Wall-attached structures of streamwise velocity fluctuations in a turbulent boundary layer over urban-type roughness

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ABSTRACT

Rough-wall turbulence is commonly found in both industrial applications and nature environments. Recently, Yoon (2024) performed direct numerical simulation of turbulent boundary layer (TBL) over 3D cubic roughness elements, revealing the presence of the log law in the streamwise turbulent intensity, which is reminiscent of attached-eddy hypothesis proposed by Townsend (1976). Here, we demonstrate the log region of turbulent intensity by identifying wall-attached structures of streamwise velocity fluctuations in rough-wall TBL. These wall-attached structures exhibit self-similarity with respect to their heights (l_y), and their population density decreases inversely with l_y, reflecting the hierarchy of attached eddies. When we reconstruct the streamwise turbulent intensity by using only self-similar structures, the log law is observed in the range $100 < y'^+ < 0.3\delta^+$. These results confirm the existence of self-similar attached eddies and their contribution to the log law in streamwise turbulent intensity, even in rough-wall flows.

KEY WORDS

Turbulent boundary layer, cubical roughness, coherent structure

1. INTRODUCTION

Townsend (1976) proposed that the primary energy-containing motions in the logarithmic region of high-Reynolds-number wall turbulence can be understood as an ensemble of self-similar eddies attached to the wall, where the size of each eddy scales with its distance from the wall. Perry and Chong (1982) extended this idea by introducing the hierarchical organization of these attached eddies, leading to the derivation of the logarithmic law for streamwise and spanwise turbulence intensities.

Rough-wall turbulent boundary layers are commonly encountered in both natural and engineering contexts. Recently, Yoon (2024) conducted direct numerical simulations (DNS) of turbulent boundary layers over 3D cubical roughness elements, confirming the presence of a logarithmic law in the streamwise turbulent intensity. This result implies the existence of attached eddies within rough-wall boundary layer flows.

The objective of this study is to analyze turbulence structures contributing to the logarithmic law of streamwise turbulence intensity in a rough-wall turbulent boundary layer ($Re_\tau \approx 800$) based on Townsend's attached eddy hypothesis. Following the methodology of Hwang and Sung (2018), wall-attached u structures are extracted from the instantaneous flow field, and their self-similar and hierarchical characteristics were examined. Finally, the contribution of these structures to the logarithmic law of streamwise turbulence intensity was analyzed.

2. Result

Figure 1(a) shows the joint probability density function (p.d.f.) of the streamwise length (l_x) and height (l_y) of wall-attached structures. For the rough wall, the streamwise length of the structures decreases compared to the smooth wall. The average streamwise length of the structures, plotted as symbols, increases proportionally with the structure height in the range ($3Re_\tau^{0.5} < l_y^+ < 0.6\delta^+$). In the rough wall case, the average streamwise length grows at a faster rate than in the smooth wall case. Additionally, the number of self-similar structures decreases linearly with increasing height, demonstrating a hierarchical distribution, which spans a broader range in the rough wall case (Figure 1b).

By superposing only the self-similar structures ($3Re_\tau^{0.5} < l_y^+ < 0.6\delta^+$), the streamwise turbulence intensity was computed, revealing a logarithmic decay in the range $100 < y'^+ < 0.3\delta^+$ (Figure 1c). These findings suggest that self-similar attached eddies exist even in rough-wall flows and contribute significantly to the logarithmic law of streamwise turbulence intensity.

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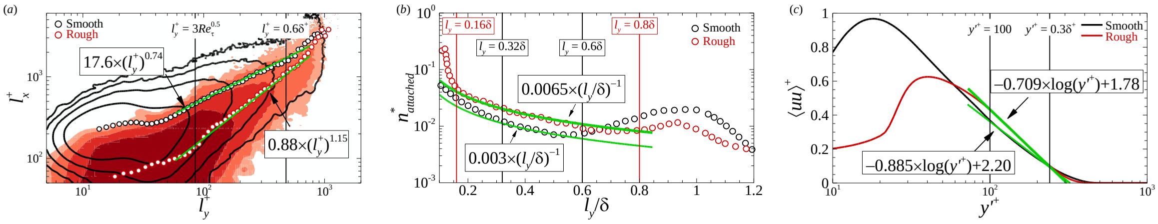

Fig. 1. (*a*) Joint p.d.f of streamwise length (l_x) and wall-normal height (l_y) and (*b*) population density of wall-attached *u* structures. (*c*) Wall-normal profiles of streamwise turbulent intensity carried by self-similar structures.