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Hydrodynamic coefficients of a yawed square cylinder in oscillatory flows

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ABSTRACT

The effect of yaw angle (α) on hydrodynamic forces and vortex shedding regime classification of a square cylinder oscillating in still water is examined. The Independent Principle (IP), which states that the Strouhal number and the drag coefficient are independent of α if the normal velocity component is used, was examined in oscillatory flows. Hydrodynamic forces were measured over a Keulegan-Carpenter number (KC) range of 3–30 and a Stokes parameter (β) range of 500–1600. For KC=8−20, the drag coefficient at α=45° is about 46% higher than that at α=0°, indicating the invalidity of the IP in oscillatory flow over this KC range. The inertia coefficient decreases with the increase of the yaw angle, except for KC=8–20, where the sudden drop in the distribution is absent at α=45°. Apart from this KC range, the inertia coefficient follows the IP better than the drag coefficient does. In addition, the lift coefficient increases with the increase of cylinder yaw angle. The results of the lift force spectra and the lift coefficients imply that the existence of the cylinder yaw angle has an intensified effect on the vortex shedding process around a square cylinder in oscillatory flows.

1. Introduction

Oscillatory flow around a cylindrical structure is of importance due to its intrinsic interest in theoretical hydrodynamic research and its relevance to practical engineering applications. Knowledge of the hydrodynamics is essential for both the design and operation of offshore structures, such as semisubmersibles and tension leg platforms. For some cylindrical structures, owning to their directionality, the sea waves and/or currents can approach the structures obliquely. In these cases, the fluid velocity in the axial direction of the structure is not negligible, which may have profound effect on the vortex instability, vortex regime classifications and force characteristics of the structure. For a yawed circular cylinder in steady current, it has been found that over a certain range of yaw angle, the normalized vortex shedding frequency, i.e. Strouhal number St_N ($\equiv f_0 D/U_N$, where f_0 is the vortex shedding frequency, D is the diameter of the cylinder, $U_N \equiv U_\infty \cos(\alpha)$ is the flow velocity component normal to the cylinder axis, and U_∞ is the free stream velocity and α is the angle between the incoming flow and the plane perpendicular to the cylinder axis) and the drag coefficient C_{DN} ($\equiv F_D/(1/2\rho U_N^2 D)$, where F_D is the drag force and ρ is the density of the fluid), are the same as those when the cylinder encounters a normal incidence flow. This is normally known as the Independent Principle (IP), or the Cosine Law. In oscillatory flows or waves, a number of studies on a yawed circular cylinder have been reported to describe the effect of the yaw angle on the hydrodynamic coefficients as a function of the Keulegan-Carpenter number KC ($\equiv U_m T/D$, where U_m is the maximum velocity of the sinusoidal oscillation and T is the oscillatory period) and the Stokes number β ($\equiv$Re/KC, where Re$\equiv U_m D/\nu$ is Reynolds number and ν is the kinematic viscosity of the fluid) (Sarpkaya, 1982; Cotter and Chakrabarti, 1984; Chakrabarti and Armbrust, 1987; Sundar et al., 1998; Franzini et al., 2009).

According to the results of a yawed circular cylinder in the harmonically oscillatory flow by Sarpkaya (1982), the IP does not apply due to the significant deviation in the normalized drag coefficients of the yawed cylinder from those of the vertical one, except in the drag-dominated high KC range (>20) where the IP may be valid. It was also concluded that in waves the IP may not apply at all. The lack of the coherent spanwise vortices for yawed cylinders results in the absence of the inertia crisis, the increase of the inertia coefficients, as well as the decrease of the drag and lift coefficients. Cotter and Chakrabarti (1984) measured the oscillatory wave forces on a fixed yawed circular cylinder at three yaw angles (i.e. α= 0°, 30° and 45°). They found that the variations in both the inertia coefficient C_{MN} ($=F_M/(1/2\rho U_{mN}^2 D)$, where F_M is the measured inertia force and U_{mN} is the maximum velocity of the sinusoidal oscillation normal to the cylinder axis) and the drag coefficient C_{DN} ($=F_D/(1/2\rho U_{mN}^2 D)$, where F_D is the measured drag force) among different angles may be ignored for KC > 5. Therefore, the IP for the yawed cylinder seems valid if the normal components of the velocity and acceleration are applied in Morison's equation. However, based on the study of the total force coefficient for a yawed circular cylinder in oscillatory flows, Chakrabarti and Armbrust (1987) pointed out that the large variations in both the drag and inertia coefficients,

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which indicate the invalidity of the IP, are observed for the cylinder yaw angles between 60° and 90° (which correspond to α=30° and 0°, respectively, based on the yaw angle definition in the present study) in KC range of 10–20. This result occurs only in oscillatory flow due to the returning of the vortices shed in the previous cycle to the subsequent cycle. While for waves, the randomness of the wake field and the less dependence on the flow history make the flow more stable and the force coefficients less sensitive to the yaw angle. The influence of the cylinder yaw angle with respect to the wave directions was also studied by Anandkumar et al. (1995) under different wave conditions. They concluded that the shedding of vortices in the long-period waves results in remarkable scattering in the measured forces. Especially, for the force normal to the cylinder axis, the changes for different yaw angles are significant subjected to the long waves. While for short waves, the force does not vary with the angle, indicating that the IP works better in short waves than that in long waves. Sundar et al. (1998) conducted some tests on cylinders yawed both against and along the direction of wave propagation with α=0–45°. It is found that the orientation angle of the cylinder with respect to the vertical axis has to be considered in the evaluation of wave pressure, especially for KC<4. The drag coefficient for α=45° is found to be slightly higher than that of other angles while the inertia coefficient for α=0° is found to be much higher than that of other angles for KC<3, which invalidates the IP at rather small KC values. Franzini et al. (2009) experimentally investigated the vortex-induced vibration of yawed cylinders which were constrained to oscillate only in the transverse direction. Both the lift and drag coefficients decrease as the yaw angle increases as expected. However, the values of the lift force coefficient for all angles follow a similar behavior over the tested KC range (3–14) as long as the normal velocity component is considered in the evaluation. In terms of the lift coefficient, it seems that the IP is satisfied better for a transversely oscillating circular cylinder than that oscillating in the in-line direction.

In offshore engineering, the slender structures may have either square or rectangular cross-sections. The generation and shedding of the vortices from these structures in currents, waves or a combination of them, which determine the fluid loading on bluff bodies, normally reveal a high dependence on the geometry of the cross-sections (Bearman et al., 1984). According to Graham (1980), the separation process of a sharp-edged cross-section is independent of Reynolds number and the geometry with a continuous surface variation may have separation points changing with respect to time. Comparisons were made in terms of the forces on two kinds of cylinders with sharp-edged cross-section represented by a normal flat plate and a diagonal square prism with those on a circular cylinder in oscillatory flows. The results indicate that the prediction of C_{MN} and C_{DN} with Morison's equation is not satisfactory for lower KC, especially for sharp-edged cylinders. It is also found that the measured forces on a square cylinder with one edge normal to the flow do not follow the trend implied by the proposed equation due to the interference between all four edges with vortices shed at different times in one cycle. Mean and fluctuating pressure results measured by Bearman and Obasaju (1982) on a square cylinder with one edge normal to the upstream flow indicate that the fluctuating lift coefficient on a square cylinder is greater than that reported for a circular cylinder. By oscillating the cylinder transversely to the incoming flow, they found that the phase of the lift force relative to the cylinder displacement is positive only towards the upper limit of the lock-in range, which is substantially different from that observed for a circular cylinder with positive values for the lift force relative to the cylinder displacement throughout the lock-in range. Bearman et al. (1984) investigated the influence of corner radius on the forces experienced by cylinders in oscillatory flows, where the non-dimensional edge radius $r/D = 0$ corresponds to the square cross-section and $r/D = 0.5$ corresponds to the circular one. The inertia coefficient C_{MN} is the highest for the square cylinder and decreases significantly with the increase of corner radius. The square cylinder also experiences higher drag coefficient C_{DN} for KC<9 whereas the C_{DN} values of the circular cylinder dominate within the KC range of 10–20. In addition, the effect of corner radius seems to be more sensitive in the oscillatory flow than that in the steady flow due to the fact that the vortices sweeping periodically and the generation of the fully turbulence delays the separation process of vortices. The sectional wave forces on square and rectangular cylinders were measured by Venugopal et al. (2006) with the cylinder axis parallel to the wave crest. They found that the drag coefficients at low KC exhibit large values and these coefficients decrease sharply with the increase of KC. For inertia coefficients, they approach the potential flow value of 2.5 at low KC and show an increase when KC becomes larger. The Stokes parameter β, however, does not have much effect on the measured drag and inertia coefficients and hence suggesting that the force coefficients are free from Reynolds number effect. Apart from experiments, numerical simulations on the interactions between the oscillatory flow and a square cylinder were also conducted by Cho and Kang (1997) and Chern et al. (2007). The former simulated the vortex shedding from a square cylinder using finite volume method and summarized that the vortex shedding frequency is half of the force frequency because of the secondary vortex, which is generated by the oscillating inlet velocity with large amplitude. The latter studied the oscillatory flow field of a square cylinder at Re=200–500 and KC=1–15 and concluded that Re does not influence the force coefficients significantly while KC dominates the variation of the force coefficients. More and more harmonics in the in-line force are observed with the increase of KC.

While the flow and hydrodynamic features of a yawed circular cylinder in oscillatory flow have been reported extensively, our knowledge about the wake characteristics of a yawed square cylinder in oscillatory flow is limited. It has been showed previously that the yaw angle of a square cylinder plays significant roles in the evolution of flow instabilities and force characteristics in steady flow (Lou et al., 2016). In the present study, a square cylinder undergoing forced sinusoidal oscillation in quiescent water was studied at four different yaw angles, namely α=0°, 15°, 30° and 45°. To investigate the application of the IP in the subcritical flow (Re=2700–38,000) regime, the in-line and lift forces were measured with a 3-component force link. The effect of the yaw angle on the hydrodynamics of a square cylinder and the comparison with a circular cylinder are demonstrated in this paper.

2. Experimental setup

The schematic diagram of the experimental setup is shown in Fig. 1. The experiments were conducted in a water flume with dimensions of 0.4 m (width)×15 m (length)×0.5 m (depth). A belt-driven linear actuator (HISAKA) was used to achieve the linear oscillating movements. A 7340-type NI (National Instrument) motion control card inserted in the main computer was used for the communication with a motion controller UMI-7764 (Universal Motion Interface). An in-house sine wave generation software with was applied to control the designed

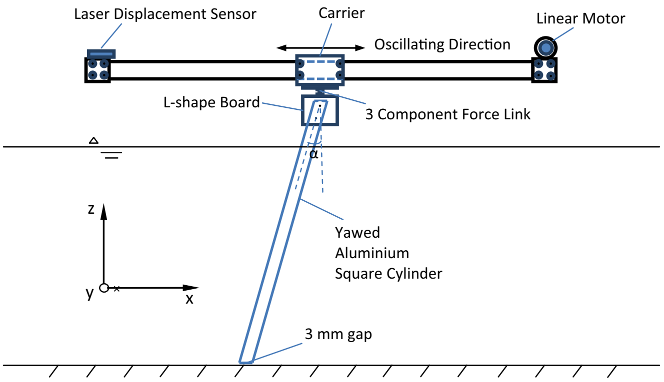

Fig. 1. Schematic diagram of the experimental setup.