EFFECTIVENESS OF SPANWISE FORCING FOR TURBULENT DRAG REDUCTION AT HIGHER RE

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Abstract The effectiveness of open-loop spanwise-forcing techniques in reducing turbulent skin-friction drag is studied via an extensive parametric study by direct numerical simulations for increasing values of the Reynolds number Re. We consider in particular the streamwise-traveling waves introduced by Quadrio *et al.*[7]. The main outcome of the study is that the control parameters strongly affect the way drag reduction depends on Re. The set of control parameters yielding the maximum drag reduction changes with Re and regions of the parameter space exist where the Re-sensitivity is low. Here, with respect to what is currently believed, increasing Re has a much less dramatic (or even beneficial) effect from an energetic standpoint, since the power required for the control action may reduce with Re faster than drag reduction.

INTRODUCTION

In the last decades, research has been devoted to study and understand spanwise-forcing techniques for the reduction of the turbulent skin-friction drag, owing to their moderate complexity and significant achievable drag reduction (DR) [4, 6]. However, most studies, either numerical or experimental, have been carried out at low values of Re, and we know today that the control performances degrade quite fast with Re due to the so-called Re-effect. We are involved in studying practical implementations with energy-efficient electroactive polymers [8], but the thorough assessment of the Re-effect is of paramount importance to determine the applicability of this class of techniques to real-world applications [6]. In this work we consider the following forcing, introduced by [7], that yields perhaps the best energetic performances at low Re; its most general form is the following spanwise wall-velocity distribution:

$$W_w(x,t) = A \sin(\kappa_x x - \omega t)$$

where A is the maximum wall velocity, κ_x is the streamwise wavenumber and ω is the oscillation frequency. When $\kappa_x = 0$ the control reduces to the case of a temporally oscillating wall, and the $\omega = 0$ case is the so-called steady wave. The main control performance estimator is the drag reduction rate R which is given by the decrease in pumping power P relative to P_0, the pumping power of the uncontrolled flow. In addition, the net power saving, S, is defined as the budget between the power saved due to the applied control ($P_0 - P$) and the power spent to apply the control P_{in}, relative to P_0.

METHOD

We have recently suggested [3] the need for an extensive re-evaluation of the available data. At the conference we will describe a complete DNS study in a plane channel flow at $Re_\tau = 1000$ and (with a more limited dataset) at $Re_\tau = 2000$, for the oscillating wall and the streamwise-traveling waves. The full parametric study considers the 3 parameters ω, κ and A. We can afford such a huge computational study because the size of the computational domain is carefully adjusted to achieve the best compromise between a shorter computing time and increased fluctuations over time of the space-averaged turbulence statistics (thus leading to a longer averaging time). We employ a statistical technique to monitor the uncertainty arising from a finite averaging time, and consistently present our results with error bars at 95% confidence level.

RESULTS

The Re-effect on R is quantified by the value of the exponent γ of the power-law $R \sim Re_\tau^\gamma$ that is traditionally assumed [1, 9] to hold with a unique coefficient $\gamma \approx -0.2$. Large negative γ imply a strong decrease of drag reduction with increasing Re. Figure 1 (left) shows (preliminary data, at $A^+ = 12$) that the effect of Re strongly depends on the control parameters: it is large in the best-performing highly drag-reducing zone at low-Re, colored in red, but reduces significantly at larger $|\omega^+|$. The Re-effect is largest when approaching the drag-increase (DI) region, colored in blue. The implication might be that the DI region looses its strength but widens its area of influence to the neighboring regions of the parameter space. Near the low-Re optimum we compute $\gamma = -0.25$ while regions exist where γ is as low as -0.05. Part of the DI region turns into slight drag reduction. This behavior can not be represented by the aforementioned power-law and strongly suggests that the function $R = R(Re)$ not only is a function of the control parameters but may also take more complex forms than a power-law. The overall scenario is that optimal control parameters move towards the less sensitive regions, namely towards higher κ_x and towards frequencies distant from the DI region.

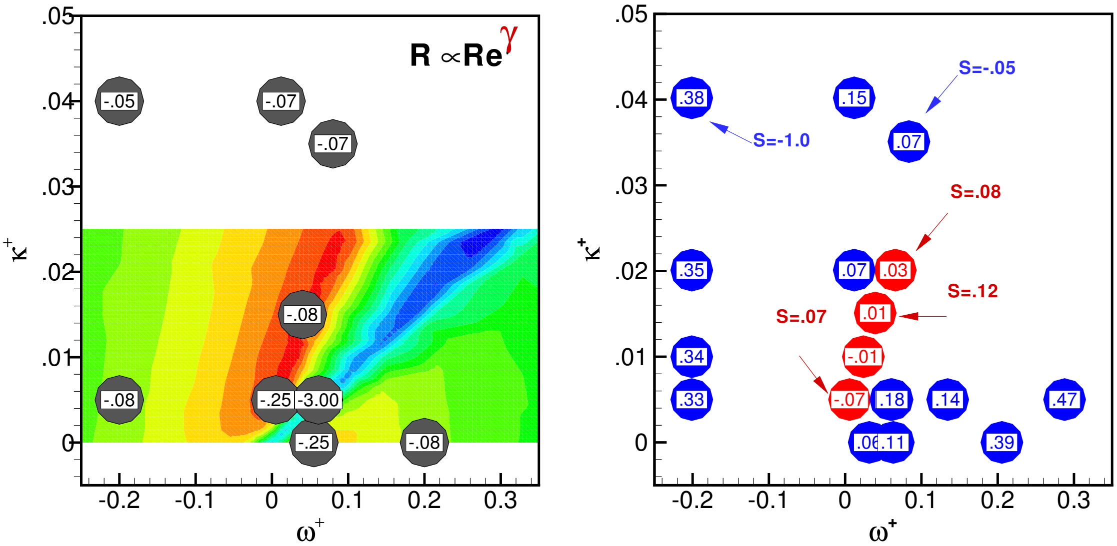

Figure 1. On the right: the Re-sensitivity coefficient γ, supposing a power law $R \sim Re_\tau^\gamma$, as function of the control parameters for Re_τ up to 1000 superimposed on the drag reduction map after Quadrio *et al.*[7]. On the left: numbers are the variation of the net power budget ΔS from $Re_\tau = 200$ to 1000, as a function of control parameters. Blue circles are data at $S < 0$, red circles are data at $S > 0$. Arrows indicate interesting values of S at $Re_\tau = 1000$.

We also report for the first time that in regions of low Re-sensitivity the input power decreases faster than the drag reduction, so that the net power saving S increases, i.e. the overall energy budget improves with Re. Figure 1 (right) reports the change $\Delta S = S(Re_\tau = 1000) - S(Re_\tau = 200)$ in power saving when increasing from $Re_\tau = 200$ to 1000. The power saving usually increase for points at $S < 0$ (blue circles). Point at high wavenumbers are increasing their S fast enough to almost approach $S = 0$ and a further increase in Re will cause their S to become positive. Points at $S > 0$ (red circles) in regions of high Re-sensitivity decrease their S. Most interestingly, points are also present that have $S > 0$ and lie in a low-sensitivity region: they exhibit an increase in S and achieved $S = 0.12$ at $Re_\tau = 1000$.

In conclusion we show the optimal set of control parameters that maximizes R and S changes due to the heterogeneous Re-effect. The scenario may be much better than expected from an energetically point of view. The ability of spatially reduced domains to capture the Re-effect moreover suggests both that Re acts via near-wall mechanisms that are only marginally affected by large-scale motions and that the cross-influence of the near-wall and bulk regions is not that important. Thus, the ability of simplified models [5] and linearized N-S equations [2] to represent main DR mechanisms is supported.

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