TURBULENT DRAG REDUCTION BY TRAVELING WAVES OF SPANWISE FORCING

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Abstract Several techniques based on spanwise focing were introduced in the last decade [2, 8] in the form of traveling waves of spanwise forcing as generalization of the spanwise-wall oscillation technique to reduce skin-friction drag in a turbulent channel flow. Here we examine all their variants (including one that has never been considered before), by addressing the type of forcing (wall movement versus body force) as well as the traveling direction (streamwise versus spanwise) of the waves. We carry out a DNS-based study within an unified framework, to compare their capability to reduce skin-friction drag and, more importantly, net energy savings. The present results confirm the potential for drag reductions for every considered forcing. The best-performing spanwise traveling wave, in terms of either drag reduction or net energy saving, is found to be the one with infinite wavelength, i.e. still the spanwise wall oscillation. The streamwise-traveling waves consistently offer the best performance, especially in terms of net savings. The conditions under which body-force based control can be meaningfully compared to wall based control are discussed.

INTRODUCTION

Skin-friction turbulent drag reduction has been attempted with several control techniques. Quadrio [6] recently reviewed those that hinge upon a spanwise forcing of the near-wall flow, and that are the subject of the present paper. First within this class is the spanwise-oscillating wall (S*p*OW) concept introduced more than 20 years ago by Jung et al. [4] and later studied by many others. In S*p*OW, the wall harmonically moves as a function of time t according to:

$$W_w = A \sin(\omega t) , \tag{1}$$

where W_w is the spanwise component of the velocity vector at the wall, A is the oscillation amplitude, and ω its frequency. The oscillating wall provides large reductions of friction drag, but the energy cost for creating the oscillation is significant, such that the maximum net energy savings are marginal [7]. Later, Du and Karniadakis [1] and Du et al. [2] introduced a control law based on a spanwise-traveling wave of spanwise forcing (S*p*TW-Fz). In this case the forcing action is a body force f_z applied in the bulk flow but in the vicinity of the wall:

$$f_z = A_f e^{-(y+h)/\Delta} \sin(\kappa_z z - \omega t) . \tag{2}$$

The spanwise forcing is modulated along the spanwise direction z with wavenumber κ_z, and ω/κ_z is the speed of the wave along z; A_f is the strength of the body force, which is maximum at the wall located at $y = -h$, and decays exponentially as y increases, with the penetration length Δ. The S*p*TW-Fz concept has been shown to be able to reduce the turbulence skin-friction drag by more than 30%. An important later development was then that by Zhao et al [9], where a DNS study of the S*p*TW concept with wall-based forcing was carried out. In this case, that we indicate with S*p*TW-w, the forcing becomes:

$$W_w = A \sin(\kappa_z z - \omega t) . \tag{3}$$

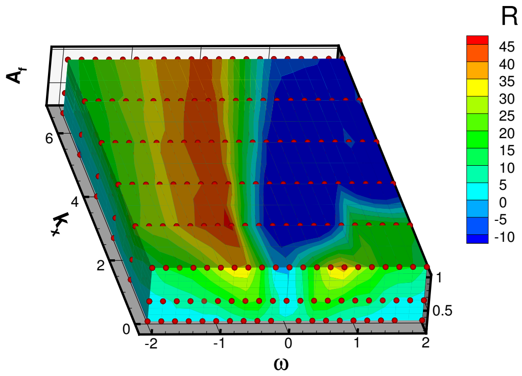
Obviously, the spanwise-oscillating wall Eq.(1) is described by Eq.(3) when $\kappa_z = 0$. Zhao et al [9] have shown that S*p*TW-w too is able to reduce friction drag. Their results, however, showed significant quantitative differences with S*p*TW-Fz, and an energy budget was presented, with negative net saving but reportedly better performance than S*p*TW-Fz. More recently, Quadrio et al. [8] introduced a variant of the traveling-wave concept where the forcing is still wall-based and applied in the spanwise direction, but the spatial modulation takes place along the streamwise direction x, which becomes the traveling direction of the waves. In this forcing, denoted by S*t*TW-w, the control law is:

$$W_w = A \sin(\kappa_x x - \omega t) \tag{4}$$

where κ_x is the streamwise wavenumber, and ω/κ_x is the wave speed along the x direction. S*t*TW-w provides very large drag reductions, reporting 48% drag reduction at $A^+ = 12$, 58% at $A^+ \approx 30$, and flow relaminarization at lower Reynolds numbers. More importantly, S*t*TW-w significantly outperforms the oscillating wall in terms of net savings, that can be as high as 28% of the total pumping energy.
The streamwise-traveling counterpart of S*p*TW-Fz is denoted in the present work by S*t*TW-Fz and to our knowledge still has to be investigated:

$$f_z = A_f e^{-(y+h)/\Delta} \sin(\kappa_x x - \omega t) . \tag{5}$$

The goal of this contribution is to sistematically study all the variants of the spanwise-forcing concept, in order to fully characterize them from an energetic viewpoint. As the focus is on the net savings brought about by the forcing, the study will be limited to not-too-large forcing intensities A and A_f.



Forcing	$100R_{max}$	$100S_{max}$
S*p*TW-w	38	10
S*p*TW-Fz	47	12
S*t*TW-Fz	47	21
S*t*TW-w	48	28

Figure 1. Left: example result, map of R for S*t*TW-Fz with $\Delta = 0.03$. Right: maximum drag reduction R_{max} and maximum net energy saving S_{max} for the whole parameter study, relative to each forcing type, ordered for increasing S_{max}. Note that in defining R_{max} points at very high A^+ available in the literature for S*t*TW-w and resulting in slightly larger R (up to relaminarization) have been excluded, as the main focus here is on comparison and the present study does not consider extremely high forcing intensities.

METHOD

In the simple geometric setting of the indefinite plane channel flow at $Re_\tau = 200$, we study with Direct Numerical Simulations (DNS) the spanwise forcings described by Eq.(2), (3) and (5).
To explore the parameter space, about 250 simulations are performed for S*p*TW-w; a significantly larger number is required for the body-force-based techniques (namely 768 for S*p*TW-Fz and 1248 for S*t*TW-Fz), owing to the presence of the additional parameter. Overall, more than 2,200 DNS simulations are carried out to investigate how the waves alter the friction coefficient

$$C_f = \frac{2\tau_w}{\rho U_b^2}, \tag{6}$$

where τ_w is the mean wall-shear stress and ρ is the density of the fluid. The large study is made affordable by using a computational domain of moderate size, as successfully done in [3]. To quantify the effect of the forcing, we adopt the control performance indices proposed by Kasagi et al. [5]: drag reduction rate R and net energy saving rate S.

RESULTS

Owing to space limitations, we report here only an example map of R (for S*t*TW-Fz at $\Delta = 0.03$) and a table with the best results in terms of maximum drag reduction R_{max} and maximum net energy saving S_{max} that have been obtained for the four considered forcings. A key point, that will be discussed at the conference, is to understand under which conditions a meaningful comparison between the amplitudes A and A_f can be carried out. The superiority of the S*t*TW family will be shown to relate to the unaltered wall-normal gradient of the wall-normal velocity component at the wall.

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