TURBULENT SKIN-FRICTION DRAG REDUCTION BY TRAVELLING WAVES INDUCED BY SPANWISE LORENTZ FORCE

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Abstract The streamwise and spanwise travelling waves induced by spanwise Lorentz force are studied for skin-friction drag reduction in a turbulent channel. The effect of the streamwise travelling wave by spanwise Lorentz force on drag reduction is comparable to that of the spanwise wall motion. The drag reduction map shows a drag reduction region and a drag increase region, depending on a time scale $\mathscr{T} = \lambda/(\mathscr{U}_c - \omega/\kappa)$. For spanwise travelling wave, a large drag reduction appears at large oscillation frequencies and small spanwise wave numbers, while all stationary wave cases give a drag increase. When the wave travels at an oblique angle to the streamwise mean flow, the maximum drag reduction is obtained in the backward travelling wave case. Generally, the backward streamwise travelling wave is found to be most efficient in drag reduction among all oblique travelling waves. Spanwise oscillation, forward streamwise travelling, spanwise travelling and backward streamwise travelling wave cases share a similar drag reduction mechanism: first, the spanwise motion directly breaks the near wall quasi-streamwise vortices structure array, which results in the shortening of streamwise streaks; second, the spanwise velocity layer maintains the asymmetry of the positive and negative quasi-streamwise vortices, which leads to a sustained drag reduction.

keywords: Flow control; Lorentz force; plasma actuator; DNS; channel flow; turbulent flow simulation

INTRODUCTION

Turbulent skin-friction can be reduced by spanwise Lorentz force via spanwise oscillation [1], spanwise travelling wave [2] and streamwise travelling wave [4]. In the current study, a serial of DNSs are performed in a $\kappa-\omega$ space at $Re_\tau = 200$ to investigate drag reduction mechanisms by spanwise Lorentz force. The spanwise Lorentz force has the following wave form as in equation (1) [3].

$$f_z = Ae^{-y/\Delta}\sin\left(\frac{2\pi}{\lambda_x}x + \frac{2\pi}{\lambda_z}z - \frac{2\pi}{T}t\right) = Ae^{-y/\Delta}\sin\left(\kappa_x x + \kappa_z z - \omega t\right), \tag{1}$$

where κ_x (or λ_x) is the streamwise wave number (or wave length), κ_z (or λ_z) is the spanwise wave number (or wave length), ω (or T) is the oscillation frequency (or period), A is the force strength, and Δ is the force penetration depth. In a general configuration, the wave can travel at an oblique angle of $\theta = \tan^{-1}(\kappa_x/\kappa_z)$. The forward streamwise (FST), spanwise (SP) and backward streamwise (BST) travelling waves correspond to $\theta = 0°$, $90°$ and $180°$, respectively.
The Navier-Stokes equations are solved using an in-house fully implicit second-order finite volume code [5] at $Re = 3150$ (based on bulk mean velocity U_m and half channel height h). The mass flow rate is kept constant by dynamically adjusting the streamwise mean pressure gradient when spanwise Lorentz force is applied on both channel walls. The skin-friction drag reduction is measured by $\mathcal{DR} = (C_{f,0} - C_f)/C_{f,0} \times 100$. Here, $C_{f,0}$ is the skin-friction coefficient of the no control flow and C_f is the skin-friction coefficient of the control case.

RESULTS

The $\mathcal{DR}$ maps for streamwise and spanwise travelling waves by spanwise Lorentz force is shown in figure 1 for $A = 0.5$ and $\Delta^+ = 10$. The drag increase ($\mathcal{DI}$) region is indicated by light yellow colour, while the drag reduction ($\mathcal{DR}$) region is indicated by dark blue colour. The $\mathcal{DR}$ map of streamwise travelling wave by spanwise Lorentz force shows some similarity to that of the spanwise wall motion [7]. It has a $\mathcal{DI}$ cone region with wave speed $c^+ = 8$ (dashed line) and two $\mathcal{DR}$ regions passing the optimal spanwise oscillation frequency $\omega^+_{opt} = 0.08$. The drag reduction by streamwise travelling wave is less effective for spanwise Lorentz force than for spanwise wall motion, and a $\mathcal{DI}$ region appears at the top-left corner of the backward travelling wave region as well. All spanwise travelling wave cases at $\omega^+ = 0$ give a drag increase. The $\mathcal{DR}$ region for spanwise travelling wave appears in large ω and small κ_z. The two vertical dash-dot lines passing $\omega^+_{opt} = 0.08$ tend to separate the $\mathcal{DR}$ and $\mathcal{DI}$ regions well. When the time scale $\mathscr{T} = \lambda/(\mathscr{U}_c - \omega/\kappa)$ is used [7], the whole $\mathcal{DR}$ map can be analogue to spanwise oscillation Lorentz force cases ($\kappa = 0$). Here $\mathscr{U}_c$ is the convection velocity of the near wall turbulent structures.
The snapshots for the velocity magnitude $\sqrt{u^2 + v^2 + w^2}$ on an $x - z$ plane at $y^+ = 5$ is shown in figure 2 for five oblique wave angles: $\theta = 0°$, $45°$, $90°$, $135°$ and $180°$. The flow direction, wave travelling direction and the Lorentz force direction are indicated by a white, green and blue arrow, respectively. The wave number and oscillation frequency are $\kappa^+ = 0.002$ and $\omega^+ = 0.06$. For $\theta = 0°$, $90°$ and $180°$, the parameter points are shown on the $\mathcal{DR}$ map in figure 1. It is clearly seen that the near wall streaks are significantly modulated by the travelling waves. Considering the near

wall structure framework proposed by Jeong *et al.* [6], it suggests that the spanwise Lorentz force can twist the quasi-streamwise structures and stop the formation of long streamwise streaks, which results in a drag reduction. This evidence is also shown in the streamwise velocity energy spectra and the conditional averaged near wall quasi-streamwise vortice behaviours (not shown here). Further analysis will be presented at the conference.

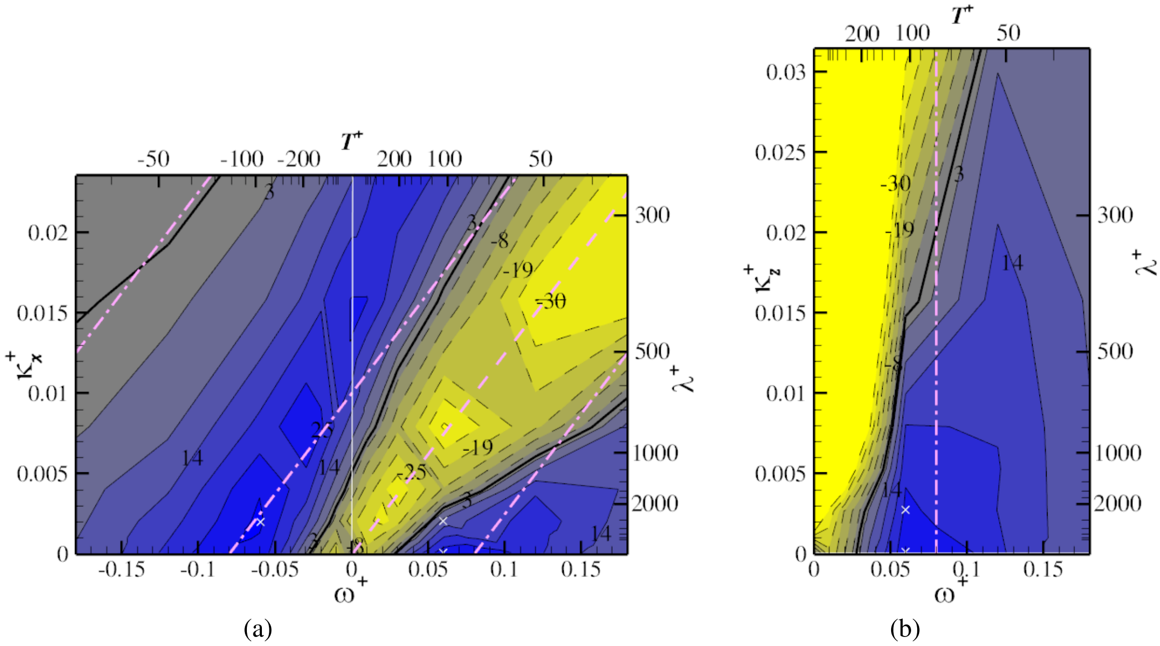

Figure 1. $\mathcal{DR}$ maps for (a) streamwise travelling wave and (b) spanwise travelling wave.

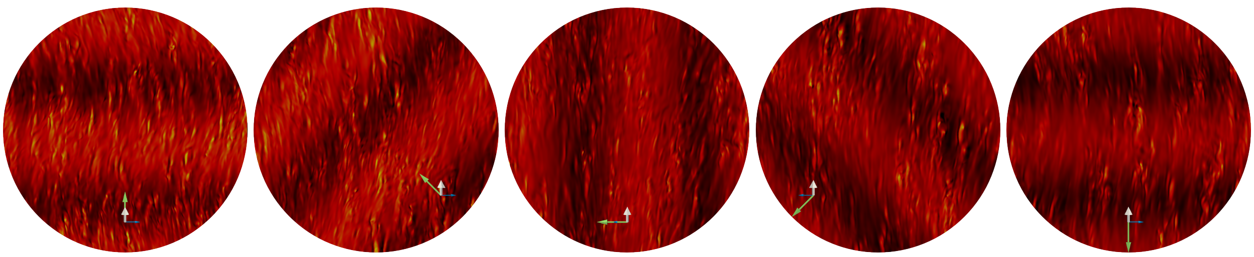

Figure 2. Instantaneous velocity magnitude $\sqrt{u^2+v^2+w^2}$ contour at $y^+=5$ for wave angles $\theta=0°$, $45°$, $90°$, $135°$, and $180°$.

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