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Skin-friction drag reduction in a high-Reynolds-number turbulent boundary layer via real-time control of large-scale structures

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ABSTRACT

While large-scale motions are most energetic in the logarithmic region of a high-Reynolds-number turbulent boundary layer, they also have an influence in the inner-region. In this paper we describe an experimental investigation of manipulating the large-scale motions and reveal how this affects the turbulence and skin-friction drag. A boundary layer with a friction Reynolds number of 14 400 is controlled using a spanwise array of nine wall-normal jets operated in an on/off mode and with an exit velocity that causes the jets in cross-flow to penetrate within the log-region. Each jet is triggered in real-time with an active controller, driven by a time-resolved footprint of the large-scale motions acquired upstream. Nominally, the controller injects air into large-scale zones with positive streamwise velocity fluctuations; these zones are associated with positive wall-shear stress fluctuations. This control scheme reduced the streamwise turbulence intensity in the log-region up to a downstream distance of more than five times the boundary layer thickness, δ, from the point of actuation. The highest reduction in spectral energy—more than 30%—was found for wavelengths larger than 5δ in the log-region at 1.7δ downstream of actuation, while scales larger than 2δ still comprised more than 15% energy reduction in the near-wall region. In addition, a 3.2% reduction in mean skin-friction drag was achieved at 1.7δ downstream of actuation. Our reductions of the streamwise turbulence intensity and mean skin-friction drag exceed a base line control-case, for which the jet actuators were operated with the same temporal pattern, but not synchronised with the incoming large-scale zones of positive fluctuating velocity.

1. Introduction

Wall-bounded flows are important to many natural and engineering applications, and given that skin-friction drag constitutes approximately 50%, 90% and 100% of the total drag on airliners, submarines and pipelines, respectively (Gad-el Hak, 1994), considerable effort has been devoted to reducing skin-friction drag over the past few decades.

Over the past 50 years or so it has been shown that turbulent boundary layers (TBLs) comprise coherent structures in both the near-wall and outer regions (Kline et al., 1967; Townsend, 1976; Kim and Moin, 1979; Robinson, 1991; Wark and Nagib, 1990; Adrian et al., 2000; Smits and Marusic, 2013). The majority of flow control studies with the aim of skin-friction drag reduction have attempted to manipulate structures within the near-wall region (Moin and Bewley, 1994; Gad-el Hak, 2000; Rathnasingham and Breuer, 1997; 2003; Karniadakis and Choi, 2003; Kasagi et al., 2009; Gouder et al., 2013; Bai et al., 2014, among others). These near-wall structures scale with viscous units, being the friction velocity $U_\tau \equiv \sqrt{\tau_w/\rho}$, where τ_w is the mean wall-shear stress and ρ is the fluid density, and inner length scale ν/U_τ, with ν being the fluid kinematic viscosity; note that superscript '+' denotes scaling with inner-variables. As such, most of the aforementioned studies tailored their control parameters in viscous-scaled units. However, when increasing the Reynolds number to more pragmatic values, the range of energetic turbulent scales grows, conceptually bounded by the outer (δ, the boundary layer thickness) and inner (ν/U_τ) length scales. We here use the friction Reynolds number, $Re_\tau \equiv \delta U_\tau/\nu$, to indicate the state of the TBL. At high, practical values of Re_τ, the physical thickness of the near-wall region and hence the size of the structures populating that region become smaller (Head and Bandyopadhyay, 1981; Robinson, 1991; Gad-el Hak and Bandyopadhyay, 1994). Due to the characteristic length [$\mathcal{O}$(μm)] and time [$\mathcal{O}$(μs)] scales in engineering applications ($Re_\tau \sim 10^4 - 10^6$), one needs to deal with micro-electromechanical systems (MEMS) for control. Both the development and operation of these sensors become demanding. At the same time, the performance of control schemes solely manipulating the near-wall region deteriorates with increasing Re_τ (Chang et al., 2002; Iwamoto et al., 2002; Gatti and Quadrio, 2013; Hurst et al., 2014).

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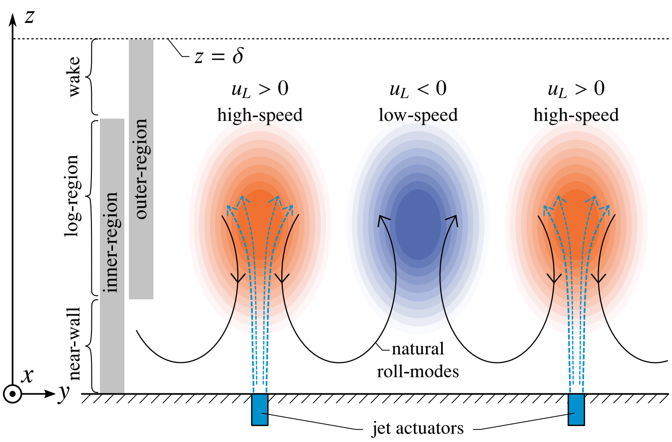

Fig. 1. Schematic of coherent streamwise flow motion in the spanwise–wall-normal plane of a high-Reynolds-number TBL. Regions with positive and negative streamwise velocity fluctuations are referred to as high- and low-speed zones, respectively. Associated natural roll-modes are indicated by the arrows. An illustration of opposition control is shown using wall-jet actuators.

An alternative approach to targeting the near-wall small-scale motions is to use a large-scale forcing scheme, as investigated in the seminal work by Schoppa and Hussain (1998) for a direct numerical simulation of a turbulent channel flow up to $Re_\tau \approx 180$. A drag reduction of up to 50% was demonstrated (using spanwise jets as a large-scale flow forcing), which was interpreted as a result of weakened longitudinal vortices near the wall, due to forcing-induced suppression of an underlying streak instability mechanism. Recently it was shown that the reported drag reduction in Schoppa and Hussain (1998) is associated with a transient nature of the flow due to the low values of Re_τ at which the turbulence is marginally sustainable (Canton et al., 2016). Moreover, Canton et al. (2016) concluded that inducing large-scale vortices for drag reduction becomes ineffective at their highest Reynolds number ($Re_\tau \approx 550$). Nevertheless, the question remains whether a large-scale control scheme can generate skin-friction drag reduction at higher Reynolds numbers, $Re_\tau > \mathcal{O}(10^4)$. Under these conditions, the large-scale motions (LSMs) and very large-scale motions (or superstructures) become the dominant contributor to the turbulent kinetic energy and its production (Hutchins and Marusic, 2007b; 2007a; Marusic et al., 2010a). For reference, when considering a pre-multiplied energy spectrogram of the streamwise velocity fluctuations (energy per wavelength throughout the TBL), the appearance of a broad spectral peak in the log-region reflecting the LSMs, is only observed for moderate Reynolds numbers (roughly $Re_\tau > 2000$ Hutchins and Marusic, 2007a). While LSMs are most energetic in the log-region at high Re_τ, they also have an influence in the near-wall region (*e.g.* Abe et al., 2004) via a direct superposition of large-scale energy and an amplitude modulation of the smaller scales (Hutchins and Marusic, 2007a; Marusic et al., 2010b). It is therefore hypothesised that controlling the LSMs at high Re_τ affects the near-wall turbulence and has the potential of reducing the mean and fluctuating components of the wall-shear stress.

Large-scale structures in the log-region can simplistically be represented as long elongated regions with a streamwise extent of $\mathcal{O}(\delta)$, comprising streamwise momentum deficit. These regions are flanked on either spanwise side by zones of streamwise momentum surplus (*e.g.* Adrian et al., 2000). The former and the latter structures are referred to as low- and high-speed zones, respectively, and are schematically shown in a spanwise–wall-normal plane in Fig. 1. Here we denote the large-scale streamwise velocity fluctuation with u_L, so that $u_L > 0$ and $u_L < 0$ indicate high- and low-speed zones. Accompanying these large-scale zones are counter-rotating roll-modes, with the respective up- and down-wash sections embodied within the low- and high-speed zones as indicated in Fig. 1 (*e.g.* Dennis and Nickels, 2011; Hutchins et al., 2012).

The aim of the present experimental investigation is to manipulate the large-scale high- and low-speed zones in real-time. For this we employ a control architecture embedded in the high-Reynolds-number boundary layer facility in Melbourne, which is introduced in Section 2. The hardware includes surface-embedded actuators, which can inject a wall-normal jet flow into the TBL so that the jets in cross-flow penetrate within the log-region. We nominally explore an opposition control framework, meaning that the actuators are activated while a high-speed zone is present. This results in the wall-normal jet flow opposing the down-wash sections of the naturally occurring roll-modes and the injection of fluid—without streamwise momentum—into the zone with a naturally positive velocity fluctuation (see Fig. 1). How the control affects the downstream flow in the log-region is presented in Section 3, after which we present a detailed boundary layer survey and wall-drag characterisation in Section 4.

2. Experimental arrangement

2.1. Facility and conditions

Experiments were conducted in the boundary layer facility at the University of Melbourne (Nickels et al., 2005; Baars et al., 2016b). A 27 m long test section ensures the formation of a high-Reynolds-number boundary layer over the wind tunnel floor, while high spatial and temporal resolutions are obtained with existing instrumentation under moderate free-stream velocities. For a zero-pressure gradient configuration, the pressure coefficient is constant to within ± 0.87% (Marusic et al., 2015) and free-stream turbulence intensities are less than 0.05% at the test section inlet. An isometric sketch of the wind tunnel, with an open-view of the test section, is shown in Fig. 2a. A coordinate system with coordinates x, y and z denotes the streamwise, spanwise and wall-normal directions of the flow, respectively, and its origin coincides with the test section inlet, the wall and spanwise centre of the tunnel.

Real-time control of the TBL was performed at a streamwise location that nominally coincided with a floating element drag balance (permanently embedded within the wind tunnel surface). This large-scale floating element drag balance, with a streamwise length $l_F = 3.000$ m and a spanwise width $w_F = 1.000$ m, is centred at $x = x_F = 21.00$ m and $y = 0$. The modular design of the flow-exposed surface of the drag balance allowed for an implementation of the control hardware, whereas directly measured wall drag data at local Reynolds numbers (Baars et al., 2016b) provided the nominal experimental conditions and assisted in calibration of hot-film sensors (discussed later on in Section 2.4). Throughout this paper, one flow condition is considered, corresponding to a nominal free-stream velocity of $U_\infty = 20$ m/s. At $x = 21.00$ m this provides a boundary layer thickness of $\delta = 0.360$ m and a friction velocity of $U_\tau = 0.641$ m/s, resulting in $Re_\tau \approx 14\,400$. These parameters were determined by fitting a composite velocity profile of Chauhan et al. (2009) to the mean velocity profile, with log-law constants $\kappa = 0.384$ and $A = 4.17$. From friction data measured with the floating element drag balance (Baars et al., 2016b), a value of $U_\tau = 0.649$ m/s is obtained, which agrees to within 1.2% with the value found via the composite profile fit. A summary of the nominal flow conditions and TBL is provided in Table 1; here, subscript ‘U’ in U_{τ_U} refers to an uncontrolled TBL flow. Finally, throughout this paper, we employ a location in the log-region that reflects the location of the outer-peak in the pre-multiplied energy spectrogram under similar conditions (Mathis et al., 2009), taken as $z_L^+ \equiv 3.9\sqrt{Re_\tau} \approx 477$. At this position, the