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NUMERICAL STUDY OF TURUBLENT SKIN-FRICTION DRAG REDUCTION VIA SPANWISE FORCING AT LARGE VALUES OF REYNOLDS NUMBER

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INTRODUCTION

Transverse near-wall forcing as a means to mitigate skin-friction drag in turbulent flows has gathered significant attention, owing to its potential for substantial environmental and economic benefits [10]. Beginning with the seminal work on spanwise wall oscillations by Jung *et al.* [4], three decades of research efforts led to important progress; however, several crucial factors still hinder the deployment of spanwise forcing to industrial settings. One of the major challenges concerns the diminishing efficacy of drag reduction with increasing Reynolds numbers Re, as industrial scenarios are often characterised by a large value of Re.

In the present work, we address the Reynolds-dependence of skin-friction drag reduction induced by streamwise-traveling waves of spanwise wall velocity (StTW) [9], thanks to their large potential for drag reduction at small energy expenditure. With StTW the following wall velocity distribution is imposed:

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

where w_w is the spanwise (z) velocity component at the wall, A is the maximum wall velocity and thus a measure of the amplitude of the spanwise forcing, κ is the streamwise wavenumber, ω is the angular frequency, and x and t are the streamwise coordinate and time, respectively.

While extremely important, the studies that addressed the Re-effect on the drag reduction potential of StTW so far suffer from some limitations. The numerical study by Gatti & Quadrio [2] is comprehensive but has been performed in computational domains of reduced size, with only few validations in regular domain sizes limited up to a friction Reynolds number based on the friction velocity of the unmodified channel of $Re_{\tau_0} = 1000$. Rouhi *et al.* [11] extended the parametric study of StTW to $Re_{\tau_0} = 4000$ but employed large eddy simulations (LES) and domain sizes marginally larger than those by Gatti & Quadrio [2]. Marusic *et al.* [5] and Chandran *et al.* [1] observed for the first time that the drag reduction potential can increase with Re but based their evidence on a comparison between high-Re experimental data and lower-Re LES data.

METHOD

A new high-fidelity direct numerical simulation (DNS) dataset of turbulent open-channel flows is produced to study the effect of the Reynolds number up to $Re_{\tau_0} = 6000$ on the reduction of turbulent drag achieved by StTW, enforced as wall boundary condition for the spanwise velocity component after equation (1). The database is designed to be high-fidelity, exploits the same method throughout the Re range and employs computational domains of regular size. Thus, it circumvents the main shortcomings of previous studies.

Re_b	Re_{τ_0}	N_{cases}	$N_x \times N_y \times N_z$	Symbol
20000	994.4	71	2304 × 165 × 1536	▲
43650	2002.2	71	4608 × 265 × 3072	▼
68600	3009.0	7	6912 × 355 × 4608	♦
148000	6010.1	3	13312 × 591 × 9216	●

Table 1: Details of the direct numerical simulations of open channel flows modified by StTW, grouped in sets of N_{cases} simulations performed at a constant value of bulk Reynolds number $Re_b = U_b h/\nu$. Re_{τ_0} is the friction Reynolds number in the reference uncontrolled channel at the same Re_b; N_x, N_y and N_z are the number of grid points in the direction indicated by the subscript. The last column indicates the color and symbol employed in the following figures to represent each set of simulations.

The open channel flow is essentially half a channel flow with a symmetry boundary condition at the centreplane, and is chosen here to halve the computational cost without affecting the drag reduction results. The computer code used for the DNS is based on the classic fractional step method with second-order finite differences on a staggered grid [3, 6].

Four sets of simulations, whose details are listed in table 1, are run at prescribed values of bulk Reynolds number $Re_b = U_b h/\nu$, by enforcing the bulk velocity U_b as described in [8]. Each set comprises one reference simulation, in which the wall is fixed, and a variable number of cases with StTW applied at different values of $\{A, \kappa, \omega\}$. In the following, we will refer to each simulation set via its (nominal) value of Re_{τ_0}. Figure 1 shows the portion of the $\{\kappa^+, \omega^+\}$-space spanned in the present study. We consider only $A^+ = 5$, value at which StTW achieve the maximal net power saving. Here the superscipt + indicates viscous units defined with the reference friction velocity u_{τ_0}, as opposed to $*$, used to indicate the same units yet defined with the actual friction velocity u_τ.

All DNS are carried out in a box with $L_x = 6\pi h$ and $L_z = 2\pi h$, which is larger than what has been adopted by [11] at similar values of Re and sufficient to accommodate large-scale turbulent structures, as shown by a comparison with results from [12]. The mesh resolution for these cases is designed based on the criteria discussed by [7].

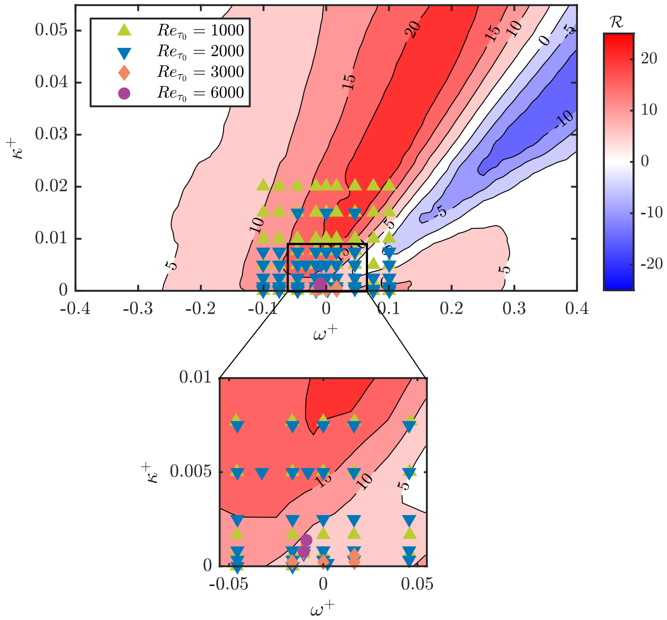

Figure 1: Portion of the parameter space spanned in the present study overlaid to the drag reduction map by [2] computed at $A^+ = 5$. Each symbol corresponds to a single simulation performed at the Reynolds number encoded by its shape, as described by the legend. All simulations are performed at $A^+ = 5$.

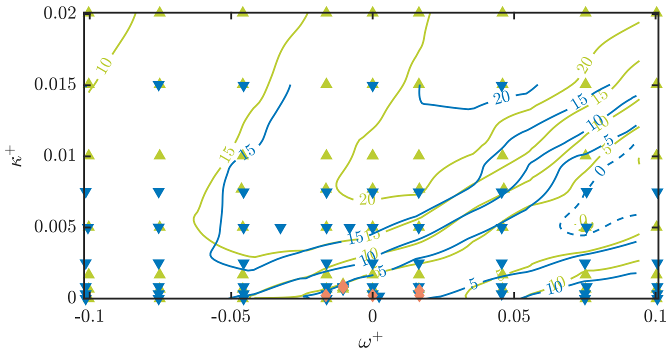

Figure 2: Maps of $\mathcal{R}$ as a function of the angular frequency ω^+ and wavenumber κ^+ of the forcing at $Re_{\tau_0} = 1000$ (———) and $Re_{\tau_0} = 2000$ (———). The symbols are colored after table 1 and show the parameters of each simulation underlying the map interpolation shown in the figure.

RESULTS

Figure 2 shows the percent drag reduction $\mathcal{R} = 1 - c_f / c_{f_0}$, defined as the relative control-induced change of skin-friction coefficient at $Re_{\tau_0} = 1000$ and $Re_{\tau_0} = 2000$. As predicted by the model proposed by Gatti & Quadrio [2], $\mathcal{R}$ is observed to decrease within the statistical uncertainty as Re increases. The maximum value of drag reduction at $Re_{\tau_0} = 2000$ is achieved at larger values of κ^+ compared to the lower value of Re.

Gatti & Quadrio [2] showed that the drag reduction effect by spanwise forcing becomes in fact constant with Re, provided it is not expressed via $\mathcal{R}$, that is *per se* a Re-dependent quantity, but through the Reynolds number-invariant parameter ΔB^*. This quantity, which expresses the main effect of StTW to induce a change ΔB^* of the additive constant in the logarithmic law for the mean velocity profile, is shown in figure 3. The figure clearly shows only minor changes of ΔB^* between the two Reynolds number considered above, confirming that at these values of Re, $\mathcal{R}$ decreases with Re itself.

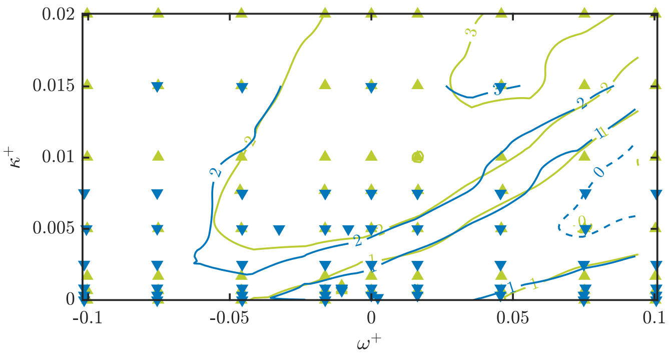

Figure 3: Maps of ΔB^* as a function of the angular frequency ω^+ and wavenumber κ^+ of the forcing at $Re_{\tau_0} = 1000$ (———) and $Re_{\tau_0} = 2000$ (———). Symbols as is figure 2. Contour lines are placed every unity with dashed lines indicating $\Delta B^* = 0$

At the conference, we will discuss the database in its entirety, including results up to $Re_{\tau_0} = 6000$ both in terms of drag reduction and net power saving.

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