Investigation of the Turbulent Boundary Layer Structure over a Sparsely Spaced Biomimetic Spine-Covered Protrusion Surface

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ABSTRACT: Multiperspective particle image velocimetry was used to investigate the turbulent boundary layer structure over biomimetic spine-covered protrusion (BSCP) samples inspired by dorsal skin of pufferfish. The comparison of BSCP samples of two sparse “k-type” arrangements (aligned and staggered) with roughness height $k^+ = 5−7$ (nearly hydraulically smooth) and smooth case were manufactured in bulk Reynolds number $Re_b = 37,091, 44,510$. The negative value of the roughness function $\Delta U^+$ shows a downward shift of the mean velocity profile of BSCP samples, which shows a drag reduction effect. The results of turbulent statistics present strong fluctuation over the aligned case in the streamwise direction, while little influence is observed in the wall-normal and spanwise direction, which promotes turbulence stability. The same phenomenon was found based on the probability density function of fluctuation velocity that the suppression of turbulent flow is better over the staggered case. It is obvious that the shear stress induced is governed by the streamwise fluctuations. Furthermore, the Q-criterion and the $\lambda_{ci}$-criterion improved with vorticity $\omega$ were introduced for vortex identification, which indicates less prograde vortex population and weaker swirling strength over BSCP samples than over the smooth one. Finally, the spatial coherent structure appeared similar and more orderly over the staggered case in the streamwise and wall-normal direction based on the analysis of two-point correlations $R_{uu}$. These results provide further guidance to reveal the mechanism of drag reduction on the BSCP surface.

1. INTRODUCTION

Turbulent flow over rough surfaces is ubiquitous in nature, which varies in geometrical properties that play fundamental roles in fluid dynamics, which have advantages in engineering systems, including momentum conservation, heat transfer, and drag reduction. Recently, the flow resistance over smooth and rough surfaces has received significant attention and has been well documented. According to the geometrical properties, the surfaces have been investigated in a variety of 2D-roughness, 3D-roughness, and irregular roughness elements. It is well established that the rough surface actually increases drag near-wall because of a down shift of the mean streamwise velocity profile in the region of the logarithmic layer. In the last few decades, although a great deal of experimental results and numerical simulations have made it possible to realize the mechanism of energy conservation, rough surfaces greatly increase the complexity of the turbulent mechanism near-wall.

In particular, plenty of research studies about geometrical properties of 3D-roughness elements have been conducted, such as cube, hemisphere, cone, pyramid, and so on. However, until now, the laws of the flow structure are not clearly revealed. The roughness function $\Delta U^+$ (superscript “+” means normalization) is represented as the shift in the mean streamwise velocity profile, which is susceptible to the roughness height $k^+$. Ligrani and Moffat suggest the relation between $\Delta U^+$ and $k^+$ in case of transitionally rough ($k^+ = 5−70$) and fully rough cases ($k^+ > 70$). The energy dissipation depends on the value of $k^+$. With increasing roughness height...
k', the form drag contribution strongly contributes more than viscous drag, where the reduction or energy conservation effect diminishes because of a positive $\Delta U^+$ according to the relation function given by Ligrani and Moffat. Therefore, form drag typically dominates under most circumstances, which increases the drag over rough surfaces. However, it is not well known that when $k' < S$, which is lower than viscous sublayer thickness, the flow becomes hydraulically smooth and the viscous drag plays a dominant role which may cause drag reduction because the roughness elements do not induce any perturbations.

Moreover, Raupach et al. point out that for 3D-roughness surfaces, the roughness function $\Delta U^+$ changes exponentially with roughness density $\lambda$. Wu et al. investigated this surface type of hemisphere with the same $k' = 20$ but different arrangement distances by DNS and reported that the situation of the spatial coherent structure is dependent on roughness density. When the roughness elements are sparsely spaced, the surface topography can be called "k-type", where the variation of $\Delta U^+$ depends on $k'$. Relatively, the narrowly spaced surface, which is called "d-type", is dependent on the outer turbulence. Therefore, it is still not understood what type of surface density is beneficial to drag reduction, and it clearly requires more scrutiny to reveal the influences. For cone-shaped rough surfaces, Okamoto et al. visualized the flow structure surrounding four types of cones in a wind tunnel with different vertex angles and suggested that the cone with a 150° vertex angle had no flow separation and induced the lowest drag compared with the other three cones. Recently, Chen and Martinuzzi presented the velocity statistics surrounding a low aspect ratio cone in an open-section suckdown wind tunnel, which reveals the shedding process, involving base and tip vortices, that induces periodic wake fluctuations for slender cones.

Pufferfish are known for their spine-covered skin, which differs significantly from other aquatic organisms in appearance; they are estimated to have a burst speed of 3.5 body length per second (BL/Uf), which is ranked highly in marine biology, as shown in Figure 1. Based on our previous work, it was found that a lower friction drag can be obtained over biomimetic spine-covered protrusion (BSCP) surfaces with roughness height $k' = 5$ and are sparsely spaced.

Thus, in this work, multiperspective particle image velocimetry (PIV) was introduced to observe the turbulent boundary layer (TBL) structure above rough surfaces inspired by the pufferfish skin and to further reveal the drag reduction property. Two bulk Reynolds numbers and three surface cases (smooth, rough-aligned, and rough-staggered) were designed, and the BSCP surface with small-scale elements and a staggered array has been proven to have a good drag reduction effect. We found the spacing distance between the rough element is fixed in "k-type", but the height of the rough element $k'$ varies from 5 to 7 depending on the $Re_w$, which is nearly a hydraulically smooth state. First, mean flow profiles with boundary layer parameters were investigated to obtain useful information on the drag reduction effect. Profile similarity between smooth and rough cases was discovered through comparison of Reynolds shear stress $\langle u'v' \rangle$, turbulent kinetic energy $\langle u'^2 + v'^2 \rangle$, and turbulent intensity. In addition, the influence of rough cases on turbulence fluctuation was obtained from the probability density function ($p.d.f.$) of instantaneous analysis. Finally, the coherent structure was revealed by vortex analysis (vortex population and swirling strength) and two-point correlation in order to explain the possible cause of the drag decrease in the outer layer.

2. METHODOLOGY

According to current literature studies, slender cone elements, or low vertex angle, are sensitive to induce wake fluctuation and pressure resistance which are negative factors for drag reduction. As shown in Figure 2, most of the body spines are embedded in the epidermis, with the tip of the spines exposing outside, which is confirmed by Byeon et al. The spines lifted the surrounding subcutaneous tissue and form a shallow conelike protrusion surface, which may be beneficial for drag reduction.

Five configurations, the diameter $D$, height $H$, center-to-center streamwise spacing $L_w$, spanwise spacing $L_s$, and overlap spanwise spacing $L_{sr}$ with bulk Reynolds number $Re_b = 37,091~44,510$ over the smooth surface and two arrangements (aligned and staggered) were considered in this experiment which is presented in Figure 3B,C. Detailed parameters of experimental BSCP samples are listed in Table 1. The configurations were selected based on the measurement of spines on pufferfish skin in the location of the dorsum which is mentioned above. Compared with the abdomen, spines on the dorsum are tiny, whose average length is about 0.2~1 mm and placed narrowly with an average distance of 3.5 mm. However, according to the dissection, half length of the spine was buried in the epidermis and fat layer. As a result of this, the height of the roughness element was chosen to be 0.2 mm, whose $k'$ is around 5 under the condition in this experiment. The BSCP samples were made using 3D-printing and the material is resin.

As shown in Figure 3A, x, y, and z represent streamwise, wall-normal, and spanwise spacing, respectively. The experiment was conducted in a circulating water tunnel at Jiangsu University of Science and Technology, whose test section is in a size of $800 \times 128 \times 128$ mm ($x \times y \times z$). It can adjust the free-stream velocity continuously from 0.4 to 1.5 m/s with a turbulence intensity of less than 1%. A 500 mm length hydraulic-smooth acrylic test plane was set in the middle of the test section with a $10^\circ$ bevel at the fore and rear. Turbulence transition was tripped by a 3 mm diameter steel trip (gray bar in the front) placed 10 mm from the top of the smooth plane. At 370 mm in the streamwise direction from the front the roughness region is set, measuring 80 mm × 12 mm × 40 mm which was produced to hold the sample with multiple rough elements (140 elements for the aligned array and 131 elements for the staggered one). Flow measurement was conducted on
smooth and rough samples with free-stream velocity $U_e = 0.6 - 1.2 \text{ m/s}$. The flow statistic information measured above the flat plane induced a zero-pressure gradient (ZPG) TBL where pressure resistance induced by the flat plane was negligible. Also, it is convenient to compare with the existing experiments on 3D-roughness surfaces under the condition of the ZPG.

In order to obtain accurate flow structure information, PIV was introduced as a nonintrusive measurement technique. In the present research, a COMS camera (pco.dimax S1, Germany) was used for particle image collection which reaches the maximum shooting speed of 4476 fps for a full resolution ($1008 \times 1008 \text{ pixels}$). A Nikkor 85 mm f/2.8 lens was installed for all measurements. A hollow glass sphere (10 $\mu \text{m}$, Dantec Dynamics, Denmark) was selected as the tracer particle. A 2 W semiconductor continuous-wave laser with a wavelength of 532 nm was used for illumination. Figure 3A

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**Figure 2.** Pufferfish. (A) Overall shape of a pufferfish. (B) Topography of the dorsal skin. (C) Spinal structure beneath the epidermis. (D) Scanning electron microscopy (SEM) images of the spine on the dried skin.

**Figure 3.** Schematics of the experimental setup. (A) Test section of the water tunnel with a test plate paralleled in the streamwise direction. (B) BSCP surface of the aligned case. (C) BSCP surface of staggered cases.

**Table 1.** Parameters of Experimental BSCP Samples, Including Diameter $D$, Height $H$, Center-to-Center Streamwise Spacing $L_r$, Spanwise Spacing $L_l$, Overlap Spanwise Spacing $L_o$, Bulk Streamwise Spacing $L_x$, Bulk Wall-Normal Spacing $L_y$, and Bulk Spanwise Spacing $L_z$

| case             | $D$(mm) | $H/D$ | $L_r/D$ | $L_l/D$ | $L_o/D$ | $L_x/D$ | $L_y/D$ | $L_z/D$ | coverage |
|------------------|---------|-------|---------|---------|---------|---------|---------|---------|----------|
| rough-aligned    | 2       | 0.1   | 1.75    | 1.75    | 0       | 235     | 30      | 60      | 4.5%     |
| rough-staggered  | 2       | 0.1   | 1.75    | 1.75    | 0.825   | 235     | 30      | 60      | 4.5%     |
| smooth           | 235     | 30    | 60      |         |         |         |         |         |          |
shows two different fields of view (FOVs) where FOV1 (80 × 40 mm) is located on the symmetrical side, perpendicular to the test plane and FOV2 (80 × 80 mm) is parallel to the test plane with a certain distance. Each measurement was repeated twice, and 20,000 pairs of particle images were recorded for 10 s at a camera configuration with a full resolution shooting rate of 2000 Hz.

The calculation interpretation area was set as 32 × 32 pixels and with a grid step of 8 × 4 pixels. The image magnification was 0.069765 mm/pixel. As most of the particles in the collected images were larger than 2 pixels, the peak lock phenomenon can be diminished. The near-wall region below the interpretation area was not analyzed for computational accuracy. All PIV analysis was supported by PIV analysis software MicroVec (ver. 3.6.1, Beijing, China).

3. RESULTS AND DISCUSSION

3.1. Mean Flow Profiles. Because of low analysis accuracy near-wall, the surface friction velocity \( (u_\tau) \) cannot be calculated with the data of the viscous sublayer \( (u' = y') \). The log-law region of the TBL profile over the ZPG plane surface can be defined by the following equation:

\[
u^+ = \frac{1}{\kappa} \ln y'^+ + B - \Delta U^+
\]

Normalized number \( u^+ = u/u_\tau \) and \( y'^+ = y'/u_\tau \) where \( y' \) is corrected with the roughness offset \( y_0 \). \( \kappa \) is the Kármán constant \( (\kappa = 0.4) \), \( B \) is the smooth-wall intercept \( (B = 5.5) \), \( \nu \) is kinematic viscosity \( (\nu = 1.011 \times 10^{-6} \text{ at a water temperature of } 20 \degree C) \), and \( \Delta U^+ \) is the roughness function which is variable-dependent on the wall situation. For the smooth wall, \( \Delta U^+ \) and \( y_0 \) is zero and the log-law region is described by equation \( u^+/u_\tau = 2.55 \ln (y^+ / \nu) + 5.5 \). When it comes to the roughness surface, an upward or downward shift of the mean velocity profile over the smooth wall exists which can be expressed by the roughness function \( \Delta U^+ \). The distribution of the velocity defect curve was introduced to figure the three unknown values \( \Delta U^+, y_0 \) and \( u_\tau \) by fitting the velocity defect curve of roughness with the smooth one. The fitting results are listed in Table 2, including the roughness height \( k^+ \), thickness of the TBL over the smooth case \( \delta_{ss} \), friction velocity \( u_\tau \), bulk Reynolds number \( Re_b \) \( (Re_b = U_\infty h/u) \), where \( U_\infty \) is free-stream velocity, \( h \) is half of the channel height), friction Reynolds number \( Re_\tau \) \( (Re_\tau = u_\tau h/u) \), roughness function \( \Delta U^+ \), and dimensionless spacing of the PIV analysis grid \( x', y' \), and \( z' \).

The mean velocity profiles above smooth and rough walls are shown in Figure 4A with two bulk Reynolds number \( Re_b \) at \( Re_b = 37,091 \) and \( \Delta U^+ = 0.05-0.11 \) for two roughness walls, but it became negative, \( \Delta U^+ = -0.23-0.2 \) when the \( Re_b \) grew up to 44,510. It seems that as the \( Re_b \) increases, the value of \( \Delta U^+ \) over rough walls decrease to negative. Ligrani and Moffat suggested that the relation between \( \Delta U^+ \) and \( k^+ \) can be defined as follows:

\[
\Delta U^+ = \left( \frac{1}{\kappa} \ln k^+ - 3.3 \right) \times \sin[0.4258(\ln k^+ - 0.811)]
\]

Figure 4B. Equation 2 was plotted with a solid line to reveal the relationship between \( \Delta U^+ \) and \( k^+ \). Clearly, the present experiment data collapse well with eq 2 although there is a little offset in the plot. The roughness type was classified into three cases: hydraulically smooth \( (k^+ < 5) \), transitionally rough \( (k^+ = 5-70) \), and fully rough \( (k^+ > 70) \) which are the plotted boundaries with dashed lines in Figure 4B. It seems that \( \Delta U^+ \) is always positive in transitionally rough and fully rough region while in hydraulically smooth, since the surface is nearly smooth, \( \Delta U^+ \) approaches zero at a particular shape that \( \Delta U^+ \) may reach a negative value. In the present research, the experimental data at \( Re_b = 44,510 \) (blue triangles in Figure 4B) achieved negative values of \( \Delta U^+ \) which gives reasons to believe

| case          | \( k^+ \) | \( k/\delta \) | \( u_\tau /U_\infty \) | \( Re_b \) | \( Re_\tau \) | \( \Delta U^+ \) | \( \Delta x^+ \) | \( \Delta y^+ \) | \( \Delta z^+ \) |
|---------------|-----------|---------------|------------------------|------------|-------------|----------------|----------------|----------------|----------------|
| smooth        |           | 0.0454        | 37,091                 | 1683       | 15.66       | 7.83           | 9.35           |                |                |
| rough-aligned | 5.79      | 0.011         | 37,091                 | 1739       | 0.05        | 16.18          | 8.09           | 9.66           |                |
| rough-staggered | 6.63    | 0.012         | 37,091                 | 1988       | -0.23       | 18.50          | 9.25           | 11.05          |                |
|               | 5.60      | 0.011         | 37,091                 | 1680       | 0.11        | 15.62          | 7.81           | 9.33           |                |
|               | 6.57      | 0.012         | 37,091                 | 1971       | -0.2        | 18.34          | 9.17           | 10.95          |                |
that in this case, the roughness wall produced the drag reduction effect.

3.2. Turbulent Statistics. The Reynolds shear stress $<u'v'>$ and turbulent kinetic energy $<u'^2 + v'^2>$ are plotted in Figure 5A, B for three wall cases and two bulk Reynolds number $Re_b$. These two turbulent statistics are calculated with fluctuation velocity $u'$ and $v'$ which directly reflect the energy exchange caused by turbulence in the TBL. As seen from Figure 5A, under the same $Re_b$, the $<u'v'>$ over two types of rough walls are lower than over the smooth one, about 10 and 20% lower for the staggered and aligned array. It is noteworthy that the $<u'v'>$ increases significantly in the outer
layer of the TBL which is above $k^+ = 120$. It shows that after reaching the peak in the log-law region, the $<u'v'>$ decrease rate slows down compared with that of the smooth, wall which is in good agreement with the reports of Kamruzzaman et al.\textsuperscript{26} Also, it seems that the aligned array achieved better $<u'v'>$ than the staggered array with a downward shift of about 10%. However, a sudden $<u'^2 + v'^2>$ decrease was found at $y^+ = 30\sim40$ where the near-wall value of $<u'^2 + v'^2>$ is larger for the aligned cases than for the staggered cases at $Re_\theta = 44,510$. This feature indicates that the energy distribution of the TBL over aligned cases became worse, leading to strong fluctuation at the streamwise direction as $Re_\eta$ increases.

Because of the spatially homogeneous over the limit roughness sublayer,\textsuperscript{7,26} the turbulent intensity is defined as $u'_{rms} = u'_{rms}/U_\infty$ where $u'_{rms}$ the root-mean-square (rms) of the fluctuation velocity $u'$ varies in the wall-normal direction. The $u'_{rms}$ and $v'_{rms}$ are described in Figure 6. It is clear that the magnitude of $u'_{rms}$ for the staggered array was much lower than that for the other two walls whose differences are $5\sim10\%$. However, the differences are not significant in terms of $v'_{rms}$. As a result, the distribution of the turbulent statistics near-wall over the staggered array was less sensitive than that of the aligned one.

3.3. Probability Density Function. Figure 7 shows the streamwise and wall-normal fluctuation velocity of the near-wall TBL at $y^+ = 60$ and 120 in a period of 10 s and the calculated p.d.f. The p.d.f highlights the wide range of velocity fluctuations at the mean value. The solid line shows $y^+ = 60$ and the dashed line shows $y^+ = 120$ at the situation of $Re_\eta = 44,510$. The fluctuation velocity at a flow field point changes with time and can be seen as a series of discrete signal data, and the p.d.f. can be used to visualize the intensity of turbulence, thus obtaining the drag reduction merits of the wall TBL at $y^+ = 60$ and 120, but the image peak for $y^+ = 60$ is higher, which means that the ratio $\eta$ of the vortex quantity as the wall-normal height increases, where $\eta = N_{prograde vortex}/N_{retrograde vortex}$.

Most of the prograde and retrograde vortices within the inner layer of the TBL were confined to the upper and lower isolation zones, respectively,\textsuperscript{29} which indicates that there are vortex structures with the same velocity and opposite rotation direction as the hairpin vortex. Figure 8 shows the change in the vortex quantity ratio $\eta$ along the wall-normal direction at two different $Re_\eta$ values, indicated by the solid and dashed lines. Each curve peaks at $y^+ = 20\sim30$ near-wall and then decreases rapidly to around 2 at $y^+ = 80\sim90$ and then flattens out, finally reaching the balance of $\eta$. A large number of hairpin vortices are generated near-wall in the TBL, and the ratio $\eta$ even exceeds 10, due to the generation, development, and fragmentation of a large number of hairpin vortices. Obviously, the rough surface effectively reduces the ratio $\eta$, especially on the aligned case, where ratio $\eta$ decreases by nearly half at $Re_\eta = 18,000$ and by about a quarter for the staggered array. It is possible that the staggered case accelerates the development and the fragmentation process of hairpin vortices. After flow around a single rough element, the vortices start to be generated, and the vortex legs of the
swirling strength will climb upward along because of the rough element next row, reaching the faster outer flow and accelerating the fragmentation process. Furthermore, as the bulk Reynolds number $Re_b$ increases, the ratio $\eta$ decreases near-wall, while $\eta$ in the logarithmic region above $y^+ = 50$ is elevated significantly, especially in the staggered case. This phenomenon also fully indicates that the coherent structure of the wall is lifted by the staggered case. Wang et al.\(^{30}\) suggested that new hairpin vortices are generated with roughness units of the cylinder which leads to an increase in the number of downward vortices in the outer layer.

The vortex swirling strength $\lambda_{ci}$ can be identified by local velocity-gradient tensor $\nabla U$.\(^{31,32}\) To better reveal the embedded vortex structure introduced by roughness elements, the swirling strength for two-dimension is defined as follows:

$$\nabla U = \begin{bmatrix}
\frac{\partial U}{\partial x} & \frac{\partial U}{\partial y} \\
\frac{\partial V}{\partial x} & \frac{\partial V}{\partial y}
\end{bmatrix} = [V_x, V_y] \begin{bmatrix}
\lambda_{ci} & \lambda_{cj} \\
-\lambda_{ci} & \lambda_{cj}
\end{bmatrix}^{-1} [V_x, V_y]^T \tag{4}
$$

However, while the swirling strength $\lambda_{ci}$ is used for embedded vortex identification, it does not produce rotational significance. Thus, the local vorticity $\omega_{ci}$ is used to determine the direction of rotation as well. The corresponding expression is $\Lambda_{ci} \equiv \lambda_{ci} \cdot \omega_{ci}/|\omega_{ci}|$. Figure 9A presents the contour of instantaneous flow fields over staggered and smooth cases via swirling strength $\Lambda_{ci}$ in the streamwise-wall-normal ($x$-$y$) plane at $Re_b = 44,510$. Furthermore, Galilean decomposition of these instantaneous fields with advection velocity (0.8$U_{in}$ for smooth case and 0.75$U_{in}$ for staggered one) was applied to reveal the spanwise vortices in the region of the log-law layer ($0.1 < y/\delta < 0.3$) in Figure 9A. The Galilean decomposition is the most used method for uncovering the local vortex motion induced by the wall. Clearly, a number of prograde vortices (red in contour) with large structures were produced over smooth cases compared with the staggered one. Natrajan et al.\(^{33}\) pointed out that some of the prograde and retrograde vortices correspond to the same hairpin vortex while most of the single prograde vortices were obtained by the head of the hairpin vortex. As most of the prograde vortices were induced by the hairpin vortex, preliminary indication of the drag reduction effect of rough surfaces on coherent structures was achieved. Figure 9B shows the $p.d.f$ of the instantaneous swirling strength $\lambda'_{ci}$ ($\lambda'_{ci} = \lambda_{ci} - \lambda_{cj}$) in a period of 10 s at height $y^+ = 60$ (within the log-law layer). All three are normally distributed, and the peak of the staggered case was much larger than the other two cases, showing excellent stability. In combination of the result of the ratio $\eta$ above, roughness surface, especially the staggered case, weakens the coherent structure both in terms of swirling strength and population which is in favor of drag reduction efficiency.

Figure 10 shows the contour of instantaneous flow fields at $y^+ = 60$ over staggered and smooth cases via swirling strength $\Lambda_{ci}$ in the streamwise-spanwise ($x$-$z$) plane at $Re_b = 44,510$. The corresponding expression is given as $\Lambda_{ci} \equiv \lambda_{ci} \cdot \omega_{ci}/|\omega_{ci}|$. This surface is tangential to the vortex foot of the hairpin vortex, as is shown in Figure 9A, which reflects the distribution of coherent structures on the surface. The prograde (red) and retrograde (blue) vortices appear in pairs, indicating the presence of a hairpin vortex. The overall quantity of vortices is slowly decreasing through all the FOV in Figure 10.
obvious that the vortices over the rough case are much less than that over the smooth case at the streamwise position $x/\delta = 2$. Fewer vortex structures directly reflect a reduction in the quantity of hairpin vortices.

### 3.5. Two-Point Correlations

Marusic\(^3\)\(^4\) pointed out that the flow extension of the fluctuation velocity correlation coefficient was related to the distribution of coherent structures along the streamwise direction. The influence of the roughness surfaces on the coherent structures in the boundary layer can be represented by the two-point correlation calculations. Two-point correlations were calculated for each FOV. In the streamwise-wall-normal plane ($x$-$y$), the correlation at reference point $y_{ref}$ is defined as:

$$R_{uu}(y_{ref}) = \frac{\langle u'_i(x, y_{ref}) u'_j(x + \Delta x, y + \Delta y) \rangle}{\sigma_u(y_{ref})\sigma_u(y + \Delta y)}$$

(5)

where $u'_i$ and $u'_j$ are the fluctuation velocity in the streamwise ($\Delta x$) and wall-normal ($\Delta y$) direction separated at two locations, and $\sigma_u$ and $\sigma_{u_i}$ are the standard deviations with 20,000 vectors from PIV.

The contours of the two-point correlation $R_{uu}$ of smooth, aligned, and staggered cases with two reference points ($y_{ref} = 60, 120$) at $Re_b = 44,510$ are presented in Figure 11. The overall contours show some similarity that elongated in the streamwise direction with an inclination angle of $8^\circ$ to $12^\circ$ for $y_{ref} = 60$ and $12^\circ$ to $14^\circ$ for $y_{ref} = 120$. The inclination angle of hairpin vortices increases slowly as the height of the reference point increases which matches well with the reports of Coccal et al.\(^3\)\(^5\) and Marusic.\(^3\)\(^4\) It is obvious that although the inclination angle of staggered cases reaches the smallest, the scope of the green section ($R_{uu} > 0.3$) over staggered cases is significantly larger than the other two cases. Hence, it appears that the impact of the roughness array became more regular in the streamwise direction.

Figure 11 shows streamwise and wall-normal slices through the reference point $y_{ref} = 60, 120$. All curves are decreasing from the reference point $R_{uu} = 1$ to the sides. Clearly, among the flow curves, the curves over the staggered cases decrease most slowly which is also shown by the large green areas in Figure 10. The lower value (red triangles in Figure 11) caused by the aligned cases may result from the destruction of the near-wall streaks by roughness elements both in the streamwise and wall-normal direction.

Contours of the two-point correlation $R_{uu}$ of smooth, aligned, and staggered cases with two reference points ($y_{ref} = 60$) at $Re_b = 44,510$ are presented shown in Figure 12A. The
spanwise slices through the reference point are also presented in Figure 12B. All slices first decrease along the spanwise distance, then increase at \( z/\delta = 0.4 \), reaching a second correlation peak at about \( z/\delta = 0.8 \). The extent \( L_{zz} \) from the first peak to \( R_{uu} = 0 \) is slightly larger for smooth cases than for rough ones where less than 10% difference was achieved. The results are in good agreement with the rough-wall \((k/\delta = 0.0114)\) result of Volino et al.36

4. CONCLUSIONS

To summarize, PIV measurement was undertaken with different perspectives over smooth and BSCP samples to investigate the effects of arrangement (aligned and staggered) of roughness elements and bulk Reynolds numbers \((Re_b = 37,091, 44,510)\) on the drag reduction and coherent structure. Mean flow profiles show that the roughness function \( \Delta U' \) is \(0.05 \sim 0.11\) for \( Re_b = 37,091 \) and \(-0.23 \sim -0.2\) for \( Re_b = 44,510 \). The negative value of \( \Delta U' \) suggested that the drag reduction effect was achieved at a higher \( Re_b \). The Reynolds shear stress \(<u' v'>\) over BSCP samples achieved a lower position than the smooth case while increasing significantly in the outer layer at \( y^+ = 120 \).

The turbulent kinetic energy \(<u'^2 + v'^2>\) is much smaller over BSCP samples and the staggered case is better which indicates that strong fluctuation at the streamwise direction was achieved over the aligned case. The magnitude of turbulent intensity \( u'_{rms} \) was 5~10% lower at the staggered case than in the other two surfaces. \( y^+ = 60 \) and 120 are higher over the staggered case, which means the suppression of turbulent pulsations is better in the staggered case than in the aligned case. Furthermore, the vortex swirling strength \( \lambda_2 \) and Galilean decomposition revealed that a number of prograde vortices with large structures were produced over smooth cases compared with BSCP samples. However, the variable spacing scale and geometry of cone roughness were also significant factors; thus, the drag reduction mechanism of BSCPs still remains to be further revealed in our future work.

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Notes
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