EXPERIMENTAL INVESTIGATION OF THE FLOW AROUND A CIRCULAR CYLINDER IN THE TURBULENT BOUNDARY LAYER

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Summary The turbulent boundary layer flow effected by a cylinder rod is measured by two dimensional time-resolved PIV form side view and the top view. The resulting instantaneous two-dimensional velocity distributions are used to quantitatively visualize the flow structures. They reveal quasi-spanwise vortices directly appear behind the cylinder, then they break up and develop into the hairpin-like structures typical of wall-bounded turbulence. For the top view case, we also can acquire that as the quasi-spanwise structure advects downstream, the non-uniformity rapidly appears in the vortex core, which is attribute to the effects of the three dimensional characteristics of coherent structure upstream the cylinder rod in the turbulent boundary layer. Then, the low-speed regions are quickly developed after the separated flow region, which are resulting from the formation of the corresponding hairpin vortices and hairpin vortices packet.

INTRODUCTION

There are situations in aeronautics and turbomachinery, most practical flow surfaces are smooth at first, then can become roughened due to various damage mechanisms, and the surface roughness significantly increases the wall shear stress and augment heat and mass transfer at the wall, resulting in an increase in the thermal loading of a system, which can severely reduce the lifetime of vital parts of many engineering systems. Therefore, a clear understanding of the impact of surface roughness on wall turbulence is imperative for successful controlling these flows and leading to profound improvements in the lifetime of the practical engineering systems. Present paper experiments a turbulent boundary layer flows though a two dimensional circular cylinder roughness. The cylinder horizontally mounted on the plate plane produces separated quasi-spanwise vortices in wall turbulence, and we focus on how these two dimensional vortices evolve into three dimensional hairpin vortices and hairpin vortex packets and their effects in the wall turbulence.

EXPERIMENTAL SET-UP AND METHOD

The experiments have been conducted in a re-circulating water where the turbulent boundary layer flow has been established along a flat plate at two different free-stream velocity of 0.15m/s and 0.25 m/s. The flow was tripped by a spanwise attached tripping 50 mm downstream of the leading edge. A thickness of the turbulent boundary layer of 31 mm was reached at the location of the measurement volume around its centre at x = 700 mm downstream the leading edge. This corresponds to $Re_\theta = 2,800$ based on the momentum thickness and free-stream velocity. The circular cylinder with the diameter of 2 mm was embed in the turbulent boundary layer 800mm downstream the leading edge. 2D TR PIV is utilized for particle images recording, storage and processing. A schematic of the test system is shown in figure 1. Seeding particles with median diameter of 10 μm and density of 1.03 g/mm^3 are illuminated by a laser sheet with thickness of about 1mm. 2D TR PIV measurement is taken in the streamwise-normal wise plane and the streamwise-spanwise plane, separately. The present sampling frequency of the camera is 300 Hz. 6400 snapshots of particle images are recorded for each region, and the resulted vectors have a spatial resolution of 1.5 mm in both streamwise and spanwise direction.

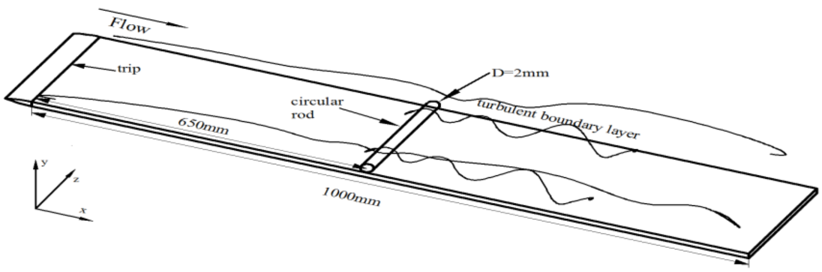

Fig. 1 Schematic diagram of the experimental set-up.

RESULTS

The average velocity vectors in the streamwise-wall-normal plane (Fig. 2) show a shear layer, separating the reversed flow near the wall from the high-speed outer flow. The velocity profiles introduce an inflection point, which is well

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known to be unstable and a source for creating turbulence. After the reversed flow region, the average flow quickly reappear a self-similarity and a turbulent boundary layer profile is redeveloped.

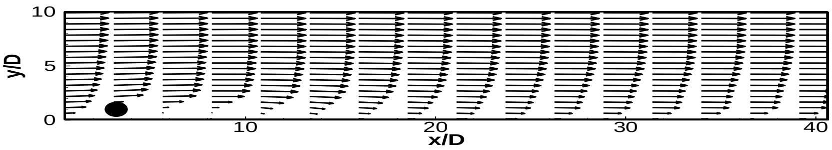

Fig. 2 Velocity vectors in the streamwise-wall-normal plane showing the separation bubble and reattachment behind the cylinder rod, which is indicated by the black circular.

The Reynolds normal stresses $\langle u'u' \rangle, \langle v'v' \rangle$ and the shear stress $\langle u'v' \rangle$ are presented in a streamwise-wall-normal plane(Fig. 3). It can be seen that the shear layer separating from the circular cylinder is associated with high levels of $\langle u'u' \rangle$ and $\langle u'v' \rangle$, and also it is clear that the redistribution of turbulent kinetic energy of the different components takes place in the region near the point of average reattachment, where the turbulence is strained by the flow moving toward the wall.

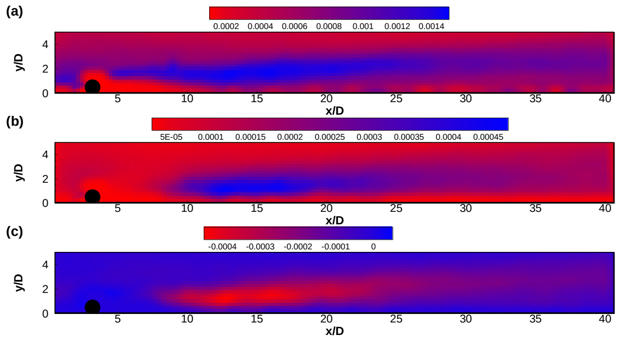

Fig. 3 Reynolds normal stresses (a–b) and Reynolds shear stress (c) in a streamwise-wall-normal plane.

Fig 4 presents an example of vortex identification via swirling strength using an instantaneous flow velocity field in the streamwise-wall-normal plane. Galilean decomposition of this instantaneous field with an advection velocity of $0.75U_\infty$ reveals the spanwise vortices advecting downstream, and these vortical motion are identified by means of the modified swirling strength [1][2]. Immediately behind the trip, within the shear layer, vorticity rolls up into spanwise swirling motions. Due to the coherent structures in the turbulent boundary layer, these vortices undulate in the spanwise direction and develop into the hairpin-like structures typical of wall-bounded turbulence.

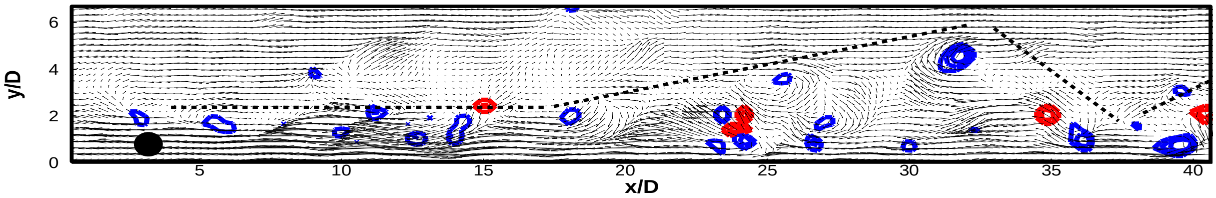

Fig. 4 Example of vortex identification and extraction in an instantaneous velocity field acquired. Galilean decomposition of the instantaneous velocity field at $U_c = 0.75U_\infty$ with contours of instantaneous Λ_{ci} in the background. Retrograde spanwise vortices are presented in red and prograde vortices in blue.

CONCLUSIONS

The turbulent boundary layer effected by a two dimensional circular cylinder trip is measured by 2D TR PIV. The present paper reveals quasi-spanwise vortices directly appear behind the cylinder, then they break up and develop into the hairpin-like structures typical of wall-bounded turbulence, and the low-speed region are quickly developed after the separated flow region, which are resulting from the formation of the corresponding hairpin vortices and hairpin vortices packet.

References

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