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Turbulent boundary layers over sparsely-spaced rod-roughened walls

Muhammad Nadeem [a], Jae Hwa Lee [b], Jin Lee [a], Hyung Jin Sung [a,*]

[a] Department of Mechanical Engineering, KAIST, 291 Daehak-ro, Yuseong-gu, Daejeon 305-701, Republic of Korea
[b] School of Mechanical and Nuclear Engineering, UNIST, 50 UNIST-gil, Eonyang-eup, Ulsan 689-798, Republic of Korea

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ABSTRACT

Direct numerical simulations (DNSs) of spatially developing turbulent boundary layers (TBLs) over sparsely-spaced two-dimensional (2D) rod-roughened walls were performed. The rod elements were periodically arranged along the streamwise direction with pitches of $p_x/k = 8$, 16, 32, 64 and 128, where p_x is the streamwise spacing of the rods, and k is the roughness height. The Reynolds number based on the momentum thickness was varied from $Re_\theta = 300–1400$, and the height of the roughness element was $k = 1.5\theta_{in}$, where θ_{in} is the momentum thickness at the inlet. The characteristics of the TBLs, such as the friction velocity, mean velocity, and Reynolds stresses over the rod-roughened walls, were examined by varying the spacing of the roughness features ($8 \leqslant p_x/k \leqslant 128$). The outer-layer similarity between the rough and smooth walls was established for the sparsely-distributed rough walls ($p_x/k \geqslant 32$) based on the profiles of the Reynolds stresses, whereas those are not for $p_x/k = 8$ and 16. Inspection of the interaction between outer-layer large-scale motions and near-wall small-scale motions using two-point amplitude modulation (AM) covariance showed that modulation effect of large-scale motions on near-wall small-scale motions was strongly disturbed over the rough wall for $p_x/k = 8$ and 16. For $p_x/k \geqslant 32$, the flow that passed through the upstream roughness element transitioned to a smooth wall flow between the consecutive rods. The strong influence of the surface roughness in the outer layer for $p_x/k = 8$ and 16 was attributed to large-scale erupting motions by the surface roughness, creating both upward shift of the near-wall turbulent energy and active energy production in the outer layer with little influence on the near-wall region.

1. Introduction

Turbulent boundary layers (TBLs) over rough walls are an important subject of research, because these are often encountered in the majority of wall-bounded flow systems in engineering applications. The characteristics of TBLs over rough-walls are affected by the roughness geometry, shape, arrangement of roughness elements, and others. Most previous studies have focused on the wall-similarity hypothesis of Townsend (1976), which states that turbulent motions outside of a roughness sublayer are independent of the surface roughness. Because the roughness effects nearly vanished under the similarity analysis, the interactions between the inner and outer layers were very weak at sufficiently large Reynolds numbers. Several review articles (Raupach et al., 1991; Jiménez, 2004) have comprehensively summarized the behaviors of wall-bounded flows in the presence of a range of surface roughness. The wall-similarity appears to be satisfied for irregular three-dimensional (3D) rough surfaces over a large range of roughness type and size (Flack et al., 2005; Volino et al., 2009).

Previous studies of TBLs over 2D transverse rough walls have displayed the existence of roughness effects in the outer layer. Krogstad and Antonia (1999) examined a flow system with a rod roughness of $p_x/k = 4$ ($\delta/k \approx 46$) and found that the Reynolds stress profiles were higher in the outer layer compared with the corresponding profile formed over a smooth wall. Similar results were obtained not only in a DNS study conducted by Lee and Sung (2007) with $p_x/k = 8$ ($\delta/k \approx 22$) but also in an experimental study performed by Volino et al. (2009) with $p_x/k = 8$ ($\delta/k \approx 32$. Note that Volino et al. (2011) also carried out the same experiment using a small roughness with $\delta/k \approx 160$, they observed the influence of the roughness element in the outer layer, indicating that the criteria for the wall-similarity in the outer layer is not universal. In addition, Djenidi et al. (2008) conducted experiments with 2D transverse square bars for $p_x/k = 8$ and 16 with $\delta/k \approx 38$ and showed that the roughness function was greater for $p_x/k = 8$ than 16, although the larger effect on the Reynolds stresses occurred for $p_x/k = 16$.

Recently, the effect of the roughness element spacing and dimensions were investigated by Lee et al. (2012) in a series of

* Corresponding author. Tel.: +82 42 350 3027; fax: +82 42 350 5027.
E-mail address: hjsung@kaist.ac.kr (H.J. Sung).

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DNSs performed over rod-roughened walls with $p_x/k = 2, 3, 4, 6, 8$, and 10 ($\delta/k \approx 16$–20). They showed that the roughness effects on the Reynolds stress extended to the outer layer, except for $p_x/k = 2$ and 3, and the increase was proportional to p_x/k. Furthermore, Krogstad and Efros (2012) conducted experiments using a 2D rod roughness at higher Reynolds numbers with $\delta/k \approx 131$ and found that the difference of the Reynolds stresses between the rough and smooth walls was reduced due to the large-scale separation, compared to the results performed at lower Reynolds number. Since the effect of the surface roughness in the outer layer has not yet been characterized at large p_x/k (>10), an examination of TBL with 2D rod roughness with large p_x/k could provide information including the establishment of the wall-similarity hypothesis in the outer layer.

Several experimental and numerical studies have been conducted to investigate the influence of the roughness on the turbulent structures in TBLs. Krogstad and Antonia (1994) showed that the streamwise extent of the streamwise correlation was reduced by the presence of roughness in a roughness sublayer and the streamwise length had larger average inclination angles to the wall over the rough walls. Using conditional averaging with an event that maximized the second-quadrant Reynolds shear stress, Lee et al. (2009) investigated the turbulent structures over 2D rough walls and showed that a dominant coherent structure in the outer layer was the hairpin-type vortex, although these structures between the rough and smooth walls differed qualitatively in shape based on the velocity vector fields. Volino et al. (2009) found the outer-layer structure of a TBL to be more sensitive to the 2D roughness ($\delta/k = 32$), but the structures of the hairpin vortex packets formed in the presence of smooth and 3D rough walls were qualitatively similar. Lee et al. (2012) showed that for small values of p_x/k, the hairpin packets and low-momentum regions in the 2D and 3D rough walls were similar to those observed in the presence of the smooth wall. For large values of p_x/k, however, larger packet-like structures extended to the outer edges of the boundary layer due to the formation of large plumes of fluid eruptions near the wall. Gaula et al. (2012) performed PIV measurements of TBLs over sparse hemispherical roughness elements and observed that the organization of these vortex packets was altered due to the length scale reduction in the near-wall region. These studies provided evidence for the presence of coherent structures in TBLs over rough walls, although the studies provide little information about the coherent structures formed in the presence of sparse 2D rough walls.

In the present study, we performed several DNSs of TBLs over rod-roughened walls with $p_x/k = 8$, 16, 32, 64 and 128 to investigate the influence of the large streamwise roughness spacing on the nature of flow characteristics of TBLs over 2D rough walls. Our primary objective was to study the effect of the surface roughness in the outer layer at large p_x/k. We examined the modification of the interaction between the inner and outer layers over the rough wall that might be relevant to the active momentum transport over the rough wall. In Section 3, the mean velocity, velocity defects, roughness function, and Reynolds stresses were obtained over the rough walls and were compared with those of a smooth wall. In Section 4, two-point amplitude modulation (AM) covariance was analyzed with spanwise energy spectra to investigate the interactions of structures between the inner and outer layers. Finally, the analysis of instantaneous flow fields was performed to reveal the modification of turbulent structures over the rough walls.

2. Numerical details

The non-dimensional governing equations for an incompressible flow are given by

$$\frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{1}{\mathrm{Re}}\frac{\partial^2 u_i}{\partial x_j \partial x_j} + f_i, \tag{1}$$

$$\frac{\partial u_i}{\partial x_i} = 0, \tag{2}$$

where x_i are the Cartesian coordinates and u_i are the corresponding velocity components. The notational convention adopted is that x, y, and z denote the streamwise, vertical, and spanwise coordinates, respectively, and u, v, and w denote the streamwise, wall-normal, and spanwise components of the velocity. All variables were non-dimensionalized by the free-stream velocity (U_∞) and the momentum thickness at the inlet (θ_{in}). The momentum thickness Reynolds number was defined as $Re_\theta = U_\infty\theta_{in}/\nu$, where ν is the kinematic viscosity. The superscript + indicates quantities normalized by the wall unit, i.e., the friction velocity and the kinematic viscosity. The governing equations were first integrated over time using the fractional step method with the implicit velocity decoupling procedure proposed by Kim et al. (2002). A block LU decomposition yielded the velocity pressure decoupling and the additional decoupling of the intermediate velocity components through an approximate factorization. The immersed boundary method was used to describe the roughness elements in the Cartesian coordinates over a rectangular domain (Kim et al., 2001). The numerical algorithm and the boundary conditions are described in detail in the paper of Lee and Sung (2007).

The first rod is placed at distance of $80\theta_{in}$ downstream from the inlet, and thus the surface condition at this point changes abruptly from smooth to rough wall, which is defined as $x = 0$. Therefore, the domain size should be sufficiently long for the flow to reach a new equilibrium state, which results in self-preservation in the computational domain. These domain sizes were confirmed to be adequate by verifying the convergence of the two-point correlation to zero for half of the present computational domain in the streamwise and spanwise directions. The inflow data over the smooth wall at $Re_\theta = 300$ was obtained by the auxiliary simulations based on the method of Lund et al. (1998). At the exit, the convective boundary condition was specified as $(\partial u/\partial t) + c(\partial u/\partial x) = 0$, where c is the local bulk velocity. The no-slip boundary condition was imposed at the solid wall, and the boundary conditions on the top surface of the computational domain were $u = U_\infty$ and $\partial v/\partial y = \partial w/\partial y = 0$.

In the present study, six simulations for five rough walls ($p_x/k = 8$, 16, 32, 64 and 128) and a smooth wall were performed. The domain size (L_i), number of grid point (N_i), and mesh resolution for each case are summarized in Table 1, and a schematic of the computational domain for $p_x/k = 8$ and 16 is shown in Fig. 1. Here, the streamwise domain size was varied from $768\theta_{in}$ to $1536\theta_{in}$ for the flows to achieve new equilibrium state after the initial step change. In each case, four locations denoted by I, II, III and IV in Fig. 1(b) were chosen to examine the streamwise-variations of the turbulent statistics along the wall-normal distance from the wall. Location I was located at the center of the roughness crest, and location II was located near the focal point of the first recirculation zone. Location III was the geometric center of two adjacent roughness elements along the streamwise direction. Finally, location IV was located in front of the leading edge of the roughness element. In the following sections, the turbulent statistics were obtained at location III, unless mentioned otherwise, with $\delta/\theta_{in} \approx 30$ and $Re_\theta \approx 1350$ to highlight the influences of the streamwise spacing, and we found little influence of p_x/k in the outer layer. The statistics were sampled for the duration of $13{,}500\theta_{in}/U_\infty$ for $p_x/k = 8$ and 16, and $20{,}000\theta_{in}/U_\infty$ for $p_x/k = 32$, 64 and 128. The flow parameters including the roughness heights and the effective sand grain roughness height are listed in