REYNOLDS NUMBER EFFECT ON TURBULENT DRAG REDUCTION

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Abstract An analytic relationship that predicts the Reynolds number effect on turbulent drag reduction by active means is developed in analogy with riblets. It is applicable to all control techniques whose action results in an upward shift ΔB of the logarithmic region of the turbulent velocity profile. In particular, we use it to address the Re-effect affecting streamwise-traveling waves of spanwise wall velocity [7], aided by a new large dataset of Direct Numerical Simulations of turbulent channel flows at increasing Re. The main outcome of this study is that the control-induced upward-shift ΔB of the logarithmic region does not vary with Re along a large part of the wave parameter space, also where high drag reduction is achieved. Here, the analytical relationship allows to extrapolate low-Re drag reduction information to high-Re flows. In the narrow regions where ΔB does vary with Re, an additional Re-effect is deemed to exist, which depends on the present control technique only and which is investigated with a three-dimensional phase conditional averaging procedure.

INTRODUCTION

Flow control techniques for turbulent skin-friction drag reduction exhibit decreasing performance for increasing Reynolds numbers, whether they be passive riblets or active strategies. The low and relatively narrow Reynolds number range at which experimental and numerical studies can be performed does not allow to confidently predict the amount of drag reduction that can be achieved at Reynolds numbers typical of most engineering applications. Only for passive riblets, whose influence on the mean velocity profile depends on the riblet geometry only, the rate at which the drag reduction degrades with Re has been predicted exploiting the concept of "protrusion height" [1, 6, 3] and found to be proportional to the square root of the baseline skin-friction coefficient [8]. Predictive tools that describe the Re-effect on drag reduction achieved via active near-wall turbulence manipulation have not been delivered yet, owing to the large spectrum of available control strategies and the complexity of their drag reduction mechanisms.

This work extends the Re-effect estimation common for riblets to one of the most performing predetermined techniques based on spanwise wall forcing: the streamwise-traveling waves of spanwise wall velocity. It requires the imposition of the following spanwise wall-velocity distribution:

$$W_w\left(x,t\right) = A \sin\left(\kappa_x x - \omega t\right) \tag{1}$$

where A is the maximum wall velocity, κ_x is the streamwise wavenumber and ω is the angular frequency. When $\kappa_x = 0$ the control reduces to the case of a temporally oscillating wall. The ability of the control to reduce turbulent drag is measured by the drag reduction rate R, which is defined as the decrease in skin-friction coefficient C_f relative to $C_{f,0}$, the skin-friction coefficient of the uncontrolled flow.

METHOD

A large dataset of Direct Numerical Simulations of turbulent channel flow at $Re_\tau = 200$ and $Re_\tau = 1000$, modified by streamwise-traveling waves, is produced and analysed. The full parametric study considers a large part of the 3D parameter space (A, κ_x, ω) at each Re, and consists of more than 4000 simulations. This huge computational study is required and is made possible by reducing the size of the computational domain to achieve the best compromise between a shorter computing time and increased fluctuations over time of the space-averaged turbulence statistics. A smaller simulation dataset of turbulent channels at regular size and same Re, both driven at constant flow rate and constant pressure gradient, is used to validate the previous results and to apply a three-dimensional conditional averaging procedure to analyse the average streamwise vortex properties at different phases of spanwise forcing.

RESULTS

We have recently shown [4] that the Re-effect can not be satisfactorily predicted by the value of the exponent γ of the power-law $R \sim Re_\tau^\gamma$, that is traditionally assumed [2, 9] to hold with a unique coefficient $\gamma \approx -0.2$. In fact, the coefficient γ is function of all the control parameters and eventually of Re itself [4, 5]. Moreover, the power law does not hold whenever R changes its sign or becomes zero after having increased Re.

Therefore, we adopt a different approach to quantify the Re-effect and predict R at high values of Re. Figure 1(a) shows how the mean velocity profile of a turbulent channel flow is modified by the imposition of drag-reducing streamwise-traveling waves. When the friction velocity of the controlled flow is used to compute the viscous "+" units, the control

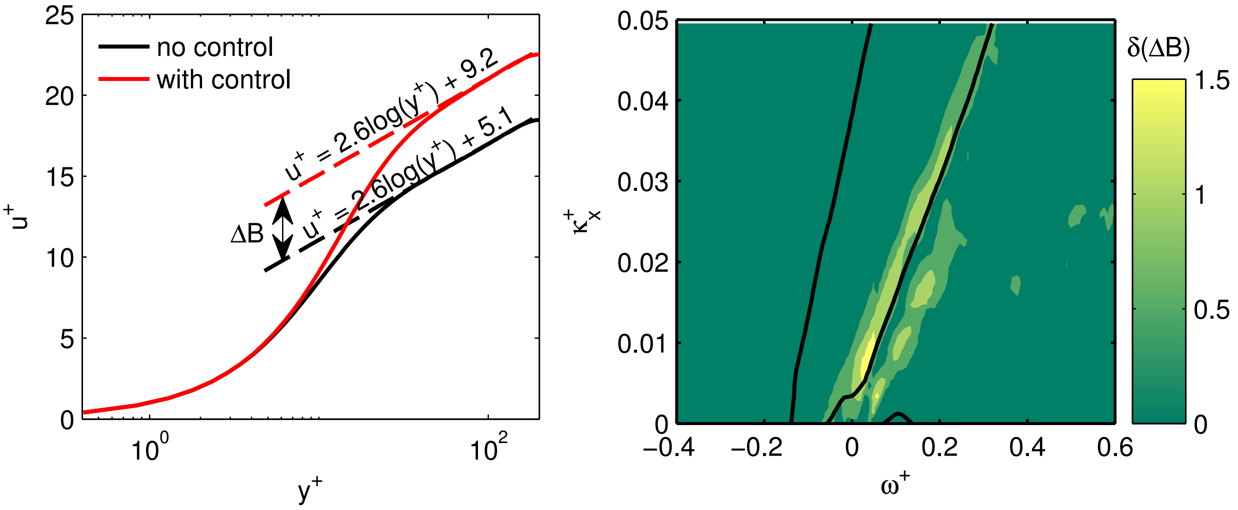

Figure 1. (a) Effect of the streamwise-traveling waves on the mean velocity profile scaled in actual wall units. Black: reference channel; red: controlled channel. (b) Map of $\delta\left(\Delta B\right) = \Delta B\left(Re_\tau = 200\right) - \Delta B\left(Re_\tau = 1000\right)$. Within the black solid line $R > 30\%$.

action results mainly in an upward-shift of the logarithmic region, as a consequence of the reduced $\langle u'v' \rangle$. This upward-shift can be quantified by the change ΔB in the wall intercept B of the logarithmic velocity profile in the logarithmic law $u^+ = (\log y^+) + B$. If we choose ΔB as figure of merit for drag reduction, we obtain drag reduction maps similar to what commonly observed for R, with a notable exception: ΔB does not significantly change if Re is increased. Figure 1(b) shows the map of $\delta\left(\Delta B\right)$, the modulus of the change in ΔB when increasing from $Re_\tau = 200$ to $Re_\tau = 1000$ for forcing at $A^+ = 12$. Clearly, ΔB is constant with Re over a large portion of the parameter space, also in regions where drag reduction rates of more than 30% are achieved. ΔB decreases significantly only along a narrow strip, located between the regions of high drag reduction and drag increase.

This result has some important implications. In regions where the upward shift ΔB is not influenced by Re, we develop an analytic relationship among ΔB, R and Re_τ, similarly to what has been done previously for riblets, which can be used to extrapolate low-Re drag reduction data to high-Re flows. Except for very high values of R, R is predicted to decay at a much slower rate than $Re_\tau^{-0.2}$. We call this Re-effect "intrinsic", since it is mainly due to the decreasing value of $C_{f,0}$ with Re. In regions of the parameter space where ΔB does change with Re, an additional Re-effect exists which is deemed to be specific to the present control technique. The present result extends to all those control strategies that cause an upward-shift ΔB of the logarithmic region, provided that ΔB is independent of Re.

At the conference, both Re-effects will be discussed and eventual differences with Re in the interaction between the spanwise generalized Stokes layer and the conditionally averaged quasi streamwise vortex are discussed as possible source of the technique-specific part of the Reynolds number effect on turbulent drag reduction by traveling-waves.

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