FLOW CONTROL BY TURBULENCE STATE MODIFICATIONS IN THE NEAR-WALL REGION

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Summary Significant drag reduction is obtained in numerical simulation of turbulent channel flow by forcing local turbulence in the near-wall layer to approach a one-component state, where only the streamwise velocity fluctuation remains. The drag reduction rate obtained with the modified layer of a thickness $y_d^+ \approx 5$ is in the order of 30%. This value is in agreement with the drag reduction rate estimated based on the FIK identity for a channel flow in which all turbulence has been suppressed in the near-wall layer. This fact suggests that the idealized damping of turbulence in the near-wall region, which has resulted in large drag reduction even at high Reynolds numbers, is achievable by a mere reorganization of turbulent fluctuations.

Since turbulent drag consumes large amounts of energy, its reduction is of great economical and ecological interest. In order to further advance the design of active and passive flow control techniques, it is important to investigate how much and which part of a turbulent flow field needs to be controlled in order to achieve flow management with the least possible effort. Iwamoto et al. [1] show that significant drag reduction can be obtained by an idealized near-wall layer manipulation by which only turbulence near the wall is damped (resulting in a laminar flow field in this region). The drag reduction rate obtained is estimated employing the FIK identity introduced by Fukagata et al. [2], and it is revealed that even at high Reynolds numbers large drag reduction can be attained without direct control of large scale turbulent structures. Since complete damping of turbulence in a certain layer would be difficult in real applications, the effect of manipulation of turbulence state in the near-wall region is investigated.

Frohnapfel et al. [3] demonstrate that the mechanism of turbulent drag reduction is associated with increased anisotropy of turbulence in the near-wall region. The highest possible value of turbulence anisotropy is related to the one-componental state of turbulence in the anisotropy invariant map (Lumley and Newman, [4]). It is shown by Jovanović and Hillerbrand [5] that for this special case the two-component motions close to the wall must additionally satisfy constraints of local axisymmetry. Based on a statistical analysis of the velocity fluctuations, they conclude that small scale turbulence whose statistical properties are invariant about the axis aligned with the mean flow direction will vanish in close proximity of solid boundaries (where the continuity equation dictates the limiting behavior of the velocity fluctuations). This analysis suggests that turbulence plotted in the anisotropy invariant map will approach the one-component state in the near-wall region before completely disappearing for the case that reverse transition to a laminar flow occurs.

Numerical experiments of a channel flow in which turbulence in the near-wall region is forced towards the one-component limit yield high drag reduction rates [3]. The forcing is applied by setting the spanwise velocity fluctuation equal to the wall-normal velocity fluctuation at grid points in a selected layer near the wall before the continuity equation is enforced at each time step. According to [5] such forcing in the vicinity of the wall will result in a trend towards one-component turbulence accompanied by significant suppression of small scale turbulence in this region.

The resulting velocity fluctuations (rms values) for the case where forcing is applied to the region $y/\delta \leq 0.028$ in comparison with the unforced channel flow case are presented in figure 1a. The spanwise (w) and wall-normal (v) velocity fluctuations are almost completely damped in the layer where the forcing is applied, whilst the streamwise velocity fluctuation (u) is reduced but not completely damped. Thus, a one-component state of turbulence is established. Figure 1b shows the Reynolds shear stress distributions for the unforced and forced cases normalized with u_τ of the uncontrolled case. For the controlled flow, $-\overline{u^+v^+}$ is drastically decreased and practically no shear stress exists in the region where the forcing is applied; this is associated with the notable suppression of v in this region. This change in the Reynolds shear stress suggests significant drag reduction.

In [1] and [2], it is demonstrated that the amount of drag reduction directly corresponds to the difference in the integrals of a weighted Reynolds shear stress distribution $\left(-\overline{u^+v^+}\right)_{weighted}$ given by:

$$\left(-\overline{u^+v^+}\right)_{weighted} = 3\left(1-\frac{y}{\delta}\right)\left(-\overline{u^+v^+}\right). \tag{1}$$

This distribution is also included in figure 1b. The difference in the areas underneath these two curves, which interpreted as the resulting drag reduction, reaches 31%. It is equivalent to the value obtained when drag reduction is based on the change in the wall shear stress:

$$DR = 1 - \frac{\tau_w}{\left(\tau_w\right)_0}, \tag{2}$$

where $(\tau_w)_0$ corresponds to the wall shear stress in the uncontrolled flow. Since the region where the forcing is applied is much thinner compared to the channel half width, $y/\delta \leq 0.028$, the difference in the area underneath the weighted Reynolds shear stress distribution is almost negligible for this region. This suggests that the drag reduction is mainly attributed to the reduction of Reynolds shear stress further away from the wall.

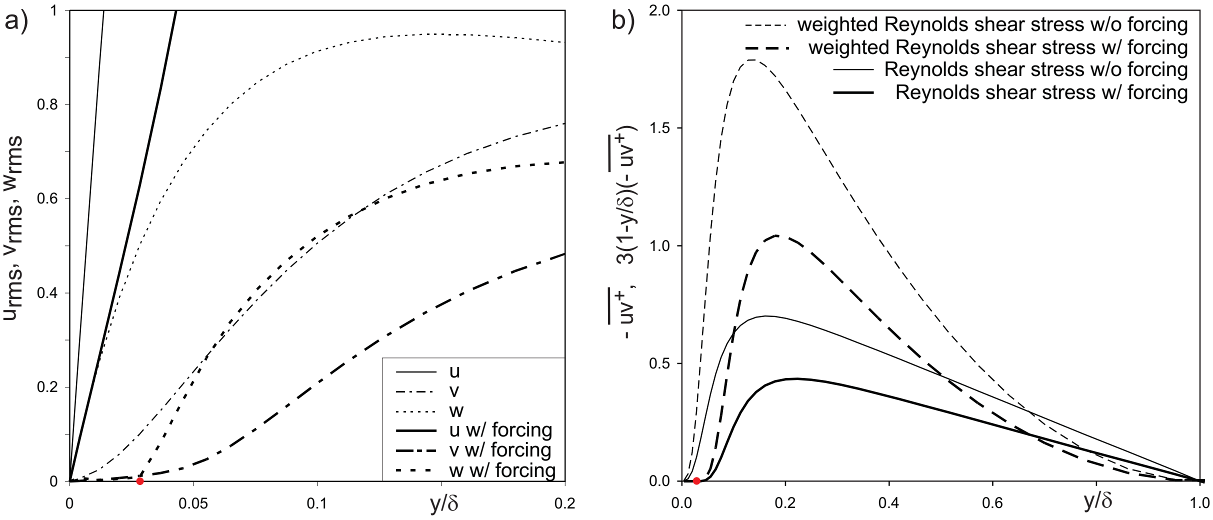

Figure 1. a) RMS velocity fluctuations in the near-wall region without and with forcing in the region $y/\delta \leq y_d/\delta \ = 0.028$. b) Original and weighted Reynolds shear stress distribution with and without forcing, normalized with the friction velocity u_τ of the uncontrolled flow. The red point marks the position of y_d/δ in both figures.

For the idealized near-wall modifications of [1], the FIK identity allows to calculate the drag reduction DR in terms of the Reynolds number Re_τ of the uncontrolled flow and the relative thickness of the damping layer y_d/δ:

$$\begin{aligned}\frac{1}{\kappa} ln Re_\tau + F = \frac{y_d}{\delta}\left(1 - \frac{y_d}{\delta} + \frac{1}{3}\frac{y_d^2}{\delta^2}\right)(1-DR)\, Re_\tau + \\ \left(1-\frac{y_d}{\delta}\right)^{3/2}(1-DR)^{1/2} \times \\ \left[\frac{1}{\kappa} ln\left\{\left(1-\frac{y_d}{\delta}\right)^{3/2}(1-DR)^{1/2}\, Re_\tau\right\} + F\right]\end{aligned} \qquad (3)$$

with $\kappa = 0.41$ and $F = 3.2$. In [1] this identity was verified for a Reynolds number range of $10^3 < Re_\tau < 5 \times 10^5$, while the damping layer thicknesses of $10 < y_d^+ < 60$ were analyzed. In the present simulations, not all turbulence in the near-wall region is damped, but one-component turbulence state is approached. The spanwise and wall-normal fluctuations are significantly damped while the streamwise component remains. The Reynolds number for the corresponding uncontrolled channel flow is $Re_\tau = 180$ and the thickness of the modified layer $y_d^+ = 5.1$. In spite of these differences, the above identity equation is employed to check whether it can be used to estimate the drag reduction rate. For $Re_\tau = 180$ and $y/\delta = 0.028$, the drag reduction rate is calculated as $DR = 29\%$. This result is in good agreement with the actual value of $DR = 31\%$.

The numerical experiment is also carried out for even thinner modified layers of $y_d^+ = 3.2$ and 2.2. For all cases, equation 3 yields reasonable predictions of the drag reduction rate. Future work will concentrate on extending the numerical experiment to a thickness of y_d^+ that correspond to the ones reported in [1] to investigate whether enforcing of one-component turbulence in a certain damping layer will yield the same drag reduction rate as the total suppression of turbulence in this region.

References

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