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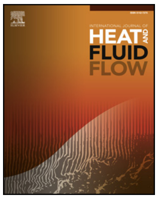

Effect of a horizontal hole on flow structures around a wall-mounted low-aspect-ratio cylinder

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ABSTRACT

To control the vortex structures and separation region of a low-aspect-ratio cylinder wake, a passive flow control method that is to drill a horizontal hole from the front side surface to the rear side surface was proposed for a short circular cylinder having an aspect ratio $H/D = 1$ with height H and diameter D of 70 mm. The PIV measurements were performed at Reynolds number of 8570 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, three kinds of the hole positions having different height h from wall were tested. It was found that the jet flow from a horizontal hole leads to suppress the vortex formation and to reduce the rear separation region. The vorticity, Reynolds shear stresses and TKE were evidently suppressed by the jet flow of the horizontal hole in the rear recirculation zone, resulting in the reduction of the drag acted on the cylinder. Meanwhile, the instantaneous large-scale vortical structures of the rear recirculation zone were broken down into several small-scale vortices by the jet. As increasing the height of hole, the downwash flow is evidently suppressed and the upwash flow is increased. Spanwise vortex shedding is altered from symmetric to asymmetric arrangement.

1. Introduction

A finite circular cylinder generates a strongly three-dimensional complex flow structure, and the aspect ratio (the ratio of the height and diameter) of the cylinder is related to the wake flow characteristics, which is different from the case of "infinite" structure (Rinoshika and Zhou, 2005, 2009), due to the effect of the free end (or tip) of the cylinder and the connection of cylinder and wall (Sumner et al., 2004; Pattenden et al., 2005; Wang and Zhou, 2009; Goncalves et al., 2015). It has many important applications on the engineering field, for example, offshore structures, buildings, chimney stacks, heat exchanger, automobile and so on. Up to now, the complex flow structures around a finite circular cylinder have been well studied. They are mainly composed of Kármán vortex shedding from the two sides of the cylinder, the horse shoe vortex (called necklace vortex) and base vortex occurring close to the ground plane of the cylinder-wall connection (Tanaka and Murata, 1999; Sumner et al., 2004) and a pair of streamwise counter-rotating vortices (called trailing vortices) generated from the free end (Kawamura et al., 1984a; Johnston and Wilson, 1996; Adaramola et al., 2006). Lee (1997) also reported that a structure like a cell of Kármán vortex decreases with the aspect ratio in the range of high aspect ratio. Although the flow structures around a low-aspect-ratio cylinder are composed of 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), alternating vortex shedding, i.e., Kárman street, can't be observed. Focusing on a lower-aspect-ratio cylinder, "arch-type vortex" formation can be seen in the near wake (Lee, 1997) because the vortex originated from the free-end surface becomes contiguous with the vortices generated from the sides before reattachment. The details concerning finite-height cylinder can be seen in Sumner (2013) and Porteous et al. (2014).

But fundamental investigation on controlling the vortex-induced vibration in the case of the low-aspect-ratio cylinder has not been well studied, which attracts interest of many engineering fields, for instance, reducing drag, lift and noise in order to design the automobile, structural vibrations, heat exchangers, offshore structures and so on. Several flow control methods applied on the boundary layer, like suction, blowing, splitter plate and surface roughness elements, have been well studied in the case of infinite-height cylinder (Choi et al., 2008). Major studies about the noise generated by the flow around the cylinder have focused on Aeolian tone from infinite-height cylinders in uniform crossflow (Ali et al., 2013). Splitter plates placed behind the circular

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cylinder may effectively reduce the transverse oscillations caused by the vortex for undersea cables and oscillating cylinders (Hu and Koterayama, 1994). However, less research focus on controlling vortices in the near wake and vortex on the free end surface of a low-aspect-ratio cylinder, which highlights the present study. Recently, Rinoshika et al. (2017) proposed a passive control technique, in which an inclined hole made from the rear surface to the free-end surface is applied to generate suction and blowing around a low-aspect-ratio cylinder. As a result, it effectively suppressed the rear separation zone of cylinder. In general, the important purpose of the flow control is to reduce the occurrence of vortices or the separation region in the wake. Until now, active and passive control methods have been performed to control the flow structure around a bluff body. In order to control the vortex shedding at low Reynolds numbers, Shi and Feng (2015) applied the inclined narrow slots to the cylinder, which is made from the front stagnation point to the locations near the upper and lower separation points. The passive control method is easier to apply and modify the flow structures with no external energy required (New et al., 2015). Thus, the present investigation focused on the passive flow control of a low-aspect-ratio cylinder (Sumner et al., 2004; Pattenden et al., 2005).

In order to suppress the separation region and vortices behind the cylinder, the present study proposed another passive control method, in which a horizontal control hole (HCH) from the front side surface to the rear surface of the cylinder is applied to induce jet flow. Then the wake flow structures of various HCH cylinders placed on a ground plane are 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 are investigated and make a comparison between the standard cylinder and the HCH cylinder. Finally, the spectral analysis is applied to clarify the dominate flow structures.

2. Experimental details

Fig. 1 shows a finite-length circular cylinder placed on a flat plate. In this study both the height H and diameter D of the circular cylinder are 70 mm, which has an aspect ratio of $H/D = 1$. The x, y, and z axes represent the streamwise, transverse and spanwise directions, respectively. A hole called horizontal controlling hole (HCH), which has a diameter of $d = 10$ mm ($d/D = 0.14$), is horizontally directed from the front side to the rear side of the cylinder in order to control the wake flow structures. For investigating the effect of the horizontal hole position, three kinds of the HCH cylinders, as shown in Fig. 2, which have difference heights as $h = 20$, 35 and 50 mm from the flat plate, are used.

The experiment was performed in the circulating water tunnel, and its turbulence intensity is less than 5%. The velocity of the external flow is $U = 0.16$ m/s, so Reynolds number Re ($\equiv UD/\nu$) equals to 8570. An averaged diameter of the PIV tracer (polystyrene) particles is 68 μm. The flow field behind the cylinder is illuminated by a high-intensity laser light sheet having a thickness of 1.0 mm. The digital images were captured by a high-speed camera (Photoron FASTCAM SA3). The frame rate is set as 250 fps (frame per second).

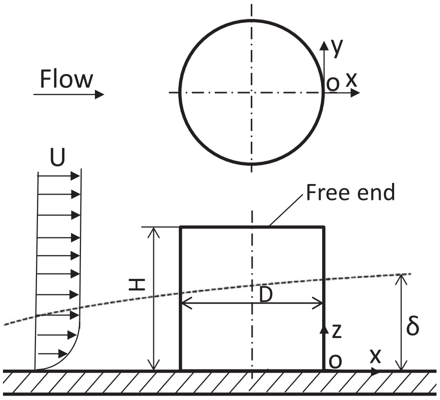

Fig. 1. Experimental setup and a finite-length circular cylinder mounted on a flat plate.

The high-speed PIV measurements are performed in the (x, z)-plane and the (x, y)-plane. The measurements in the (x, y)-plane are carried out at the height of $z = 20$ mm, 35 mm and 50 mm. The measured area is about 200 mm × 200 mm with a resolution of 1024 × 1024 pixels. PIV interrogation window size is set as 24 × 24 pixels with 50% overlapping. The time interval of two successive images is 4 ms and the shutter speed of each frame equals to 1 ms. The PIV measurement of the uncertainty of velocity is presumed at ± 1.5% (the reliability is 95%).

PIV is also adapted to measure its mean streamwise velocity and turbulent intensity profiles in order to evaluate the boundary layer of the flat plate. The time-averaged streamwise velocity ($\overline{u}$) and turbulence intensity (u_{rms} and w_{rms}) profiles normalized by external flow velocity (U) are provided in Fig. 3. The streamwise location is at $x = 250$ mm ($x/D = 3.6$) (all data obtained at the condition of no cylinder). At the location of the cylinder, the boundary layer thickness δ was 39.6 mm, and this boundary layer provided a thickness-to-diameter or -height ratio of $\delta/D = 0.57$. The thickness of the boundary layer is well known to have an important effect on the wake characteristics of a finite-length cylinder. A significant upwash flow induced by the base vortex can be observed at $\delta/D \approx 1.02$ (Wang et al., 2006), and the thickness of the boundary layer may cause the stronger upwash flow, which affects the wake flow structures largely.

3. Results and discussion

3.1. Time-averaged streamlines and velocity fields

Fig. 4 shows the time-averaged streamlines and contours of time-averaged streamwise velocity $\overline{u}/U$ of the standard and HCH cylinders in the (x, z)-plane. Here the contour area of negative u-component velocity is surrounded by a dash line of $\overline{u}/U = 0$, which represents the rear reverse zone. In the standard cylinder wake, as shown in Fig. 4(a), a mean small vortex, which center is located at about 0.43D from the leading edge of cylinder, can be seen on the free end surface. On the other hand, a mean large vortex generated from side of the rear surface and edge of the free end surface can be evidently observed. It indicated that a strong downwash flow (downward motion of the separated shear layer over the free-end) is formed from the free end surface at the downstream in the streamwise direction and the downwash flow dominates the near wake. The center of the vortex is located at about 0.71D height from the ground plane. The distance from the cylinder to reattachment point on the flat plate is usually defined as the recirculation length (Pattenden et al., 2005). In this study a reattachment point of $x/D = 1.5$ expresses the boundary streamline of large rear separation region.

Focusing on the case of HCH cylinders, the positive velocity area appears near the hole (Fig. 4b–d). The downwash flow dominates the flow structures of the near wake. As indicated in Fig. 4(b), the rear separation region of HCH cylinder with $h = 20$ mm is slightly longer than that of standard cylinder, and its reattachment point locates at $x/D = 1.6$. However, the large vortex is blown further by the jet flow from the hole, which leads to the reduction of the rear separation region based on the area of negative u-component velocity surrounded by a dash line. In the case of the HCH cylinders with $h = 35$ mm and 50 mm, the rear separation zones become smaller because of the effect of the jet flow (Fig. 4c and d). The positions of streamline reattached point on the flat plate appear at $x/D = 1.5$ and 1.7, respectively. It is clear that the height of the large vortex becomes smaller than that of the standard cylinder. The phenomenon can be especially seen in the case of $h = 35$ mm. Since the strong jet flow from the hole suppresses the formation of large vortex or downwash flow, the separation region of the HCH with $h = 35$ mm is smallest. In the case of the HCH of