EFFECT OF A HORIZONTAL HOLE ON FLOW STRUCTURES AROUND A WALL-MOUNTED LOW-ASPECT-RATIO CYLINDER

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ABSTRACT

To control the wake structures of a low-aspect-ratio cylinder, a passive flow control method that is to use a horizontal hole from the front side surface to the rear side surface was proposed for a circular cylinder having an aspect ratio *H/D* = 1 with height *H* and diameter *D* of 70 mm. The high-speed PIV 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 horizontal hole, there kinds of the horizontal holes having different height *h* of hole from wall were tested. It was found that the rear recirculation zone of horizontal hole cylinders with *h* = 35 and 50 mm becomes evident smaller than that of the standard cylinder. The Reynolds shear stresses were evidently suppressed by the jet flow of the horizontal hole, resulting in the reduction of the drag force of the cylinder.

INTRODUCTION

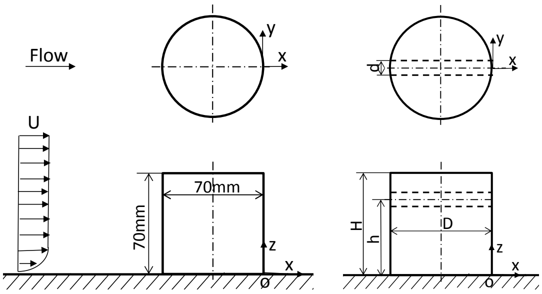
The flow around a finite-length circular cylinder causes a strongly three-dimensional complex flow field, and the aspect ratio of the cylinder influences the flow structure, which is different from ''infinite'' structure (Rinoshika and Zhou, 2005, 2009), due to the effect of the circular cylinder's free end (or tip) and the cylinder-wall junction (Sumner et al., 2004; Pattenden et al., 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 (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., Kárman 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 flow structures around low aspect ratio cylinders are few in the literature. Less research focus on the control of flow structures around low aspect ratio cylinders, which motivates the present investigation. Recently, Rinoshika et al. (2017) proposed a passive control method, in which a controlling hole passing from the free-end surface to the side of the rear surface is made to generate both suction and blowing flows around a low-aspect-ratio cylinder, and effectively reduced the rear separation region of cylinder.

In the present study, a horizontal hole is made from the front side surface to the rear side surface in a low-aspect-ratio cylinder to control the wake structures. This method is proposed to apply to offshore structures for controlling the local scour around the bluff body. Firstly, the controlling and non-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. Then the mean streamlines, mean velocity components and Reynolds shear stresses were examined and compared between the controlling and non-controlling cylinders. Finally, the POD (Proper Orthogonal Decomposition) technique used to reveal energy distribution of the controlling and non-controlling wake structures.

EXPERIMENTAL SETUP

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. To control the flow structures, a hole with a diameter of d = 10 mm, called the controlling hole (CH), is horizontally made from the front side surface to the rear side surface (Fig.1b). For studying the effect of CH position, three kinds of CH models, which vary the height of CH at h = 20mm, 35mm and 50mm. 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 high-speed PIV measurements are carried out, and 6,000 digital images are analyzed by PIV software and PIV interrogation window size is set as 24×24 pixels with 50% overlap.



(a) Standard cylinder (b) Cylinder with a hole

Figure 1 Experimental setup and cylinder models

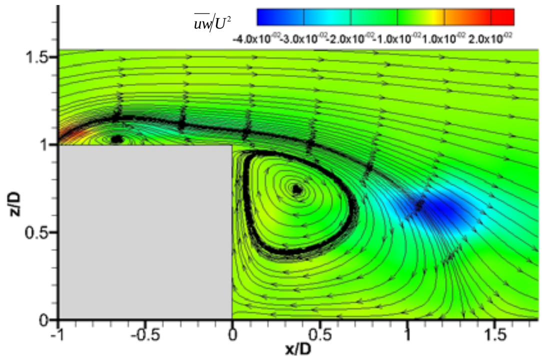
RESULTS AND DISCUSSION

Time-averaged turbulent flow structures

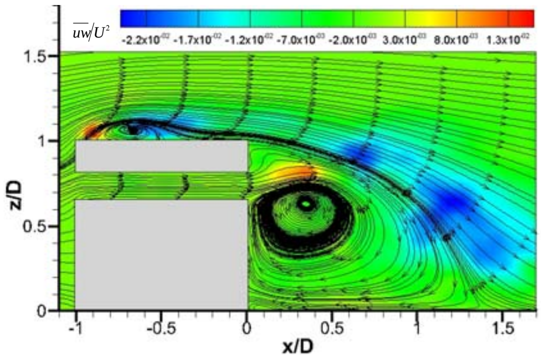
Figure 2(a) shows the contours of the normalized Reynolds shear stress $\overline{u'w'}/U^2$ and mean streamlines around a standard cylinder (no-hole) in the (x, z)-plane of y/D=0, calculated by the measured instantaneous velocity. It indicates that the fluid flows over the tip and separates from the free end. A mean small recirculation region or small vortex appears on the free end surface. On the other hand, a mean large rear recirculation region or large vortex originating from side of the rear surface and leading edge of the free end is clearly observed. 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. A small region of positive Reynolds shear stress on the free end and a large region of negative Reynolds shear stress in the near-wake are evidently observed. The maximum magnitude is -0.04 around the location of x/D=1.2 and z/D=0.7.

The Reynolds shear stress contours $\overline{u'w'}/U^2$ and time-averaged streamlines around the CH cylinder for different height holes are shown in Fig.2 (b)-(d).

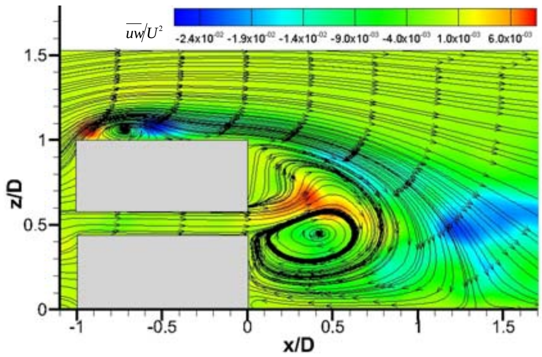
Comparison with the standard cylinder, the rear recirculation zone is evidently decreased by the jet flow from the CH of h = 35 and 50mm although the position of streamline reattached point on the flat plate has no evident variation. The Reynolds shear stresses with CH are also decreased and distributed along the boundary of the rear recirculation zone. However, the reattached point of CH (h = 20 mm) on the flat plate (x/D=1.6), as showed in Fig.2 (d), is longer than that of standard cylinder. The rear recirculation zone of CH (h = 20 mm) is also larger than that of the standard cylinder even if its Reynolds shear stresses become weaker than that of standard cylinder.



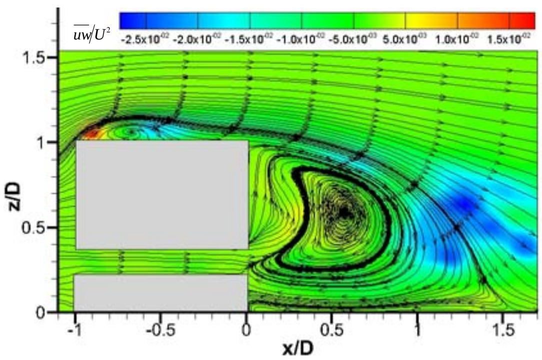
(a) Standard cylinder



(b) CH cylinder with h = 50 mm

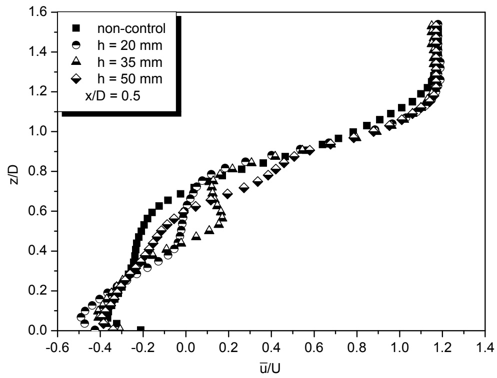


(c) CH cylinder with h = 35 mm

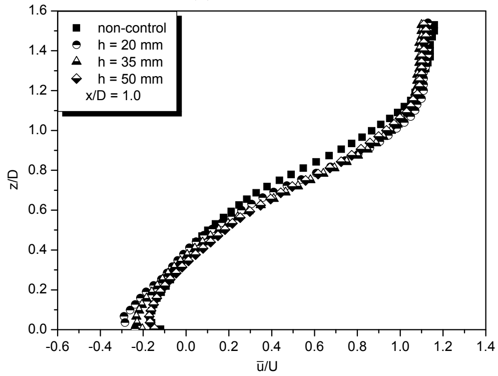


(d) CH cylinder with h = 20 mm

Figure 2 The Reynolds shear stress contours and time-averaged streamlines in the (x, z)-plane at y/D=0

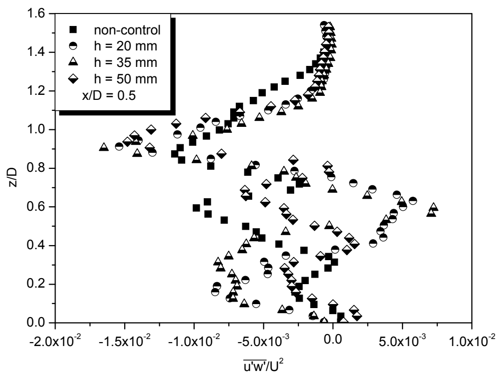


(a) $x/D = 0.5$

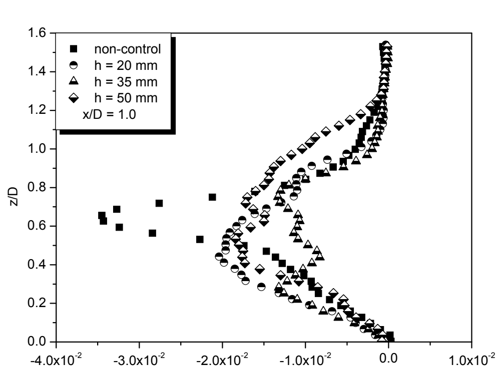


(b) $x/D = 1.0$

Figure 3 Profiles of time-averaged streamwise velocity in the (x, z)-plane



(a) $x/D = 0.5$



(b) $x/D = 1.0$

Figure 4 Profiles of Reynolds shear stress $\overline{u'w'}/U^2$ in the (x, z)-plane

Profiles of time-averaged streamwise velocity $\overline{u}/U$ at the locations of x/D = 0.5 and 1.0 are plotted in Fig.3. For comparing to the standard cylinder, $\overline{u}/U$ of CH increase behind cylinder at the location of x/D = 0.5, and near the height of hole $\overline{u}/U$ exhibits higher value due to the jet flow. Especially, at position of z/D = 0.5, $\overline{u}/U$ of h = 35mm reaches at 0.2. But the standard cylinder of $\overline{u}/U$ is about -0.25. therefore, The rear recirculation zone of CH cylinder becomes smaller than that of the standard cylinder. At the location of x/D = 1.0, the difference between the standard cylinder and CH becomes small due to the weak of jet flow.

Figure 4 presents profiles of Reynolds shear stress $\overline{u'w'}/U^2$ in the (x, z)-plane at the locations of x/D = 0.5 and 1.0. It is evident that $\overline{u'w'}/U^2$ of CH is larger than that of the standard cylinder behind cylinder at the location of x/D = 0.5 because of effect of the jet flow. At downstream of x/D = 1.0, however, $\overline{u'w'}/U^2$ of the standard cylinder exhibits the largest magnitude near the height of z/D = 0.65. On the other hand, $\overline{u}/U$ of h = 35mm shows the smallest magnitudes among controlling and non-controlling cylinders, which may result in the reduction of the drag force.

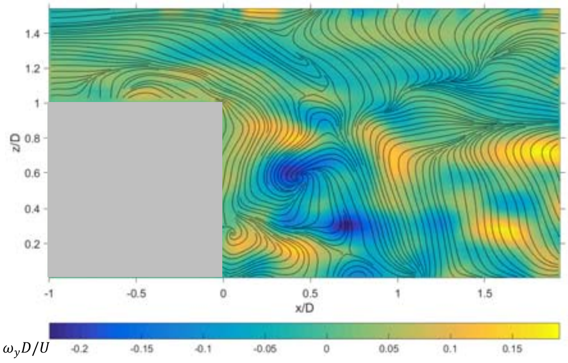
Above results indicate that the position of CH largely effects or changes the flow structures of wake, and controls the separation and Reynolds stresses.

POD analysis of turbulent flow structures

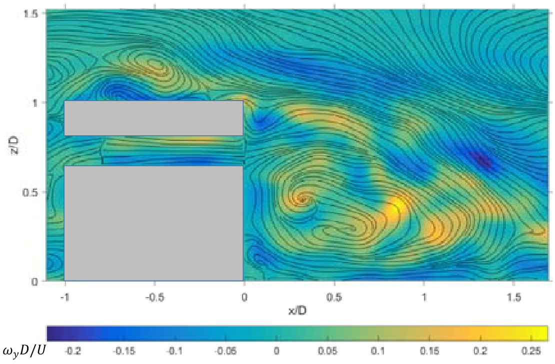
POD can decompose a complex flow structures into more simple modes in every spatial point. In this work, the snapshot POD technique is applied to analysis of the PIV data, with a view to flow structures in terms of the POD coefficients and the energy distribution of the POD modes.

In the snapshot POD method, each instantaneous PIV data is considered as a random snapshot of the flow field. The first step of snapshot POD procedures is to remove the mean velocity field from each of instantaneous snapshots. The next step works on the cross-correlation between individual snapshots of fluctuating velocity, and the aim is to find a new orthogonal basis (i.e. modes) with a maximum average projection of the fluctuations on the basis. The new basis or mode can be re-ordered after its contribution to the turbulent kinetic energy (TKE) in the flow. That is to say, the first mode (i.e. eigenvector) would contain the highest portion of TKE, the second mode (i.e. eigenvector) would contain a little bit lower TKE, and so on.

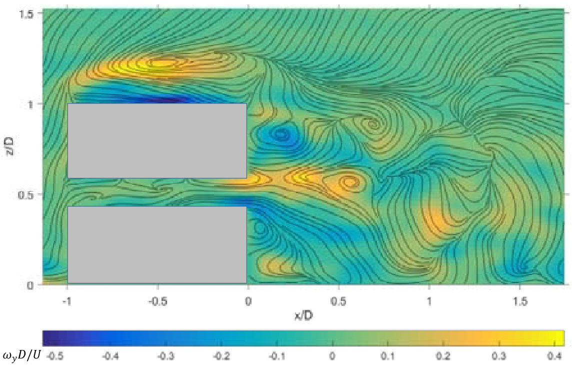
In this work, the relative TKE contribution of each mode (no shown) indicates that TKE of first mode contributes around 18%, 21%, 13%, and 20% to the standard cylinder, 20mmCH, 35mmCH and 50mmCH, respectively. The contributions of other modes fall down very quickly. It implies that this first mode catches a most of coherent structure.



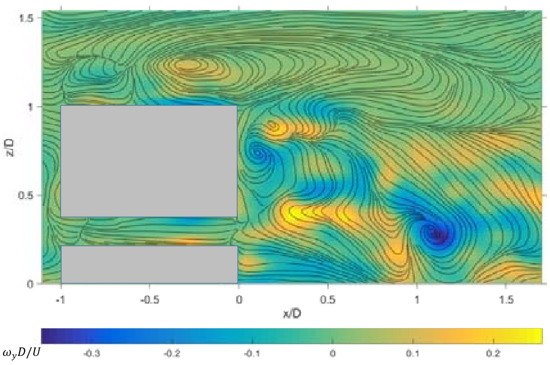
(a) Standard cylinder



(b) CH cylinder with *h* = 50 mm



(c) CH cylinder with *h* = 35 mm



(d) CH cylinder with *h* = 20 mm

Figure 5 The vorticity contours and streamlines of POD mode 1 in the (*x*, *z*)-plane at *y*/*D*=0

Figure 5 displays the vorticity contours and streamlines of POD mode 1 for the standard cylinder, 20mmCH, 35mmCH and 50mmCH. It is evident that the coherent structures of the standard cylinder appear behind the cylinder. However, the coherent structures or vortices of CH cylinder distribute near the free end and rear recirculation region since the CH generates jet flow to diminish the large-scale structures. Especially for the CH of *h* = 35mm (Fig.5c), several vortices are clearly observed near the outlet of CH.

CONCLUSIONS

A passive control technique to control the rear separation region and the Reynolds stress around a low-aspect-ratio cylinder is proposed. Making a comparison between controlling and no-controlling wakes, the following main results can be drawn.
(1) The rear recirculation zone of CH cylinder with h = 35 and 50 mm becomes evident smaller than that of the standard cylinder.
(2) The Reynolds shear stresses are evidently suppressed by the jet flow of the horizontal CH, which may result in the reduction of the drag force of the cylinder.
(3) The CH cylinder with *h* = 35 mm evidently reduces the rear recirculation zone, the concentration of vorticity, Reynolds shear stress and the turbulent kinetic energy.
(4) The most of TKE contribution comes from POD first mode, and CH jet diminishes the large-scale structures in the near wake.

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