Drag Reduction Via Spanwise Transversal Surface Waves at High Reynolds Numbers

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Abstract The impact of transversal spanwise traveling surface waves on the wall-shear stress distribution of high Reynolds number turbulent boundary layer flows is analyzed using high-resolution large-eddy simulations. The Reynolds numbers based on the friction velocity are $Re_\tau = 540, 906, 1908, \text{ and } 2250$. The surface wave motion defined by the amplitude, the wavelength, and the phase speed in inner coordinates is constant for the investigated $Re_\tau$ range. When the Reynolds number is increased, the drag reduction decreases from 11 % to 1 %. That is, in contrast to the result in the literature for actuated channel flow, which shows the drag reduction (DR) as a function of the Reynolds number based on the friction velocity to be proportional to $Re_\tau^{-0.2}$ for $Re_\tau \leq 1000$, the current analysis for evolving turbulent boundary layers over actuated surfaces leads to $DR \sim Re_\tau^{-1}$. The detailed analysis of the velocity profiles in the viscous sublayer clearly shows that the major difference in the velocity gradient occurs above the trough where the velocity gradient is reduced by increasing Reynolds number. At low Reynolds numbers, the peak value of the wall-normal vorticity distribution above the moving wave crest and above the moving wave trough is much smaller than that of the non-actuated wall resulting in a pronounced drag reduction. At increasing Reynolds number, the difference in the wall-normal vorticity distribution in the near-wall region for the actuated and the non-actuated wall becomes smaller leading to a lower drag reduction. The analysis of the anisotropy map shows that the wall actuation excites the two-component turbulence in the viscous sublayer above the crest and the trough. That is, unlike passively controlled flow, the drag reducing mechanism is related not to the one-component but to the two-component state in the anisotropy map.

Keywords Drag reduction · Turbulent boundary layer · Large-eddy simulation · Active control · Spanwise traveling wave

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1 Introduction

The increasing need in energy caused by the growing demand of transportation along with the increasing environmental awareness has led to a high interest in research of energy saving methods for technical applications. Since the power consumption of moving slender bodies is directly related to friction, special attention has been put on reducing the wall-shear stress distribution on the wetted surface area. When, for instance, the flow field over an aircraft is considered, viscous drag reduction is extremely significant since it accounts for about 50% of the total drag.

An efficient way to reduce the skin-friction distribution can be achieved by passive or active control means to influence the turbulent boundary layer. Especially, the introduction of artificial or real wall motion into the near-wall flow field has proven effective in reducing the drag. Interesting overviews over the possible mechanisms and the different investigations are given in Karniadakis and Choi [1] and more recently also by Quadrio [2].

The first numerical studies of influencing the drag of channel flow by transverse motion were presented by Jung et al. [3] and Akhavan et al. [4] aiming at a sustained lower drag state. Using a DNS of a channel flow at a Reynolds number based on the friction velocity $Re_\tau = 200$ subjected to spanwise wall oscillation of different periods $T^+$ in the range from 25 to 500, they were able to reduce or increase the drag. At the period $T^+ = 100$ the intensities of the fluctuating velocity were reduced by 30%. The mean velocity profile showed a thickened viscous sublayer and a decreased gradient at the wall resulting in the maximum sustained drag reduction of 40%. Among many other studies, Quadrio et al. [5] focused on a wide parameter analysis of the oscillation parameters and obtained similar values in drag reduction for channel flows at similar Reynolds numbers. Note that most numerical studies regarding oscillating wall motion were performed for generic channel flow at Reynolds numbers $Re_\tau$ on the order of 200 and only a few exist at higher Reynolds numbers. Recently, Touber and Leschziner [6] and Agostini et al. [7] investigated the impact of the spanwise oscillating wall on the near wall flow field by the direct numerical simulation of channel flow at $Re_\tau = 500$ and $Re_\tau = 1000$. Both studies give detailed statistical data, energy budgets, and enstrophy balances to clarify the drag-reduction mechanism. The results confirm that the reduction of the wall-normal component of the vorticity is directly connected with the observed drag decrease. Furthermore, the findings reveal a hysteresis over one oscillation cycle, where the drag-reduction phase is extended compared to the following drag-increase phase in the cycle. This behavior is attributed to the asymmetric motion of the Stokes layer disrupting the near wall turbulence regeneration mechanism when the skewness is high and prevents the regeneration when the phase of low skewness is lower than the time needed by the streaks to regenerate.

The introduction of spanwise transversal surface waves, which is another promising technique to influence the near-wall momentum to achieve drag reduction, was also mainly analyzed for internal, i.e., channel flow. The excitation is primarily achieved either through wall deformation or volume forces. The latter can be applied to electric conducting fluids, i.e., through electromagnetic tiles. This approach is discussed in Du et al. [8] showing 30% drag reduction for a $Re_\tau = 150$ channel flow configuration and a specific choice of wave parameters. The volume force is confined within the viscous sublayer and the maximum wavelength in inner coordinates was $\lambda^+ = 840$. A similar drag reduction was obtained.

1The superscript + denotes inner coordinates, i.e., the friction velocity $u_\tau$ and the kinematic viscosity are used to nondimensionalize the relevant quantities.