Experimental study on the near wake characteristics of an inclined square cylinder

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SUMMARY:
The present study is concerned with the validity of the independence principle (IP) for a square cylinder inclined in steady currents. For this purpose, the near wake vortex structures and Strouhal number of an inclined square cylinder in steady currents were investigated using a particle image velocimetry (PIV) technique. Based on the results for Strouhal numbers, it was found that the IP is no longer applicable when the inclination angle (α) is larger than 45°. The PIV results show that the elongated vortex formation length, the distorted vorticity contour, and the reduction of the vorticity strength may be responsible for the invalidity of the IP at large angles. The generation of the flow from the base along the cylinder axial direction prevents the communication of the upper and lower shear layers and hence weakens the vortex shedding process. The long afterbody behind the inclined cylinder tends to make the shear layers stretched in the streamwise direction and prevents the separation of the flow. In addition, the present results suggest that the inclination angle has a stronger effect on the wake of square cylinders than that on circular ones.

Keywords: inclined square cylinder; independence principle; particle image velocimetry

1. INTRODUCTION

Two parameters which are widely used to evaluate the bluff body wake dynamics are drag coefficient and Strouhal number, which are normally defined as

$$C_D = \frac{F_D}{0.5\,\rho U^2 LD}, \text{ and } St = \frac{f_v D}{U}, \tag{1}$$

respectively, where F_D is the force in the flow direction, or termed as drag, ρ is the density of the fluid, D and L are the diameter, or the height of the cylinder projected on a plane perpendicular to the flow, and the length of the cylinder, respectively, U is the free stream velocity, and f_v is the vortex shedding frequency. In reality, the flow sometimes approaches a cylindrical structure obliquely owing to the directionality of the structure. To simplify the analysis, normally the velocity component perpendicular to the cylinder axis is used to quantify the hydrodynamic forces and the vortex shedding frequency of the cylindrical structure. This is commonly known as the cosine law, or the independence principle (IP). Based on the IP, the drag coefficient (C_{DN}) and the

Strouhal number (St_N) are quantified as

$$C_{DN} = \frac{F_D}{0.5\, \rho U_N^2 L D}, \text{ and } St_N = \frac{f_v D}{U_N}, \quad (2)$$

respectively, where U_N ($\equiv U \cos \alpha$) is the velocity component normal to the cylinder axis, α is the angle between the flow direction and the plane perpendicular to the cylinder axis. When α = 0, $U_N = U$, and the above parameters are the same as those in a cross-flow (Eq. (1)), i.e. $St_0 = St$. For an inlcined circular cylinder, the validity of the IP in steady flows has been investigated extensively (e.g. Zhou et al., 2009; Zhao et al., 2009) and the consensus maximum angle α for the validity of the IP is about 40°~45°. In the present study, the validity of the IP for a square cylinder was examined at four different angles (α = 0°, 15°, 30° and 45°) in the near-wake ($x/D \leq 6$) in terms of the vortex shedding process and the wake properties. The results will then be compared with that reported by Lou et al. (2016) and Hu et al. (2017) for square cylinders and Zhou et al. (2009) and Zhao et al. (2009) for circular cylinders.

2. EXPERIMENTAL SETUP

The experiments were conducted in a water flume with dimensions of 0.4 m (width) × 0.5 m (depth) × 15 m (length) (Fig. 1). Square rods with a side width D = 20 mm are employed in the tests. They were cut at four different angles (α = 0°, 15°, 30° and 45°) on both ends to make the end cross-sections parallel with the side walls of the flume. The freestream turbulence intensity of the flume is about 2%. Experiments were carried out at a freestream velocity of 0.17 m/s, corresponding to a Reynolds number Re = 3400, where Re is defined as UD/ν with ν being the kinematic viscosity of water.

The digital PIV system employed a 5-Watt continuous wave Argo-ion laser sheet to illuminate the flow. The thickness of the laser sheet is about 1 mm. The images were captured by a high-speed camera (Photron, FASTCAM SA3) with an image resolution of 1024 pixels × 768 pixels at a frame rate of 250 frames/s. The images were analyzed using software PIVlab (Thielicke et al. 2014). The averaging uncertainty in the measurement of velocities was approximately 5%. More details related to the experimental setup and data analyzing procedures can be found in Sun et al. (2021).

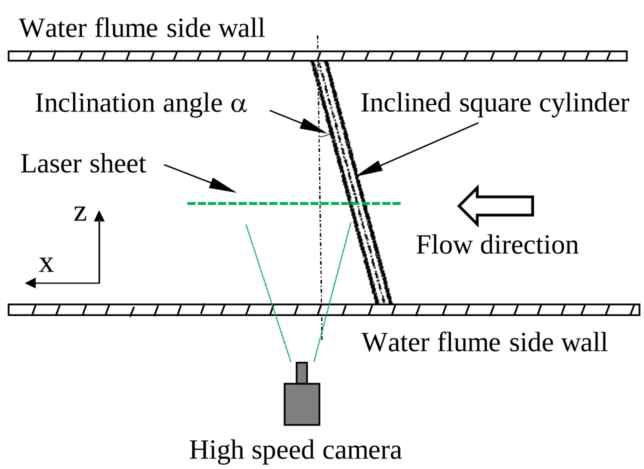

Figure 1. Schematics of the experimental setup (top view) and the definition of the coordinate system.

3. RESULTS AND DISCUSSION

The vortex shedding frequency and the corresponding Strouhal numbers St and St_N for different angles are listed in Table 1. The vortex shedding frequency is obtained by conducting a fast Fourier transform (FFT) to the transverse velocity component obtained on the wake centreline at $x/D = 3$ for different angles and the results are shown in Fig. 2. At $\alpha = 0°$, the spectrum shows a sharp and narrow-banded peak centred at a vortex shedding frequency of 1.12 Hz, corresponding to a Strouhal number of 0.132. This value agrees well with the results reported previously for a square cylinder (e.g. Okajima, 1982); Lyn et al., 1995). As α is increased to 15°, the peak magnitude reduces by half and the peak range is enlarged, reflecting the reduction of the vortex shedding intensity and the breakdown of the large-scale structures into smaller ones. As α is further increased to 30°, the peak magnitude is reduced to only 20% of that at $\alpha = 0°$, and the peak frequency (0.91 Hz) is about 20% lower than the value at $\alpha = 0°$. Besides, the frequency band is even enlarged, indicating a reduction of vortex shedding process. At $\alpha = 45°$, the spectrum does not show an apparent peak, indicating that there are no apparently dominated vortical structures. The differences of St_N at other angles compared with that at $\alpha = 0°$ (St_0), as shown in Table 1, are about 3%, 6% and 10% for $\alpha = 15°$, 30° and 45°, respectively. Considering the turbulent intensity of the water flume and the uncertainty in the PIV measurement, the uncertainty of the Strouhal number is estimated to be less than 8% using the propagation of errors. Therefore, the present results denote the invalidity of the IP at $\alpha = 45°$ if a tolerance of ±8% is allowed.

Furthermore, by analysing the vortex structures at various cylinder inclination angles, it is found that the generation of the axial flow near the base of the cylinder limits the communication between the shear layers and hence influences the shedding process of the spanwise vortices. These results manifest the strong three-dimensionality of the wake flow at large inclination angles, which leads to the invalidity of the IP when $\alpha \geq 45°$. However, due to the limitation of page number, the results about the dependence of the vortex structures on cylinder inclination angle will be shown during the oral presentation.

Table 1. 1 Vortex shedding frequencies (Hz) and the corresponding Strouhal numbers at different inclination angles.

Angle	Shedding frequency f_v	Strouhal number St	Strouhal number St_N	Differences of St_N compared with St_0
0°	1.12	0.132	0.132	0
15°	1.05	0.124	0.128	3%
30°	0.91	0.107	0.124	6%
45°	0.71	0.084	0.119	10%

4. CONCLUSIONS

Experimental studies on the inclined square cylinder wakes in steady flow at $Re = 3400$ were conducted in a water flume. The effects of the cylinder inclination angle on vortex shedding frequency, velocity evolution along the centreline and the vortex structures were examined. It is found that the vortex shedding energy and frequency decrease with the increase of the yaw angle. When the vortex shedding frequency is normalized by the velocity component normal to the cylinder axis, the corresponding Strouhal number St_N at $\alpha = 45°$ deviates from that at $\alpha = 0°$ by about 10%. Allowing a tolerance of 8% due to the experimental uncertainty, the present study indicates that the IP is no longer valid when the yaw angle exceeds 45°. In exploring the reasons for the invalidity of the IP at $\alpha = 45°$, the elongated vortex formation length, the distorted vorticity contour and the reduction of the vorticity strength indicate the significant effects of yaw angle on wake flow.

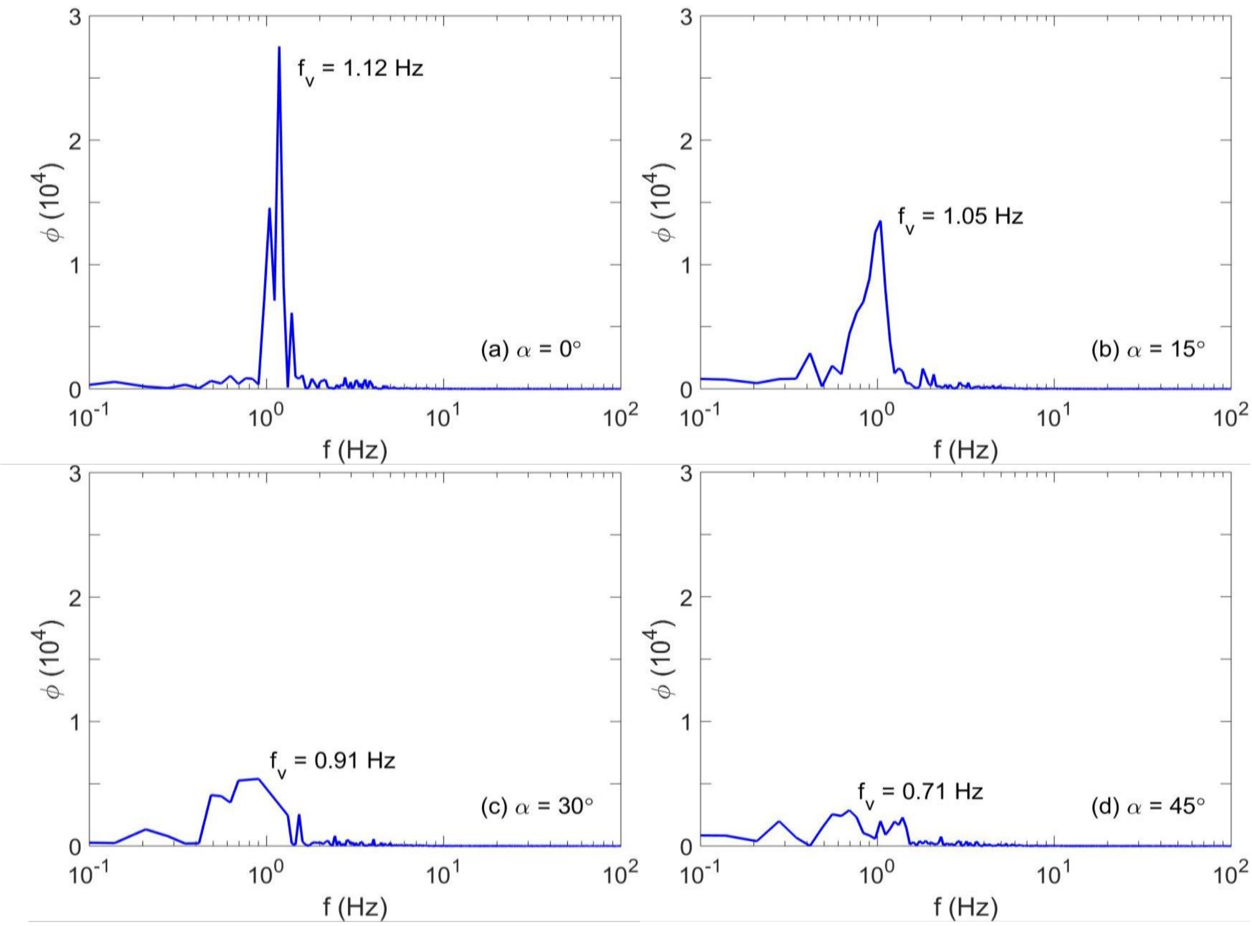

Figure 2. Spectra of the transverse velocity ν on the centerline of the square cylinder at *x/D* = 3 for different angles.

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