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Scale-by-scale energy budget in a turbulent boundary layer over a rough wall

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ABSTRACT

Hot-wire velocity measurements are carried out in a turbulent boundary layer over a rough wall consisting of transverse circular rods, with a ratio of 8 between the spacing (w) of two consecutive rods and the rod height (k). The pressure distribution around the roughness element is used to accurately measure the mean friction velocity (U_τ) and the error in the origin. It is found that U_τ remained practically constant in the streamwise direction suggesting that the boundary layer over this surface is evolving in a self-similar manner. This is further corroborated by the similarity observed at all scales of motion, in the region $0.2 \leqslant y/\delta \leqslant 0.6$, as reflected in the constancy of Reynolds number (R_λ) based on Taylor's microscale and the collapse of Kolmogorov normalized velocity spectra at all wavenumbers.

A scale-by-scale budget for the second-order structure function $\langle(\delta u)^2\rangle$ ($\delta u = u(x+r) - u(x)$, where u is the fluctuating streamwise velocity component and r is the longitudinal separation) is carried out to investigate the energy distribution amongst different scales in the boundary layer. It is found that while the small scales are controlled by the viscosity, intermediate scales over which the transfer of energy (or $\langle(\delta u)^3\rangle$) is important are affected by mechanisms induced by the large-scale inhomogeneities in the flow, such as production, advection and turbulent diffusion. For example, there are non-negligible contributions from the large-scale inhomogeneity to the budget at scales of the order of λ, the Taylor microscale, in the region of the boundary layer extending from $y/\delta = 0.2$ to 0.6 (δ is the boundary layer thickness).

1. Introduction

The investigation of a turbulent boundary layer over rough walls is of fundamental and practical importance. From a fundamental view point, the knowledge of how a boundary layer responds to roughness (size and geometry, for example) can help in terms of understanding the dynamics of the boundary layer. This should in turn help to devise better management control strategies in flow situations, e.g., heat exchangers, or flow over a river bed, which involve flow over rough surfaces. The motivation for studying rough wall flows is well summarized by Antonia and Djenidi (2010) as follows:

> *"Apart from the wide engineering applications associated with rough walls (e.g.,* Nikuradse, 1933; Perry et al., 1969; Raupach et al., 1991 *and* Jiménez, 2004*) there are several compelling scientific reasons for studying flows over rough walls. First, our understanding of the turbulence structure near the vicinity of rough walls has lagged significantly behind that for the canonical smooth wall, for which streaks are observed throughout the viscous region and are important in the context of bursting. Eliminating the viscous layer through the introduction of roughness elements and examining the effect this has on both the inner and outer regions should be sufficient incentive for studying rough wall flows with vigour. Secondly, it is almost intuitive that the turbulence close to a drag-augmenting surface should be more isotropic than that over a smooth wall, thus facilitating somewhat the modelling of the near-wall region. Thirdly, a turbulent boundary layer which develops over a rough wall is more likely to satisfy the requirements of self-preservation (self-similarity along the streamwise direction) than a smooth wall boundary layer."* (taken from Antonia and Djenidi (2010)).

Of particular interest amongst rough surfaces, is the rough wall consisting of transverse circular rods or square bars, which has attracted a lot of attention, (see, for example, Raupach, 1981; Bandyopadhyay and Watson, 1988; Bakken et al., 2005; Keirsbulck et al., 2002; Krogstad and Antonia, 1999). The reason for this interest relies on the relatively simple geometry of the roughness elements which allows parametric studies (e.g., Leonardi et al., 2003; Krogstad et al., 2005). However, although a

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larger number of studies of a turbulent boundary layer over this particular 2D rough wall have already been undertaken (Raupach, 1981; Bandyopadhyay and Watson, 1988; Krogstad and Antonia, 1994; Djenidi et al., 1999; Keirsbulck et al., 2002; Leonardi et al., 2003; Lee and Sung, 2007), there are still unresolved issues. For example, there is no consensus yet on whether the outer region of the boundary layer on this rough wall is affected by the roughness when compared to that of a smooth wall boundary layer (e.g., Krogstad et al., 1992; Antonia and Krogstad, 2001; Jiménez, 2004; Schultz and Flack, 2005; Antonia and Djenidi, 2010), casting doubt on the validity of Townsend's wall-similarity hypothesis (Townsend, 1976). Also, the accurate measurement of the skin friction velocity is problematic and challenging and can lead to erroneous conclusions if incorrectly obtained.

It is further relevant to note that most of the studies of turbulent boundary layers focused mainly on one-point statistics (e.g., mean velocity, Reynolds stresses). While these statistics are of great importance and provide information on the dynamical response of the boundary layer to the surface changes, they do not shed light on how the energy transfer amongst various scales in the flow might be altered. Relatively few studies of turbulent boundary layers over rough walls used two-point statistics to gain some insight into the structure of the flow (Saikrishnan et al., 2007, 2012). These were mainly aimed at measuring the spatial correlations.

We carry out a two-point analysis of a turbulent boundary layer over a 2D rough wall with the aim to assess the energy distribution at any particular scale r (ranging from the smallest to the largest in the flow) as well as the way the energy is transferred amongst the scales. The focus of the work reported in this paper is on the scale-by-scale analysis of the second-order velocity structure function, $\langle(\delta u)^2\rangle$ ($\delta u = u(x_1 + r) - u(x_1)$, where u is the streamwise velocity fluctuation and r is the streamwise separation; the angular brackets denote time averaging). Notice that when r is very large then $\langle(\delta u)^2\rangle = 2\langle u^2\rangle$. If local isotropy is assumed, then the transport equation of $\langle(\delta u)^2\rangle$ is given generically by Danaila et al. (2001),

$$-\langle(\delta u)^3\rangle + 6\nu\frac{\partial}{\partial r}\langle(\delta u)^2\rangle + I_u = \frac{4}{5}\langle\epsilon\rangle r, \tag{1}$$

where ν is the kinematic viscosity of the fluid, and $\langle\epsilon\rangle$ is the mean turbulent kinetic energy dissipation rate. The first and second terms of the left side of Eq. (1) represent the energy transfer and the viscous diffusion of energy, respectively. The third term, I_u, accounts for the inhomogeneity or non-stationarity associated with the large scales; it can also account for the mean shear that exists in wall-bounded flows. Eq. (1) corresponds to the two-point velocity correlation function, first written by Von Karman and Howarth (1938) and effectively represents the scale-by-scale (SBS) budget of the turbulent energy at a location in the flow. At large r, Eq. (1) reduces to the (one-point) energy budget equation; in the limit $r \to 0$, it reduces to the (one-point) transport equation of $\langle\epsilon\rangle$ (e.g., Danaila et al., 1999). Different versions of Eq. (1) have been proposed for a turbulent channel flow (Danaila et al., 2001) and self-preserving turbulent round jet (Burattini et al., 2005). The term I_u is different between these two cases and reflects the difference in the one-point energy budget. For example, in the case of a channel flow, where the flow is stationary, I_u near the wall includes the effects of shearing and the spatial inhomogenity while on the centre-line of a round jet, I_u accounts for the non-stationarity and spatial inhomogeneity. Clearly, I_u not only varies from flow to flow, but it also varies from location to location within the same flow.

The objective of the present work is to extend the SBS approach to a turbulent boundary layer over a rough wall. Saikrishnan et al. (2007, 2012) performed a SBS analysis in a turbulent boundary layer and turbulent channel flow over a smooth wall. The motivation for considering a rough wall stems from the fact that the flow should be more isotropic in comparison to a smooth wall (see, for example, Shafi and Antonia, 1995, 1997; Antonia and Shafi, 1999) and thus one may expect that local isotropy is more adequately satisfied, thus making Eq. (1) more suitable for studying rough walls than smooth walls.

2. Experimental facility and measurements

The wind tunnel measurements are conducted in a turbulent boundary layer developing over a rough wall made up of circular rods mounted transversely on the tunnel floor and spanning the full width of the test section with $w/k = 8$, where w is the streamwise pitch and k is the roughness height (see Fig. 1). The roof of the wind tunnel is adjusted to obtain a nominally zero-pressure gradient ($\Delta p/(1/2\rho U^2) = \pm 0.5\%$) in the streamwise direction. The velocity fluctuations are measured using a single hot-wire probe. The hot-wire (diameter, $d = 2.5$ μm, and length, $l/d = 200$) is etched from a coil of Pt-10% Rh and operated using an in-house built constant temperature anemometer (CTA) with an over-heat ratio of 1.5. The hot-wire is calibrated *in situ* against the Pitot-static tube positioned in the undisturbed free stream flow before and after every experiment at 15 different speeds ranging between 0 m/s and 16 m/s. A linear interpolation in time (see Talluru et al., 2014) is employed between the two calibrations to correct for any drift in the hot-wire voltage that occurs during the course of an experiment. Only a minimal drift is noticed in the hot-wire due to short duration of our experiments. For the results reported here, measurements are made at a streamwise distance $x = 2.54$ m and 40 logarithmically spaced points are taken between $0.001 \leqslant y/\delta \leqslant 1.5$ in the wall-normal direction. At each measurement point, samples are collected for a duration of 120 s at a sampling frequency of 20 kHz. Experiments were taken at different free stream speeds giving Re_θ (Reynolds number based on the momentum thickness) in the range of 7000 and 14,000 while the ratio δ/k (δ is the boundary layer thickness) remained nominally about 60. In addition, measurements are made at five different streamwise

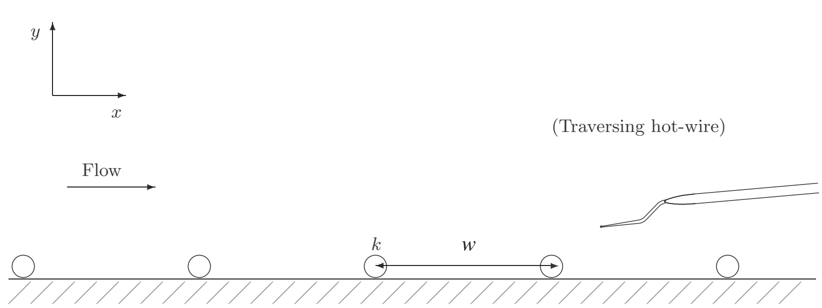

Fig. 1. Schematic representation of the rough wall and hot-wire probe used in the experiment.