Analysis of Vortical Structure over a Sinusoidal Riblet by Dual-Plane Stereoscopic PIV

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Abstract Vortical structures in wall turbulence over a sinusoidal riblet surface are investigated by means of a dual-plane stereoscopic particle image velocimetry (DPSPIV) measurement in a channel flow at a friction Reynolds number of 150. The sinusoidal riblet is different from ordinary ribs, i.e., the lateral spacing of the sinusoidal riblet varies in the streamwise direction and 12% of the drag reduction rate has been confirmed. The DPSPIV measurement system consists of four CCD cameras satisfying Scheimpflug condition and two laser light sheets. The laser light sheets are generated by two double-pulsed Nd: YAG lasers with an additional optical system. The laser sheets are provided on streamwise and wall-normal planes and separated 0.5 mm in the spanwise direction to each other. The profiles of a mean streamwise velocity, a Reynolds shear stress, and root-mean-square values of velocities for the smooth surface show a good agreement with those of a direct numerical simulation. Those of the sinusoidal riblet surface decrease in near-wall region as compared with the smooth surface. Since all velocity components can be measured on both the planes simultaneously, an instantaneous velocity deformation tensor can be obtained and vortical structures can be identified by a second invariant of the tensor. According to the conditional sampling method, vortical structures are deteriorated owing to the sinusoidal riblet.

1. Introduction

Skin friction drag in turbulent flows significantly increases owing to activity of vortical structures near walls. However, it is known that skin friction drag decreases due to riblet surfaces which are grooves aligned in the streamwise direction on wall surfaces. Up to now, numerous types of riblet surfaces have been investigated experimentally and numerically (e.g., Walsh, 1980; Walsh, 1982; Walsh, 1983; Choi et al., 1993; Bechert et al., 1997; El-Samni et al., 2007). Bechert et al. (1997) optimized the riblet shape and found 10% of the maximum drag reduction rate. They considered two-dimensional (2-D) ribs of which lateral spacings are kept constant in the streamwise direction. The lateral spacing of 2-D ribs are smaller than the diameter of quasi-streamwise vortical structures (referred as QSV) and the downwash motion of vortices are suppressed, resulting in drag reduction.

Inspired by two-dimensional riblets, three-dimensional riblets have been developed since these have possibility to provide a higher drag reduction effect than that of the optimized 2-D riblet. The ‘three dimensional riblet’ means that a riblet shape varies in the streamwise direction. Sasamori et al. (2012a) evaluated one of three-dimensional riblets, i.e., a sinusoidal riblet surface which provides up to 11.7% of the drag reduction rate in a turbulent channel flow. They concluded that the drag reduction mechanism of the sinusoidal riblet is similar to that of the 2-D riblet while the average of the lateral spacing of the sinusoidal riblet surface is larger than the diameter of vortices. A two-dimensional PIV measurement on the streamwise and wall-normal plane over the sinusoidal riblet surface shows decreases of the root-mean square values of velocity fluctuation and Reynolds shear stress. The PIV measurement on the streamwise and spanwise plane reveals an attenuation of streaky structures (Sasamori et al., 2012b). Although Sasamori et al. (2012a, b) revealed the decreases of the statistics and streaky structures due to the sinusoidal riblet, an influence of the sinusoidal riblet on QSVs is not clear yet. QSVs are well known to sustain high skin friction drag in wall turbulence. The $Q$ criterion, the second invariant of the velocity deformation tensor, is well employed to identify vortical structures (Hunt et al., 1988), while it is difficult to evaluate $Q$ criterion due to the limitation on velocity measurements: the $Q$ criterion requires all nine velocity gradients. Therefore, the investigation has been restricted in numerical simulations (e.g., Kasagi et al., 1995; Jeong et al., 1997). However, in recent decades, thanks to the development of PIV measurement techniques, all velocity gradients without applying any assumptions have been able to be obtained (Hu et al., 2001; Mullin et al.,...
2005). Furthermore, the evaluation of QSVs by means of a multi-plane PIV or tomographic-PIV has been performed (Tanahashi et al., 2002; Tanahashi et al., 2008; Elsinga et al., 2010; Ghaemi et al., 2012).

In the present study, we focus on the vortical structures over the sinusoidal riblet surface in order to reveal the relationship between the drag reduction effect and the turbulent structures in detail. The vortical structures are identified according to the $Q$ criterion by means of a dual-plane stereoscopic PIV (referred as DPSPIV, hereafter) measurement. The DPSPIV can provide all the velocity components and its deformation tensors. The objective of the present study is to obtain the statistics of the velocities around the vortical structures.

2. Experimental setup

The DPSPIV measurement is performed in a turbulent channel flow at $Re_s=150$. Here, the skin friction Reynolds number $Re_s$ is defined by a channel half width $\delta$, a kinematic viscosity $\nu$, and a friction velocity $u_*$ on the smooth surface. The channel wind tunnel consists of a developing section and a test section: the former is 3m long and the latter is 4m long. The cross section is $200\times200\text{mm}^2$. The sinusoidal riblet is installed on the bottom wall at the test section. Figure 1 shows the geometry of the sinusoidal riblet surface. The length of the sinusoidal riblet $L_x$ is 360 and the lateral spacing of it varies in the streamwise direction sinusoidally. An averaged lateral space $L_{z,\text{ave}}$ is 36, which is larger than that of the 2-D riblet (e.g., Choi et al., 1993). Here, the superscript of plus denotes a wall unit, i.e., the variables are nondimensionalized by $u_*$ and $\nu$.

The DPSPIV measurement is conducted at 3.7 m downstream from an entrance of the test section where the fully developed flow has been confirmed. The DPSPIV measurement consists of two individual stereoscopic PIV systems and two laser light sheets. The laser light sheets with 532 nm of wavelength are generated by two double-pulsed Nd: YAG lasers with an additional optical system and illuminate two streamwise and wall-normal planes. Note that the optical system for generating two laser sheets is the same as that by Tanahashi et al. (2008). In order to separate the scattered light onto the other plane, two double pulsed lasers are polarized in both the vertical and horizontal directions and separated by beam splitters installed in front of the cameras. The alignment of laser sheets and cameras is shown in Fig. 2. The horizontally polarized laser sheet is aligned at the center of the sinusoidal riblet, while the other one is separated 0.5mm in the spanwise direction. Oil particles of normal 1-2 $\mu$m diameter are produced with an array of Laskin nozzles and introduced passively at the upstream from the developing section. All cameras are adjusted in backward scatter configuration satisfying a Scheimpflug condition. An angle between the lens axis and the spanwise axis (orthogonal direction of measured planes) is set to be 30 degrees. The scattering particle images in a size of $26\times20\text{mm}^2$ are captured by high-speed CCD cameras $(1284\times1024\text{ pixel}^2)$ with 45$\mu$s pulse separation.

The velocity vectors are yielded by cross correlation with a size of $32\times8$ pixel$^2$ ($0.72\times0.18 \text{ mm}^2$) interrogation window. Here, an overlap of the interrogation windows is not employed in order to avoid the influence from a high frequency noise on the velocity gradients as reported by Tanahashi et al. (2002). Since all instantaneous velocity vector fields of 2500 frames are totally acquired on each plane, all nine velocity gradients can be calculated by using a second order central difference scheme.
3. Results

Figure 3 shows the mean streamwise velocity profiles of the smooth and riblet surfaces. Figures 4 and 5 show the root-mean-square values of velocities and the Reynolds shear stress, respectively. All the statistics are interpolated at the center of the two laser sheets. Here, $u$, $v$, and $w$ denote the velocity component of the streamwise, the wall-normal, and the spanwise directions, respectively. The statistics of the smooth surface are displayed together with those of a direct numerical simulation (Iwamoto et al., 2002). A good agreement is confirmed. The statistics of the riblet surface shows that the mean velocity, the rms values, and the Reynolds shear stress are found to decrease below those of the smooth surface.

Figure 6 shows the contribution of each quadrant of the Reynolds shear stress. The sum of four quadrants equals to the Reynolds shear stress as shown in Fig. 5. The Q2 ($v^+<0$ and $w^+>0$) and Q4 ($w^+>0$ and $v^+<0$) events correspond to the ejection and sweep motions, respectively, and contribute to increase the Reynolds shear stress. The Q1 ($u^+>0$ and $v^+>0$) and Q3 ($u^+<0$ and $v^+<0$) events contribute to decrease the Reynolds shear stress. It is found to decrease of the Q2 and Q4 events over the sinusoidal riblet as compared with the smooth surface, while the Q1 and Q3 events are nearly unchanged. This trend is also found in the 2-D riblet surface as reported by Choi et al. (1993) and El-Samni et al. (2007).

Since all the nine velocity gradients are obtained at the center of the two laser sheets, the second invariant of the velocity deformation tensor $Q^* = (\Delta u_i^*/\Delta x_i^*) (\Delta u_j^*/\Delta x_j^*)$ can be provided. A negative value of the second invariant is known to use to identify a QSV (Kasagi et al., 1995). Figure 7(a) shows an instantaneous flow field near the smooth surface. The color contour shows the distribution of the Reynolds shear stress and the black line is an isoline of $Q^* = -0.01$. Here, the spatial resolutions are $\Delta x^+ = 10.8$, $\Delta y^+ = 2.8$ and $\Delta z^+ = 7.7$. Vortical structures are observed and the large positive Reynolds shear stress is found around the vortical structures. The spanwise velocity fluctuation is also observed around the vortical structure as shown in Fig. 7(b). Figures 8(a) and (b) show those over the sinusoidal riblet. Unfortunately, it is difficult to find differences between the instantaneous flow fields for the smooth and riblet surfaces because of at most 10% decrease of velocity fluctuations as shown in Figs. 4 and 5.

In order to examine the effect of the sinusoidal riblet on QSVs quantitatively, a conditional sampling is employed: the velocity field around the local minimum of the second invariant is extracted; the results are shown in Fig. 9. The $Q$ value and the rms value of the spanwise velocity are found to decrease in case of the riblet surface as compared with that of the smooth surface, indicating that the QSVs are attenuated due to the riblet surface.
Fig. 3 Mean profiles of streamwise velocity over the smooth and riblet surfaces.

Fig. 4 Profiles of root-mean-square of velocity fluctuation component over the smooth and riblet surfaces.

Fig. 5 Reynolds shear stress profiles over the smooth and riblet surfaces.

Fig. 6 Reynolds shear stress from each quadrant over the smooth and riblet surfaces.
Fig. 7 Instantaneous distributions of (a) Reynolds shear stress and (b) spanwise velocity fluctuation for the smooth surface. The black line is the isoline of $Q^+ = -0.01$.

Fig. 8 Instantaneous distributions of (a) Reynolds shear stress and (b) spanwise velocity fluctuation for the riblet surface. The black line is the isoline of $Q^+ = -0.01$. 
4. Conclusions

The dual-plane stereoscopic PIV measurement for the turbulent channel flow over the smooth and sinusoidal riblet surfaces has been performed. In the case of the riblet surface, the fluid drag decreases. The statistics of the flow over the smooth surface (the mean streamwise velocity, velocity fluctuation and Reynolds shear stress) show good agreements with those by the direct numerical simulation. The statistics for the riblet surface decrease below those of the smooth surface in the region near the wall. Since all the nine velocity gradients are obtained, the second invariant of the deformation tensor is calculated and quasi-streamwise vortical structures are identified. The conditional sampling for the flow field around the vortical structures is done by detecting the local minimum value of the second invariant of the deformation tensor. It is revealed that the quasi-streamwise vortices are deteriorated owing to the riblet surface as compared with those over the smooth surface.

5. References


