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# Hydrodynamics of flow over a transversely oscillating circular cylinder beneath a free surface

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ABSTRACT

In this paper, hydrodynamic force coefficients and wake vortex structures of uniform flow over a transversely oscillating circular cylinder beneath a free surface were numerically investigated by an adaptive Cartesian cut-cell/level-set method. At a fixed Reynolds number, 100, a series of simulations covering three Froude numbers, two submergence depths, and three oscillation amplitudes were performed over a wide range of oscillation frequency. Results show that, for a deeply submerged cylinder with sufficiently large oscillation amplitudes, both the lift amplitude jump and the lift phase sharp drop exist, not accompanied by significant changes of vortex shedding timing. The near-cylinder vortex structure changes when the lift amplitude jump occurs. For a cylinder oscillating beneath a free surface, larger oscillation amplitude or submergence depth causes higher time-averaged drag for frequency ratio (=oscillation frequency/natural vortex shedding frequency) greater than 1.25. All near-free-surface cases exhibit negative time-averaged lift the magnitude of which increases with decreasing submergence depth. In contrast to a deeply submerged cylinder, occurrences of beating in the temporal variation of lift are fewer for a cylinder oscillating beneath a free surface, especially for small submergence depth. For the highest Froude number investigated, the lift frequency is locked to the cylinder oscillation frequency for frequency ratios higher than one. The vortex shedding mode tends to be double-row for deep and single-row for shallow submergence. Proximity to the free surface would change or destroy the near-cylinder vortex structure characteristic of deep-submergence cases. The lift amplitude jump is smoother for smaller submergence depth. Similar to deep-submergence cases, the vortex shedding frequency is not necessarily the same as the primary-mode frequency of the lift coefficient. The frequency of the induced free surface wave is exactly the cylinder oscillation frequency. The trends of wave length variation with the Froude number and frequency ratio agree with those predicted by the linear theory of small-amplitude free surface waves.



## 1. Introduction

Flow over a circular cylinder transversely oscillating beneath a free surface has many realized and potential applications in the design of hydraulic, offshore, and marine structures, underwater vehicles and appendages, marine pipelines and

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water-based power plant. However, very little literature can be found on this subject. The present study aims to understand thoroughly and deeply this topic by systematically investigating effects of relevant parameters on hydrodynamic characteristics and flow structures involved in this physical process.

Important dimensionless parameters of the present problem include the normalized submergence depth, $h/D$, normalized amplitude of oscillation, $A/D$, frequency ratio, $f_e/f_o$, the Reynolds number, $\mathrm{Re} \equiv \rho_2 UD/\mu_2$, the Froude number, $\mathrm{Fr} \equiv U/(gD)^{1/2}$, the density ratio, $\rho_2/\rho_1$, and the dynamic viscosity ratio, $\mu_2/\mu_1$. The involved variables are defined as follows. $U$: inflow velocity, $g$: gravitational acceleration, $D$: cylinder diameter, $A$: amplitude of oscillation, $f_e$: frequency of oscillation, $h$: distance between still fluid surface and cylinder top when the cylinder moves to the equilibrium position, $\rho_i$ and $\mu_i$: respectively mass density and dynamic viscosity of the $i$-th fluid phase, and $f_o$: the vortex shedding frequency of a similar flow in which the circular cylinder is fixed and deeply submerged. We assume $\rho_2 > \rho_1$. Fig. 1 shows the schematics of the present problem.

Large amount of literature can be found on a circular cylinder which is fixed beneath a free surface, or oscillating in deep submergence. However, cylinder oscillating beneath a free surface attracts much less interest of researchers. The state-of-the-art of the researches on the above topics is reviewed as follows:

### 1.1. Fixed cylinder beneath a free surface

Miyata et al. (1990) reported asymmetric pressure distributions around the cylinder surface when the cylinder is located close to a free surface. They conducted experiments and numerical simulations at $\mathrm{Re} = 4.96 \times 10^4$ and $\mathrm{Fr} = 0.24$. They found that at very small values of $h/D$, though unsteadiness still appears, the periodic fluctuation of the near wake was essentially eliminated, indicating that vortex shedding is suppressed when the cylinder is very close to a free surface. Sheridan et al. (1997) conducted experiments using the PIV technique and found that close to a free surface the near-wake structure falls under a number of modes which are very different from those of the deeply submerged cylinder wake.

Carberry (2002) observed three different wake states (modes I, II, and III) as $h/D$ decreases. They presented these wake states in terms of both the lift force on the cylinder and the structure of the near wake. These three wake states agree with the wake structures reported in other experimental (Sheridan et al., 1997) and numerical (Reichl et al., 2005) studies. The mode I wake is essentially a modified Kármán wake: the mode of vortex shedding is very similar to the deeply submerged case. However, the amplitude of the fluctuating lift force is larger than that of the latter case. The mode II and then mode III wakes occur when $h/D$ decreases. The periodic vortex shedding appears to be suppressed and the lift varies little with time in these two modes. The flow over the top of the cylinder remains attached to and separates from the free surface for the modes II and III respectively. In the mode III wake, the separated flow forms a jet which can either remain attached to the cylinder or flow downwards obliquely.

### 1.2. Deeply submerged oscillating cylinder

Many studies on flow over a cylinder subject to forced oscillation can be found in literature. The hydrodynamic forces (especially the lift force) and wake structures for $f_e/f_o$ near unity are two focuses of interest. On one hand, Bishop and Hassan (1964) found a simultaneous jump in the phase and amplitude of the lift force as $f_e/f_o$ passes through unity. Then many researchers (Mercier, 1973; Staubli, 1983; Gopalkrishnan, 1993; Sarpkaya, 1995; Carberry et al., 2001; Carberry, 2002) have reported this phenomenon in a large amount of cases with different $A/D$ and Re. On the other hand, over this range of frequency, Williamson and Roshko (1988), Ongoren and Rockwell (1988), Gu et al. (1994), Lu and Dalton (1996), Carberry et al. (2001), and Carberry (2002) have observed changes of the near-wake structure in terms of vortex shedding mode or timing. Carberry et al. (2001) identified the correspondence of the lift-force jump to the wake-structure transition. Specifically, the low-frequency wake exhibits largely 2P mode, with two counter rotating pairs shed per oscillation cycle. Vortices in the high-frequency wake are shed in 2S mode, with two single vortices being shed per oscillation cycle. They have discussed in detail on the evolution of the low- and high-frequency wakes. Particularly for low Reynolds numbers, Koopmann (1967) established a lock-on region on the frequency-amplitude plane. Here lock on is defined as the condition in which the vortex shedding frequency coincides with the oscillation frequency. Anagnostopoulos (2000), Nobari and Naderan (2006), and Placzek et al. (2009) performed low-Re numerical investigations. Their works reported no change of vortex shedding mode mentioned above. Meanwhile, they observed frequency modulation, or beating, phenomenon in the time history of lift coefficient for most cases with high frequency ratios.

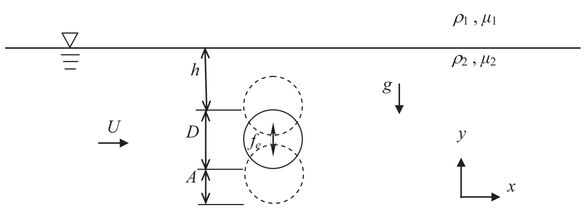


**Fig. 1.** Definition of problem. $U$: inflow velocity, $g$: gravitational acceleration, $D$: cylinder diameter, $A$: amplitude of oscillation, $f_e$: frequency of oscillation, $h$: distance between still fluid surface and cylinder top when the cylinder moves to the equilibrium position, $\rho_i$: mass density of the $i$-th fluid phase, $\mu_i$: dynamic viscosity of the $i$-th fluid phase.

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