Flow control of circular cylinder with a V-grooved micro-riblet film

Sang-Joon Lee\textsuperscript{a}, Hee-Chang Lim\textsuperscript{b,\ast}, Manhee Han\textsuperscript{a}, Seung S. Lee\textsuperscript{a}

\textsuperscript{a}Department of Mechanical Engineering, Pohang University of Science and Technology, Pohang 790-784, Korea
\textsuperscript{b}School of Engineering Sciences, University of Southampton, Highfield, Southampton, SO17 1BJ, UK

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Abstract

Flow structure around a circular cylinder with a V-grooved micro-riblet is investigated experimentally. The results are compared with that of a smooth cylinder having the same diameter. A flexible V-shaped micro-riblet with peak-to-peak spacing of 300 μm is made using a MEMS fabrication process of PDMS (Polydimethylsiloxane) replica. The flexible micro-riblet is attached on a circular cylinder with which grooves are aligned with the streamwise flow direction. Drag force acting on the cylinder is measured for Reynolds numbers based on a cylinder diameter ($D = 18$ mm) in the range $Re_D = 2.5 \times 10^3$–$3.8 \times 10^4$. At $Re_D = 3.6 \times 10^3$ ($U_0 = 3$ m/s), the V-grooved micro-riblet cylinder reduces drag coefficient by 7.6%, compared with a cylinder with smooth PDMS surface. However, it increases drag coefficient about 4.2% at $Re_D = 3.6 \times 10^4$ ($U_0 = 30$ m/s). Flow field around the micro-riblet cylinder is measured by using a 2-frame PIV velocity field measurement technique. Several hundreds instantaneous velocity fields are ensemble-averaged to get the spatial distributions of turbulent statistics including turbulence intensities and turbulent kinetic energy. For the case of drag reduction at $Re_D = 4.8 \times 10^3$, the vortex formation region behind the V-grooved MRF cylinder is reduced about 10%, compared with the smooth cylinder due to enhanced entrainment of ambient inviscid fluid into the wake region. In addition, the total number of secondary vortices located inside the near wake region is decreased about 20%.

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1. Introduction

Since the global “energy crisis” of the 1970s, drag reduction has received a great deal of attention in a variety of engineering applications. Recent advances in microfabrication and active feedback control have made it possible to reduce drag force and acoustic noise by means of artificial manipulations. Because drag reduction is closely related to energy saving, extensive efforts have been made over recent decades to reduce the drag acting on moving vehicles.

In order to reduce the drag force acting on a bluff body, it is necessary to accurately predict and effectively control the flow around the body. The drag acting on a body can be reduced by changing the near-wall flow structure, especially the coherence structure (Cantwell, 1981; Robinson, 1991). Although flow control for drag reduction is very important in practical engineering applications and basic research, there are still many problems to be solved in this area.

There are two types of flow control technique: active and passive. Active flow control methods require an energy input; for example, suction or blowing to delay transition, modification of fluid viscosity with polymers, or changing fluid temperature. On the other hand, passive control methods modify the flow structure by changing the surface configuration or by attaching additive devices such as riblets or large Eddy breakup devices (LEBU) onto the main body (Gad-el-Hak, 1989). Passive control methods are cost-effective because they do not require additional energy input. The installation of riblets with longitudinal grooves on surfaces is well known as an effective flow control technique that reduces drag and enhances heat transfer (Gad-el-Hak, 1989). However, the performance of this technique is very sensitive to the groove configuration.

Walsh (1983) investigated the drag reduction achieved by installing longitudinal ribs on a flat surface for various rib shapes. He found that the drag reduction was associated with a decrease of momentum thickness and turbulent velocity fluctuations, and depended mainly on the configuration of the ribs as determined by parameters such as the height \( h \), spacing \( s \) and shape. He obtained a maximum of 8% drag reduction for a symmetric V-groove surface of depth \( h^+ < 25 \) and spacing \( s^+ < 30 \) (\( h^+ \) and \( s^+ \) are dimensionless parameters in wall units). He found that the riblet with sharp peaks is among the best riblet shapes for drag reduction.

Bacher and Smith (1985) observed that the spacings between adjacent streaks formed above riblet surfaces are wider than those above a flat plate, and that the flow within the riblet valleys is slow and quiescent. They conjectured that the secondary vortices at the riblet tips weaken the streamwise vortices and inhibit the spanwise movement of streaks, thereby restricting momentum exchange in the lateral direction. Bechert and Bartenwerfer (1989) found that the sharp ridges of the riblets impede cross-flow in the viscous sublayer and that the presence of riblets decreases turbulent momentum exchange in the boundary layer, reducing the wall shear stress.

Choi (1989) investigated the near-wall structure over smooth and grooved surfaces. He found that the restriction of spanwise movement of longitudinal vortices was a key mechanism for drag reduction over riblet surfaces. Park and Wallace (1994) used a miniature hot-wire probe to measure streamwise velocity profiles over a flat surface with V-shaped riblet grooves of \( h^+ = 14 \) and \( s^+ = 28 \). They obtained about 4% drag reduction and showed that the riblets reduced the vertical flux of streamwise momentum within the riblet valleys. Recently, Lee and Lee (2001) investigated the near-wall turbulence structure over riblets with semi-circular grooves for the drag-decreasing \( (s^+ = 25.2) \) and drag-increasing \( (s^+ = 40.6) \) cases. They measured 1000 consecutive instantaneous velocity fields over the semi-circular riblets using a particle image velocimetry (PIV) velocity field measurement technique and ensemble-averaged them.
to extract the spatial distributions of the turbulence statistics. To investigate the effect of riblet surfaces on the flow around a bluff body, Ko *et al.* (1987) and Leung and Ko (1991) measured the mean pressure distribution and Strouhal number for several V-groove circular cylinders. They found that the V-groove and smooth cylinders had almost the same drag coefficient when the hydraulic diameter was used.

In a numerical study, Chu and Karniadakis (1993) simulated channel flow over riblets using a spectral element Fourier method. They found that riblets numerically inhibit the spanwise motion of the low-speed wall streaks, leading to a decrease in ejection events. Choi *et al.* (1991) carried out direct numerical simulations of the instantaneous turbulent structures over V-shaped riblets with \( s^+ = 20 \) and 40. For the drag increasing surface \( (s^+ = 40) \), streamwise vortices of about 30 wall units in diameter move freely inside the riblet valleys. At \( s^+ = 20 \), however, most of the streamwise vortices stay above the riblets, leading to drag reduction.

The height and spacing of the riblet grooves must be optimized to reduce drag effectively. Walsh (1983) suggested the optimized riblet height is about 76 \( \mu \)m at a cruise altitude of 12.2 km, a Mach number of 0.8 and a Reynolds number of \( 10^6 \). However, most previous studies have employed macro-scale riblets because of the difficulties associated with fabricating micro-scale riblet grooves. Simple dimensional analysis shows that the size of riblets used for practical applications such as automobiles and airplanes should be less than several hundred micrometers. 3M Company developed a flexible micro-riblet film made of polyvinylidene fluoride that can be prepared using conventional plastic rolling or casting processes (Marentic and Morris, 1992). However, the 3M micro-riblet film is not commercially available, even for the purposes of academic basic research. Caram and Ahmed (1991) applied the micro riblets of \( s = 23–152 \) \( \mu \)m to an airfoil and obtained drag reduction of 2.7–13.3%. In their products, however, the surface of micro-riblet is contaminated and peaks of the riblet are a little blunt.

Despite the importance of flow control as a way to reduce drag in practical engineering applications, the wake structures behind bluff bodies modified with riblet grooves are still not fully understood. From an aerodynamic viewpoint, it is also important to investigate the modification of the wake structure by the micro-riblet surface in order to effectively control the cylinder wake.

In the present study, we experimentally investigate the near wake structure and drag properties of circular cylinders with V-shaped micro-riblet grooves and compare these properties with those of smooth cylinders under the same conditions. A flexible micro-riblet film (MRF) is fabricated from a silicon wafer using a micro-electro-mechanical system (MEMS), and the pattern is replicated using a polydimethylsiloxane (PDMS) micro-molding technique. The drag forces acting on the cylinders with and without MRFs are directly measured by using a precise load-cell and the velocity fields behind cylinders are acquired by using a 2-frame PIV velocity field measurement technique in a subsonic wind tunnel.

2. **Experimental apparatus and method**

2.1. *Fabrication of the micro-riblet film*

The mold of a V-grooved micro-riblet is fabricated using anisotropic etching technique (Waggener, 1970). When a (1 0 0) silicon wafer is etched with anisotropic etchants, V-grooves with a base angle of 54.74° formed on the wafer surface. Two hundred V-grooves are formed on a wafer of dimensions 6 cm \( \times \) 6 cm, as shown in Fig. 1. The height of each groove is 180 \( \mu \)m and the spacing between grooves is 300 \( \mu \)m. In general, it is difficult to prepare an array of uniform microstructures over such a large area. For
example, misalignment between the patterns on the ultra-violet (UV) mask and the crystal lines of silicon wafer, as well as dislocations or impurities on the silicon wafer, can cause defects in the grooves. To minimize such groove defects, we use a high-quality premium grade silicon wafer and pay great attention to the process of aligning the UV mask and silicon wafer. To make an MRF, the grooves on the silicon mold are replicated using a PDMS micro-molding technique. The resulting MRFs have sharp peaks and are flexible enough to attach onto a curved surface (Jo et al., 2000).

Fig. 2 shows a schematic flow diagram of the MRF fabrication process. A thermal silicon oxide layer of thickness 1 μm is grown on a (1 0 0) silicon wafer. After patterning the front side of the oxide layer, the silicon is bulk etched in 20 wt% TMAH at 90 °C for about 7 h to form the V-grooves. The next step is the removal of the remaining oxide layer. The patterned surface of the silicon mold is silanized by exposure to a small amount of Trichloro (3,3,3 tri-fluoropropyl) silane for 8 h in a desiccator to remove undercut of the oxide layer. This procedure facilitates the peeling-off of the completed MRF from the silicon surface. PDMS prepolymer and curing agent are mixed in a 10:1 weight ratio and degassed in a desiccator until no gas bubbles remain in the mixture. The degassed mixture is then poured onto the mold and a polyester film of thickness 380 μm is placed on the border to determine the thickness of the flat base of the MRF. After removing gas bubbles generated in the pouring process, another thin film is carefully placed onto
the mixture to prevent the formation of gas bubbles at the interface and a metal weight is placed on the film, as shown in Fig. 2(g). The film facilitates the removal of the metal weight from the cured PDMS layer. The PDMS mixture is cured for 2 h at 85 °C in an oven. Finally, a thin PDMS replica, the flexible micro-riblet film, is peeled off the mold. Additional MRFs of the same configuration can be fabricated by repeating the molding processes illustrated in Figs. 2 (e) through (h) for about 3 h, without the silanization process. Fig. 3 shows the photos of the fabricated silicon mold and a replicated MRF.

2.2. Experimental set-up and flow measurement system

Cylinder flow experiments are carried out in a closed-return-type subsonic wind tunnel with a test section of 15 cm wide, 15 cm high and 1.8 m long. The free stream turbulence intensity in the test section is less than 0.1% at the free stream velocity of $U_0 = 7$ m/s. The Reynolds number based on the cylinder diameter ($D = 18$ mm) is varied over the range $Re_D = 2.5 \times 10^3$–$3.8 \times 10^4$.

Two circular cylinders of equal diameter ($D = 18$ mm) with different surface configurations are tested in this study. One cylinder is wrapped with a smooth PDMS surface (base thickness $= 340 \mu$m) and the other cylinder is covered with an MRF with longitudinal V-grooves (base thickness $= 230 \mu$m) made of
the same PDMS material. The main cylinder is a glass pipe of length $L = 200$ mm. Several MRFs are anodically bonded to the glass cylinder to cover the entire surface. A schematic diagram of the V-grooved micro-riblet cylinder and coordinate system used in this study are shown in Fig. 4.

A rectangular end-plate of thickness 1 mm is installed at the end of the cylinder model to minimize the development of a boundary layer along the tunnel sidewalls and to maintain two-dimensional flow characteristics (Stansby, 1974). The formulas of Allen and Vincenti (1944) are employed to correct the measured flow velocity and pressure data taking account of the blockage ratio and wall interference effects due to presence of the cylinder model.
For measuring the drag force acting on the cylinder, a load-cell is attached at the end of the cylinder model. In addition, a concentric hollow dummy cylinder is installed at another side-wall of the wind tunnel test section to avoid three-dimensional flow interferences acting on the cylinder. The aerodynamic forces are measured using a 3-component load-cell (Nissho LMC-3502) whose nonlinearity is less than ±0.5% in the full range. The load-cell is coupled with a DC strain amplifier (DSA-100) connected to an A/D converter (DT2838). The drag coefficient based on the effective frontal area ($A$) of the cylinder model is defined as follows:

$$C_D = \frac{2 \times \text{Drag}}{\rho U_0^2 A}. \tag{1}$$

Instantaneous velocity fields in the wake behind the cylinder model are measured using a high-resolution 2-frame PIV system. The PIV system consists of a two-head Nd:Yag laser, a 2k × 2k Kodak CCD camera, a frame grabber, a delay generator and an IBM PC, as shown in Fig. 5. The maximum energy of the pulse laser is greater than 25 mJ per pulse. Since the two-head Nd:Yag laser pulse has a short pulse width of about 7 ns, the highly turbulent eddy motions can be clearly captured in the images. A delay generator is used to synchronize the Nd:Yag laser and 2k × 2k CCD camera. This delay generator controls the
time interval $\Delta t$ between consecutive frames. During the time interval $\Delta t$, some particles move into and others move out of the laser light sheet. Therefore, the time interval $\Delta t$ depends mainly on the maximum particle displacement in the interrogation window. The laser light sheet used in the experiments has a thickness of about 4 mm. Details of the 2-frame PIV velocity field measurement system and its accuracy are described in Lee (2001).

PIV measurements are carried out at two planes: (i) the longitudinal $(x, z)$ plane just behind the cylinder, to obtain plane view information; and (ii) the sagittal cross-section $(y, z)$ plane at the downstream location of $x/D = 3$. A steering mirror is installed at the location $x/D = 10$, through which particle images in the sagittal plane are captured. For each measurement plane, the mean velocity field is obtained by ensemble-averaging 500 instantaneous velocity fields. The vorticity is calculated using the following discretization equation (Raffel and Kompenhans, 1996):

$$\omega_x = \frac{1}{2} \left( \frac{\partial W}{\partial y} - \frac{\partial V}{\partial z} \right) \approx \frac{1}{2} \left( \frac{2W_{i+2,j} + W_{i+1,j} - W_{i-1,j} - 2W_{i-2,j} - 2V_{i,j+2} + V_{i,j+1} - V_{i,j-1} - 2V_{i,j-2}}{10\Delta y} \right).$$

The turbulence kinetic energy $k$ for isotropic flows is evaluated using the following equation (Ciocan et al., 2000):

$$k = \frac{1}{2} \rho (\bar{u}^2 + \bar{v}^2 + \bar{w}^2) \approx \frac{3}{4} \rho (\bar{v}^2 + \bar{w}^2).$$

Due to the assumption of isotropic flow structure, the real turbulence kinetic energy may differ slightly from the present results in the regions of non-isotropic three-dimensional flow structure.

2.3. Uncertainty analysis

Uncertainty analysis is carried out on the results of drag measurement to assess their confidence level, following the method suggested by Coleman (1989). The total error consists of bias error and precision error. The bias error can be minimized by careful calibration of the measuring instruments.

The $t$-distribution, a theoretical probability density distribution used to obtain a certain level of confidence in small number of samples (Bendat and Piersol, 1971), is applied for statistical analysis. To evaluate the precision error, the standard deviation of five independent sample records is calculated for the velocity and force data measured for each cylinder. In this study, the value of the $t$-distribution for 95% confidence with five samples is 2.776. The error for the drag coefficient $C_D$ is estimated to be less than 1.3% with 95% confidence level.

3. Results and discussion

3.1. Drag force

Ko et al. (1987) reported that the transitions from subcritical to critical regimes occur at lower Reynolds numbers for the V-grooved cylinder than for the smooth cylinder. In the results presented here, however, although the flow regime does not reach the critical Reynolds number, the drag coefficients for the two cylinder types show different variations with respect to the Reynolds number.
Fig. 6 shows the variation of the drag coefficient with increasing Reynolds number. Also shown in this figure (depicted as a bar chart) is the relative drag reduction effect of the micro-riblet cylinder with respect to the smooth cylinder. The drag coefficient of the smooth PDMS cylinder gradually decreases up to a Reynolds number of $9 \times 10^3$, above which it remains almost constant at a value of around 1.1 with increasing Reynolds number. The drag coefficient of the MRF cylinder shows a trend different to that of the smooth cylinder. As the Reynolds number increases beyond $Re_D = 1 \times 10^4$, the drag coefficient of the MRF cylinder gradually increases.

Walsh (1983) found that riblet grooves constrain the oscillations and growth of low-speed streaks, and reduce the total drag at lower flow speeds. This indicates that the height of the riblets is important in drag reduction and the increase of riblet spacing decreases the effect of drag reduction. As the velocity increases, therefore, the riblet size in terms of wall unit increases and becomes not effective in drag reduction.

In the present study, the V-grooved MRF reduces the drag coefficient by about 7.6% at $Re_D = 3.6 \times 10^3$, in comparison to the cylinder with the smooth PDMS surface. However, at $Re_D = 3.6 \times 10^4$ the presence of the riblets increases the drag coefficient by about 4.2%. To investigate the flow structure around the micro-riblet surfaced cylinder, the velocity fields are measured at the near wake using 2-frame PIV.

3.2. Ensemble-averaged mean velocity fields (side view)

PIV is used to measure the velocity fields in the flows behind circular cylinders with and without the V-grooved MRF. To investigate the wake structure at lower and higher Reynolds numbers, the experiments are carried out at two free-stream velocities, $U_0 = 4$ and 12 m/s. The drag coefficient variations at the corresponding Reynolds numbers based on the cylinder diameter ($D = 18$ mm) are a 5.1% drag reduction at $Re_D = 4.8 \times 10^3$ and a 0.4% drag increase at $Re_D = 1.4 \times 10^4$, respectively. For each experimental condition, 500 instantaneous velocity fields are obtained. These fields are ensemble-averaged to extract the spatial distributions of the vorticity and turbulence kinetic energy. In general, the contours of the vorticity and turbulence statistics measured in the longitudinal $(x, z)$ plane are symmetric with respect
to the wake centerline ($z/D = 0$), irrespective of the freestream velocity and the presence of micro-riblet grooves.

Fig. 7 compares the streamlines tangent to the velocity vectors measured at the cylinder mid-section for the two cylinder types. The arrows denote the vortex formation region formed behind the cylinders. The vortex formation region extends up to $x/D = 3.8$ and 3.4 for the smooth and MRF cylinders, respectively. Thus, the MRF V-grooves work to reduce the region by about 10% in size.
Fig. 8 shows contour plots of the spanwise vorticity ($\omega_y$) in the longitudinal $(x, z)$ plane for the smooth and MRF cylinders. The arrows inside the figure designate the spreading direction of large-scale vortex in the near wake region. The spanwise vorticities at the side edges of the cylinders show large magnitudes and opposite signs due to the formation of large-scale vortices. It is seen that the spanwise vortices behind the MRF cylinder tend to remain inside the formation region and concentrate toward the wake center ($z/D = 0$) compared with those behind the smooth cylinder.

Figs. 9 and 10 show the streamlines and spanwise vorticity contours in the same longitudinal plane at $U_0 = 12$ m/s ($Re_D = 1.4 \times 10^4$). Unlike the drag reduction case at $Re_D = 4.8 \times 10^3$, the streamlines show that the MRF V-grooves elongate the vortex formation region about 15% at $Re_D = 1.4 \times 10^4$ ($x/D = 2.4$ for smooth cylinder and 2.8 for MRF cylinder).
Fig. 9. Streamlines in the longitudinal \((x, z)\) plane at \(Re_D = 1.4 \times 10^4\): (a) smooth cylinder; (b) MRF cylinder.

Increasing the freestream velocity reduces the size of the large-scale vortices for both the smooth and MRF cylinders (compare Figs. 8 and 10). At the higher Reynolds number, for which the drag is 0.4% higher for the riblet-surfaced cylinder, the V-grooves of the MRF cylinder cause a slight elongation of the contours of the spanwise vorticity \(\omega_z\) in the near-wake, compared with the smooth cylinder.

From these results, we can see that the formation region seems to be closely related with the wake flow behind the cylinder. At the lower Reynolds number in particular, it is judged that 10% contraction of separation bubble behind the MRF cylinder increases the base pressure and reduces the drag acting on the cylinder.
3.3. Ensemble-averaged mean velocity fields (saggital plane view)

Figs. 11 and 12 show the ensemble-averaged turbulent kinetic energy distributions measured in the cross-sectional sagittal plane at the downstream location of \(x/D = 3\) for \(Re_D = 4.8 \times 10^3\) and \(1.4 \times 10^4\). For the drag reduction case of \(Re_D = 4.8 \times 10^3\), the cross-sectional views reveal the three-dimensional flow structure induced by the secondary longitudinal vortices shed from a cylinder. The high-intensity turbulent kinetic energy widely occupies in the central region behind the smooth cylinder. However, compared with the smooth cylinder case, the equivalent high-intensity turbulent kinetic energy region is relatively reduced and shows equidistance peaks of about \(y/D = 2\) along the spanwise direction. This
flow behavior may be attributed to the suppression of the formation of secondary vortices in the region just behind the V-grooved MRF cylinder; the secondary vortices seem to be broken into smaller eddies by the sharp peaks of the longitudinal V-shaped grooves. This is consistent with observation that at this Reynolds number the drag coefficient of the MRF cylinder is lower than that of the smooth cylinder.

Fig. 12 shows the cross-sectional view of the ensemble-averaged turbulent kinetic energy distribution for the case of drag increase at $Re_D = 1.4 \times 10^4$. The results are opposite to those obtained at the lower Reynolds number of $Re_D = 4.8 \times 10^3$. For the V-grooved MRF cylinder, the high-intensity turbulent kinetic energy region appears in the central region of the near wake, compared with the smooth cylinder.
The growth of turbulence fluctuations in the central region just behind the vortex formation region seems to be closely related to a reduction of eddy size, even smaller than the riblet spacing ($s = 300 \mu m$), as a result of the higher Reynolds number. This indicates that the MRF riblet grooves do not suppress the formation of secondary vortices, but rather enhance flow separation from the cylinder surface. In other words, for the case of drag reduction at $Re_D = 4.8 \times 10^3$, the near wake is relatively little disturbed by riblet grooves and the high-intensity kinetic energy is reduced behind the cylinder. On the other hand, at a higher Reynolds number, the oncoming flow interacts actively with longitudinal grooves of micro-riblet, increasing the drag coefficient and turbulent kinetic energy.

Figs. 13 and 14 show the spatial distributions of the vertical velocity component ($W$) in the cross-sectional plane at $x/D = 3$ measured at $Re_D = 4.8 \times 10^3$ and $1.4 \times 10^4$. Here, $W_0$ is the averaged...
maximum vertical velocity measured in the free stream. The vortices shed from the two side edges of each cylinder cross the wake center axis at the end of the vortex formation region. At $Re_D = 4.8 \times 10^3$, the vertical velocity has positive and negative values in the lower and upper wake regions, respectively, indicating that the flow moves toward the wake center region. The contour shapes are roughly symmetric with respect to the wake centerline $z/D = 0$. Compared with the smooth cylinder, the vertical velocity component of the MRF cylinder has larger values and shows spanwise variation in the wake region. This indicates that the MRF micro-grooves enhance the entrainment of inviscid flow into the wake behind the cylinder for the case of drag reduction.

At the Reynolds number for which the drag is higher on the MRF cylinder than on the smooth cylinder, however, the magnitude of the vertical velocity is a little reduced and shows an almost uniform distribution

Fig. 13. Spatial distributions of vertical velocity component ($W$) in the cross-section at $x/D = 3$ ($Re_D = 4.8 \times 10^3$): (a) smooth cylinder; (b) MRF cylinder.
in the wake center region. One reason for this is the measurement section at $x/D = 3$ which is located a little behind the formation region as shown in Fig. 9. However, the smooth cylinder has larger vertical velocity values than the MRF cylinder at the same flow speed. In addition, the spanwise variation of the vertical velocity component is less clear in the wake center region.

From these experimental results, we can see that the MRF V-grooves enhance the entrainment of inviscid flow into the wake region for the case of drag reduction at lower Reynolds numbers.

3.4. Distribution of vorticity centers

We are measuring only the stream-wise vorticity component, $\omega_x$, in the sagittal plane at $x/D = 3$. When the local maximum vorticity is larger than a present threshold value (Lim and Lee, 2003), we assume that
this position might correspond to the center location of longitudinal vortices. Although it is impossible
to pick up the longitudinal vortices completely in ordinary experiments at this stage, we would like to emphasize the difference between the smooth and MRF cylinders.

The results obtained from 500 consecutive instantaneous velocity fields are shown in Figs. 15 and 16. The central gray area denotes the projection of the cylinder \((-0.5 < z/D < 0.5)\). In the cross-sectional sagittal \((yz)\) plane behind the smooth cylinder, the local maximum vorticities are almost uniformly distributed. For the case of 5.1% drag reduction at \(Re_D = 4.8 \times 10^3\), the total number of the vortices \((N = 398)\) behind the MRF cylinder is about 20% smaller than the smooth cylinder \((N = 478)\). The reduction in the number of longitudinal vortices by the MRF V-shaped grooves is particularly pronounced.
in the wake center region, as shown in Fig. 15(b). This may be due to the suppression of the formation of secondary vortices behind the V-grooved micro-riblet cylinder along with the disruption of the large-scale secondary vortices and longitudinal vortices into smaller eddies by the sharp peaks of the longitudinal V-shaped grooves. Fig. 15 shows the differences in the vortex structures in the near wake region of the smooth and MRF cylinders.

For the Reynolds number at which the drag of the MRF cylinder has higher than that of the smooth cylinder (Fig. 16), the general distribution pattern is similar for the two cylinder types. However, the number of the local maximum vortices identified for the MRF cylinder ($N = 1214$) is somewhat greater
than for the smooth cylinder \((N = 1038)\). These results are consistent with the vorticity contours and turbulent kinetic energy distributions discussed in previous sections.

From these results, at a low Reynolds number for which the drag is decreased, on average, the size of the streamwise vortices formed above the cylinder surface seems to be relatively larger than the riblet spacing. On the other hand, for the case of drag increasing, the streamwise vortices are very active, and most of them would be located near the riblet surface. In addition, the size of longitudinal vortices must be relatively smaller than the riblet spacing between two adjacent grooves, which means that the streamwise vortices can penetrate into the riblet valleys, and contact directly with the riblet surface. This increases the friction and drag on the surface.

4. Conclusions

The detailed flow structure of the wake behind a circular cylinder with a micro-riblet surface is investigated experimentally. A flexible micro-riblet film with V-grooves of peak-to-peak spacing 300 \(\mu\)m is made using a MEMS fabrication process of PDMS replicas. To examine the flow characteristics behind the micro-riblet cylinder, the drag force is measured and ensemble-averaged mean velocity fields are obtained using the 2-frame PIV velocity field measurement technique.

The results are summarized as follows: Firstly, the micro-riblet film (MRF) fabricated using a PDMS micro-molding technique has V-shaped micro-grooves with sharp peaks and is sufficiently flexible that it can be attached to a curved surface. Secondly, the V-grooved MRF cylinder reduces the drag coefficient at low Reynolds numbers (maximum reduction of 7.6% at \(Re_D = 3.6 \times 10^3\)), compared with the cylinder with a smooth PDMS surface. However, at higher Reynolds numbers the MRF surface increases the drag coefficient (maximum increase of about 4.2% at \(Re_D = 3.6 \times 10^4\)). Thirdly, for the drag reduction case at \(Re_D = 4.8 \times 10^3\), the turbulent kinetic energy in the near wake region behind the MRF cylinder has relatively small values, compared with the smooth cylinder. The size of the vortex formation region behind the V-grooved MRF cylinder is about 10% reduced, compared with the smooth cylinder due to enhanced entrainment of ambient inviscid fluid into the wake region. In addition, the near wake is relatively little disturbed by riblet grooves and the kinetic energy is reduced behind the cylinder. On the other hand, at a higher Reynolds number, the oncoming flow interacts actively with longitudinal grooves of micro riblet, increasing the drag coefficient and turbulent kinetic energy. Fourthly, the total number of longitudinal vortices behind the V-grooved riblet cylinder is smaller than the number behind the smooth cylinder; the reduction of longitudinal vortices in the wake region is particularly dominant. Finally, in the cross-sectional sagittal plane at \(x/D = 3\), near the end of the vortex formation region, the high-intensity turbulent kinetic energy for the MRF cylinder is relatively reduced and slightly greater spanwise variation at \(Re_D = 4.8 \times 10^3\), compared with smooth cylinder. This flow behavior may be due to the suppression of the formation of secondary vortices in the region just behind the V-grooved MRF cylinder, the secondary vortices seem to be broken into smaller eddies by the sharp peaks of the longitudinal V-shaped grooves.

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