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MODIFICATION OF TURBULENT FRICTION DRAG BY STREAMWISE-TRAVELING WAVES OF SPANWISE WALL VELOCITY

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INTRODUCTION

The control of turbulent wall-bounded flows with the aim of reducing the wall-shear stress is one of the most important topics in modern fluid mechanics research. Such a reduction of wall friction has enormous beneficial effects in numerous technological and industrial applications. One consequence is for example that less fuel may be consumed in aeronautical applications or for propelling gas along pipelines.

Drag reduction techniques may be classified as active or passive, depending on whether or not an external input of energy is required. In the first class, a considerable interest has been devoted to modifying the turbulence by imposing a large-scale forcing along the spanwise direction, either by a wall motion or a body force (see Karniadakis & Choi 2003 for a review). One way of enforcing the near-wall motion is to generate traveling waves in the very proximity of the wall. Relevant works in this field are the numerical investigations by Du & Karniadakis (2000), Du *et al.* (2002), Zhao *et al.* (2004) and the experimental study by Itoh *et al.* (2006). These efforts show that skin-friction reductions up to 40% may be obtained.

In this paper, we present Direct Numerical Simulations results on the effects of wall velocity waves on the near-wall turbulence in the geometry of a plane channel. More results and details will be published elsewhere (Quadrio & Viotti 2008). Sinusoidal waves of spanwise velocity traveling along the streamwise direction are considered:

$$w_w(x,t) = A\cos(\kappa_x x - \omega t), \tag{1}$$

where A is the amplitude of the wave, κ_x is the streamwise wavenumber, and ω is the frequency. The wave moves forward or backward with a phase speed

$$U_t = \frac{\omega}{\kappa_x}.$$

A schematic of the flow domain in presented in figure 1. The previously studied cases of temporal forcing (the oscillating-wall technique, Jung *et al.* 1992, Choi *et al.* 1998, Choi 2002, Ricco 2004, Quadrio & Ricco 2004) and steady forcing (Viotti *et al.* 2008) represent particular cases of (1), respectively of a wave traveling at infinite speed ($\kappa_x = 0$) and of a stationary wave ($\omega = 0$). The main objective of the present work is to quantify the effects of the wall waves on the near-wall turbulence, and in particular on the friction drag.

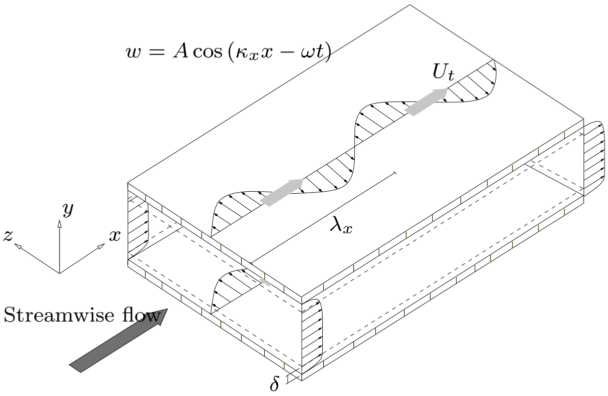

Figure 1: Schematic of the physical domain for channel flow with forward wall traveling waves. δ is the thickness of the Stokes-like layer, λ_x is the streamwise wavelength of the wall forcing, and U_t is the phase speed.

RESULTS

A first result is that the spanwise turbulent flow averaged along the homogeneous, x and z, directions shows good agreement with the corresponding laminar flow, namely when the streamwise turbulent flow is replaced by the canonical laminar Poiseuille flow. The two flows are almost identical when the phase speed of the wave is very different from the convection velocity of the near-wall turbulent fluctuations (Quadrio & Luchini 2003), while small differences occur when these two velocities are comparable.

It is found that the spanwise flow assumes the form of a thin, near-wall viscous layer, referred to as the generalized Stokes layer (GSL). This layer is both unsteady and spatially modulated along the streamwise direction, and it coincides with the classical Stokes layer when $\kappa_x = 0$. Similarly to the oscillating-wall technique, the shearing action of GSL is recognized as responsible for altering the near-wall turbulence-producing cycle, thus leading to a friction drag modification.

The modification of friction drag is shown in the contour plot of figure 2 as function of the frequency ω^+ and of the

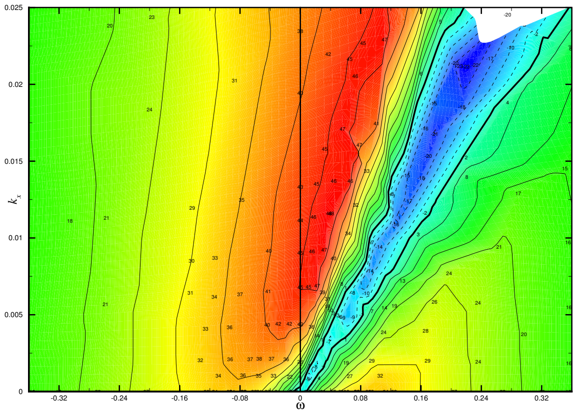

Figure 2: Contour of percent of turbulent friction drag modification as function of ω^+ and κ^+, where + indicates scaling by inner variables of the modified flow.

streamwise wavenumber κ_x^+, where the + sign indicates scaling by inner variables of the drag-reducing flow. Only the upper half of the $(\omega^+ - \kappa_x^+)$ plane is shown because the map is symmetric with respect to the origin of the plane. Straight lines from the origin are loci of constant phase speed, so forward traveling waves are represented in the first quadrant, and backward traveling waves in the second quadrant. The oscillating-wall flow lies on the horizontal $\kappa_x^+ = 0$ axis ($U_t^+ \rightarrow \pm\infty$), while the standing-wave flow is confined to the vertical $\omega^+ = 0$ axis ($U_t^+ = 0$).

The friction drag is reduced over most of the domain (the red portion of the diagram indicates high amounts of drag reduction); the maximum drag reduction occurs for waves traveling forward at $U_t^+ \approx 2$ for $k_x^+ > 0.005$, and roughly on a straight line connecting the points ($\omega^+ = -0.05, \kappa_x^+ = 0$) and ($\omega^+ = 0, \kappa_x^+ = 0.005$) for $k_x^+ < 0.005$. An overall maximum of about 48% is computed when ($\omega^+ = 0.06, \kappa_x^+ = 0.02$). The most interesting result is the friction increment (blue portion of the diagram) when $U_t^+ \approx \mathcal{U}_w^+$, where $\mathcal{U}_w^+ \approx 10$ is the convection velocity of the near-wall turbulent fluctuations (Quadrio & Luchini 2003). Drag increase is observed when $9 < U_t^+ < 13$ and the maximum value occurs when the wave travels almost exactly at the value of the convection velocity of the near-wall turbulent structures. It can be recognized as a resonance condition and it corresponds to a steady forcing in a reference frame relative to the near-wall turbulent structures. The increment of drag is a somewhat unexpected finding in that neither the oscillating-wall nor the standing-wave techniques present such a behaviour.

Our future work will focus on investigating the physical mechanisms behind the turbulent friction drag modification. Our first step will be to study in more detail the above-mentioned spanwise laminar flow engendered by the wall motion. Such an analysis, prompted by the close agreement of such a flow with the corresponding turbulent flow, is likely to shed light on the modification of the near-wall turbulence, similarly to previous works on the oscillating-wall technique (Choi 2002, Quadrio & Ricco 2008).

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