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Turbulent Boundary Layer Control via a Streamwise Travelling Wave Induced by an External Force *

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Turbulent boundary layer control via a streamwise travelling wave is investigated based on direct numerical simulation of an incompressible turbulent channel flow. The streamwise travelling wave is induced on one side wall of the channel by a spanwise external force, e.g., Lorenz force, which is confined in the viscous sublayer. As the control strategy used in this study has never been examined, we pay our attention to its efficiency of drag control. It is revealed that the propagating direction of the travelling wave, i.e., the downstream or upstream propagating direction with respect to the streamwise flow, has an important role on the drag control, leading to a significant drag reduction or enhancement for the parameters considered. The coherent structures of turbulent boundary layer are altered and the underlying mechanisms are analysed. The results obtained provide physical insight into the understanding of turbulent boundary layer control.

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Turbulence control in wall-bounded flows is of great importance in fundamentals and applications.[1] The relevant work has been performed experimentally and numerically using extensive turbulence control means, e.g., wall oscillation[2−4] and external force.[5−9] A typical approach has been recognized using electromagnetic turbulence control, which can be achieved based on an array of tiles covering the controlled region of a flat plate.[6,9] Then, the produced Lorenz force in stationary or pulsing form, which can be easily accomplished via an electro-control, is subjected to the flow control. Early works involved imposing the Lorenz force along the flow direction[9] or the wall-normal direction;[8] however, no conclusive evidence of a drag reduction has been reported. Then, some work using the Lorenz force along the spanwise direction has been carried out. Berger *et al.*[5] numerically dealt with a turbulent channel flow with an oscillating spanwise Lorenz force applied to one side wall of the channel and found a drag reduction 40% approximately. Du *et al.*[6,7] also studied wall-bounded turbulent flow with a spanwise travelling wave induced by the spanwise Lorenz force and revealed a drag reduction around 30%.

In this study, we deal with turbulent boundary layer control via a streamwise travelling wave induced by a spanwise Lorenz force. To our knowledge, this kind of control strategy has never been studied. Thus, it is highly desirable to examine the efficiency of drag control via a streamwise travelling wave.

A configuration used here is an incompressible turbulent channel flow with one side wall imposed by force control. The incompressible Navier–Stokes equations are used for direct simulation of fully developed turbulent flow. To normalize the governing equations, the bulk mean velocity u_b is used as the velocity scale, and the half-height of the channel δ as the length scale. The non-dimensional governing equations are given as

$$\frac{\partial u_i}{\partial x_i} = 0, \quad (1)$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial (u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{1}{Re_b}\frac{\partial^2 u_i}{\partial x_j \partial x_j} + F_z\delta_{i3}, \quad (2)$$

where Re_b is the Reynolds number defined as $Re_b = u_b\delta/\nu$ with ν the kinematic viscosity, p is the pressure, and $u_i (i = 1, 2, 3)$, corresponding to u, v and w, represents the velocity components in the streamwise (x), wall-normal (y) and spanwise (z) directions, respectively. F_z denotes the Lorenz force and is imposed on the lower wall of the channel via a streamwise travelling wave, i.e.

$$F_z = Ie^{-y/\Delta}\sin\Big(\frac{2\pi}{\lambda}x \mp \frac{2\pi}{T}t\Big), \quad (3)$$

where I is the non-dimensional amplitude of the travelling wave excitation, Δ is the penetration length of the control force, λ is the streamwise wavelength, and T is the period. Usually, the phase speed of the travelling wave is a key parameter for this problem and is defined as $C = \pm\lambda/T$, corresponding to the propagating direction of travelling wave in Eq. (3) along the $\pm x$-direction, i.e., the downstream and upstream direction, respectively. It is realized that the travelling wave direction has a significant influence on the drag control.

The parameters in the present calculation are typically chosen as follows: $Re_b = 3000$, or $Re_\tau \approx 200$ based on the friction velocity u_τ of the uncontrolled

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flow, $I = 2.25$, and $\Delta = 0.02$, or $\Delta^+ \approx 4$, lying in the viscous sublayer, where the superscript + indicates that variables are normalized by wall-unit scale with respect to the uncontrolled flow and used throughout this paper. The wavelength and period of travelling wave are set as $\lambda = \pi, 2\pi$ and 4π, and $T^+ = 50$, 100 and 200, respectively. Since a fully developed turbulent channel flow is assumed, periodic boundary conditions are employed in the streamwise and spanwise directions. No-slip velocity condition is imposed on the walls.

To solve Eqs. (1) and (2), a fractional-step method is employed. Spatial derivatives are discretized with a second order central difference on a staggered grid for all the terms in the equations. Time advancement is carried out by the third-order Runge–Kutta scheme. It is worthwhile to mention that the performance and reliability of the numerical method employed have been verified carefully based on our extensive direct numerical simulations (DNS) of turbulent flows.[10−12] In addition, the relevant numerical method with the second-order accuracy has been successfully used in the DNS of turbulent and transitional flows.[13,14]

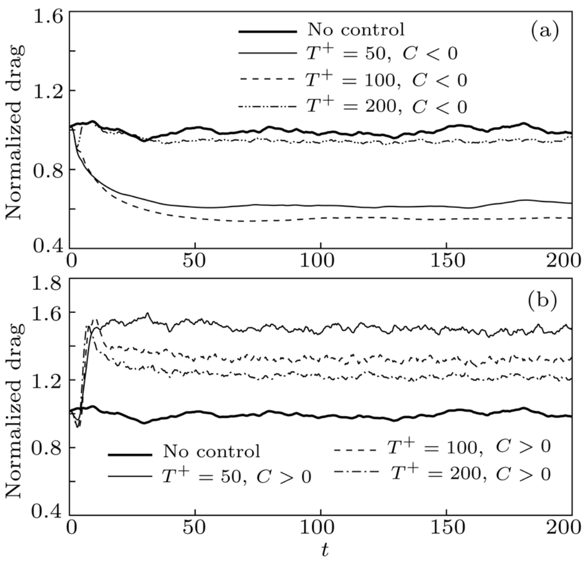

Fig. 1. Time histories of normalized drag force for $\lambda = \pi$ with several periods: (a) $C < 0$, (b) $C > 0$.

In the present calculation, the computational domain is chosen as $4\pi\delta \times 2\delta \times 2\pi\delta$ with the grid number of $193 \times 161 \times 129$ in the x, y and z-directions, respectively. A stretching transformation is employed with the grid point close to the wall located at $y^+ = 0.15$ approximately. Extensive validations have been performed to confirm that the grid system is enough to resolve all essential scales of the low-Reynolds number turbulence and contains the largest scale structures in the channel. The Lorenz force in Eq. (3) is imposed after the flow field has statistically reached a fully developed turbulent state. Some typical results are discussed in the following.

The time histories of normalized drag force are shown in Figs. 1(a) and 1(b) for $\lambda = \pi$, $T^+ = 50$, 100 and 200 with both the propagating directions, i.e., $C < 0$ and $C > 0$, respectively. The uncontrolled case is also exhibited for comparison. It is seen that the drag is reduced for $C < 0$ and enhanced for $C > 0$. Quantitatively compared with the drag variation due to the control, the time-averaged value of the normalized drag force is calculated after the controlled flow reaching statistical steady state, and its ratio with respect to the uncontrolled case is listed in Table 1, including the results for $\lambda = 2\pi$ and 4π. As shown in Table 1, the drag is reduced for $C < 0$ in most cases, even the drag reduction as much as 46% for $\lambda = \pi$ and $T^+ = 100$. Correspondingly, the drag is enhanced for $C > 0$ in most cases. Note that such behaviour is different from the turbulent flow over a streamwise travelling wavy wall, in which the drag force can be reduced when the travelling wave propagates downstream (i.e., $C > 0$) owing to reducing separation and suppressing turbulence.[15] Based on the present results, it is interested to indicate that the propagating direction of the travelling wave has a significant influence on the drag control, including the drag reduction and enhancement.

Although the present results indicate that the Lorenz force can be used to achieve substantial drag control, similar to the finding by Berger *et al.*,[5] the control efficiency is smaller using seawater as a fluid medium. The primary cause of this inefficiency is the low conductivity of seawater.[5] However, this control strategy is still helpful in understanding the physical mechanisms and achieving an optimization to yield high control efficiency.

Table 1. Drag change with several parameters for $C < 0$ (upper table) and $C > 0$ (lower table).

$C < 0$	$\lambda = \pi$	$\lambda = 2\pi$	$\lambda = 4\pi$
$T^+ = 50$	−38%	−40%	−42%
$T^+ = 100$	−46%	−18%	−8%
$T^+ = 200$	−6%	+11%	+21%

$C > 0$	$\lambda = \pi$	$\lambda = 2\pi$	$\lambda = 4\pi$
$T^+ = 50$	+50%	−15%	−39%
$T^+ = 100$	+32%	+53%	+23%
$T^+ = 200$	+22%	+39%	+56%

For the cases listed in Table 1, we have carefully examined the phase-averaged turbulent quantities including the averaged streamwise velocity, turbulence intensities and Reynolds shear stress, and identified that they are very similar during the period. To clearly present the results, the quantities based on the phase-averaged operation are used to analyse the flow behaviour for a typical wave length $\lambda = \pi$ with several periods.

The mean streamwise velocities $< u^+ >$ at $T^+ =$ 50, 100 and 200 are shown in Figs. 2(a) and 2(b) for $C < 0$ and $C > 0$, respectively. The slope of the velocity profiles in the linear region decreases for the cases of the drag reduction, and the thickness of viscous sublayer increases correspondingly. The rms values of turbulent velocity fluctuations are exhibited in Figs. 3(a) and 3(b) for $T^+ = 100$. For $C < 0$ in Fig. 3(a), the turbulence intensities near the controlled wall (i.e., $y = -1$) are suppressed, and the spanwise Lorenz force can profoundly reduce the kinetic energy of the turbulence, resulting in the drag reduction. In contrast, for $C > 0$ in Fig. 3(b), the turbulence intensities near the controlled wall are considerably strengthened, leading to the drag enhancement. The spanwise intensity w^+_{rms} exhibits a highest peak and acts as a dominated component, which is excited by the spanwise Lorenz force in Eq. (3). Furthermore, the corresponding vorticity fluctuations are shown in Figs. 3(c) and 3(d), where the vorticity fluctuations are normalized by wall-unit scale with respect to the uncontrolled flow and defined as $\omega^+_{irms} = \omega_{irms}\nu/u^2_\tau$.[16] As is expected, the vorticity fluctuations, in particular the streamwise component ω^+_{1rms}, are suppressed for $C < 0$ with a drag reduction and strengthened for $C > 0$ with a drag enhancement near the controlled wall. Thus, it is identified that the drag control is more related to the streamwise vorticity control in the viscous sublayer.

The present control in Eq. (3) is placed within the near-wall region only. Similar to Stokes' oscillating plate problem, the force penetration depth may be an important parameter related to the drag reduction or enhancement. To demonstrate the penetration depth, the phase-averaged spanwise velocity profiles during one period are shown in Fig. 4. The penetration depth in Fig. 4(a) reaches in the buffer layer and the external force can efficiently suppress the turbulent intensities and vorticity fluctuations near the controlled wall in Figs. 3(a) and 3(c). Correspondingly, the disturbance induced by the force penetrates deeply into the flow field in Fig. 4(b), leading to strengthening the spanwise turbulence intensity and the streamwise vorticity fluctuation significantly in Figs. 3(b) and 3(d). Although the spanwise Lorenz force in Eq. (3) is imposed in the viscous layer, we notice that its influence related to the penetration depth may limit in the near wall region with a drag reduction or spread into the core region of the channel with a drag enhancement. Thus, the penetration depth induced by the external force is a key parameter for drag control. The relevant behaviour is also associated with strengthening or suppressing the near-wall vortices and will be further discussed based on flow structures.

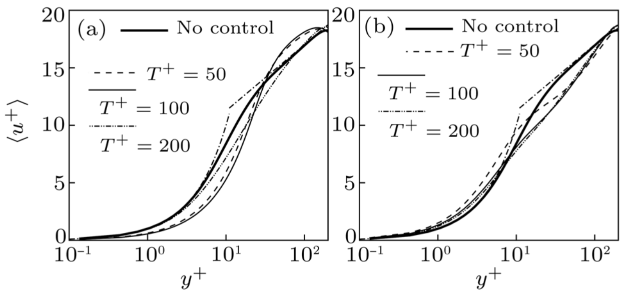

Fig. 2. Mean streamwise velocity profiles for $\lambda = \pi$ with (a) $C < 0$ and (b) $C > 0$, where the line $-\cdot-$ denotes $< u^+ >= y^+$ for $y^+ < 11$, and $< u^+ >= 0.25 \ln y^+ + 5.5$ for $y^+ > 11$.

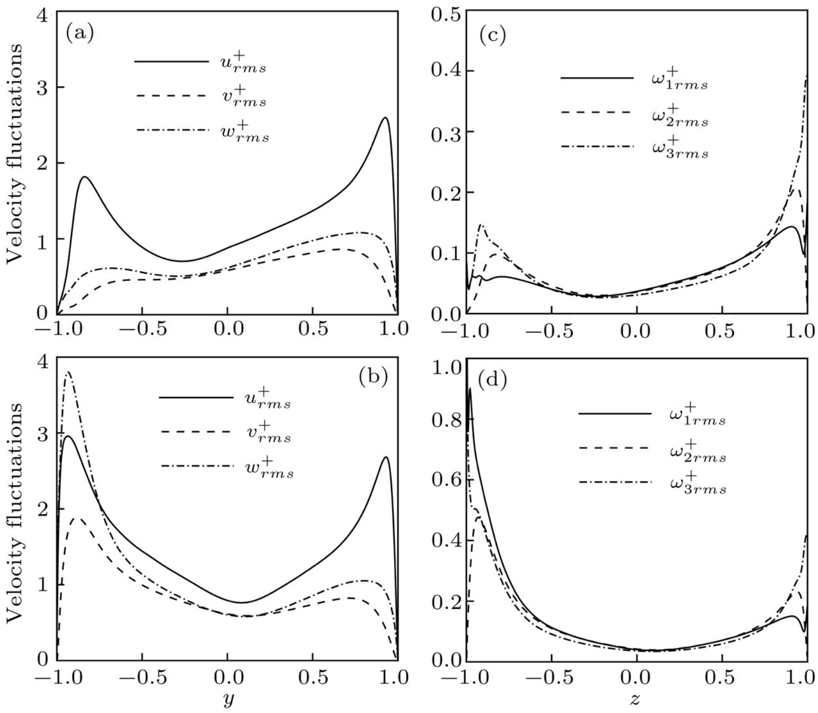

Fig. 3. Turbulence intensities for (a) $C < 0$ and (b) $C > 0$ as well as the vorticity fluctuations for (c) $C < 0$ and (d) $C > 0$ in $T^+ = 100$ and $\lambda = \pi$ with the controlled wall at $y = -1$ and uncontrolled wall at $y = 1$.

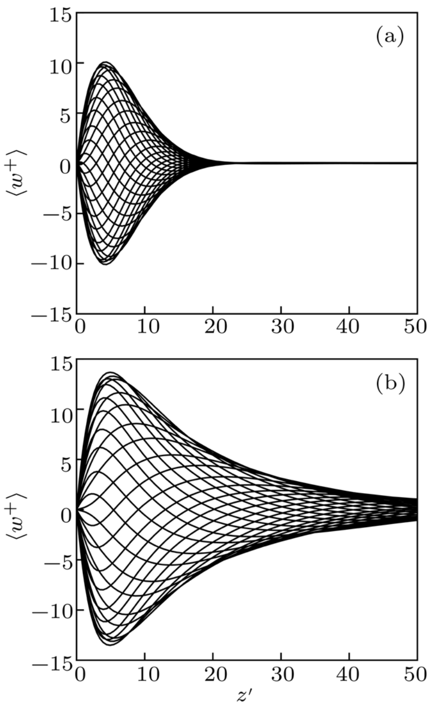

Fig. 4. Phase-averaged spanwise velocity profiles during one period in $T^+ = 100$ and $\lambda = \pi$ for (a) $C < 0$ and (b) $C > 0$.

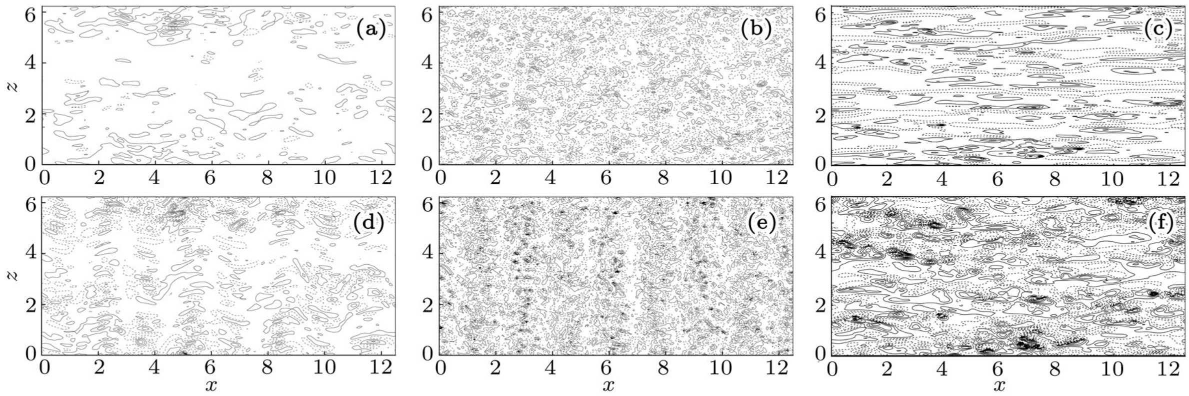

Fig. 5. Instantaneous streamwise velocity fluctuations in $\lambda = \pi$ and $T^+ = 100$ for (a) $C < 0$ ($\Delta_c = 0.02$), (b) $C > 0$ ($\Delta_c = 0.15$), and (c) uncontrolled case ($\Delta_c = 0.1$) and the corresponding streamwise vorticity fluctuations for (d) $C < 0$ ($\Delta_c = 0.5$), (e) $C > 0$ ($\Delta_c = 7.5$), and (f) uncontrolled case ($\Delta_c = 0.5$). Here Δ_c means an increment of the contours. Solid lines represent positive values and dashed lines negative values.

Structures of the velocity and vorticity fluctuations are of great help in exhibiting the influence of the spanwise Lorenz force on turbulence coherent structures in the near-wall region. The contours of the instantaneous streamwise velocity and vorticity fluctuations in a plane parallel to the wall at $y^+ = 4$ are shown in Fig. 5. To exhibit clearly the flow structures, the increments in the contours are different. For $C < 0$ with a drag reduction in Fig. 5(a), the streamwise velocity fluctuations are significantly suppressed and absent streaky structures occur with a nearly quiescent flow. For $C > 0$ with a drag enhancement in Fig. 5(b), dense streaky structures in the contour plots of the streamwise velocity fluctuation appear, associated with the higher succession of ejection and sweeping events. The events may induce a large penetration depth in Fig. 4(b). For comparison, the pattern near the uncontrolled wall is shown in Fig. 5(c) and relatively elongated streaky structures are generated. Thus, the spanwise Lorenz force can break off the streaks to form smaller scale structures in Fig. 5(b).

The corresponding streamwise vorticity fluctuations are also shown in Figs. 5(d)–5(f). Similarly, there exist absent streaky structures in Fig. 5(d) and dense streaky structures with relatively small size in Fig. 5(e), compared with the structures in Fig. 5(f) for the uncontrolled case. Thus, the spanwise Lorenz force has been exhibited to suppress or strengthen the turbulence intensities in Fig. 3, leading to the drag reduction or enhancement. The relevant mechanism is that the external force has a significant influence on the generation and development of the near-wall vortices, closely associated with the propagating direction of the travelling wave in Eq. (3).

In summary, direct numerical simulation of an incompressible turbulent channel flow is performed to investigate turbulent boundary layer control via a streamwise travelling wave induced by a spanwise external force. Here, we should remind that, even though drag control usually represents a drag reduction in most cases, drag enhancement is also an attractive topic, e.g., a recent work on drag enhancement with polymers.[17] Based on the results obtained here, the present control strategy can easily reach a purpose of the drag reduction and enhancement, mainly dependent on the propagating direction of the travelling wave. The penetration depth induced by the external force is a key parameter for drag reduction and enhancement, which is also associated with strengthening or suppressing the near-wall vortices. The spanwise Lorenz force can profoundly reduce the kinetic energy of the turbulence, resulting in the drag reduction. Oppositely, the turbulence intensities near the controlled wall, in particular the spanwise intensity excited by the spanwise Lorenz force, are considerably strengthened, leading to the drag enhancement. The results obtained provide physical insight into the understanding of turbulent boundary layer control by means of a streamwise travelling wave.

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