Active Feedback Control of Wall Turbulence with Wall Deformation

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Abstract

Direct numerical simulation (DNS) of active feedback control of channel flow with wall deformation is performed. The wall motion is determined with the virtual sensors inside the flow domain. Turbulent friction drag is reduced as large as 20% when the wall velocity is the opposite to the normal velocity at $x_2/\delta = 0.1$. Near-wall coherent structures are visualized and the longitudinal vortices and high-speed regions are found to be diminished when the drag is reduced.

1 Introduction

Turbulence control for reducing friction drag or increasing heat transfer is very important for many engineering and environmental problems. Recently, active feedback control with distributed micro sensors and actuators is paid much attention, since large alteration to flow field is expected with small control input. Several different kinds of actuators are proposed, and their prototypes are fabricated with the aid of the MEMS technique[1]. Among them, actuators with wall deformation is attractive for practical use, because they should be robust in hostile environment and have little unwanted effect of fouling. The objective of the present study is to evaluate wall deformation in turbulent drag reduction and optimize spatio-temporal scales of the actuators. To do this, we employ DNSs of turbulent channel flow and near-wall coherent structures on the deformed wall are investigated when a simple feedback law is imposed on the wall motion.

2 Numerical Procedures

The governing equations are the incompressive Navier-Stokes equation, and the continuity equation. Boundary fitted coordinate system is employed, and the second-order finite difference scheme and the four-step time advancement scheme[2] are used for the spatial and temporal discretizations, respectively. One of the channel wall is assumed to be deformed, while the opposite wall is kept flat. The computational domain is $1.25\pi\delta \times 2\delta \times 0.375\pi\delta$ for streamwise (x_1), wall normal (x_2) and spanwise (x_3) directions, respectively. Number of grid points are $48 \times 97 \times 48$. Non-slip boundary condition is imposed on both walls, while periodic boundary condition is employed for x_1 and x_3 direction. The Reynolds number Re_m based on the bulk mean velocity (U_m) and the channel half-width (δ) is 4600, which corresponds to $Re_\tau = 150$ based on the friction velocity u_τ and δ in the plane channel flow. In the present computations, the flow rate is kept constant, and the drag is calculated with the streamwise pressure gradient.

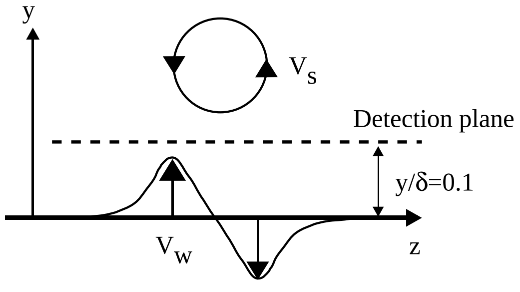

Figure 1. Schematic diagram of control algorithm.

Choi et al.[3] reported by using their DNSs that the turbulent friction drag of channel flow is reduced as large as 30% with local injection and suction at the wall. In the present study, a simple feedback algorithm is assumed for the wall motion as shown in Fig. 1. The present control is similar to that used by Choi et al.[3], and the normal velocity of the wall is given by

$$v_w^{n+1} = -\alpha y_w^n + \beta \left(v_s^n - < v_s^n > \right) \quad (1)$$

where v_w is the normal velocity of the wall, v_s is wall normal velocity component sensed at $x_2/\delta = 0.1$, and $< >$ denotes ensemble average over $x_1 - x_3$ plane. The second term is to cancel near-wall longitudinal vortices responsible for the turbulent skin friction near the wall[4], while the first term is devised to damp the wall deformation with a time scale of $1/\alpha$ in order to assure stable computation. Control parameters α and β are listed in Table 1.

3 Results and Discussions

Temporal evolution of streamwise pressure gradient is shown in Fig. 2. In Case 1, the drag is gradually decreased with time, and 20% drag reduction is obtained at around $t^* = 50$. Thus, it is proved that the drag can be reduced with the wall motion with the opposite velocity to the v at the sensing plane. Near-wall coherent structures at $t^* = 9.75$ and $t^* = 60.0$ are visualized in Figs 3 and 4. At $t^* = 60.0$, low pressure regions (white contour), which correspond to longitudinal vortices are diminished, and high-speed regions responsible for high skin friction are also disappeared. Low-speed streaks (Black contour) are relatively straight in the streamwise direction, which often observed in drag-reducing turbulent flows. On the other hand, for Case 2, the drag is increased, and the near-wall structures are significantly agitated (not shown here).

Currently, more systematic computation is undertaken, and the spatio-temporal scales required for drag reduction will be evaluated for designing practical wall-deformation actuators.

	α	β
Case1	1	-1
Case2	1	1

Table 1. algorithm parameters

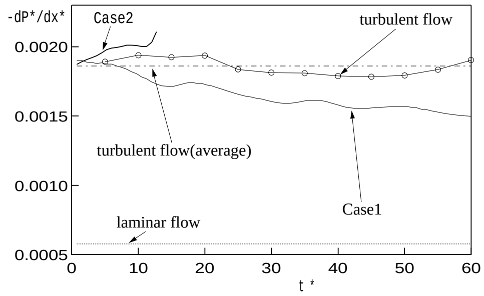

Figure 2. Temporal evolution of mean pressure gradient.

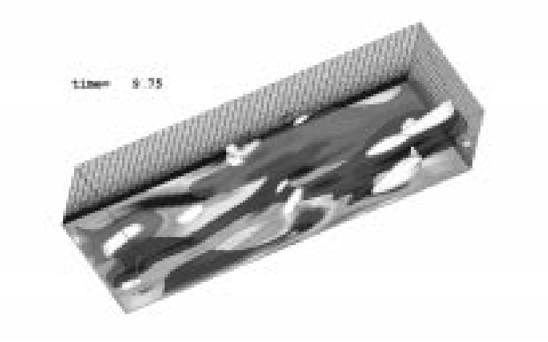

Figure 3. Instantaneous flow field at $t^* = 9.75$.

Figure 4. Instantaneous flow field at $t^* = 60.0$.

References

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