Formation of low-speed ribbons in turbulent channel flow subject to a spanwise travelling wave

L. P. Huang\textsuperscript{1,2}, K. S. Choi\textsuperscript{2}, B. C. Fan\textsuperscript{1}
\textsuperscript{1} Science and Technology on Transient Physics Laboratory, NUST, Nanjing 210094, China
\textsuperscript{2} Faculty of Engineering, University of Nottingham, Nottingham, NG7 2RD, UK
E-mail: Kwing-So.Choi@nottingham.ac.uk

\textbf{Abstract.} Turbulent flow control with skin-friction drag reduction subject to spanwise travelling wave (STW) induced by Lorentz force is investigated by direct numerical simulation (DNS) in a channel. The results show that STW produces a set of distinct longitudinal vortices, suppressing the regeneration of near-wall turbulence structures. It is also shown that the formation of low-speed ribbons by STW is associated with these longitudinal vortices, which weaken the sweep and ejection events in the near-wall region. At the same time, the production of counter-gradient Reynolds stresses is increased, leading to up to 30\% of turbulent drag reduction by STW.

1. Introduction

Lorentz force can be used to induce motion in the electrically conducting fluids which might then lead to turbulence suppression and drag reduction. It is possible to carry out many different types of Lorentz force control by simply rearranging the electrodes and magnets. Du, Karniadakis (2000) and Du et al. (2002) reported that an efficient drag reduction can be achieved by using a pseudo-three dimensional electromagnetic body force control scheme. They firstly tested an idealized force that varies spatially and temporally. The form of this force is

\begin{equation}
\label{eq:1}
f_z = I e^{-y/\Delta} \sin \left( \frac{2\pi}{\lambda_z} z - \frac{2\pi}{T} t \right),
\end{equation}

where $y$ and $z$ are vertical and spanwise coordinates, respectively, $I$ is the amplitude of excitation of the electromagnetic actuator, $\Delta$ is the effective penetration of the Lorentz force, $\lambda_z$ is the wave length along the spanwise direction, $T$ is the period of the oscillation, and $t$ is the time. This force transmits energy resembling a travelling wave along the spanwise direction in electrically conducting fluids. It was found that more than 30\% reductions in skin-friction drag could be obtained. A wide “ribbon” of low speed velocity near the wall was formed in the study, which extended over 200 wall units in the spanwise direction. They argued that the mechanism of the skin-friction reduction by STW was due to the stabilisation of low-speed streaks, suppressing the turbulence regeneration cycle. This work was experimentally followed by Xu and Choi (2007) in a turbulent boundary layer and obtained a skin-friction reduction of 30\%. They also found that the low speed streaks were substantially altered during travelling wave excitation. A DNS study on STW by a flexible wall was carried out by Zhao et al. (2004), who believed that the drag reduction was due to the change in boundary vorticity by the flexible wall. Recently, Choi et al.
(2011) studied the turbulent boundary layer control by STW technique, which was implemented by an assay of plasma actuator. They suggested that there appeared to be a streamwise vortex system playing some role in the boundary layer control.

Despite of these investigations, the spanwise travelling wave control technique has not been fully understood, and a number of important issues related to the drag-reduction mechanisms of STW remain. Most importantly, how the wide “ribbon” of low-speed region is formed? Here we studied the flow physics of a turbulent boundary layer subject to a spanwise travelling wave by performing DNS to answer this question. Instantaneous flow visualization techniques were used to observe the dynamic responses of near-wall velocities, vorticities and the low-speed streak structures to STW.

2. Numerical scheme

The incompressible non-dimensional Navier-Stokes equations with a body-force term are used in this study to describe the turbulent channel flow:

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \frac{1}{Re} \nabla^2 \mathbf{u} + \mathbf{f}, \quad (2)$$

$$\nabla \cdot \mathbf{u} = 0. \quad (3)$$

Here, all variables are non-dimensionalised by the centreline velocity $U_c$ and the channel half height $h$. $Re$ is the Reynolds number, $\mathbf{u}$ is velocity vector, $t$ the time, $p$ the pressure, $\nu$ the kinematic viscosity, and $\mathbf{f}$ the body force per unit mass given by

$$\mathbf{f} = (0, 0, f_z). \quad (4)$$

The spanwise forcing has the form given in Eq. (1), which is applied at the lower wall of the channel. Due to the exponential decay of the Lorentz force field, the turbulence structure over the upper wall is practically unaffected by the forcing. When $\lambda_z \to \infty$, the spanwise travelling wave becomes spanwise-flow oscillation (Berger et al., 2000). The numerical method adopted here is the standard Fourier-Chebyshev spectral method based on Gibson (2007), whose detail is given in our previous work (Huang et al., 2010). The size of the computational domain is $L_x^+ = 754$ by $L_y^+ = 360$ by $L_z^+ = 377$, in the streamwise, normal, and spanwise directions with grid sizes of $64 \times 65 \times 32$, respectively. All variables with superscript + (wall variables) used throughout this paper are non-dimensionalised by the friction velocity $u_f$ in the unperturbed turbulent channel and the kinematic viscosity $\nu$. The longitudinal flow rate is kept constant during the simulations, and the bulk velocity $U_b$ is equal to $2/3 U_c$. The Reynolds number based on $U_b$ and $h$ is kept constant in our study at $Re_b = 2670$ ($Re_e = 180$ based on $u_f$ and $h$).

3. Results and discussions

Simulation results show that drag reduction over 30% can be achieved in certain combinations of $\lambda_z$, $T$, $I$ and $\Delta$ values. Here we take a representative case of $\lambda_z = 2.1$ ($\lambda_z^+ = 377$), $T = 5$ ($T^+ = 40$), $I = 1.0$ and $\Delta = 0.02$ ($\Delta^+ = 3.6$) to carry out a detailed study of near-wall turbulence structure under STW control. A snapshot of streamwise velocities in the near-wall region ($y^+ = 5.4$) and the vortical structure in the channel ($y^+ < 120$) are shown in Fig. 1 and Fig. 2, respectively. Here, the vortices are visualized by the imaginary part of the complex eigenvalue of the velocity gradient tensor (zhou et al., 1999). Fig. 1 and Fig. 2 indicate that STW produces a set of distinct longitudinal vortices, suppressing the regeneration of near-wall turbulence structures. It is also shown that the formation of low-speed ribbons by STW is associated with these longitudinal vortices, which weaken the sweep and ejection events in the
near-wall region, and at the same time, the production of counter-gradient Reynolds stresses is increased, as shown in Fig. 3 and Fig. 4, which leads to up to 30% of turbulent drag reduction by STW.

**Figure 1.** Snapshot of near-wall low-speed streaks at $y^+ = 5.4$. (a) No control; and (b) under STW control with $\Delta = 0.02$, $I = 1.0$ $T^+ = 40$, and $\lambda_z^+ = 377$.

**Figure 2.** Streamwise vorticity together with vortex structures in the near-wall region, $(y^+ < 120)$, where the white areas represent the positive streamwise vorticity, while the negative streamwise vorticity is shown by the black in each $y-z$ plane. The gray colour represents vortex structures. (a) No control; and (b) under STW control with $\Delta = 0.02$, $I = 1.0$ $T^+ = 40$, and $\lambda_z^+ = 377$.

**Figure 3.** Mean and quadrant-averaged Reynolds stresses with and without STW control.
Figure 4. Distribution of phase-averaged Reynolds stress at both $y^+ = 5.4$ and $x^+ = 360$, and streamwise velocity at $x^+ = 360$ together with the vortex structures in the near-wall region under STW control with $\Delta = 0.02$, $I = 1.0$, $T^+ = 40$, and $\lambda_2^+ = 377$.

4. Conclusion

As the spanwise oscillation is transmitted along spanwise direction in turbulent channel flow, a set of distinct longitudinal vortices are created, regulating the quasi-streamwise vortices as they travel with the wave and forming the wide ribbons of low-speed fluid. The wavy streamlines around the travelling longitudinal vortices cause the ejection of high-speed fluid and the sweep of low-speed fluid, reducing the Reynolds stress to nearly a half across the entire channel, which leads to a large drag reduction.

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