International Journal of Heat and Fluid Flow 57 (2016) 58–78

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

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

Two-degree-of-freedom vortex induced vibration of low-mass horizontal circular cylinder near a free surface at low Reynolds number

Meng-Hsuan Chung*

Department of Naval Architecture and Ocean Engineering, National Kaohsiung Marine University, No. 142, Haijhuan Rd., Nanzih District, Kaohsiung City 811, Taiwan, ROC

ARTICLE INFO

Article history:
Received 24 May 2015
Revised 21 October 2015
Accepted 28 October 2015

Keywords:
Vortex induced vibration
Free surface
Horizontal circular cylinder
Two degree of freedom
Low Reynolds number
Adaptive Cartesian cut-cell/level-set method

ABSTRACT

Two-degree-of-freedom vortex induced vibration (VIV) of a low-mass zero-damping circular cylinder horizontally placed near a free surface at $Re = 100$ was numerically studied with an adaptive Cartesian cut-cell/level-set method. Two Froude numbers and various normalized submergence depths were considered. The results reveal that the Froude number affects the critical normalized submergence depth and possible physical mechanisms are proposed. The in-line vibration amplitude cannot be neglected. Proximity to a free surface strengthens and suppresses the VIV for low and high Froude numbers, respectively; increases the occurrence of amplitude modulation; and in general enhances the magnitude of the time-averaged lift coefficient, which is always negative. The phase lag of the transverse displacement behind the lift coefficient jumps at some reduced velocity, which strongly depends on the Froude number and normalized submergence depth. Regular trajectories exist only in cases with a small vibration amplitude or a large normalized submergence depth. The vortex structures in any case with large transverse amplitude basically originate from the alternative vortex shedding with the negative vortex weaker than the positive one. For the higher Froude number, an extra free surface positive vortex interacts with the vortices from the cylinder surface. The vibration frequency deviates from the natural structure frequency in fluids in the large-amplitude regime.

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1. Introduction

Flow over a circular cylinder has attracted much interest among researchers. Vortex shedding in the wake of the circular cylinder frequently occurs and causes periodic forcing to the cylinder. If the cylinder is allowed to vibrate freely (or spring supported) in the flow, the vortex shedding and the cylinder motion will influence each other, eventually causing some type of cylinder vibration, called vortex induced vibration (VIV). When the frequency of the wake vortex mode matches that of the cylinder vibration, the "lock-in" (also called "resonance" or "synchronization") phenomenon occurs. The vibration amplitude is not necessarily large when lock-in occurs. For the sake of brevity, the term "lock-in" in the present study implies the lock-in with large vibration amplitude.

Hydrodynamic characteristics of VIV are expected to drastically change when the circular cylinder is placed close and parallel to a free surface. However, hardly any literature can be found on this subject. Below reviewed is literature on studies of a circular cylinder deeply submerged or near a free surface.

1.1. VIV of an isolated circular cylinder

VIV of an *isolated* circular cylinder, rigid or flexible, has been studied extensively in the literature. The parameters involved are the mass ratio $m* (= m/m_d)$, damping ratio ζ $(= c/c_{crit})$, reduced velocity $U* (= U/f_{nw}D)$, and Re $(= UD/\nu)$ where m = cylinder mass, m_d = displaced fluid mass, c = structural damping, c_{crit} = critical damping, U = free-stream velocity, f_{nw} = natural structure frequency in fluids, D = cylinder diameter, and ν = kinematic viscosity. Some researchers defined the reduced velocity based on other velocity scales and/or natural structure frequency in vacuum. Much of the previous research is reviewed in Williamson and Govardhan (2004) and Bearman (2011).

Particularly, there have been many publications on transverse VIV with low mass-damping value. The great progress made by Khalak and Williamson (1996, 1999) and Govardhan and Williamson (2000) can be summarized as follows. The response amplitude A versus U presents three distinct branches; namely the *initial*, *upper*, and *lower* branches. In the upper branch, the vibration amplitude can be twice as large as that for the classical high mass-damping value of Feng (1968). Meanwhile, the "lock-in" zone is dramatically extended in contrast to that of Feng (1968). Moreover, the mode of vortex shedding is 2S (two single vortices shed per cycle) in the initial branch and 2P (two pair vortices shed per cycle) in the lower branch. The

* Tel.: +886 7 3617141x3076; fax: +886 7 3646481.
E-mail address: mhsuan@webmail.nkmu.edu.tw, meng.hsuan.chung@gmail.com

http://dx.doi.org/10.1016/j.ijheatfluidflow.2015.10.004
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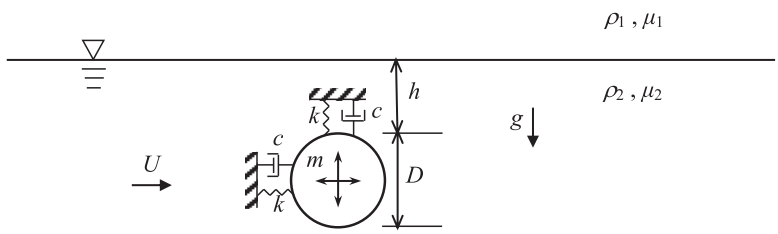

Fig. 1. Definition of problem. U: inflow velocity, g: gravitational acceleration, D: cylinder diameter, m: cylinder mass, k: spring constant, c: structural damping coefficient, h: distance between quiescent free surface (numerically modeled as a fluid interface) and cylinder top in the static-equilibrium status, ρ_i: mass density of the ith fluid phase, μ_i: dynamic viscosity of the ith fluid phase.

2P mode was also observed in the upper branch, but the second vortex of each pair is much weaker than the first one. Some numerical studies have also reported the 2P mode (Blackburn et al., 2000; Lucor et al., 2005). On the other hand, their works and others mentioned in Khalak and Williamson (1999) had confirmed that the vibration frequency normalized by f_{nw}, within the regime of large amplitude response, increases as m^* is reduced such that the vibration frequency considerably deviates from f_{nw} for a small m^*. Williamson and Govardhan (2008) briefly summarized fundamental results and discoveries related to VIV with very low mass-damping value.

More and more researchers investigated VIV by computational fluid dynamics (CFD) techniques (Guilmineau and Queutey, 2004; Wanderley Juan et al., 2008). Al Jamal and Dalton (2005) reviewed some important numerical studies.

1.2. Fixed cylinder beneath a free surface

Two additional parameters have to be considered for this problem configuration, that is, the Froude number, Fr (defined as $U/(gD)^{1/2}$ with g denoting the gravitational acceleration), and the normalized submergence depth, h/D (h = distance from the cylinder top to the quiescent free surface). Miyata et al. (1990) found that vortex shedding is suppressed when h/D is very small at $Re = 4.96 \times 10^4$ and $Fr = 0.24$. Sheridan et al. (1997) experimentally observed that the near-wake structure for small h/D falls under a number of modes which are very different from those for $h/D = \infty$.

Carberry (2002) observed three different wake states (Modes I, II, and III) as h/D decreases, agreeing with the wake structures previously reported by Sheridan et al. (1997) and Reichl et al. (2005). Mode I wake is essentially a modified Kármán wake with the amplitude of the fluctuating lift force larger than that for $h/D = \infty$. The periodic vortex shedding appears to be suppressed and the lift varies little with time in both Modes II and III. The flow over the top of the cylinder remains attached to and separates from the free surface for Modes II and III, respectively. In Mode III, the separated flow forms a jet which can either remain attached to the cylinder or flow downwards obliquely.

1.3. Oscillating cylinder beneath a free surface

For this problem configuration, we define A and f_e as the oscillation amplitude and frequency respectively and f_o the vortex shedding frequency for an isolated fixed circular cylinder. Cetiner and Rockwell (2001) experimentally investigated the streamwise oscillations with $A/D = 3/\pi$ and $h/D = 0.06$, 0.19, and 11.23 at $f_e/f_o = 1$ and 0.44, corresponding to $Fr = 0.07$ and 0.16, or $Re = 917$ and 2075. They found that the transverse force is phase-locked to the cylinder motion when $h/D \approx 0$ and such locked-in states are destabilized because of an instantaneous jet-like flow mentioned above when h/D is finite. Vortex structures exist at locations both upstream (generated from the free surface) and downstream of the cylinder. The numerical study of Bozkaya et al. (2011) considered $A/D = 0.13$, $Fr = 0.2$, and $Re = 200$ with $h/D = 0.25$, 0.5 and 0.75 at $f_e/f_o = 1.5$, 2.5, 3.5. They reported the effects of h/D and f_e/f_o on the mode, period, and geometry of vortex shedding as well as the lock-in phenomena.

For a transversely oscillating circular cylinder, Carberry et al. (2004) considered $A/D = 0.5$, $h/D = 11/16$, 7/8, and 10.5, $Fr = 0.166$, and $Re = 2100$, while $0.76 < f_e/f_o < 1.05$. The most important finding is the lift-phase jump at $f_e/f_o \approx 0.82$ for various h/D considered. The vortex shedding appears to be inhibited but not eliminated when h/D decreases. The lift force is negative in all the study cases. Chung (2015) numerically studied cases with $A/D = 0.2$–0.6, $h/D = 0.4$, 0.8, and ∞, $Fr = 0.2$–0.8, and $Re = 100$, while $0.25 < f_e/f_o < 2$. He also reported jump of the amplitude and phase of lift, however not accompanied by considerable changes of vortex shedding timing. The vortex shedding mode tends to be double-row for deep and single-row for shallow submergence. Magnitude of the negative time-averaged lift increases with decreasing h/D. The cylinder approaching to a free surface suppresses occurrence of beating in the temporal variation of lift.

1.4. VIV of a circular cylinder near a free surface

To the author's knowledge, similar works have been rarely seen in the literature. Saelim (1999) investigated the one-degree-of-freedom (one-DOF) transverse VIV of an elastically mounted rigid horizontal circular cylinder beneath a free surface with $m^* = 2.7$, $\zeta = 0.0006$, $h/D = 0$–3, $Fr = 0.072$–0.432, corresponding to $Re = 321$–1927. The results showed that, for small h/D, very large regions of hysteresis occur in the variation of vibration amplitude as a function of reduced velocity. For large values of h/D, the vibration frequency is higher than f_{nw} and lower than f_0 in the lock-in zone; for very small h/D, the vibration frequency takes on values close to f_0, hence much higher than f_{nw}. Rockwell et al. (2003) later presented some typical vortex shedding regimes for $h/D = 0$.

In view of the two earlier works, the present numerical study aims to understand thoroughly and deeply the two-degree-of-freedom (two-DOF) VIV of a low-mass ($m* = 2$) zero-damping circular cylinder near a free surface in the low Reynolds number regime ($Re = 100$). We focused on the effects of Froude number and normalized submergence depth on the cylinder trajectories, hydrodynamic force coefficients, and vortex structures as function of reduced velocity. Also, the present study reexamines various characteristics of low-mass-damping VIV which has been reported for the transverse VIV with much higher Reynolds numbers (Khalak and Williamson, 1999) than the present one. In other words, we would like to recheck the existence of the upper-branch response and 2P mode of vortex shedding with $Re = 100$, particularly in proximity to a free surface. No similar works have been ever published. Fig. 1 shows the schematics of the present problem.

2. Governing equations

The free surface is regarded as the interface between two fluids with highly different values of density and viscosity. Relevant dimensionless parameters thus include, besides those for the single-phase

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