Numerical study on the influence of heave motion on gap resonance between two floating boxes

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HIGHLIGHTS

This study aims to find out the influence of the heave motion of floating boxes on gap resonance. This paper compares the gap resonance of two floating boxes system against that of two fixed boxes system (Gao et al., 2019) in the same scale. And the numerical study is conducted in a two-dimensional numerical wave tank based on the OpenFOAM® package.

1 INTRODUCTION

The phenomenon that drastic water surface oscillations occur in a narrow gap between two floating structures is normally defined as “gap resonance”. Because side-by-side placed multiple floating structures are common configurations in coastal and offshore engineering, the gap resonance, which threats the stability of these structures due to the drastic oscillations, are considered as a challenge to be extensively investigated.

As for the research methods, theoretical analyses, physical experiments and numerical simulations are used in these studies. Numerical simulations are widely used because they are more accurate than theoretical analyses and more affordable than physical experiments due to vast parametric investigations in gap resonance studies. The numerical simulations are so far mainly based on the classical potential flow model employing the boundary element method and scaled boundary finite element method. These methods based on potential flow theory have been shown to predict the gap resonance well. Nevertheless, they were reported to significantly over-estimate the resonant wave height inside the gap and the wave forces on the floating bodies, because the physical energy dissipation due to the fluid viscosity cannot be considered in the context of potential flow theory. To overcome this problem, several particular numerical techniques that artificially introduce wave energy dissipation term into the potential flow model were developed so far. However, the introduction of artificial damping term seems somewhat arbitrary for the rigorous potential flow theory, and it was found to be difficult to obtain a unique value of the damping parameter under some conditions. The CFD simulation has gradually become an alternative method in investigating the gap resonance problem with the fast developments of computing technology, OpenFOAM® is one mature option for CFD simulations.

Meanwhile, based on literature survey, it is found that most of the researchers concentrate on the gap resonance only induced by incident waves, which occurs as the incident wave frequency is close to the natural frequency of water mass trapped in the narrow gap. The motions of structures are neglected in these studies on the gap resonance induced by incident waves. The gap resonance, which is jointly excited by forced body motions (radiation problems) and by incident waves (diffraction problems), has been discussed by Li (2019) numerically based on potential flow theory and the influence of the motions of structures on gap resonance has been proved. However, based on the aforementioned consideration on potential flow theory, this paper aims to explore the gap resonance of two floating boxes by using OpenFOAM® to get accurate results and predictions. And the comparisons with previous work by OpenFOAM® on gap resonance of two fixed boxes systems in Gao et al. (2019) will be presented in this abstract to show the differences induced by heave motion.

2 NUMERICAL MODEL

For this study, the solver, *interDyMFoam* within OpenFOAM® package, is employed for dynamic mesh to simulate fluid-floating structure interactions. Waves are generated and dissipated by using the relaxation-based wave generation toolbox *waves2Foam* proposed by Jacobsen et al. (2012). The Navier-Stokes equations, which is introduced below, are utilised for *interFOAM* and *interDyMFOAM* to describe the motion of fluid continuum. These equations are written as a mass conservation equation and momentum equation by Newton's second law, which are showed below respectively:

$$\nabla \cdot \vec{U} = 0 \tag{1}$$

$$\frac{\partial \rho \vec{U}}{\partial t} + \nabla \cdot \left(\rho \vec{U}\vec{U}\right) - \nabla \cdot \left(\mu \nabla \vec{U}\right) - \rho \vec{g} = -\nabla p - \vec{f_\sigma} \tag{2}$$

Where $\vec{U}$ is the flow velocity vector, ρ is the density of fluid, μ refers to the dynamic viscosity, $\vec{g}$ is the acceleration of gravity, p is the pressure of fluid, and the last term $\vec{f_\sigma}$ is the surface tension which has minor effects in civil engineering issues. Thereinto, three components of the velocity vector in three dimensions of Cartesian coordinates and the fluid pressure are unknown variables in governing equations.

To track the shape and position of the free surface, the volume of fluid (VOF) method has been employed in OpenFOAM®. The transport equation of the VOF field can be yielded as:

$$\frac{\partial \gamma}{\partial t} + \nabla \cdot \left(\vec{U}\gamma\right) = 0 \tag{3}$$

Where, γ is the volume fraction. $\gamma = 0$ is for air, 1 is for water and intermedia value is for the mixture of two fluids at the interface. This equation shows the relationship between the velocity field and γ in each cell. While, in order to keep tracking accurate free surface, an additional convective is included in the transport equation to provide a sharper interface resolution. The velocity field is modelled by the corresponding gas and liquid velocities denoted by $\vec{U}_g$ and $\vec{U}_l$, respectively. The velocity field can be yielded by weighed averages as $\vec{U} = \gamma\vec{U}_l + (1-\gamma)\vec{U}_g$. According to this equation for velocity field, the new transport equation of VOF can be written as:

$$\frac{\partial \gamma}{\partial t} + \nabla \cdot \left(\vec{U}\gamma\right) + \nabla\left[\vec{U}_r\gamma(1-\gamma)\right] = 0 \tag{4}$$

Where $\vec{U}_r = \vec{U}_l - \vec{U}_g$. In the simulation of OpenFOAM®, two immiscible fluids are considered as one effective fluid throughout the flow domain. The physical properties, including density and dynamic viscosity, can be denoted as weighed averages by using volume fraction γ.

$$\phi = \gamma\phi_{water} + (1-\gamma)\phi_{air} \tag{5}$$

Based on this method, these physical properties can be equal to the properties of each fluid in their corresponding occupied regions and varying only across the interface.

3 NUMERICAL MODEL SETUPS

The numerical wave tank in OpenFOAM® utilised in the present study is in a 2D domain. Figure 1 illustrates the sketch of the numerical wave tank. Because the setup of 2D domain in OpenFOAM®, the width of numerical wave tank should contain one mesh cell, the width W=0.02m in this study. The origin of the coordinate system is located at the still water level (SWL) of the left inlet boundary. The x-axis is in the wave propagation direction, and the y-axis is in the upward direction. Two identical floating boxes are placed at the middle of the wave tank, and the motion of boxes is restricted to heave motion along the direction of y-axis only. The box height is H = 0.5 m, the breadth is B = 0.5 m, the draft d = 0.25 m, the gap width B_g = 0.05 m, the water depth is h = 0.5 m. To eliminate the influence of reflected waves, two relaxation zones are setup in the inlet and outlet boundaries, respectively. Four wave gauges, G_1-G_4, are arranged to record the free-surface elevations. G_1 and G_2 are used to decompose the incident and reflected waves, G_3 are installed to obtain the amplification of waves inside the gap, G_4 are utilised to record transmitted waves.

The meshes around the boxes are also presented in Figure 1, which are generated by a built-in mesh generation utility, "blockMesh". Based on convergence test, the mesh sizes around the boxes are defined as H_0/16 in y-axis and λ/240 in x-axis, in which H_0 is incident wave height and λ is wavelength.

The numerical model in OpenFOAM® has been validated to be able to represent wave amplification in narrow gap in Gao et al. (2019) and the motion of two floating boxes interacted by waves in Ding et al. (2019). Thus, it is convincing to use OpenFOAM® to implement the following simulations.

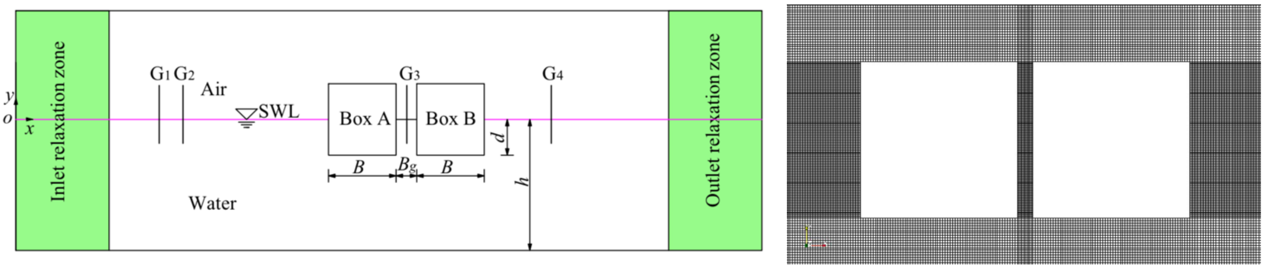

Figure 1. the sketch of numerical wave tank and the meshes around the boxes in the computational domain in OpenFOAM®

4 RESULTS AND DISCUSSIONS

Figure 2 shows the comparisons of free-surface elevation in the gap between floating boxes system and fixed boxes system when incident wave height $H_0 = 0.05$ m. $H_g^{(i)}/H_0$ refers to wave height amplification. The first-order harmonic components are found to be the major components in both floating boxes system and fixed boxes system. It is obvious that the floating boxes system has smaller wave height amplifications than fixed boxes system, and the differences are more significant in lower frequency region (kh<1.7). In higher frequency region (kh>1.7), the motion of boxes will be smaller, and the differences between two systems are smaller. Thus, the motion of structures makes the most contributions to the differences of wave amplifications, and the motion can reduce the wave amplification in the gap. As for the tendency of wave amplifications with kh, the curves of fixed boxes system generally have one peak for the largest wave amplification, and the peak point is just at the frequency of dash line which is the natural frequency of the water trapped in the narrow gap. In another word, the frequency of dash line is the frequency of the gap resonance only induced by the incident waves of fixed boxes system. While, the curves of floating boxes system have multiple peaks for the wave amplification. The peak at the right side of the dash line are supposed to be the frequency of the gap resonance induced by incident waves, the heave motion of boxes may induce the decrease of the water mass trapped in the gap, smaller mass will induce higher natural frequency. Thus, the frequency of the gap resonance induced by the incident waves of floating boxes system will shift to right. Another peak of floating boxes system may be influenced by both the motion of structures and the incident waves.

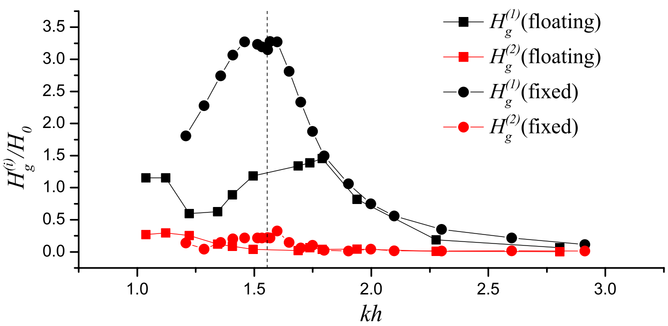

Figure 2. the first two order harmonic components of the free-surface elevation in the gap when incident wave height is 0.05m.

Figure 3 presents the horizontal wave forces and vertical wave forces on the two boxes. Similar to the curves of free-surface elevation, the curves of fixed boxes system have one peak for each situation, and all of the peak frequencies are around the frequency of the gap resonance induced by the incident waves. Thus, the increase of forces on structures will be affected by the gap resonance induced by the incident waves. Nevertheless, the curves of floating boxes system have multiple peaks. Similar to the fixed boxes system, the right peaks will be influenced by the gap resonance induced by the incident waves. While, the left peaks can be induced by both the motion of structures and the incident waves, and the left peaks have larger forces on the Box B than the right peaks. In summary, for the dual floating structures system, not only the gap resonance induced by the incident waves will influence the stability of structures, but also the motions of structures will affect the forces on the structures especially for the lee-side structures.

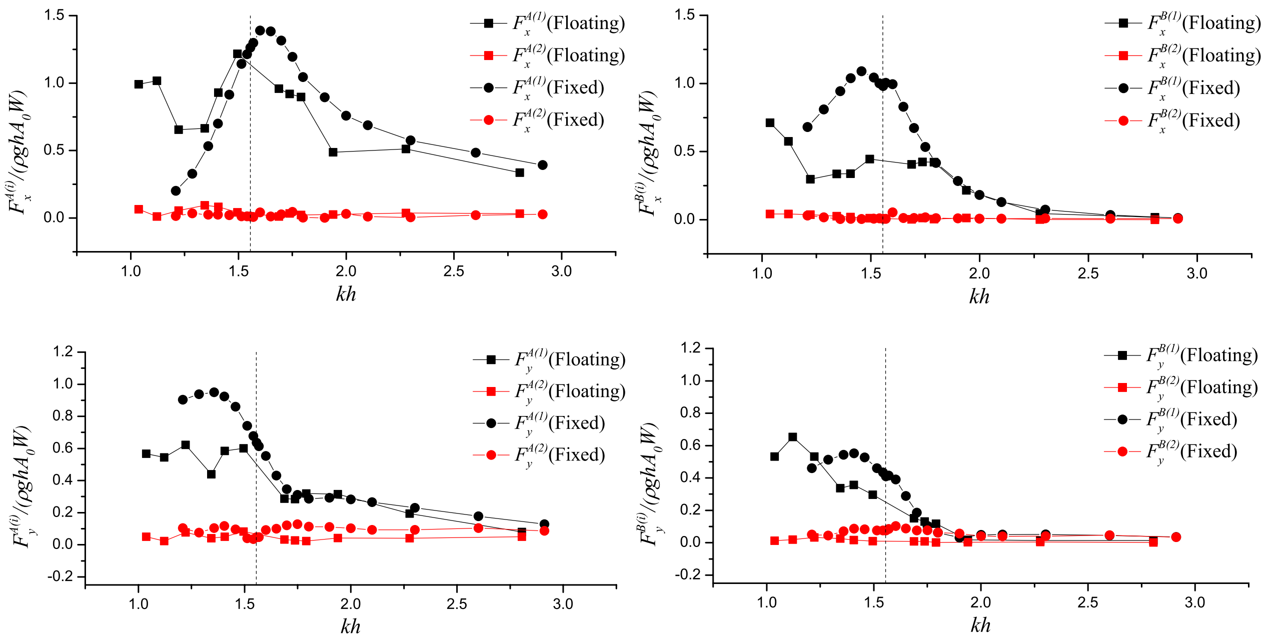

Figure 3. the first two order harmonic components of the horizontal (F_x) and vertical (F_y) wave forces on Box A and B. (A_0 is wave amplitude equals to 0.025 m, W is the width of structure or the width of numerical wave tank, W = 0.02 m)

Further research on the gap resonance between two floating boxes will be presented during the workshop. Different wave heights and gap widths will be discussed to show how the motion will influence the gap resonance under different conditions.

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