Journal of Wind Engineering & Industrial Aerodynamics 168 (2017) 134–140

Contents lists available at ScienceDirect

Journal of Wind Engineering & Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia

Short communication

Particle Image Velocimetry measurement of flow around an inclined square cylinder

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ARTICLE INFO

Keywords:
Inclined cylinder
Particle Image Velocimetry
Flow field
Axial flow

ABSTRACT

This study investigated flow around an inclined square cylinder by using Particle Image Velocimetry technique in a wind tunnel. Two types of inclinations, i.e. forward inclination and backward inclination, were tested. Two inclination angles, i.e. $\alpha = 15^\circ$ and 30° were tested for each type of inclinations. It was found that the forward inclination enhances the downwash that originally appears behind the upper part of the vertical cylinder, whereas weakens the upwash that is exhibited behind the base part of the vertical cylinder. When the forward inclination angle is large enough, the downwash is enhanced to a downward axial flow, whereas the upwash is completely suppressed. On the contrary, the backward inclination depresses the downwash, while enlarges the upwash. As the backward inclination angle increases, the upwash evolves into an upward axial flow.

1. Introduction

Recently, aerodynamic behaviours of an inclined square cylinder have been investigated comprehensively in a series of studies (Hu et al., 2016, 2015a, 2015b, 2015c), due to its practical significance for bridge pylons, such as Alamillo Bridge in Spain, Kumdang Bridge in Korea, Hong Shan Bridge in China, Shenzhen Bay Bridge, a yawed tower bridge in the South of Italy as recently introduced by Marra et al. (2017). The prevalence of the inclined pylon is due to not only its aesthetic superiority but also its favourable mechanics performance.

The inclination of the cylinder from the vertical direction was found to play a crucial role in aerodynamic characteristics and instabilities of the square cylinder (Hu et al., 2015a, 2015b). The crucial role is attributed to very different flow regimes around the cylinder for different inclinations (Hu et al., 2016, 2015c, Lou et al., 2017, 2016, 2012). For instance, the forward inclination, inclined toward the upstream direction, was found to amplify the downwash to a downward axial flow, whereas the backward inclination promotes the upwash to an upward axial flow. The presence of the axial flow significantly alters the aerodynamic instabilities of the inclined cylinder. As reported by Matsumoto et al. (2010), dry galloping of an inclined cable is excited by axial flow. Hu et al. (2016) found that the axial flow behind an inclined square cylinder with a finite length suppress, or prevent, roll-up of the shear layer. The suppression, or prevention, of the roll-up is considered to cause a shrinkage of the shear layer and hence increase in the shear layer curvature. The change in the shear layer curvature alters the pressure on the side face of the inclined cylinder, and therefore the transverse force coefficient is changed. Finally, the galloping response of the inclined cylinder is different from that of a vertical cylinder (Hu et al., 2015a).

The axial flow in an inclined cylinder was revealed by large eddy simulations and the smoke-wire visualization technique by Hu et al. (2015c). Due to the significance of the unique flow regime for the inclined square cylinder, it is worth further studying the flow regime by using some advanced flow visualization techniques. In this study, Particle Image Velocimetry (PIV) technique was used to visualize the flow field around the inclined square cylinder in a wind tunnel to further verify the findings in the previous studies.

2. Wind tunnel model tests

Wind tunnel tests were conducted in the boundary layer wind tunnel at the University of Hong Kong. The wind tunnel is of the closed circuit type with a working section of 3 m in width, 1.8 m in height, and 12 m in length. A square cylinder with a width D = 25.4 mm, a height H = 304.8 mm, and hence an aspect ratio (AR) of 12 was mounted on a horizontal plate with a thickness of 20 mm which locates at 0.5 m higher than the wind tunnel floor as shown in Fig. 1. The base of the cylinder was 1 m away from the upstream and downstream edges of the plate, and

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http://dx.doi.org/10.1016/j.jweia.2017.06.001
Received 27 February 2017; Received in revised form 30 May 2017; Accepted 7 June 2017

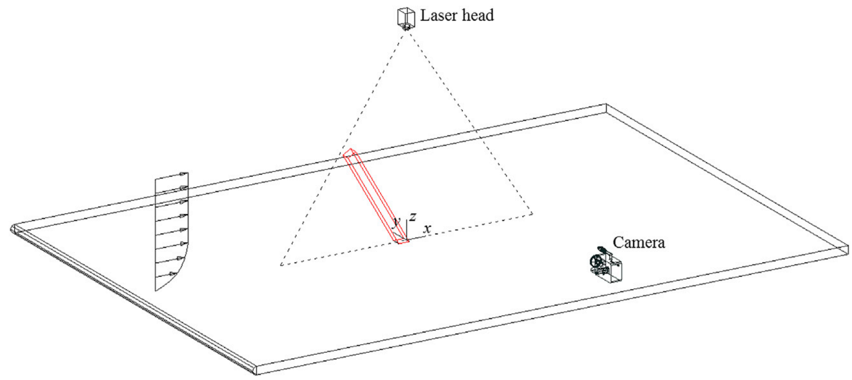

Fig. 1. Test inclined square cylinder with the PIV system.

0.5 m from its two sides. Forward inclination cases, backward inclination cases, and one vertical case were tested. Each type of inclinations included two inclination angles, i.e. $\alpha = 15°$ and $30°$. The inclination angle was defined as the included angle of the vertical direction and the cylinder axis. Hereafter, the positive angle represents a forward inclination, while the negative one denotes a backward inclination.

The wind flow condition experienced by the square cylinder is shown in Fig. 2. It was measured by using a Cobra Probe (TFI, Pty. Ltd), which is capable of resolving 3-components of velocity and can measuring flow fluctuations in excess of 2000 Hz. The mean longitudinal wind speed and turbulence intensity (Ti) at the height corresponding to the vertical cylinder top were 9.34 m/s and 4% respectively. This velocity was defined as a reference velocity (U_{ref}). The Reynolds number based on the reference velocity and the cross section width was 1.57×10^4. The thickness of the shear layer over the horizontal plate was approximately 61 mm, which provides a thickness-to-height ratio of $\delta/H = 0.2$ (see Fig. 2).

The turbulence intensity of the flow in the transverse direction was approximately 3.3% above 0.1H and 5.2% below this height. The blockage ratio was approximately 0.14% which is much lower than the threshold, 5%, suggested by Holmes (2015).

The flow field was measured by using a Dantec standard PIV system as shown in Fig. 3. The measurements were performed on the spanwise center plane ($y = 0$) parallel to the oncoming flow direction as shown in Fig. 1. The plane was illuminated by a thin laser sheet generated from the laser beam of a double-cavity Q-switched Nd: YAG laser (Nano 50-100, Litron). A 1:1 mixture of DEHS liquid and sunflower seed oil was used to produce a fog of seeding particles using a high volume liquid seeding generator (10F03, Dantec Dynamics). Flow images were captured by a high-speed CCD camera (Flowsense EO, Dantec Dynamics), for which the pixel size is 7.4 μm and the resolution is 640 pixel × 480 pixel. The framing speed was set at 100 double-image/s to capture a time sequence of particle images with a totally number of 1825 images. The time interval in the double pluses was set at 250 μs. PIV vectors were obtained on interrogation areas of size 32 × 32 pixels and with a 50% overlap.

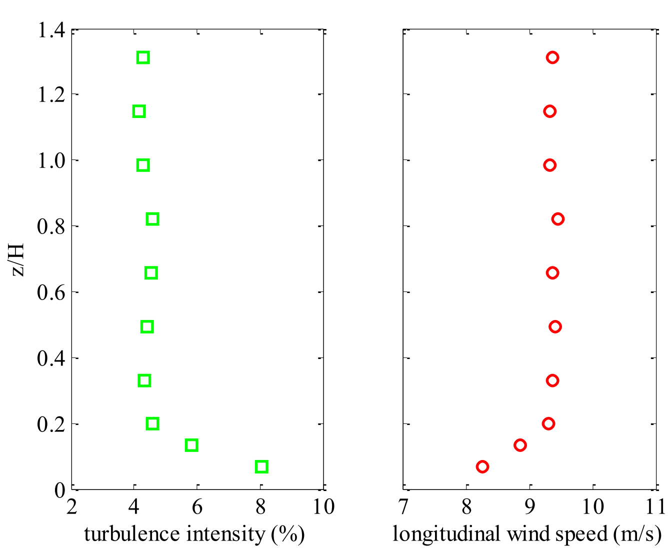

Fig. 2. Turbulence intensity profile and longitudinal mean wind speed profile.

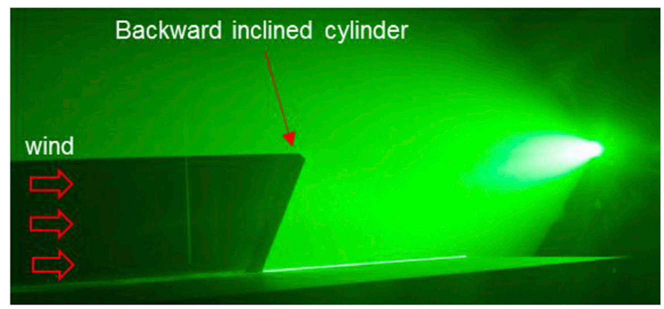

Fig. 3. PIV test on the square cylinder with a backward inclination in the wind tunnel.

3. Flow field around inclined cylinders

3.1. Mean velocity field

The mean velocity vector fields along the wake centerline corresponding to $y = 0$ for different inclined cylinders are shown in Fig. 4. The mean vertical velocities (w) in the vicinity of the inclined cylinders are made dimensionless with the reference velocity (U_{ref}) and given in Fig. 5. The negative value represents a downward velocity. As shown in Fig. 4(a), the widely reported downwash is observed in the upper part of the near wake of the vertical cylinder, while in the very lower part, the upwash is observed (Rostamy et al., 2012; Sumner, 2013; Wang and Zhou, 2009; Wang et al., 2013). The downwash encounters the upwash at the height of approximately 0.2H, around 1.5D from the leeward face and forms a saddle point over there. The maximum downwash velocity is 0.8U_{ref} occurring at the height of 0.85H and the upwash velocity is 0.1U_{ref} near the cylinder base. The maximum downwash velocity and the upwash velocity are consistent with the observations in the wake of a circular cylinder as reported by Rostamy et al. (2012) (for AR = 9, $Re = 4.2 \times 10^4$, $\delta/H = 0.18$, Ti < 0.6%) in spite of the difference in both the aspect ratio and the cross section shape.

For the forward inclined cylinder with $\alpha = 15°$, the downwash is not only enhanced in magnitude but also extended to a lower height. The maximum downwash velocity reaches the magnitude of U_{ref}, which is 20% larger than that behind the vertical cylinder. Meanwhile, the downwash velocities over the whole span in the near wake are all enlarged by the inclination. As a consequence, the upwash is almost