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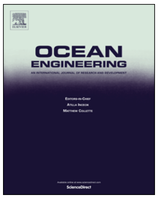

Comparison of flow fields induced by fixed and oscillatory vertical cylinders in regular waves using 3D numerical model

Yi Han[a], Jie-Min Zhan[a,*], Wei Su[a], Yok-Sheung Li[b], Quan Zhou[a]

[a] *Department of Applied Mechanics and Engineering, SunYat-sen University, Guangzhou 510275, PR China*
[b] *Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong*

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ABSTRACT

The influences of a flexibly mounted cylinder and a fixed cylinder on the flow field in regular waves are studied numerically. Performances of the flexibly mounted cylinder oscillating freely in still water and in regular waves are first simulated. Then the in-line forces on the two cylinders in regular waves are compared to the theoretical results. All results indicate the present model is valid. Then the entire flow fields induced by the two cylinders are analyzed in detail. The windward and leeward regions of the cylinder are each divided into eight sections. Results of the windward side are complex because of the superposition of incoming and reflected waves. Results of the leeward side show that the sectional average wave height decreases as the wave frequency increases. In general, the flexibly mounted cylinder attenuates wave energy more effectively. Moreover, the wave frequency is a major factor influencing the flow field. When the incident wave frequency approaches the natural frequency of the cylinder, differences of the two data sets become significant. Distance between the section and the cylinder is another influential factor. The two sets of results become more similar as the distance increases, especially in cases of low incident wave frequencies.

1. Introduction

Many coastal and offshore structures have circular-cylinder-like components, such as bridge piers, cables, tension leg platforms and wave attenuation devices. The flow field induced by the interaction between these structures and the ocean wave is complicated, which may cause either favorable or adverse effects on objects nearby. Therefore, it is necessary to study this kind of fluid–structure interaction (FSI) and the resulting flow field. In the past decades, large amounts of research works on the flow field around a circular cylinder in unidirectional oscillatory waves have been carried out. Comprehensive reviews of this topic can be found in various publications (Sarpkaya and Isaacson, 1981; Sumer and Fredsøe, 2006).

Experimental measurement and numerical method are possible ways to investigate the coupled problem of the interaction between structures and fluids. So far, the interaction between a fixed cylinder and wave has been well studied. Chau and Taylor (1992) provided a detailed analysis of the second-order diffraction problem of a uniform vertical circular cylinder in regular waves. Their analysis contained results of the cylinder surface and the free surface in the fluid domain surrounding the cylinder. Kim et al. (2006) developed a finite element method to solve the fully nonlinear diffraction problem by vertical circular cylinders. They used a scheme that matches the Stokes wave solution in the far field with the diffracted nonlinear wave in the near field. They also compared the wave elevation and run-up on the cylinder with the available theoretical and experimental results. Park et al. (1999) developed a three-dimensional NS–MAC numerical wave tank to investigate the nonlinear interaction of a vertical truncated circular cylinder with large-amplitude waves. They claimed that their numerical results, through comparison with the experimental results, are more reliable for higher harmonic pressure, run-up, and forces. Bai and Taylor (2007) applied a higher-order boundary element method to solve the wave propagation and diffraction around a vertical circular cylinder in a numerical wave tank. By comparing with experimental data, they found that their domain decomposition technique is efficient and accurate. Similar works like those mentioned above have been carried out by many researchers (Büchmann et al., 1998; Boo, 2002; Faltinsen et al., 1995; Li and Lin, 2001; McIver, 1993; Nam et al., 2012; Yang and Ertekin, 1991). However, few of them focus on the flow field around the cylinder.

On the other hand, characteristics of the excited oscillation of a flexibly mounted cylinder in wavy flow field are well studied by experiments. Yang and Rockwell (2004) used techniques of high-image-density particle image velocimetry (PIV) to characterize the three-dimensionality of the flow structure around a vertical cylinder

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[*] Corresponding author. Tel./fax: +86 20 8411 1130.
E-mail addresses: stszjm@mail.sysu.edu.cn, cejmzhan@gmail.com (J.-M. Zhan).

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in deep-water wave. Downes (1999), Downes and Rockwell (2003) and Ozgoren and Rockwell (2007) used the same technique to make in-depth research works on various aspects of similar problems. Li et al. (2007) investigated the in-line response of a vertical flexibly mounted cylinder in regular and random waves with experiment and theoretical analyses. They also analyzed the energy dissipation of the flow field induced by the oscillatory cylinder using records of wave gages. Comparing to experimental achievements, there are very few numerical investigations on this topic. Although similar studies, such as vortex-induced vibration (VIV) (Anagnostopoulos and Iliadis, 1998; Guilmineau and Queutey, 2004; Jauvtis and Williamson, 2004; Pan et al., 2007; Shiels et al., 2001; Zhao et al., 2012a, 2012b) or response of floating cylinders in wave (Liu et al., 2001; Wu and Hu, 2004; Yeung and Sphaier, 1989; Zeng and Tang, 2013), are available, further studies on this topic should be carried out to fill the gap.

To the knowledge of the authors, few studies compare the detailed flow fields induced by fixed and moving structures. Ozgoren and Rockwell (2007) studied the detailed flow patterns due to a stationary and a lightly damped vertical cylinder in a deep-water wave with experimental method. Bai and Taylor (2009) simulated the fully nonlinear wave interactions with fixed and floating vertical cylinders and flared structures by means of a higher-order boundary element model using the domain decomposition technique.

One of the advantages of numerical simulation is the feasibility of determining any physical variable at any arbitrary point inside the computational domain and hence it is utilized to investigate the interaction between wave and cylinders, and its effect on the flow field, the details of which could not be obtained by physical experiments. In this paper, the influence of a flexibly mounted cylinder and a fixed cylinder on the flow field in regular waves is studied numerically. The flow field is solved by a three-dimensional, unsteady, incompressible numerical model. The free surface is tracked by the volume of fluid (VOF) model. A dynamic mesh scheme is used to update the grid system in accordance with the motion of the cylinder. The equation for the oscillation of the cylinder is solved by the fourth-order Runge–Kutta algorithm. A wave absorbing method based on the porous media model is utilized to eliminate the reflected waves (Zhan et al., 2010). Boundary conditions and other details of the mentioned models are given in Han et al. (2015).

2. Numerical procedure

In this paper, the in-line response of a flexibly mounted vertical cylinder in regular waves is first calculated. Then the cylinder is fixed and the flow field is calculated under the same operating conditions.

Fig. 1 displays a sketch of the computational domain, which is set up in accordance with the experiment conducted by Li et al. (2007). The flexibly mounted cylinder is made from a plastic tube with an outside diameter of 215 mm and a length of 1.0 m. The cylinder is positioned vertically by two steel plates having a cross-section of 30 mm × 2 mm at its bottom. The mass of the cylinder is 14.7 kg. Detailed information on the experimental study can be found in Li et al. (2007).

The numerical wave flume is 1.5 m in width, with water depth of 0.6 m. The total length of the flume is $9L$ where L is the wave length. The diameter of the circular cylinder, D, is 0.215 m. The cylinder locates at $5L$ from the wave inlet boundary. The wave absorbing zone starts from $7L$ to the end of the flume. Five wave gages are installed near the cylinder to capture the variations of the wave height. There are 80 nodes around the perimeter of the circular cylinder. The minimum mesh size in the radial direction (adjacent to the cylinder surface) is $\Delta_r = 0.01D$. The total number of grids in the moving zone is 350,000, while that in the whole computational domain is about 2.2 millions. The time step size is set to $\Delta t = T/640$, and the total calculation time of each case is $30T$, where T is the wave period.

The motion of the cylinder is governed by the following equation:

$$m\ddot{X} + c_s\dot{X} + k_s X = F_x \tag{1}$$

where the values of the structural damping and stiffness coefficients, c_s and k_s, are assigned according to the experimental data. X is the displacement of the cylinder in the in-line direction with respect to the static balance position, m is the mass of cylinder. The force term, F_x, can be considered as a constant within a small

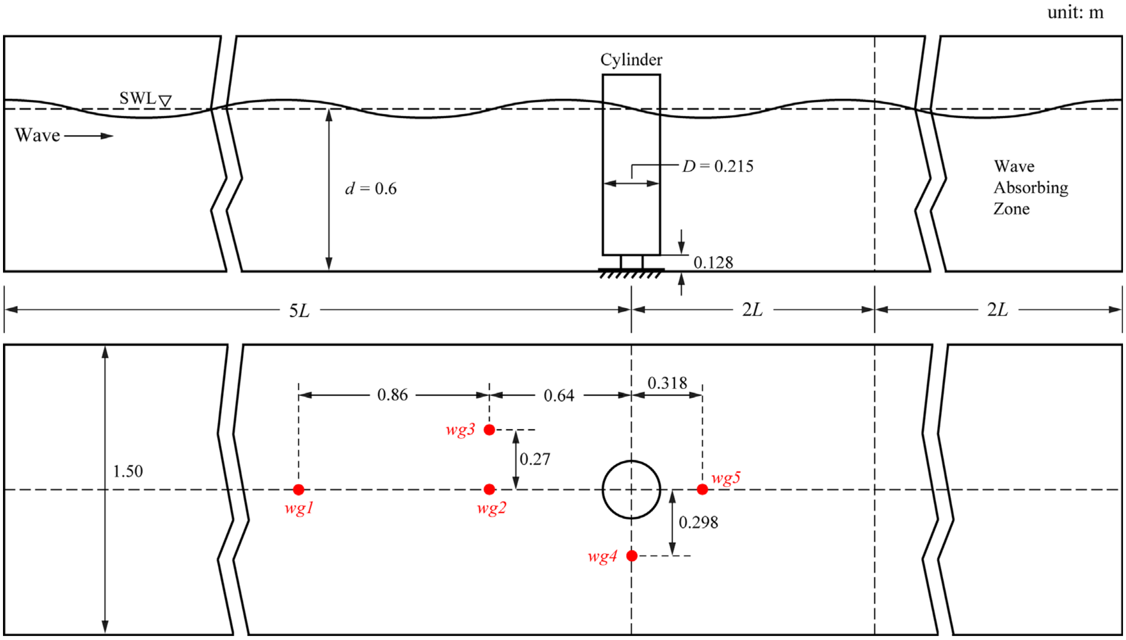

Fig. 1. Sketch of computational model.