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Passive Control of Near-Wall Turbulence By Means of Roughness Elements

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Abstract

The present work experimentally investigates the effect of roughness elements onto zero-pressure-gradient turbulent boundary layer. We use an array of spanwisely-aligned cylindrical roughness elements attached on the wall surface to regulate the near-wall low-speed streaky structures. With both qualitative visualization and quantitative measurement, it is found that the regularization only occurs in the region below the height of the roughness element, where the local streamwise turbulent fluctuation intensity can be reduced with about 10%. Moreover, it is also found that if the spanwise spacing of roughness elements increased to be larger than the mean streak spacing in the smooth wall turbulence, there is no streak-regularization effect in the buffer region, so that the near-wall streamwise turbulent fluctuation intensity doesn't reduce.

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Keywords: Turbulent coherent structures; Low-speed streak; Flow control

1. Introduction

Wall-bounded turbulence is widely encountered in both flow around high-speed transportation vehicles and atmosphere boundary layer. It is well known that the skin friction in the turbulent boundary layer is significantly larger than that in the laminar case with equivalent Reynolds number, thus providing the most dominant source of the total drag. Moreover, the transportation process of the sand storm mainly relies on the dynamics of turbulent atmospheric motion; in this sense, passive turbulent control provides efficient way to inhibit the sand-uplifting process and their near-ground transportation characteristics.

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Recent advances in understanding the physics of turbulence promote both inspiring theoretical foundation and feasible realization ideas, which in turn stimulate the development of new turbulent control technique. Since Kline *et al.*[1] discovered the existence of low/high-speed streaky structures in the turbulent boundary layer in the 60s of last century, people began to accept the fact that turbulence was not totally random, instead it contains multi-scaled coherent structures with varied pattern, among which the most important one is low-speed streaks: they universally exist in the buffer region and the lower part of the log region, their instability relates with both the burst event and the generation of high-order vortical structures, thus contributing to the generation of turbulent kinetic energy.

Based on these findings, the prevailing idea of turbulent boundary layer control is to destroy the turbulent self-sustaining mechanisms by manipulating the related coherent structures. Early efforts main used groove surface[2, 3], riblet[4] and oscillating wall[5], with the basic idea of restricting the spanwise oscillation of low-speed streaks, thus reducing the generation of Reynolds shear stress related with burst. Recently, regularly-placed roughness element becomes a promising control strategy due to its simple geometry and reliable performance. Sirovich *et al.*[6] used surface micro-protuberance to control turbulent boundary layer, their investigation showed that the distributed micro-protuberance could achieve a drag reduction of about 10% in some case. Frasson *et al.*[7] further used such technique onto the control of boundary layer transition. By placing cylindrical roughness elements onto the wall surface, they introduced steady low-speed streaks with moderate strength in the downstream, which effectively inhibited the amplification process of T-S wave, thus delayed the transition process. Wang *et al.*[8] and Pan *et al.*[9] applied this technique onto wake-induced bypass transition control, where the introduction of roughness elements accelerated the early transition process, but suppressed the formation of large-scale structures. In addition, Lu *et al.*[10, 11] investigated the effect of geometric parameters of roughness elements onto near-wall coherent structures in turbulent boundary layer.

The primary aim of the present work is to investigate the effect of roughness element onto the near-wall streak structures of a turbulent boundary layer. By manipulating these energetic coherent structures which are associated with the sand-uplifting process, we hope that the feasibility of this passive control method can be demonstrated. Both qualitative visualization and quantitative measurement is utilized to investigate the variation of streak spacing statistics and velocity fluctuation intensity in the inner region. Moreover, the effect of element spacing is also discussed.

2. Experiment Method

The present experiment was carried out in a low-speed water channel in Beijing University of Aeronautics and Astronautics. The test section of this water channel is 4800mm×600mm×600mm with optical access on both side-walls. The oncoming free-stream velocity was U_∞=86.1mm/s, and the corresponding turbulence intensity was Tu<0.8%. The boundary layer was developed on the surface of a plexiglas flat-plate with 4:1 elliptical leading edge. The flat-plate, with size of 10mm×600mm×2000mm (thickness×width×length), was horizontally positioned 200mm above the bottom of the water channel. The coordinate system was defined in a right-hand manner: x axis directs into downstream, y axis along the wall-normal direction and z axis parallel to the flat-plate leading edge, and the coordinate origin is the intersection point between the leading edge and the symmetric plane. Transition was tripped by a 6-mm-in-diameter rod transversely stuck to the wall at x=70 mm downstream from the leading edge, resulting in a fully developed turbulent boundary layer after x=700 mm. The velocity profile and turbulent intensity profile of the boundary layer at x=1020~1050mm is shown in Fig.1, which evidences that the turbulent boundary layer has been fully developed. The corresponding characteristic parameters are listed in Table.1. More details about this zero-pressure-gradient turbulent boundary layer can be referred to Pan *et al.*[12].

Cylindrical roughness elements with diameters d=4mm and height k=8mm were attached on the wall surface at x=1400mm, forming one spanwisely aligned row. The local boundary layer has thickness of $\delta\approx$40mm, leading to a height-to-thickness ratio of h/δ=0.2. In the present work, we tested two different roughness spanwise spacing: Δz=20mm and 40mm, and the smooth wall turbulence was also measured to form a baseline case for direct comparison. Hydrogen bubble visualization and two-dimensional Particle Image Velocimetry (PIV) was taken in the planview (x,z) plane with various height. In the PIV measurement, seeding tracers with median diameter of 5μm and density of 1.05 g/mm^3 were illuminated by a continuous laser sheet with thickness of about 1mm and energy output of 1.5W. A high-speed CCD camera (640×480 pixels) captured the sheet-sliced flow field with maximum sampling