WALL TURBULENCE CONTROL BY SPANWISE TRAVELING WAVES

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Abstract The turbulence drag reduction properties of spanwise forcing in the form of spanwise-traveling wave are studied via two types of implementations: wall motion and body force. Studies have been performed in a 3D/4D parametric space respectively. The control parameters yielding the best drag reduction and energetic performance are identified in the parametric space. Different flow statistics suggest that the turbulence structure is significantly altered by such control strategies. Considering the energy budget shows that such forcing is rather ineffective, and that the spatial non-uniformity of the forcing is always detrimental with respect to the net savings.

INTRODUCTION

Drag reduction in flow control has been studied extensively due to the potential of reducing energy consumption and gas emissions. Spanwise-traveling wave of spanwise forcing was found capable of reducing the turbulence drag up to more than 30% by Du and Karniadakis [1]. They employed a control strategy based on body force (Lorentz force) to excite the fluid. Du et al [2] expanded the study and shown that the turbulent flow structure was modified by the traveling wave. Zhao et al [3] used a similar traveling wave but based on in-plane wall deformation and found comparable results concerning drag reduction and flow statistics. However, both Du et al [2] and Zhao et al [3] carried out too limited number of simulations to conclude the reliably assess the true dependence of drag reduction and energetic performance on the forcing parameters.

SPANWISE TRAVELING WAVE

As previously stated, the spanwise-traveling wave could be implemented in two ways: body force and wall motion. Eqs. (1) (based on body force) and (2) (based on wall motion) mathematically characterize the spanwise-traveling wave of these two types. κ_z and ω are the wavenumber and frequency of the traveling wave, A_f and A are the amplitude of body force and wall motion in the spanwise (z) direction and F_z and w are the spanwise body force and wall velocity amplitudes, respectively. The most significant difference between these two implementations lies in the exponential factor $e^{-y/\Delta}$. Δ is the effective penetration length of the Lorentz force. This factor indicates that the Lorentz force decays exponentially as the distance to the wall increases. Therefore, instead of affecting only the boundary as in Eq. (2), a layer of fluid with thickness of the order Δ is affected by the Lorentz force.
It is worth mentioning that Eq. (1), the model for Lorentz force, is just one possibility of the body force implementation. Other possibilities might have different wall normal direction dependence other than the exponential factor $e^{-y/\Delta}$.

$$F_z = A_f e^{-y/\Delta} \sin(\kappa_z z - \omega t) \tag{1}$$

$$w = A \sin(\kappa_z z - \omega t) \tag{2}$$

Xie and Quadrio [4] recently presented the global maps for drag reduction R and net energy saving S in the 3D parametric space $\omega - \kappa_z - A$ of the wall motion strategy. They found that the global optimal control in terms of net energy savings always lies on the plane identified by $\kappa_z = 0$, which corresponds to a special case of spanwise traveling wave: the spanwise wall oscillation. This result suggests that a retrospect of the work of Du et al [2] may be in order, since relevant results, which we believe are crucial, are missing.

DNS RESULTS

In the 4D parametric space $\omega - \kappa_z - A_f - \Delta$, around 1000 DNS simulations are performed in a channel flow at Reynolds number $Re_\tau = 200$. Figure 1 shows the DNS simulation points at $\Delta = 0.01$ and the corresponding results in terms of drag reduction rate R. The overall dependency on the force intensity A_f is similar to what is reported in Xie and Quadrio [4] for the wall-based forcing: as A_f increases, both drag reduction DR and drag increase DI tend to increase in absolute value, and the maximum DR and maximum DI both occur on the plane $A = 2$. From Figure 1, the point with maximum DR rate R_m is found at $\omega = 0.5$, $\kappa_z = 0$ and $A = 2$. As the penetration length Δ increases, the R_m point shifts slowly to larger ω and lower A. Nevertheless, R_m is always found to be on the plane $\kappa_z = 0$. Similar patterns are identified in the map of net energy saving S. All the 3D ($\omega - \kappa_z - A$) optimal points are located on the plane $\kappa_z = 0$. It can be concluded that a spanwise-traveling wave type of forcing for turbulence drag reduction is always outperformed by the spatially-uniform oscillatory excitation.

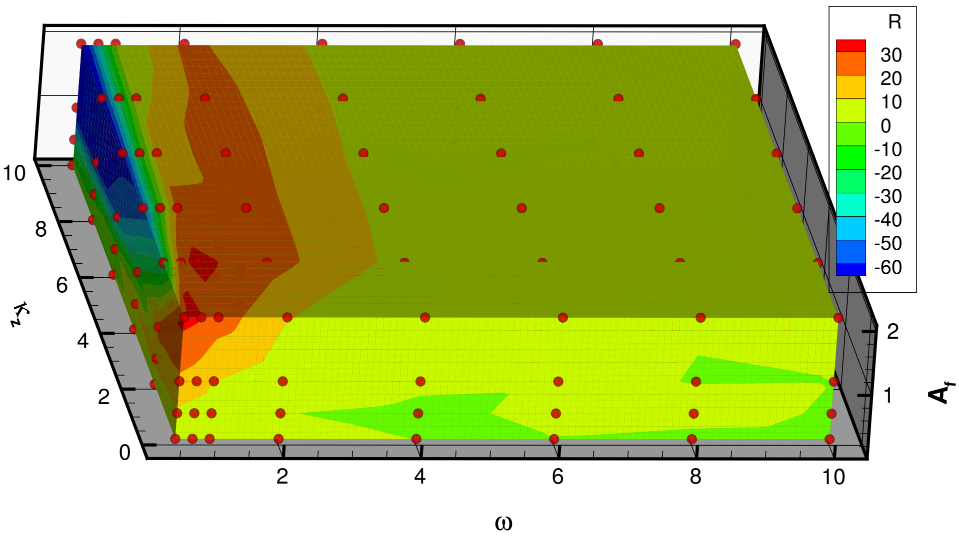

Figure 1. The map of drag reduction in parametric space $\omega - \kappa_z - A$ at $\Delta = 0.01$. Each red dots on the map correspond to a DNS simulation. The contour of $R(\%)$ is drawn based on linear interpolation. $R > 0$ indicates drag reduction while $R < 0$ indicates drag increase cases.

As described by Du et al [2], the turbulence structure near the wall is strongly modified by the forcing. The distribution of the Reynolds stress $\overline{u'v'}$ (averaged in streamwise and spanwise directions as well as in time) along the wall normal direction is significantly altered in the DI and DR cases. The Reynolds stress $\overline{u'v'}$ directly determines the total turbulence drag as shown by Fukagata et al [5]. Moreover, same as observed in Xie and Quadrio [4], a non-negligible spanwise flow rate appears in most of the simulation cases, although the spanwise pressure gradient was set to 0. However, the relationship between the flow rate and the wave speed $c = \dfrac{\omega}{\kappa_z}$ does not exhibit strong linearity as in Xie and Quadrio [4] and Hoepffner and Fukagata [6].

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