Applied Mathematics and Computation 272 (2016) 498–507

Contents lists available at ScienceDirect

Applied Mathematics and Computation

journal homepage: www.elsevier.com/locate/amc

Impact of transversal traveling surface waves in a non-zero pressure gradient turbulent boundary layer flow

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ARTICLE INFO

Article history:
Available online 2 July 2015

Keywords:
Drag reduction
Turbulent boundary layer
Large-eddy simulation
Transversal spanwise traveling surface wave
Non-zero pressure gradient

ABSTRACT

The impact of non-zero pressure gradient flow in a turbulent boundary layer flow over a surface undergoing spanwise transversal traveling waves is investigated via large-eddy simulations. While it is known that in zero-pressure gradient flow spanwise surface waves can lead to drag reduction, this question still remains open for non-zero pressure gradient flows. In the present analysis, the effect of a linear pressure gradient is investigated and compared to the zero-pressure gradient flow at a momentum thickness based Reynolds number $Re_\theta = 2000$ for a constant surface wave, i.e., the wave length is $\lambda^+ = 500$, the amplitude $A^+ = 50$, and the wave speed is $c^+ = 6.25$. The results show a drag reduction of about 10% for the zero-pressure gradient flow, 6% for the adverse-pressure gradient, and a drag increase of 4% for the favorable-pressure gradient flow. The analysis of the velocity profiles shows a reduced gradient at the trough region for all actuated setups. At the crest, an increased gradient is obtained. Furthermore, the viscous sublayer is extended. The streamwise turbulent intensity is reduced for all configurations compared to the non-actuated reference case at the crest. At the trough, the shift off the wall is only present for the zero-pressure gradient flow and the adverse pressure gradient flow. The hypothesis based on numerous zero-pressure gradient flow investigations of a reduced wall-normal vorticity component at the crest and trough indicating drag reduction is corroborated. That is, for the adverse-pressure gradient flow the wall-normal component distribution is lowered and for the favorable pressure gradient flow, which possesses a drag increase, the distribution at the trough is similar to that of the reference non-actuated case.

1. Introduction

The increasing environmental awareness as well as the limited resources of fossil-based fuels have led to high research interests for energy-saving methods in technical applications. The energy consumption of moving slender bodies such as aircraft is significantly determined by the viscous drag, which accounts for about 50% of the total drag. Since this friction drag is determined by the shear stress distribution over the wetted surface, methods aiming at influencing the skin friction are of special interest. A very promising method to influence the shear stress distribution is to introduce spanwise motions into the near-wall turbulence field. A good overview over different mechanisms and different investigation methods of actively influencing the near wall flow field is given by Karniadakis and Choi [7] and recently by Quadrio [16]. Most of the methods given in the aforementioned overviews focus on flows in a generic channel with moderate Reynolds number based on the skin friction velocity ($Re_\tau \approx 200$)

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http://dx.doi.org/10.1016/j.amc.2015.05.094
0096-3003/

and only a few deal with influencing the drag in external flow problems such as turbulent flat plate boundary layers at zero pressure gradient.

Among the many techniques to realize a positive effect on the skin friction, a very promising method is by altering the near wall turbulence field through transversal traveling surface waves, i.e, adding a wavy wall-normal deflection to the surface. Du et al. [3] used volume forces in a channel flow at $Re_\tau = 150$ to simulate transversal traveling waves in electric conducting fluids. This behavior is similar to that produced by electromagnetic tiles in experimental investigation. The volume forces were confined within the viscous sublayer and a drag reduction of 30% was found for a wave length $\lambda^+ = 840$ and a penetration depth of the volume force of $\Delta^+ = 6$, where the superscript + denotes inner coordinates. Zhao et al. [22] investigated transversal traveling waves over a flexible sheet in a channel flow at $Re_\tau = 180$ with a wave length of $\lambda^+ = 1131$ and obtained similar drag reduction results.

Other than in fully developed channel flows, turbulent boundary layers undergo a streamwise development which needs to be taken into account in the analysis. Itoh et al. [6] experimentally investigated the impact of transversal traveling waves with a wave length of $\lambda^+ = 3620$ in a turbulent boundary layer at $Re_\theta = 1328$ based on the momentum thickness. They found up to 7.5% drag reduction. In a more recent analysis extending the previous investigation Tamano and Itoh [21] achieved 13% drag reduction. Klumpp et al. [8,10] performed large-eddy simulations (LES) of turbulent boundary layers at $Re_\theta = 887$ over transversal traveling surface waves. Through the analysis of two distinct parameter configurations $\lambda^+ = 174$ and $\lambda^+ = 870$ it was possible to reveal a different impact on the skin-friction distribution. The short wave length case showed an 8% drag increase whereas the higher wave length showed 9% drag decrease. Through the analysis of both setups, excited by the same mechanism, it was shown, that a crucial parameter indicating drag reduction is the reduction of the near-wall distribution of the wall-normal vorticity component at the crest and trough. More recently, Koh et al. [11,12] analyzed the impact of the Reynolds number ranging from $1000 \le Re_\theta \le 7000$ and amplitude $30 \le A^+ \le 70$ on the wall-shear stress distribution of a turbulent boundary layer undergoing transversal spanwise surface waves. It was shown that with increasing Reynolds number, the drag reduction effect weakens. On the other hand, with increasing amplitude a higher drag reduction was obtained. Similar to the results of [10] they also found a strong correlation between the drag reduction and the reduction of the wall-normal vorticity component.

Although the analysis of the generic flat plate problem yields promising results considering drag reduction, it has to be kept in mind that in technical flow problems an adverse or favorable pressure gradient influences the near-wall flow. The flow in diffusers, in turbine cascades, and over lifting bodies are just a few prominent examples. For this reason, it is necessary to investigate the impact of drag influencing methods by introducing transversal spanwise wall motion into the near wall flow field in flows subjected to a pressure gradient. The aim of the present study is to shed light into the effect of an adverse and favorable pressure gradient on the drag reduction that can be achieved by introducing a transversal spanwise surface wave motion.

The paper is organized as follows. First, the flow configuration is described, followed by the numerical method and the computational setup. Then, in Section 4, the results are presented based on a detailed analysis of the turbulence statistics. Finally, the major findings are summarized in Section 5.

2. Flow configuration and computational setup

The present analysis focuses on the flow over a turbulent boundary layer undergoing spanwise transversal traveling surface waves with an adverse and a favorable pressure gradient. The reference case is that of a flat plate with zero pressure gradient. The Reynolds number $Re_\theta = 2000$ is based on the momentum thickness at the inlet.

Fig. 1 shows a schematic of the three-dimensional computational setup, where the x, y, z–coordinates define the streamwise, wall-normal, and spanwise direction in the Cartesian frame of reference. In the region $x_i \le x \le x_0$, the setup possesses a

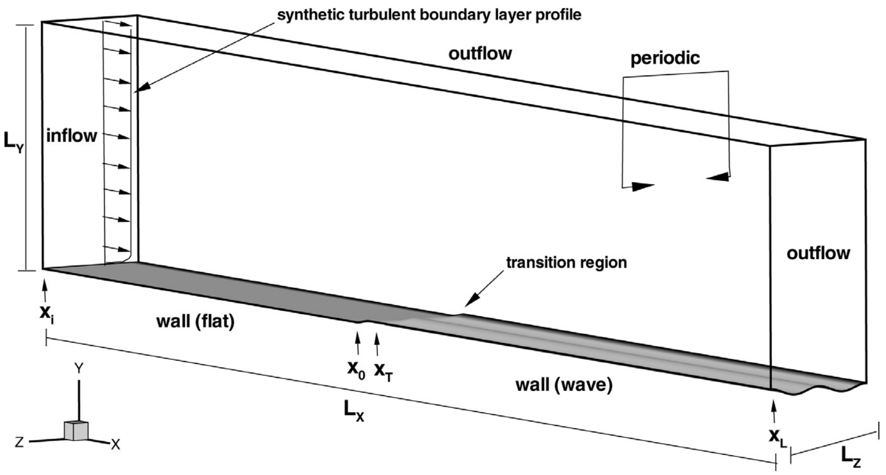

Fig. 1. Schematic of the actuated wall configuration, with the streamwise extent L_x, the wall-normal extent L_y and the spanwise extent L_z. The streamwise positions x_i denote the position at the inlet, x_0 the onset of the transition between the non-actuated and the actuated wavy surface, and x_L the outflow position.