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Turbulent boundary layer flow with a step change from smooth to rough surface

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A B S T R A C T

A direct numerical simulation (DNS) dataset of a turbulent boundary layer (TBL) with a step change from a smooth to a rough surface is analyzed to examine the characteristics of a spatially developing flow. The roughness elements are periodically arranged two-dimensional (2-D) spanwise rods, with the first rod placed $80\theta_{in}$ downstream from the inlet, where θ_{in} denotes the inlet momentum thickness. Based on an accurate estimation of relevant parameters, clear evidence for mean flow universality is provided when scaled properly, even for the present roughness configuration, which is believed to have one of the strongest impacts on the flow. Compared to previous studies, it is shown that overshooting behavior is present in the first- and second-order statistics and is locally created either within the cavity or at the leading edge of the roughness depending on the type of statistics and the wall-normal measurement location. Inspection of spatial two-point correlations of the streamwise velocity fluctuations shows a continuous increase of spanwise length scales of structures over the rough wall after the step change at a greater growth rate than that over smooth wall TBL flow. This is expected because spanwise energy spectrum shows presence of much energetic wider structures over the rough wall. Full images of the DNS data are presented to describe not only predominance of hairpin vortices but also a possible spanwise scale growth mechanism via merging over the rough wall.

1. Introduction

For several decades, the study of TBLs has been performed extensively for engineering applications related to fluid dynamics, as TBLs are present wherever there is a fluid flow over a solid surface or a wall. However, much less is known with regard to flows over areas of surface roughness despite the significance of such flows in industrial application—for example, over the hulls of automobiles, ships, airplanes, and turbine blades and over the surface of the earth. Because the fundamental characteristics of heat and momentum transfer are significantly influenced by the surface roughness, understanding the fundamental nature of TBLs over rough walls will improve the modeling and control processes in these important applications.

There have been a number of attempts to develop useful correlations between the surface skin-friction coefficient and the boundary layer parameters over a wide range of three-dimensional (3-D) surface roughness elements. Based on the assumption of a universal two-parameter form of the mean velocity profile in TBL, Hama (1954) examined the correlation using wire meshes with various roughness scales and showed the existence of universality of the roughness effect on the mean profiles regardless of the outside flow conditions for a fully 3-D roughness element. In addition to earlier studies which showed evidence of the classical formation with a small value of k/δ over the 3-D surface roughness (Acharya et al., 1986), a recent experimental study by Castro (2007) provided strong evidence using large and 3-D cubical roughness that classical universality adequately describes the mean flow profile of fully rough wall boundary layers independent of the nature of the roughness and its size. However, because the previous measurements for the universality have been often carried out over 3-D rough wall boundary layers, it has not been reported if the universality is achieved in TBL with 2-D surface roughness in which the interaction between the flow and the roughness is more active. Since 2-D rod type roughness forming a regular cavity is likely to behave differently especially in the near-wall region compared to 3-D surface roughness, it is necessary to examine the universality over 2-D surface roughness.

Furthermore, because all of the previous analyses were performed in experiments which used a fitting method for the mean velocity profile and the Reynolds shear stress, their indirect and dependent measurements may induce some uncertainties in estimating the correlation. It should be noted that even for a

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smooth-wall boundary layer experiment, large differences in turbulent statistics have been reported (Fernholz and Finley, 1996). In general, DNS results are believed to be more accurate than experimental results due to the very good agreement between the simulations of channel flows at low Reynolds numbers; thus, it is valuable to investigate the correlations between the friction coefficient and the boundary layer parameters using DNS data for a rough-wall TBL with high accuracy.

Although significant effort to understand for rough-wall turbulent flows has been made to reveal the characteristics of flows when they reach a new equilibrium state after a step change from a smoother to a rougher surface, few studies for the characterization of the transient response of the flow to a step change have been reported in the meteorological research community (Antonia and Luxton, 1971: smooth to rough, Cheng and Castro, 2002; Pendergrass and Arya, 1984; Bradley, 1968: smoother to rougher). This type of research is of particular importance, because an abrupt change of the surface roughness is an example of one of the simplest types of complex terrain features that is commonly encountered. Previous results describing the consequences of a step change on the surface roughness are summarized below.

(1) When a fluid moves over a rough surface, an internal boundary layer develops over the roughness, and very close to the wall an equilibrium layer exists. The internal boundary layer is essentially determined by the rougher surface (Jackson, 1976), and the growth rate of the internal boundary layer depends on the downstream roughness element (Bradley, 1968).
(2) It was shown that the growing equilibrium layer has first to encompass the roughness sublayer before the thickness of the inertial sublayer can be developed (Cheng and Castro, 2002).
(3) As the flow undergoes a transient process, overshoot of the turbulent shear stress and turbulent intensities behind the step change has been observed (Pendergrass and Arya, 1984; Andreopoulos and Wood, 1982). Overshoot of the Reynolds stress has been shown to be strongly dependent on the precise location with respect to the roughness element (Cheng and Castro, 2002).
(4) The streamwise distance required to reach a state of equilibrium in which a new self-preserving state is established is affected by the roughness geometry (Antonia and Luxton, 1971; Lee et al., 2012).

Despite the fact that most experimental studies have examined the characteristics of TBLs, the majority of DNS studies for rough-wall turbulent flows have been performed on turbulent channel flows of two basic types: flows with a symmetric channel and flows with an asymmetric channel with one rough wall and one smooth wall. This difference can be attributed to the difficulties of simulating TBLs with a non-periodic boundary condition in the streamwise direction. Because the flow spatially develops in the streamwise direction in the TBL, an auxiliary simulation for the inlet boundary condition is required for a rough wall. However, simulating the turbulent inflow characteristics of a flow over a rough wall has been nearly impossible thus far; the DNS of a TBL with a rough wall must use smooth wall inflow data, leading to a significant step change from a smooth to a rough wall. The continuous boundary layer DNS data along the streamwise direction with a step change allows us to perform a detailed analysis of the transient response from the smooth to rough walls compared to previous experimental data in which turbulent statistics have been measured at fairly restricted streamwise locations with uncertainties or no attempt has been made to take measurements between roughness elements.

The question of whether hairpin vortices are predominant in smooth-wall TBLs has been a topic with much controversy (Marusic, 2009; Wu and Moin, 2010; Jiménez et al., 2010; Schlatter and Örlü, 2012), and this issue is at the heart of uncovering the main organizing mechanism of wall turbulence. Based on the DNSs of zero-pressure-gradient flat-plate boundary layers, one school has provided direct evidence showing that hairpin vortices are densely populated throughout the transitional region and in the turbulent region up to $Re_\theta = 1950$ (Wu and Moin, 2010). However, although the dominance of hairpins is well accepted within the transition-dominated region, another school has shown that these structures are no longer considered to be dominant neither in the near-wall region nor in the outer layer in TBL flows with higher Reynolds numbers (Schlatter and Örlü, 2012). In addition, Jiménez et al. (2010) reported that although there are many hairpins in a flow field, most of them are randomly oriented rather than streamwise alignment with coherence (Adrian, 2007).

There have been a few experimental and numerical attempts to investigate hairpin structures over a rough surface in TBLs. Lee et al. (2009) investigated a turbulent structure using DNS data with a 2-D rod roughness element and showed that the dominant outer coherent structure given by conditionally averaging based on the event that maximizes the Reynolds shear stress is a hairpin-type vortex. However, these structures have qualitative differences in their shapes compared to those over a smooth wall, consistent with the characteristics of turbulent Reynolds stress in the outer layer. Volino et al. (2007) examined turbulent structures, as documented through the spectra of the velocity fluctuations, swirl strength, and two-point correlations between the velocity fluctuations and swirl through particle image velocimetry (PIV) measurements on a woven mesh surface over the TBL. They found that the turbulent structures over the 3-D rough wall are both qualitatively and quantitatively in agreement with those over the smooth-wall TBL. Furthermore, Volino et al. (2009) compared the turbulence structures over a 2-D rod and a 3-D woven mesh and showed significant changes of the Reynolds stresses in the outer layer due to the large-scale turbulent motions emanating from the 2-D rough wall, whereas the structures of the hairpin vortex packets for smooth and 3-D rough walls were qualitatively similar. Recently, Wu and Christensen (2010) performed PIV experiments with realistic roughness of an actual turbine blade damaged by the deposition of foreign materials. They showed that hairpin vortex packets exist in the outer layer of the rough-wall flow and that these contribute considerably to the Reynolds shear stress, consistent with the smooth-wall flow. Although these studies have suggested the existence of hairpins in TBLs with rough walls, direct evidence for the dominance of hairpins and their dynamics when the flow moves from smooth to rough walls has not been reported in any previous numerical and experimental investigations of TBLs.

In the present study, we performed DNS of a TBL with a step change from smooth to rough walls to examine the transient response of a spatially developing flow. The DNS code is identical to that used in Lee and Sung (2007). The roughness is numerically designed to have the form of 2-D spanwise rods which are periodically arranged in the streamwise direction with a streamwise pitch of $\lambda = 8k$ ($=12\theta_{in}$) and a roughness height of $k = 1.5\theta_{in}$, which corresponds to $k/\delta = 0.045 \sim 0.125$ and $k^+ = ku_\tau/\nu = 32 \sim 45$ along the downstream direction, with δ being the boundary layer thickness. We examine the universality of the mean flow with 2-D rod-roughness to provide further evidence of this formulation, especially without the use of a fitting method to estimate the drag-related quantities. The first-order and second-order turbulent statistics are scrutinized to characterize the transient effects through the region between the first and seventh rods, and quadrant analysis and weighted joint probability density function