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SKIN-FRICTION DRAG REDUCTION BY SPANWISE FORCING: THE REYNOLDS-NUMBER EFFECT

M. Quadrio
Department of Aerospace Science and Technologies, Politecnico di Milano, Campus Bovisa, Milano Italy

D. Gatti
Institute of Fluid Mechanics, Karlsruhe Institute of Technology, Germany

INTRODUCTION

Flow control research and in particular the study of turbulent drag reduction techniques are often limited for obvious practical reasons to low values of the Reynolds number Re, for both experimental and numerical work, which is mostly carried out by DNS. So far, several techniques for skin-friction drag reduction have demonstrated their effectiveness in a number of basic studies. Besides (before) addressing the obvious technological challenge of finding a suitable way to implement them in real-world applications in a cost-effective way, one basic information is still missing: we need to know their expected performance at the large values of Re which are typical in most applications.

In this contribution, we focus on the streamwise-travelling waves introduced by [5], that have been demonstrated to be best within the whole class of spanwise-forcing techniques, and explore via DNS their behaviour at higher Re. This continues the work reported in [3], where it was first discovered that the optimum at low Re might not remain such at higher Re. We thus build a large dataset of drag reduction and energy saving performance at $Re_\tau = 200$ and $Re_\tau = 1000$, and start with deducing the various trends via comparison of the two datasets. We will then consider conditional averages of turbulent structures to link them to the Generalized Stokes Layer induced by the waves, and attempt to describe the performance of the waves in analogy with riblets.

METHOD

This work considers the streamwise-travelling waves of spanwise wall velocity [5], imposing 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 waves become a spatially-uniform 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.

A large dataset of Direct Numerical Simulations of turbulent channel flow at $Re_\tau = 200$ and $Re_\tau = 1000$, modified by streamwise-travelling 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 large-scale study is made affordable by using a computational domain of reduced size, to achieve the best compromise between faster calculations and longer averaging times needed to smooth out temporal fluctuations. A more limited dataset of turbulent channels at regular size, driven both at constant flow rate and constant pressure gradient, is used to validate the previous results. The three-dimensional conditional averaging procedure mentioned below and meant to analyse the average streamwise vortex properties at different phases of spanwise forcing is also carried out on the database built with this subset of large-domain simulations.

RESULTS

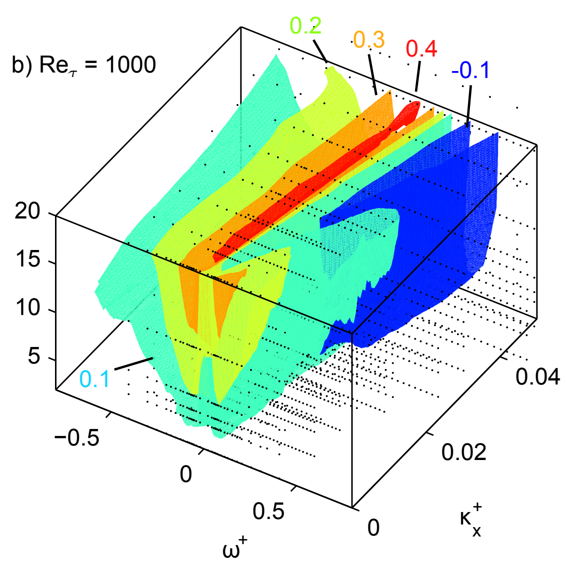

Figure 1: Three-dimensional drag reduction map at $Re_\tau = 1000$. The tiny dots indicate where a DNS measurement of the friction coefficient has been carried out. The colored iso-surfaces denote constant drag reduction rate, with negative numbers implying drag increase.

The raw dataset coming out from our computational study looks like what is plotted in figure 1 (only $Re_\tau = 1000$ is shown). It is important to notice that our parameter study also includes a reasonable sample of forcing amplitudes. The figure contains results obtained from DNS of channel flow driven at constant flow rate, and scaled in inner units defined with the friction velocity of the reference flow. Plotting them with the alternative scaling obtained by using the modified friction velocity is also possible and sometimes revealing.

This wealth of information allows us to confirm that the Re-effect can not be satisfactorily predicted via a simple power law $R \sim Re_\tau^\gamma$ that is often invoked [1, 6] with a costant value $\gamma \approx -0.2$. In fact, the coefficient γ is function of all the control parameters and eventually of Re itself [3, 4].

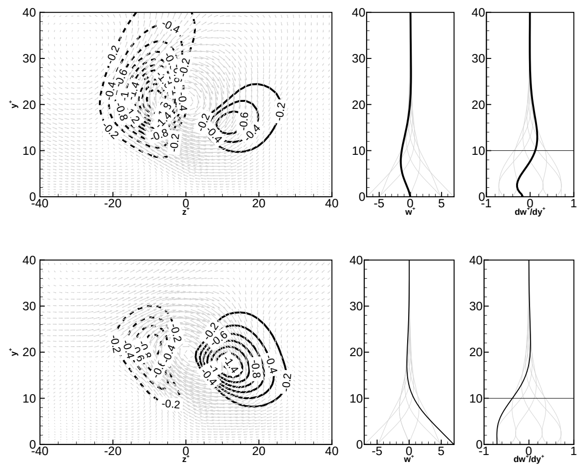

Figure 2: Conditionally-averaged flow structure for the drag-reducing travelling waves at two phases along the cycle. For each phase, the leftmost plot reports the cross-sectional velocity field in a cross-flow ($y-z$) plane, alongside with contours of Q2 (solid line) and Q4 (dashed lines) events. At the right, the profiles of the velocity and the shear of the GSL are plotted.

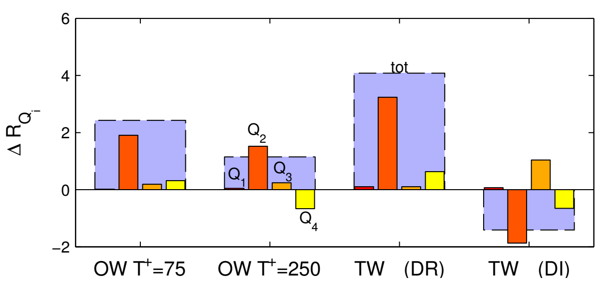

Figure 3: Quadrant contributions of the weighted Reynolds shear stress for oscillating wall (left) and travelling waves (right), both at optimal and suboptimal conditions.

The smaller dataset from the simulations in the full domain driven either at constant flow rate and constant pressure gradient are used to build a study, based on conditional averages, aimed at emerging the dominant near-wall vortical structure, and investigate its space-time relation with the control-induced Generalized Stokes Layer. The idea here is to extend the work by Yakeno et al [7, 8] who eventually derived a predictive formula for the spanwise-oscillating wall. Figure 2 contains two sample slices of the conditionally-averaged structure, at two different phases, alongside with the velocity and shear profiles of the GSL. As in [8], we carry out a quadrant analysis of the FIK-weighted contribution of the Reynolds stresses to drag, and highlight similarities and differences between the oscillating wall and the travelling waves (figure 3).

Lastly, we make use of mean velocity profiles like those plotted in figure 4 to measure the shift ΔB of the mean longi-

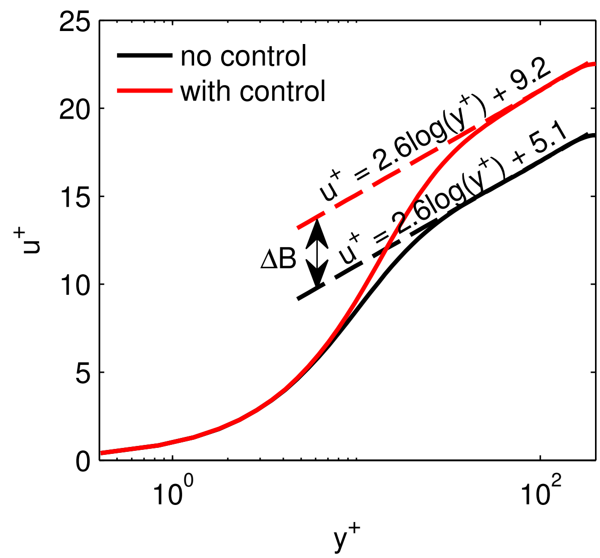

Figure 4: Effect of the streamwise-traveling waves on the mean velocity profile scaled in actual wall units.

tudinal velocity profile, expressed in the law-of-the-wall form $U^+ = A \log y^+ + B + \Delta B$ and examine the idea of using ΔB as an indicator of drag reduction, in analogy with what is often done for riblets [2]. Indeed, ΔB presents the considerable advantage of being cleared from most of the Re-effect.

REFERENCES

[1] J.-I. Choi, C.-X. Xu, and H. J. Sung. Drag reduction by spanwise wall oscillation in wall-bounded turbulent flows. *AIAA J.*, 40(5):842–850, 2002.

[2] R. Garcia-Mayoral and J. Jiménez. Hydrodynamic stability and the breakdown of the viscous regime over riblets. *J. Fluid. Mech.*, 678:317–347, 2011.

[3] D. Gatti and M. Quadrio. Performance losses of drag-reducing spanwise forcing at moderate values of the Reynolds number. *Phys. Fluids*, 25:125109(17), 2013.

[4] E. Hurst, Q. Yang, and Y.M. Chung. The effect of reynolds number on turbulent drag reduction by streamwise travelling waves. *J. Fluid Mech.*, 759:28–55, 11 2014.

[5] M. Quadrio, P. Ricco, and C. Viotti. Streamwise-traveling waves of spanwise wall velocity for turbulent drag reduction. *J. Fluid Mech.*, 627:161–178, 2009.

[6] E. Touber and M.A. Leschziner. Near-wall streak modification by spanwise oscillatory wall motion and drag-reduction mechanisms. *J. Fluid Mech.*, 693:150–200, 2012.

[7] A. Yakeno, Y. Hasegawa, and N. Kasagi. Interpretation of the optimal frequency for skin friction drag reduction with spanwise wall-oscillation control. In *ETMM10*, 2010.

[8] A. Yakeno, Y. Hasegawa, and N. Kasagi. Modification of quasi-streamwise vortical structure in a drag-reduced turbulent channel flow with spanwise wall oscillation. *Phys. Fluids*, 26:085109, 2014.