant heat flux on two walls (CHF). The Prandtl number is Pr = 1.0 in all calculations. The Stanton numbers St obtained under the two boundary conditions are plotted in the lower part of Fig. 4. Here, the Stanton number is normalized by St_0, while the subscript of 0 represents the value in the uncontrolled case. Basically, the time development of the Stanton number is similar to that of the friction coefficient. The effect of thermal boundary condition on St is rather small. The time-averaged friction coefficient Cf and Stanton number St are listed in Table 1. These results imply strong similarity between heat and momentum transfer in the present control scheme.

In the oral presentation, we will also consider a control input which changes not only in space but also in time as given by Eq. (1), and discuss the most effective spatio-temporal mode for achieving the maximum net energy saving.

Table 1: Friction coefficient and Stanton number under oscillatory and stationary controls

	Oscillatory control ($w_0^+ = 5$, $T^+ = 125$)	Stationary control ($w_0^+ = 5$, $\lambda^+ = 1178$)
Cf / Cf_0	0.76	0.55
St/St_0	0.70 (CHF) 0.75 (CWT)	0.50 (CHF) 0.52 (CWT)

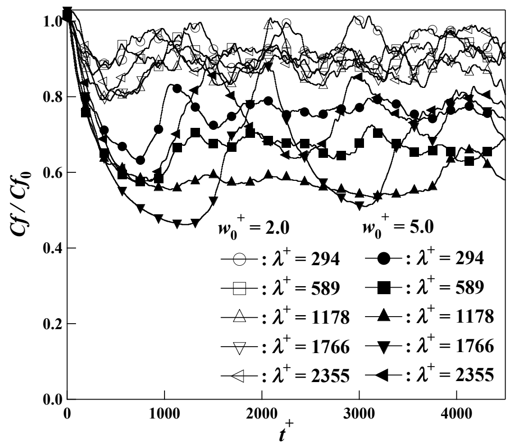

Figure 2: Time trace of friction coefficient Cf normalized by the value in the uncontrolled case.

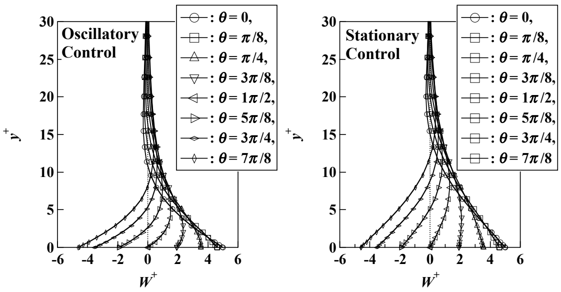

Figure 3: Phase-averaged spanwise velocity
left: oscillatory control ($w_0^+ = 5$, $T^+ = 125$)
right: stationary control ($w_0^+ = 5$, $\lambda^+ = 1178$).

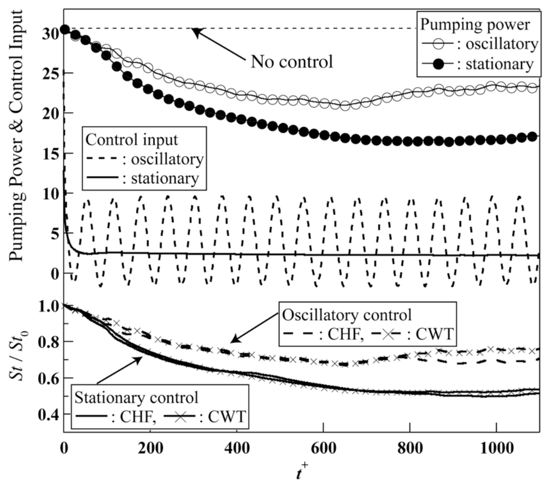

Figure 4: Time trace of pumping power and control input (upper figure), and Stanton number (lower figure) under oscillatory ($w_0^+ = 5$, $T^+ = 125$) and stationary ($w_0^+ = 5$, $\lambda^+ = 1178$) controls.

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