PHASE DEPENDENCY OF NEAR-WALL STREAMWISE VORTICES AND ASSOCIATED REYNOLDS SHEAR STRESSES CLOSE TO SPANWISE OSCILLATING WALL

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Abstract Direct numerical simulation of fully-developed turbulent channel flow subjected to spanwise harmonic wall oscillation is carried out. The quantitative contributions of quadrant Reynolds shear stresses to the skin friction drag are calculated on the basis of so-called FIK identity [1]. It is found that the Q2 event characterized by upwelling of low-speed fluid away from the wall contributes to the skin friction drag reduction in all oscillation frequencies considered, whereas the Q4 event characterized by downwelling of high speed fluid toward the wall first contributes to drag reduction at small oscillation periods, and then to drag increase significantly with increasing the oscillation period. The conditional averaging technique is applied to near-wall streamwise vortices in order to explain different behavior of Q2 and Q4 with respect to the oscillation period.

BACKGROUND & OBJECTIVES

The spanwise wall-oscillation control is one of the most conventional predetermined control schemes to achieve skin friction drag reduction in wall turbulence. Although more than 40 % drag reduction is achieved by such a simple control strategy [2], the net energy saving, i.e, the reduction of the total power consumption for pumping and control, is limited to at most 7.3% even when the oscillation period T and the amplitude W are set to their optimal values as $T^+ = 125$ and $W_0^+ = 4.5$, where the superscript of $+$ indicates normalization by the friction scales. In order to develop a more energy efficient control strategy, deep understanding of drag reduction mechanism is necessary. Despite huge amount of work conducted in the last few decades, the drag reduction mechanism of spanwise wall oscillation is not fully understood yet. Considering that mechanisms of turbulence production and dissipation are closely related to coherent structures near the wall [3], it would be meaningful to consider the effect of the wall oscillation on near-wall turbulence structures in order to elucidate the physical factors leading to drag reduction. In the present study, we apply three-dimensional conditional averaging technique to the streamwise vortex at different phases of wall oscillation. This turns out to be quite useful to discuss how the wall motion at each phase modifies the near-wall turbulence structures, and therefore associated momentum transfer between the bulk of fluid and the wall.

NUMERICAL CONDITION

We consider a fully developed turbulent flow between two parallel plates. All simulations are performed under a constant pressure gradient in order to keep the friction Reynolds number constant, i.e., $Re_\tau = 150$, and therefore minimize possible Reynolds number effects arising from the applied control. The computational domain is $2.5\pi\delta \times 2\delta \times \pi\delta$ in the streamwise (x), wall-normal (y) and spanwise (z) directions, respectively. The second-order finite difference method is used to discretize the computational domain with grid numbers of $(N_x, N_y, N_z) = (64, 129, 64)$ in each direction.
As for the control input, we impose a spanwise sinusoidal velocity component $w^+_{wall} = W_0^+ \sin\phi$ on the two walls in phase, where $\phi = 2\pi t^+/T^+$ is a phase of a periodic control. In this study, the oscillation amplitude is set to be $W_0^+ = 7.0$, while the oscillation period is changed as $T^+ = 16, 50, 75, 125, 200, 250$ and 500.

RESULTS

Fukagata et al. [1] first derived a mathematical relationship between the wall skin friction and different dynamical contributions. This so-called FIK identity can be easily extended to a flow under a constant pressure gradient as:

$$U_b^+ = \frac{Re_\tau}{3} - \int_0^{Re_\tau} \left(1 - \frac{y^+}{Re_\tau}\right)\left(-\overline{u'v'}^+\right) dy. \tag{1}$$

Note that the drag reduction effect manifests itself in the increase of the bulk mean velocity U_b under a constant pressure gradient in contrast to the wall friction under a constant flow rate. The first term on the right-hand-side corresponds to the laminar contribution and is constant once Re_τ is fixed. Therefore, the bulk mean velocity is determined by the weighted integral of $\overline{u'v'}$ appearing as the second term in Eq. (1).

Figure 1 shows the increase of U_b from the uncontrolled value as a function of the oscillation period. The contributions from four quadrant of $\overline{u'v'}$ are also plotted. Note that the sum of four quadrant contributions is identical to the increase of U_b. It is confirmed that the drag reduction effect becomes maximum around $T^+ = 75$. Although the positive contribution from Q2 dominates the overall drag reduction effect at relatively small oscillation periods up to $T^+ < 125$, the negative contribution from Q4 becomes prominent at larger periods and causes rapid deterioration of the drag reduction effect.

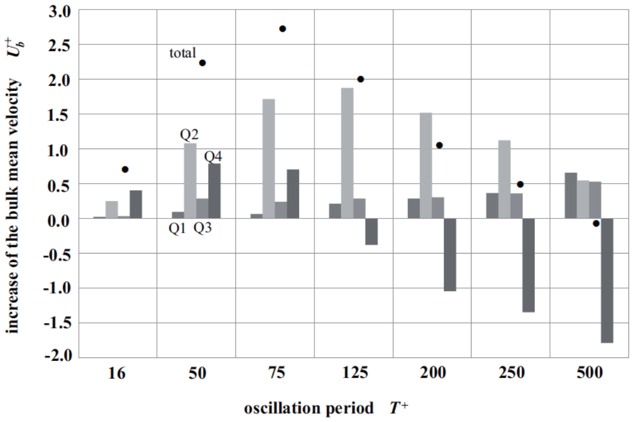

Figure 1. The increase of U_b and the dynamical contributions from four quadrants of $\overline{u'v'}$ to U_b as a function of oscillation period.

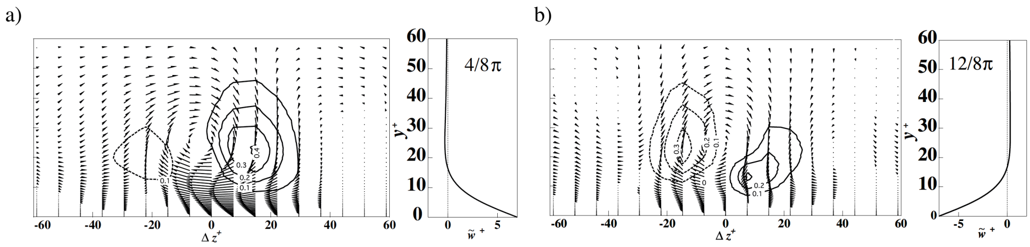

Figure 2. Conditionally averaged velocity vectors in $y - z$ plane around the streamwise vortices near the wall when $W_0^+ = 7.0$ and $T^+ = 250$. The dotted and solid lines are isolines of Q2 and Q4, respectively.

In order to further investigate the increase/decrease of the contributions from Q2 and Q4, the conditional averaging technique is applied to near-wall streamwise vortices. More specifically, we first detect locations where the second invariant Q^+ of the deformation tensor is smaller than -0.02 within the position of $y^+ = 10 \sim 40$. Within the detected area, the local minimum of the pressure is chosen as a vortex core. Then, the velocity field is averaged with respect to the vortex cores for a sufficiently long period. Note that the averaging is conducted at each oscillation phase. The resultant velocity fields in the $y - z$ plane at $\phi = 4\pi/8$ and $12\pi/8$, and the corresponding Stokes layer profiles are shown in Figure 2. The isolines of Q2 and Q4 induced by the streamwise vortices are also depicted. It is found that both Q2 and Q4 strongly depend on the oscillation phase. In the final paper, we will discuss the phase dependency of Q2 and Q4 around the conditionally-averaged streamwise vortices in order to clarify the drag reduction mechanism at a wide rage of the oscillation period.

References

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