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Effect of uniform blowing/suction in a turbulent boundary layer at moderate Reynolds number

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ABSTRACT

A number of well-resolved large-eddy simulations (LES) of a spatially evolving turbulent boundary layer with uniform blowing or suction is performed in order to investigate the effect on skin friction drag as well as turbulence statistics and spectral composition at moderate Reynolds numbers up to $Re_\theta = 2500$, based on the free-stream velocity and the momentum-loss thickness. The amplitude of uniform blowing or suction is set to be 0.1% of the free-stream velocity with different streamwise ranges of the controlled region.

The boundary layer is thickened by blowing and thinned by suction. The Reynolds shear and normal stresses are increased by blowing and decreased by suction, most prominently, in the outer region. Through spectral analysis of the streamwise velocity and cross-spectra of the Reynolds shear stress, the enhancement and reduction of the fluctuation energy in the outer region by blowing and suction are found, respectively. It is also found that the emergence of a second peak in the outer region is promoted by blowing, while it is inhibited in the case of suction.

In spite of the weak amplitude of the control, more than 10% of drag reduction and enhancement are achieved by means of blowing and suction, respectively. In the case of blowing, where drag reduction is achieved, the mean drag reduction rate increases as the blowing region extends because the local reduction rate, i.e. the streamwise gradient of the mean drag reduction rate, grows in the streamwise direction. The net-energy saving rate and the control gain have the same trends. It is found that a more effective skin friction drag reduction and control efficiency can be achieved with a wider control region that starts at a more upstream location.

1. Introduction

Commercial transports such as the bullet trains or aircrafts have a great role in the present society. As the technology develops, people have pursued higher speed devices. Since the industrial revolution in the 19th century, the use of aircrafts or trains increased drastically instead of horses or other man-powered devices (Banister et al., 2011). From the fluid dynamical point of view, the formation of a boundary layer due to the viscosity causes skin friction drag on solid surfaces, which drastically increases by turbulent transition of the flow. The skin friction drag has a huge impact on the global environment due to the consumption of fuels. Once the boundary layer transition from a laminar to a turbulent state takes place, the skin friction drag increases drastically compared to its laminar counterpart. In order to reduce the skin friction drag, various drag reducing methods have been devised. Compared to pressure drag, which is reduced by streamlined shapes, skin friction drag reduction has not been achieved in practical applications.

Numerical simulations are nowadays a powerful tool to investigate wall turbulence. Shortly after the pioneering direct numerical simulation (DNS) by Kim et al. (1987) of a turbulent channel flow, Spalart (1988) performed the first DNS of a spatially evolving turbulent boundary layer. Thanks to the progress of computer performance and numerical schemes, various drag reducing methods could be examined numerically.

So, for instance, passive control methods such as riblets (Garcia-Mayoral and Jiménez, 2011), compliant (Fukagata et al., 2008) or superhydrophobic (Türk et al., 2014) walls as well as additives (White and Mungal, 2008) have been examined. Recently, active control methods aiming at higher control performances have become attractive. The opposition control was found to achieve reduction of skin friction drag by destruction of quasi-streamwise vortex structures near the wall (Choi et al.,

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1994). Feedback control schemes for skin friction drag reduction have been established; see e.g. the reviews by Kim (2003) and Kim and Bewley (2007) on linear control theory, and Kasagi et al. (2009) on the related hardware.

Recently, the focus has shifted towards active flow control with predetermined input, since it does not need any sensors, which are expensive and difficult to implement. Drag reduction by adding wave-like motion from the wall has been examined. The streamwise traveling wave-like blowing and suction in the turbulent channel flow is examined by Min et al. (2006). Nakanishi et al. (2012) and Tomiyama and Fukagata (2013) performed drag reduction by wall-deformation and they found the turbulent flow to be relaminarized by a streamwise wave but not by a spanwise wave. Spanwise wall oscillations can also reduce skin friction drag, see e.g. Quadrio and Ricco (2004). The aforementioned simulations have mostly been limited to internal flows such as channels and pipes. The existence of an open boundary in external flows may not guarantee the same drag reduction effect applied in internal flows because of, for instance, the pumping mechanism (Hoepffner and Fukagata, 2009). Recently, skin friction drag reduction control has been expanded to external flows such as the spatially developing turbulent boundary layer (STBL). Kim et al. (2003) performed DNS of a STBL with blowing or suction from a spanwise localized slot. Pamiès et al. (2007) applied the opposition control to STBL by means of large eddy simulations (LES). However, the effective and practical drag reduction in external flows still requires further investigations.

Modification of the shear flow by flow injection or suction is used for engineering applications such as film cooling on turbine blades or slotted wings. Sumitani and Kasagi (1995) performed DNS of turbulent channel flow with uniform wall injection and suction at a constant mean pressure gradient. As a result, with the wall injection at 0.1% of the free-stream velocity U_∞, more than 10% of drag reduction was achieved and higher amplitudes achieved larger drag reduction despite of the simple constant input from the wall. On the other hand, the decrease of the Reynolds shear stress and decrease of the turbulent vortices are confirmed by the wall suction. The aforementioned friction drag reduction by the wall injection and turbulent stabilization by the suction have been attractive for practical applications, e.g. for drag reduction or delaying transition to turbulence. Kornilov and Boiko (2012) reported drag reduction effects of blowing generated by a microblowing plate. Suction control, on the other hand, was examined by e.g. Yoshioka et al. (2004) and Fransson and Alfredsson (2003), mainly investigating the special case of a laminar asymptotic suction boundary layer.

Fukagata et al. (2002) introduced an identity equation which decomposes the skin friction drag into different contributions: one from the laminar component and one from the turbulent component for canonical internal flows such as channels or pipes. This equation indicates that the reduction of the Reynolds shear stress is directly connected to friction drag reduction. This so-called FIK identity can contribute not only to investigate the drag reduction control mathematically and physically, but also provides the means to develop a strategy for drag reduction control. In contrast, the FIK identity for the spatial developing flow like the spatially developing turbulent boundary layer cannot be simply decomposed into the laminar and turbulent (i.e., Reynolds shear stress) components due to its spatially developing feature. The identity has the contributions from boundary layer thickness, the Reynolds shear stress, mean wall-normal convection, and spatial development.

Kametani and Fukagata (2011) performed a DNS of the spatially evolving turbulent boundary layer with uniform blowing and suction. For the uncontrolled flow, the decomposed skin friction by the FIK identity indicates that the Reynolds shear stress has the largest contribution and the mean wall-normal convection, which is the product of the mean streamwise and the mean wall-normal velocities, works as a reduction factor of skin friction. The mean wall-normal convection term is enhanced by blowing, while it turns into a drag-increasing factor by suction. Their DNS was performed at a low Reynolds number, based on free-stream velocity (U_∞) and momentum-loss thickness (θ), of $Re_\theta \approx 300$. The effect of blowing or suction in the plane turbulent boundary layers has been investigated not only numerically but also experimentally; see e.g. Kornilov and Boiko (2012) and Yoshioka et al. (2004).

In engineering applications, however, the Reynolds number is much higher and high Reynolds number effects appear on turbulent structures such as large scale structures (Marusic et al., 2010; Wallace, 2012). Recently, turbulent boundary layers at relatively high Reynolds number have been studied by mean of numerical simulation (Schlatter and Örlü, 2010). Due to the recent increase of computing performance, the vortical composition of fully developed turbulent boundary layers has been confirmed through DNS, see e.g. Sillero et al. (2013), Prozzoli and Bernardini (2013), and more recently Schlatter et al. (2014). Eitel-Amor et al. (2014) performed a well-resolved LES of a turbulent boundary layer up to $Re_\theta = 8300$ and analyzed the turbulent structure by spanwise and temporal spectra of streamwise velocity fluctuation.

By combining the FIK identity and the spectral analysis, the skin friction drag can be investigated by the turbulence structures. Deck et al. (2014) performed detached eddy simulations (DES) and investigated the relationship between turbulent structures in the outer region. A fully-resolved investigation by DNS, however, is still a challenging issue.

The control efficiency is another issue that should be considered, see e.g. Frohnapfel et al. (2012) and Hasegawa et al. (2014). A theoretical limit of the active friction drag reduction control, i.e. the relationship between drag reduction effect and input power, for control of a plane channel (Bewley, 2009) and of arbitrary ducts was discussed (Fukagata et al., 2009). The existence of such a limit for the external flows, however, is still unclear.

In this paper, the effect of uniform blowing and suction with the finite streamwise length of the blowing/suction region will be investigated. The effect of blowing or suction is studied through statistics and spectral analysis of the turbulent structures. In case of blowing, also the control efficiency, due to its practical relevance, is discussed.

2. Numerical simulation

The governing equations are the incompressible continuity and Navier–Stokes equations. The present large-eddy simulation uses the ADM-RT model (Schlatter et al., 2004). The momentum equation for the resolved velocity $\overline{u}_i$ and pressure $\overline{p}$ is written as

$$\frac{\partial \overline{u}_i}{\partial t} = -\overline{u}_j \frac{\partial \overline{u}_i}{\partial x_i} - \frac{\partial \overline{p}}{\partial x_i} + \frac{1}{Re}\frac{\partial^2 \overline{u}_i}{\partial x_j \partial x_j} - \chi H_N \otimes \overline{u}_i. \quad (1)$$

The equations are non-dimensionalized by the free-stream velocity U^*_∞ and the inlet displacement thickness, $\delta^*_{d,in}$, i.e. the computational Reynolds number is defined as $Re = U^*_\infty \delta^*_{d,in}/\nu^* = 450$, where ν denotes the kinematic viscosity. The superscript $*$ denotes dimensional values. The relaxation term $\chi H_N \otimes \overline{u}_i$ is based on a high-order three-dimensional filter operation where $H_N \equiv (I - G)^{N+1}$ is convoluted with $\overline{u}_i$, and G is a lower-order, low-pass filter. The computational domain is $L_x \times L_y \times L_z = 3000 \times 100 \times 960$ with $N_x \times N_y \times N_z = 2048 \times 257 \times 1536$ spectral collocation points in the streamwise, wall-normal, and spanwise directions, respectively. In the physical space, the number of grid points in the streamwise and spanwise direction increases by a factor of 3/2 due to dealiasing. The maximum grid