Passive control on flow structure around a wall-mounted low aspect ratio circular cylinder by using an inclined hole

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Abstract
To control and reduce the rear separation region and the vortex of the free-end surface, a passive flow control method that is to use an inclined flow controlling hole (FCH) passing through the free-end surface to the side of the rear surface was proposed for a low aspect ratio (=1) circular cylinder. The high-speed PIV (Particle Image Velocimetry) measurements were performed at Reynolds number of 8,570 in a circulation water tunnel in order to compare the flow characteristics between the controlling and no-controlling wakes. Furthermore, to study the position effect of the FCH, there kinds of the FCH models were tested. It was found that the fluid flows from the large rear recirculation zone upwards to the small recirculation zone on the free end surface through the FCH. The size of rear recirculation zone was reduced by the FCH cylinders with \( h = 50 \) mm, and the FCH cylinders with \( h = 20 \) and 35 mm effectively diminished the separation region of the free end surface. Meanwhile, vorticity, Reynolds shear stresses and turbulent kinetic energy were also decreased by the FCH cylinders with \( h = 50 \) mm comparing with the standard cylinder and other FCH models. Spectral analyses suggest that the dominate frequency of vortex shedding from the cylinder surface increases.

Key words : Flow controlling hole, Passive control, PIV, Low aspect ratio cylinder, Vortex, Wake, Wavelet transform

1. Introduction
The flow around a finite-length circular cylinder causes a strongly three-dimensional complex flow field, and the aspect ratio of the cylinder influences the flow structure, which is different from “infinite” structure (Rinoshika and Zhou, 2005, 2009), due to the effect of the circular cylinder’s free end (or tip) and the cylinder-wall junction (Sumner et al., 2004; Pattenden, 2005; Wang and Zhou, 2009; Goncalves et al., 2015). It is important for many engineering applications, such as offshore structures, buildings, chimney stacks, heat exchanger, automobile and so on. Until now the three-dimensional flow structures around a finite-length circular cylinder have been well studied, consisted mainly of Kármán vortex shedding from the sides of the cylinder, the horse shoe vortex (called necklace vortex or base vortices) forming near the ground plane of the cylinder-wall junction (Tanaka and Murata, 1999; Sumner et al., 2004) and streamwise counter-rotating vortex pairs (called trailing vortices) originating from the free end (Kawamura et al., 1984a; Johnston and Wilson, 1996; Adaramola et al., 2006). However, the wake structures generated by a low aspect ratio circular cylinder are characterized by tip-vortices (Okamoto and Yagita, 1973; Kawamura et al., 1984b; Roh and Park, 2003) and a horse shoe vortex (Krajnović, 2011; Rostamy et al., 2012), in which alternating vortex shedding, i.e., Kármán street, does not present. In the case of a very low aspect ratio cylinder, “arch-type vortex” formation appeared in the near-wake region (Lee, 1997) since flow separating from the free-end surface becomes contiguous with the vortices shedding from the sides before reattaching. The detailed reviews on finite-height cylinder can be found in Sumner (2013) and Porteous et al. (2014).

However, fundamental works about controlling VIV (Vortex-induced vibration) of low aspect ratio cylinders are few in the literature, which is of practical interest of many fields in engineering, such as reducing drag, lift and noise in
designing automobile, structural vibrations, heat exchangers, offshore structures and so on. Although some flow control techniques of the boundary layer, such as suction, blowing, splitter plate and surface roughness elements, have been well studied in “infinite” structure (Choi et al., 2008), less research focus on the control of vortices in the rear recirculation region and vortex appearing on the free end surface around a low-aspect-ratio cylinder, which motivates the present investigation. In generally, the main purpose of the flow control is to destroy or decrease the occurrence of vortices or the separation region behind the cylinder. Until now, active and passive control techniques have been performed to control the flow around a bluff body. The passive control technique is easier to apply and modify a flow structures without external energy expenditure (New et al., 2015). Therefore, this study focused on the passive flow control of a low-aspect-ratio cylinder (Sumner et al., 2004; Pattenden, 2005).

To control and reduce the rear separation region of cylinder and the vortex on the free-end surface, the present study first proposed a passive control method, in which a flow controlling hole (FCH) passing from the free-end surface to the side of the rear surface is made to generate both suction and blowing flows. Then the controlling wake structures of the low aspect ratio circular cylinder mounted normal to a ground plane were measured by PIV in a circulation water tunnel. The mean streamlines, mean velocity components, mean vorticity, Reynolds shear stresses, turbulent kinetic energy and the instantaneous flow structures were examined and compared between the controlling and non-controlling cylinders. Finally, the spectral analysis and continuous wavelet transform were used to reveal multi-scale flow structures.

2. Experimental details

A three-dimensional standard circular cylinder model, as shown in Fig. 1(a), having an aspect ratio $H/D = 1$ with height $H$ and diameter $D$ of 70 mm, is mounted on a flat plate. The $x$, $y$, and $z$ axes indicate the streamwise, transverse and spanwise directions, respectively. To control the flow structures, a hole with a diameter of $d = 10$ mm ($d/D = 0.14$), called the flow controlling hole (FCH), is made from the free-end surface to the side of the rear surface. For studying the effect of the FCH position, three kinds of the FCH models, which vary the central positions of the FCH on the side of the rear surface $h = 20$, 35 and 50mm ($h/D = 0.29$, 0.5, 0.71) and fix the central position of the FCH on the free-end surface at $L = 30$mm (Fig. 1(b)). Here the central line of the FCH lies in the $(x, z)$-plane of $y = 0$.

The circulating water tunnel that has turbulence intensity of less than 5% was used, and the experiment was performed at a constant free stream velocity of $U = 0.16$ m/s corresponding to Reynolds number $Re (\equiv UD/\nu) = 8,570$. The PIV tracer (polystyrene) particles of an averaged diameter 68 µm were used. A high-intensity laser light sheet with a thickness of 1.0 mm was employed to illuminate the flow field behind the experimental model. The digital images were captured by a high-speed camera (Photon FASTCAM SA3) with the frame rates of 250 fps (frame per second).
The high-speed PIV measurements, as shown in Fig. 2, are carried out in the \((x, z)\)-plane, \((x, y)\)-plane and \((y, z)\)-plane. Here the measurements in the \((x, y)\)-plane (Fig. 2(b)) and the \((y, z)\)-plane (Fig. 2(c)) in the \((y, z)\)-plane were respectively performed at the positions of \(z = 50\) mm \((z/D = 0.71)\) and \(x = 10\) mm \((x/D = 0.14)\). The measured flow area is about \(200\) mm \(\times\) \(200\) mm with a resolution of \(1,024 \times 1,024\) pixels. \(7,000\) digital images (the acquisition duration is \(28\) s) are analyzed by PIV software and PIV interrogation window size is set as \(24 \times 24\) pixels with \(50\%\) overlap. The interval time of two successive images is \(4\) ms and the shutter speed of each frame is set at \(1\) ms. This PIV measurement of the uncertainty of velocity is estimated at \(\pm 1.5\%\) within the reliability of \(95\%\).

To evaluate the boundary layer on the flat plate, PIV was also used to measure its mean streamwise velocity and turbulent intensity profiles. Figure 3 shows the time-averaged streamwise velocity \((\bar{u})\) and turbulence intensity \((u_{rms}\) and \(w_{rms}\)) profiles, which are normalized by free stream velocity \(U\), at the streamwise locations of \(x = 250\) mm \((x/D = 3.6)\) (all data acquired with the cylinder removed). At the location of the cylinder (in the absence of cylinder), the boundary layer thickness \(\delta\) was \(24.6\) mm, and this boundary layer provided a thickness-to-diameter or -height ratio of \(\delta/D = 0.35\). It is well-known fact that the boundary layer thickness has an important influence on the flow structure behind a finite-length cylinder. A significant upwash flow related to the base vortex appears at \(\delta/D \approx 1.02\) (Wang et al., 2006), and the boundary layer thickness may enhance the upwash flow.

3. Results and discussion

3.1 Time-averaged turbulent flow structures

Fig. 4(a) shows the mean streamlines around a low-aspect-ratio standard cylinder (no-hole) in the \((x, z)\)-plane of \(y/D = 0\), calculated by the measured instantaneous velocity. It indicates that the fluid flows over the tip and separates from the free end. A mean small recirculation region or small vortex appears on the free end surface and is centred at about \(0.43D\) from the leading edge. On the other hand, a mean large rear recirculation region or large vortex originating from side of the rear surface and edge of the free end surface is clearly observed and its height is centred at about \(0.71D\).
from the flat plate. A strong downwash flow is originated at immediately downstream of the cylinder in the streamwise direction due to the free end. A streamline reattached on the flat plate at $x/D=1.32$ represents boundary streamline of large rear recirculation zone.

To reduce the rear recirculation region, a FCH with a diameter of $d = 0.14D$ is made to connect the central positions of two recirculation regions, i.e. from the free end surface to the side of the rear surface with $L = 0.43D$ and $h = 0.71D$ (Fig. 1(b)). The role of the FCH can be said as that the pressure difference between two recirculation regions drive the fluid to flow and generates suction flow to the rear recirculation region and blowing flow to the free end surface.

The time-averaged streamlines around the FCH cylinder in the $(x, z)$-plane of $y/D=0$ are shown in Fig. 4(b). It is interesting to find that the fluid of the large rear recirculation zone flows upwards to small recirculation zone of the free end surface through the FCH. It indicates that the pressure of the free end surface is lower than that of the rear surface side. As comparing with the standard cylinder (Fig. 4(a)), the size of rear recirculation zone becomes clearly smaller than that of the standard cylinder since the FCH generates suction flow to reduce the rear separation region. The reattached point appears at $x/D=1.17$ on the flat plate and is more close to cylinder than that of standard cylinder ($x/D=1.32$).

To consider the influence of FCH position, another two kinds of FCH models, which vary the central positions of FCH on the side of the rear surface at $h = 0.29D$ and $0.5D$ and fix the central position of FCH on the free-end surface at $L=0.43D$, are also measured by PIV, and their time-averaged streamlines around the FCH cylinder in the $(x, z)$-plane of $y/D=0$ are displayed in Figs. 4(c) and 4(d). It is evident that the fluid of the side of the rear surface also flows upwards to the free end surface through the FCH. Although the size of rear recirculation zone has no evident decrease (separation attachment point locates at about $x/D=1.32$), the recirculation zone of the free end surface becomes clearly smaller than that of the standard cylinder and the FCH cylinder with $h=0.71D$. As the FCH position approaches to the flat plate (Fig. 4(d)), the recirculation zone of the free end surface decreases. It suggests that the large blowing angle of inclined FCH reduces the separation bubble of the free end surface since the $x$-component velocity of the blowing flow from the outlet of the FCH becomes weak and supplies the flow energy to the separation zone suitably.

![Fig. 4 The time-averaged streamlines in the $(x, z)$-plane at $y/D=0$. (a) Standard cylinder; (b) FCH cylinder with $h=0.71D$; (c) FCH cylinder with $h=0.5D$; (d) FCH cylinder with $h=0.29D$.](image-url)
Fig. 5 Contours of time-averaged streamwise velocity $U^*/U$ in the ($x$, $z$)-plane at $y/D=0$ (Minimum contour magnitude $-0.3$, Maximum contour magnitude $1$, contour increment $0.1$). (a) Standard cylinder; (b) FCH cylinder with $h = 0.71D$; (c) FCH cylinder with $h = 0.5D$; (d) FCH cylinder with $h = 0.29D$.

Fig. 6 Contours of time-averaged spanwise velocity $W^*/U$ in the ($x$, $z$)-plane at $y/D=0$ (Minimum contour magnitude $-0.4$, Maximum contour magnitude $0.4$, contour increment $0.05$). (a) Standard cylinder; (b) FCH cylinder with $h = 0.71D$; (c) FCH cylinder with $h = 0.5D$; (d) FCH cylinder with $h = 0.29D$. 
(a)                                                (b)

Fig. 7 The cross-sectional averaged velocity across the inlet of FCH on the rear surface. (a) $\overline{U_{in}}/U$ ; (b) $\overline{U_{win}}/U$ .

(a)                                                  (b)

(c)                                                 (d)

Fig. 8 Contours of time-averaged vorticity $\overline{\omega_y}/D/U$ in the ($x, z$)-plane at $y/D=0$ (Minimum contour magnitude –8, Maximum contour magnitude -2, contour increment of 1). (a) Standard cylinder; (b) FCH cylinder with $h=0.71D$; (c) FCH cylinder with $h=0.5D$; (d) FCH cylinder with $h=0.29D$.

To further compare the near-wake behavior between the standard and FCH cylinders, the contours of the normalized mean streamwise ($u$-component) and spanwise ($w$-component) velocities are shown in Figs. 5 and 6. Adaramola et al. (2006, 2010) and Rostamy et al. (2012) used the similar approach.

The mean recirculation region is indicated by a zone of negative $\overline{U}/U$ (streamwise velocity) immediately behind cylinder and is bounded by a line of zero $\overline{U}/U$ in the contours of Fig. 5. It is evident that the length of recirculation zone for FCH cylinder with $h=0.71D$ (Fig. 5(b)) becomes smaller than that for the standard cylinder (Fig. 5(a)). As decreasing the height $h$ of FCH position, as shown in Figs. 5(c) and 5(d), the height of recirculation zone decreases and negative velocity appears in FCH. It implies that the suction flow of the FCH from the side of the rear surface decreases the recirculation zone. It is noted that as the FCH with $h=0.71D$ is
located at the same height as the mean central of large rear separation bubble, the suction flow of the rear surface acts directly on central recirculation zone and results in the reattachment point on the flat plate moving closer to the cylinder (Figs. 4(b) and 5(b)).

The contours of mean spanwise (plate-normal \( w \)-component) velocity component, as shown in Fig. 6, a large downwash (downward-directed, negative contour) flow region extended to the flat plate dominates flow structures near the cylinder. However, an evident upwash (upward-directed, positive contour) flow region appears immediately behind the cylinders, just like an “ear” pattern of the cylinder. In comparison with the standard cylinder, the upwash flow regions of FCH cylinder with \( h = 0.71D \) and \( 0.5D \) (Figs. 6(b) and 6(c)) are reduced due to the suction flow generated by the FCH, which results in the increase of downwash flow region. Furthermore, the downwash flow of the FCH cylinder (Figs. 6(b), 6(c) and 6(d)) becomes weaker than that of the standard cylinder near the ground plane. It may infer that the drag reduction of cylinder having such flow structures (Rostamy et al., 2012). These flow structures are different from high aspect ratio, where a small region of upwash flow closed to the free end was observed in the case of aspect ratio 3 (Rostamy et al., 2012). As decreasing the height \( h \) of FCH position on the side of the rear surface, an evident positive \( w \)-component velocity is observed in the FCH, indicating the increase of upwash flow in the FCH.

Fig. 7 shows the relationship between the cross-sectional averaged velocity across the inlet of FCH and FCH position on the rear surface. As the FCH position decreases, \( \bar{u}_w/U \) and \( \bar{w}_w/U \) increase. Especially the FCH cylinder with \( h = 0.5D \) exhibits the largest \( \bar{w}_w/U \) and indicates strong upwash flow in the FCH.

The normalized mean transverse vorticity contours \( \bar{\omega}_y/D/U \) of the \( (x, z) \)-plane at \( y/D=0 \) are indicated in Fig. 8. The negative vorticity that distributes above the free end and extends downstream is observed. Due to the blowing effect of FCH on the free end, the concentration of vorticity is higher than that of the standard cylinder. Close to immediately behind the cylinder and near the cylinder-plate junction, several small regions of positive vorticity are found, which were also observed in Rostamy et al. (2012). As decreasing the FCH position, the concentration of vorticity increases due to blowing and suction flows. The negative vorticity is spread downwards to the flat plate, approaching the FCH location of the rear surface.

Fig. 9 shows the normalized mean spanwise vorticity contours \( \bar{\omega}_z/D/U \) in the \( (x, y) \)-plane of \( z/D=0.71 \), which is located the same height as the FCH with \( h = 0.71D \). Here a half contour is given due to the asymmetric vorticity with respect to the wake center plane at \( x/D=0 \). A vorticity peak of the standard cylinder with \( \bar{\omega}_z/D/U = -5 \) is observed at \( y/D=0.6 \), which is similar to that obtained by Goncalves et al. (2015). Comparing with the standard cylinder, the maximum vorticity peak of the FCH with \( h = 0.71D \) is close to the wake center plane at \( y/D=0.56 \) and the maximum concentration of vorticity \(( \bar{\omega}_z/D/U = -4 ) \) decreases. It implies that the suction flow of the FCH cylinder with \( h = 0.71D \) suppresses vortex shedding and reduces the vorticity near the shear layer.

![Fig. 9 Contours of time-averaged vorticity \( \bar{\omega}_z/D/U \) in the \( (x, y) \)-plane at \( z/D=0.71 \) (Minimum contour magnitude -5, Maximum contour magnitude -1, contour increment of 1). (a) Standard cylinder; (b) FCH cylinder with \( h =0.71D \).](image)

The contours of the normalized mean streamwise vorticity \( \bar{\omega}_x/D/U \) in the \( (x, y) \)-plane of \( x/D=0.14 \) is plotted in Fig. 10. Here a half contour is also given due to the asymmetric vorticity with respect to the wake center plane at \( y/D=0 \). The streamwise vorticity indicates a dominant counter-rotating vortex pair near the free end for both standard cylinder and FCH cylinder with \( h = 0.71D \), which is generated by the free end and is referred to as the tip vortex. The tip vortex position of the FCH cylinder is higher than that of the standard cylinder due to the effect of blowing flow from the FCH (with \( h =0.71D \)) of the free end surface. Besides, the horse shoe vortex is also observed near the flat plate for two cylinders.
Fig. 10 Contours of time-averaged vorticity \( \overline{\omega} D/U \) in the (y, z)-plane at \( x/D = 0.14 \). Solid contour lines represent positive vorticity, and dashed contour lines represent negative vorticity (Minimum contour magnitude \(-2.5\), Maximum contour magnitude \(1.5\), contour increment of \(0.5\)). (a) Standard cylinder; (b) FCH cylinder with \( h = 0.71D \).

Fig. 11 Contours of Reynolds shear stress \( \overline{u'w'}/U^2 \) in the (x, z)-plane of \( y/D = 0 \) (Minimum contour magnitude \(-0.035\), Maximum contour magnitude \(0.02\), contour increment of \(0.005\)). (a) Standard cylinder; (b) FCH cylinder with \( h = 0.71D \); (c) FCH cylinder with \( h = 0.5D \); (d) FCH cylinder with \( h = 0.29D \).

3.2 Reynolds shear stresses and turbulent kinetic energy

The contours of the normalized Reynolds shear stress \( \overline{u'w'}/U^2 \) for the standard and FCH cylinders in the (x, z)-plane of \( y/D = 0 \) are shown in Fig. 11. A small region of positive Reynolds shear stress on the free end and a large region of negative Reynolds shear stress on the free end and in the near-wake are evidently observed. Furthermore, the
region of negative shear stress for the standard cylinder is closer to the flat plate and the maximum magnitude is -0.035. However, the Reynolds shear stress of the FCH cylinder with $h = 0.71D$, as shown in Fig. 11(b), decreases comparing with the standard cylinder and maximum magnitude is -0.02 due to the effect of suction and blowing of the FCH, and an isolated zone of positive shear stress appears near the flat plate. For the FCH positions of $h = 0.29D$ and $0.5D$, $u'w'/U^2$ increases and the maximum magnitude reaches at -0.04 due to relatively high velocity of blowing and suction flows from the FCH.

Fig. 12 shows the normalized Reynolds shear stress $u'v'/U^2$ in the $(x, y)$-plane of $z/D = 0.71$. A half contour is plotted due to the asymmetric distribution of Reynolds shear stress with respect to the wake center plane at $x/D = 0$. The maximum magnitude of $u'v'/U^2$ is -0.02 for standard cylinder (Fig. 12(a)). However, the maximum magnitude of $u'v'/U^2$ (-0.015) for the FCH cylinder with $h = 0.71D$ (Fig. 12(b)) decreases and its position appears to move towards the cylinder due to the effect of suction flow from the FCH. It suggests that the suction flow of the FCH suppresses and reduces the generation of the Reynolds shear stress.

![Fig. 12](image1)

A comparison between the standard cylinder and FCH cylinder with $h = 0.71D$ by using the contour of the normalized Reynolds shear stress $v'w'/U^2$ in the $(y, z)$-plane of $x/D = 0.14$ is displayed in Fig. 13. From the distribution of $v'w'/U^2$ contour, it is inferred that most of $v'w'/U^2$ are mainly originated by the free end surface, the cylinder side surface and the flat plate. Comparing with the standard cylinder, the contours appear to converge towards the center plane of $y/D = 0$ and $v'w'/U^2$ becomes weaken since the suction of the FCH suppresses the separation bubble and reduces the Reynolds shear stress.

![Fig. 13](image2)
The vortical structures and turbulent features are closely associated with the turbulent kinetic energy. In this study, the turbulent kinetic energy TKE (Lim and Lee, 2003; Oruc, 2012) of the \((x, z)\)-plane is calculated based on the streamwise and spanwise Reynolds normal stresses \( \left( \overline{u'^2/U^2}, \overline{w'^2/U^2} \right) \) by

\[
TKE = 0.75 \overline{u'^2/U^2} + \overline{w'^2/U^2}
\]

The contours of the turbulent kinetic energy (TKE) for the standard and FCH cylinders in the \((x, z)\)-plane are depicted in Fig. 14. It is clearly that the peak magnitude of TKE for the FCH cylinder with \( h = 0.71D \) is equal to 0.05 in the near wake, and is smaller than that for standard cylinder (TKE=0.07). It implies that the concentration of the contours weakens due to the presence of the FCH control element. The decrease of TKE may result in the reduction of the drag force acted on the cylinder (Lim and Lee, 2003). However, in the case of FCH cylinders with \( h = 0.29D \) and \( 0.5D \), the TKE increases and is higher than that of the standard cylinder and FCH cylinder with \( h = 0.71D \). The maximum magnitudes of \( h = 0.29D \) and \( 0.5D \) reach at 0.09 and 0.08, respectively, which are caused from relatively high velocity in the FCH.

From above results, it can be concluded that the FCH cylinder with \( h = 0.71D \) may evidently reduce the rear recirculation zone, the concentration of vorticity, Reynolds shear stress and the turbulent kinetic energy. However, the FCH cylinders with \( h = 0.29D \) and \( 0.5D \) may effectively diminish the separation region of the free end surface.

3.3 Instantaneous turbulent flow structures

In order to compare the flow structures between the standard cylinder and FCH cylinder with \( h = 0.71D \), Fig. 15 plots the instantaneous streamlines and corresponding normalized vorticity contours of \( \omega zD/U \) in the \((x, z)\)-plane of \( y/D=0 \). The color mappings have been assigned to the vorticity values and the highest and lowest concentrations are respectively displayed as red and blue. It is clearly observed that five vortical structures with different size and strength appear behind the standard cylinder in the rear recirculation zone (Fig. 15(a)). In the case of the FCH cylinder with \( h = 0.71D \), however, only two vortical structures can be respectively identified on the free end surface and behind the cylinder due to the blowing and sucking flows from the FCH (Fig. 15(b)). Therefore, it is inferred that that the FCH suppresses vortex shedding and therefore reduces the rear separation region.

Fig. 14 Contours of TKE in the \((x, z)\)-plane at \( y/D=0 \) (Minimum contour magnitude 0.01, Maximum contour magnitude 0.07, contour increment of 0.01). (a) Standard cylinder; (b) FCH cylinder with \( h = 0.71D \); (c) FCH cylinder with \( h = 0.5D \); (d) FCH cylinder with \( h = 0.29D \).
Fig. 15 Instantaneous streamlines and corresponding vorticity contours in the \((x, z)\)-plane at \(y/D=0\). (a) Standard cylinder; (b) FCH cylinder with \(h=0.71D\).

Fig. 16 The spectral \(Sw\) of streamwise velocity component \(w\) at \(x/D=0.3\), \(z/D=0.8\) and \(y/D=0\). (a) Standard cylinder; (b) FCH cylinder with \(h=0.71D\).

3.4 Spectral characteristics

Fig. 16 plots the power spectral density functions \(Sw\) of streamwise velocity component \(u\) obtained by PIV for the standard cylinder and FCH cylinder with \(h=0.71D\) in the near-wake region at the location of \(x/D=0.3\), \(z/D=0.8\) and \(y/D=0\), which is approximately on the vortex path in the \((x, z)\)-plane of \(y/D=0\). Here \(Sw\) is weighted by frequency \(f\) to indicate the energy distribution with \(f\).

The three pronounced peaks in the standard cylinder wake are observed around 0.53 Hz, 0.85 Hz and 1.1Hz, corresponding to Strouhal number of \(St = 0.23\), 0.37 and 0.48, respectively. However, pronounced peaks of FCH cylinder wake appears at 0.61 Hz, 0.85 Hz and 1.6Hz (\(St = 0.27\), 0.37 and 0.70, respectively), and the dominate frequencies (Strouhal numbers) of vortices shedding from the cylinder surface increase by comparing with the standard cylinder wake due to the flow control of the FCH.

4. Conclusions

A passive control technique to control and reduce the rear separation region and the vortex on the free-end surface around a low aspect ratio circular cylinder is proposed and the flow structures of the controlling and no-controlling wakes are experimentally measured by using the high-speed PIV. By comparing with the no-controlling wake, the following conclusions can be drawn.

1. In the controlling hole the fluid flows from the large rear recirculation zone upwards to the small recirculation zone on the free end surface.
2. The rear recirculation zone of FCH cylinder with \(h=0.71D\) becomes evident smaller than that of the standard cylinder. The FCH cylinders with \(h=0.29D\) and \(0.5D\) effectively reduce the separation region of the free end surface.
3. The upwash flow region is reduced, and downwash flow region is increased. Furthermore, the downwash flow becomes weaken near the ground plane.
(4) The FCH cylinder with $h = 35$ mm ($h/D=0.5$) exhibits the highest cross-sectional averaged velocity across the inlet of the FCH among the three FCH models.

(5) The concentration of vorticity, the Reynolds shear stresses ($\overline{\omega w}/U^2$, $\overline{u' v'}/U^2$, $\overline{v' w'}/U^2$) and the turbulent kinetic energy are evidently suppressed by the suction flow of the FCH with $h = 0.71D$, which may result in the reduction of the drag force the cylinder.

(6) Spectral analyses indicate that the dominate frequency of vortex shedding from the cylinder surface of the FCH with $h = 0.71D$ increases.

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