PREDICTION OF SKIN-FRICTION REDUCTION BY OPPOSITION CONTROL IN TURBULENT CHANNEL FLOW

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Summary A strengthened opposition control scheme to achieve turbulence drag reduction is proposed. By enhancing the control input when the detection position is less than 20 wall units, a drag reduction rate up to 34% can be achieved at $Re_\tau = 180$, which is much higher than the best value of 25% reported in literature. Based on the similarity of the distribution of Reynolds shear stress between the controlled and uncontrolled flows, a formula to predict the drag reduction rate by opposition control is suggested.

INTRODUCTION

It is known that the origin of the high skin friction in turbulent flows is closely related with near-wall stream-wise vortices, and by actively manipulating these structures sustained turbulence drag reduction can be achieved. This idea was first tested by Choi *et al* [1], in which the so-called "opposition control" scheme was proposed. By imposing blowing/suction at the wall just instantaneously in opposite to the vertical velocity detected at a small distance to the wall, they obtained 25% drag reduction rate. Hammond *et al* [2] studied the influence of the detection position y_d, and suggested that the optimal y_d^+ was around 15 in terms of drag reduction rate, and the controls with $y_d^+ > 20$ would result in drag increase. Very recently, Chung *et al* [3] extended the opposition control scheme to the range of $y_d^+ > 20$ by reducing the control strength, and found that the weakened opposition control could also successfully reduce skin-friction drag. In present study, we found that the strengthened opposition control for $y_d^+ < 20$ was far more effective than the original and the weakened control scheme. And hence the dependence of drag reduction rate on the two control parameters, detection position y_d and control input modulation A, are studied. Based on the virtual wall concept, which was first adopted by Hammond *et al* [2] to explain the mechanism for drag reduction by opposition control, a formula that can predict the behaviour of opposition control is proposed.

RESULTS

Direct numerical simulations using Fourier-Chebyshev spectral method are performed to turbulent channel flows with constant mass flux subjected to strengthened opposition control. The friction Reynolds number for uncontrolled flow is $Re_\tau = 180$. The computational domain is selected to span $4\pi\times2\times2\pi$ in streamwise (x,u), wall-normal (y,v) and spanwise (z,w) directions, respectively, and 128×129×128 girds are used. The control is imposed via boundary condition at the wall, $v(x,\pm1,z,t) = -Av(x,y_d,z,t)$. In present study, the detection positions in the range of $5 < y_d^+ < 20$ with control input modulation $A = 1\sim8$ are tested.

Drag reduction rates obtained with different detection position y_d^+ and different amplitude modulation A are shown in Fig.1(a). For the same detection position, it can be seen that DR increases with A greatly in the range of $A = 1\sim3$, and gradually tends to a limit corresponding to the maximum drag reduction rate that can be achieved at this given y_d. For a given A, $y_d^+ \approx 15$ is still the optimal detection position concerning the drag reduction rate, which is identical to Hammond [2] and Chung [3]'s work. At $y_d^+ = 15.4$ and A=8, the maximum DR of about 34% is achieved, which exceeds about 50% the best drag reduction rate of 25% reported in literature. The relationship between the wall blowing/suction amplitude v_w^+, a direct measurement of the control input, and DR is shown in Fig.1(b). It can be seen that DR increases with v_w^+ for each detection position in the range of $y_d^+ = 5.5 \sim 19.2$. For the same drag reduction, the control scheme with lower detection position seems more economic. Hence, taking both drag reduction rate and control efficiency into consideration, the more suitable choice of detection position should be $y_d^+ = 10.5 \sim 15.4$.

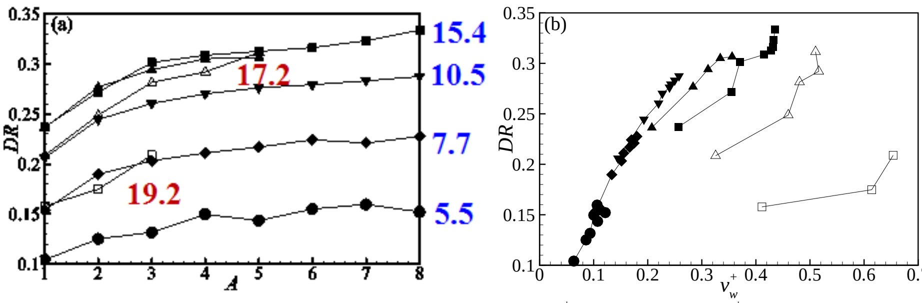

Fig.1 Drag reduction rate as a function of (a) A and (b) v_w^+ with different y_d^+ as indicated in (a).

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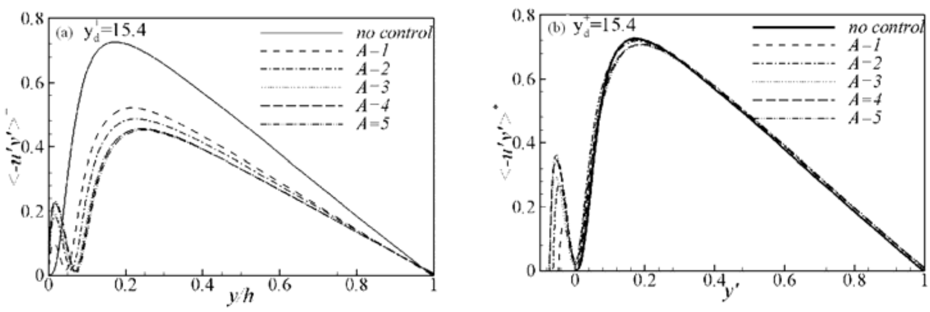

Fig.2 Distribution of Reynolds shear stress. (a) scaled by u_τ in y coordinate and (b) scaled by u_* in y' coordinate.

When the control is imposed, a local minimum will occur in the wall-normal velocity fluctuation intensity between the real wall and the detection plane, indicating the hindrance of momentum transport in wall-normal direction by the control. This effect was considered to be equivalent to the establishment of a "virtual wall" there as was first nominated by Hammond *et al* [2]. In turbulent channel flow, for both controlled and uncontrolled, the Reynolds and viscous shear stresses satisfies the linear relationship $\mu\partial U / \partial y - \rho < u'v' > = \tau_w(1 - y / h)$. Let $y_{\rm vw}$ denote the position of the virtual wall, we use the total shear stress at $y_{\rm vw}$ to define the local friction velocity at the virtual wall, $u_* = u_\tau(1 - y_{\rm vw} / h)^{1/2}$, in which u_τ is the friction velocity at the real wall. Let y^0 represents the position where the uncontrolled Reynolds stress scaled by u_τ is equal to the controlled Reynolds shear stress scaled by u_* at virtual wall. Moving the coordinate origin to the virtual wall and transforming y coordinate into $y' = (y - y_{\rm vw}) / (h - y_{\rm vw})\,(1 - y^0 / h) + y^0 / h$, we find that a similarity of Reynolds shear stress distribution exists between the controlled and uncontrolled flows if they are respectively scaled by the virtual wall and the real wall friction velocity, as is shown in Fig.2.

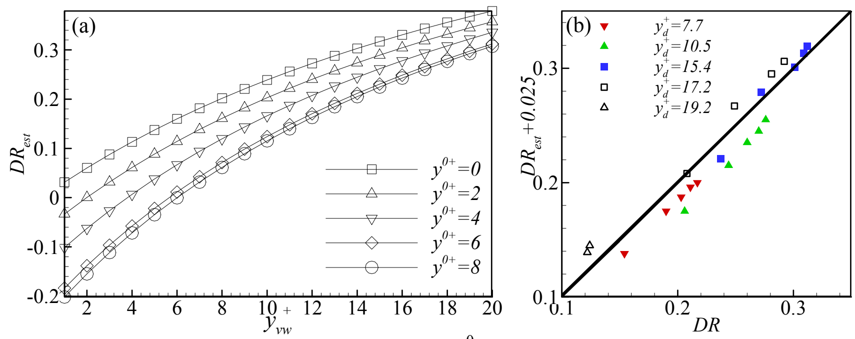

Fig.3 (a) Distribution of estimated DR with $y_{\rm vw}$ at different y^0; (b) comparison between estimated DR and real DR.

According to the linear dependence on y of the total shear stress, the skin friction coefficient in turbulent channel flow can be expressed as the sum of the friction coefficient of the laminar flow at the same flow rate and the weighted integral of Reynolds shear stress. Using the property that the controlled Reynolds stress above the virtual wall is similar to that of the uncontrolled above the real wall, and neglecting the contribution from Reynolds shear stress between real wall and virtual wall, DR can be estimated as

$$DR_{est} = 1 - \frac{1 - 3I_{no}}{1 - 3I_{no}\left(1 - \bar{y}_{vw}\right)^2 / \left(1 - \bar{y}_0\right)}$$

where I_{no} is the weight integral of uncontrolled Reynolds shear stress, $\bar{y} = y / h$. As shown in Fig.3(a), DR increases with $y_{\rm vw}$, but decreases with y^0, which is a measure of the residual Reynolds shear stress at the virtual wall. If the virtual wall is perfectly established, $y^0 \approx 0$, and DR only depends on $y_{\rm vw}$, which can be roughly estimated from A and y_d as $y_{\rm vw} = y_d\, A \,/\, (\, A + 1\,)$. Fig.3(b) compares the hence estimated DR with that obtained from DNS. The DNS results show a good agreement with $DR_{\rm est}$+0.025.

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