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A NUMERICAL STUDY ON HYDRODYNAMIC INTERACTION FOR A SMALL 3-D BODY FLOATING FREELY CLOSE TO A LARGE 3-D BODY IN WAVES

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ABSTRACT

This paper investigates the first order wave exciting forces and motion responses due to hydrodynamic interaction between two unequal-sized freely floating three dimensional rectangular boxes in regular waves. The three dimensional source distribution method has been adopted to carry out the numerical investigation. The validation of the computer code developed for this purpose has been justified by comparing the present results with that of the published ones for simple geometrical shaped floating bodies. The numerical computations have been carried out for different wave heading angles and separation distances (gaps) between the floating rectangular boxes. To illustrate the hydrodynamic interaction phenomena, the computed results for an isolated body case are also presented along with the multi-body results. Finally some conclusions have been drawn on the basis of the present analysis.

Keywords: Hydrodynamic interaction, 3-D rectangular boxes, Source distribution technique.

1. INTRODUCTION

Recently, there is a significant increase in the number of activities that involves applications of offshore structures, where two or, more bodies are floating in sufficiently close proximity. As a result of the wave motion, these bodies will experience the hydrodynamic interaction. The hydrodynamic analysis of multiple floating bodies is different from that of a single floating body, because one body is situated in the diffracted wave field of others. The bodies will experience incident as well as scattered waves impinges upon them. Now if these waves arrive in phase then there will be a considerable escalation in the magnitude of the wave exciting forces on the floating bodies compared to a body in isolation. On the other hand, if these waves arrive out of phase then there will be a significant reduction of wave force. Moreover, each body will also experience radiated waves due to the motion of other bodies. The actual importance of interaction effect depends on the configuration of the multi-body system, which means the size and shape of the floating bodies and the separation distances (gaps) between them.

Understanding hydrodynamic interaction is particularly important while a small body is floating close to a large body in waves. As for example, a supply vessel is operating close to a large ocean going vessel at sea. The wave exciting forces and the motion responses of the small vessel will be affected significantly due to the presence of neighboring large vessel. The interaction between multiple floating bodies will play an important role for the safety and performance of the floating bodies. For this reason, it is necessary to have an insight into the mechanism of the influence of gap between the floating bodies as well as the wave heading influence on the wave exciting forces and motion responses of the bodies floating at close vicinity.

There are many investigations related to the hydrodynamic interaction between multiple floating bodies in waves. Ohkusu [1] extended the classical solution for a single heaving circular cylinder to the case of two cylinders in a catamaran configuration. Faltinsen & Michelsen [2] used panel method for direct numerical solution of wave effects on 3-D floating bodies. The panel method was further extended for two independent bodies by van Oortmerssen [3]. Matsui and Tamaki [4] calculated hydrodynamic coefficients and wave exciting forces for simple vertical floating cylindrical bodies in close proximity. Choi & Hong [5] used the higher-order boundary element method to solve the interaction problem between multiple floating bodies. Recently, Wang *et al*. [6] investigated the problems experienced during tandem offloading operations of Floating Production, Storage and Offloading (FPSO) using a Time-domain simulation technique considering hydrodynamic interaction between the vessels.

In this paper, the 3-D source distribution method has been adopted to calculate the hydrodynamic coefficients and wave-exciting forces for two unequal-sized rectangular boxes by taking into account the effect of hydrodynamic interaction among the two bodies and the coupled equations of motions are solved directly. Based on the formulation, a computer code has been developed to investigate the hydrodynamic interaction phenomena. In order to justify the validity of the code, some published results have been verified for two freely floating vertical cylindrical bodies. Then the numerical computations are performed for the case of two floating boxes as well as for an isolated box case, varying the wave headings and the separation distances (gaps). It is observed from the present study that the wave exciting forces and motion responses due to hydrodynamic interaction vary significantly with wave headings and gaps between the floating boxes.

2. FORMULATION OF THE PROBLEM

2.1 Assumptions and Boundary Conditions

Consider a group of N 3-dimensional bodies of arbitrary shape, oscillating in water of uniform depth. The amplitudes of the motions of the bodies and waves are assumed to be small, whereas the fluid is supposed to be ideal and irrotational. Two right-handed Cartesian coordinate systems of axes with origin at the free surface are considered. In regular waves a linear potential Φ, which is a function of space and of time, can be written as a product of space-dependent term and a harmonic time-dependent term as follows:

$$\Phi(x,y,z;t)=\phi(x,y,z)\,.\,e^{-i\omega t} \tag{1}$$

The wave circular frequency ω can be written as

$$\omega=\frac{2\pi}{T} \tag{2}$$

where T is the wave period. The potential function ϕ can be separated into contributions from all modes of motion of the bodies and from the incident and diffracted wave fields as follows:

$$\phi=-i\omega\left[(\phi_0+\phi_7)\zeta_a+\sum_{m=1}^{N}\sum_{j=1}^{6}(X_j^m\phi_j^m)\right] \tag{3}$$

where ϕ_0 is the incident wave potential, ϕ_7 is the diffracted wave potential, ϕ_j^m represent potentials due to motion of body 'm' in j-th mode i.e., radiation wave potentials, X_j^m is the motion of body 'm' in j-th mode and ζ_a is the incident wave amplitude. The incident wave potential can be expressed as

$$\phi_0=\frac{g}{\omega^2}\frac{\cosh[k(z+h)]}{\cosh kh}e^{ik(x\cos\chi+y\sin\chi)} \tag{4}$$

where χ is the wave heading angle measured from $+X$-axis, h is the depth of water, g is the acceleration due to gravity and k is the wave number. The individual potentials are all solutions of the Laplace equation, which satisfy the linearized free surface condition and the boundary conditions on the sea floor, on the body's surface and at infinity.

2.2 Source Density and Velocity Potentials

The potential function at some point (x,y,z) in the fluid region in terms of surface distribution of sources can be written as:

$$\phi_j^m(x,y,z)=\frac{1}{4\pi}\sum_{n=1}^{N}\iint_{S^n}\sigma_j^m(\xi,\eta,\zeta)\,G(x,y,z;\,\xi,\eta,\zeta)\,dS \tag{5}$$

where (ξ,η,ζ) is a point on surface S and $\sigma(\xi,\eta,\zeta)$ is the unknown source density. The solution to the boundary value problem is given by Equation (5), which satisfies all the boundary conditions. And since Green's function (G) satisfies these conditions, applying the kinematics boundary condition on the immersed surface yields the following integral equation:

$$\frac{\partial\phi_j^m(x,y,z)}{\partial n}=-\frac{1}{2}\sigma_j^m(x,y,z)+\frac{1}{4\pi}\sum_{n=1}^{N}\iint_{S^n}\sigma_j^m(\xi,\eta,\zeta)\,\frac{\partial}{\partial n}G(x,y,z;\,\xi,\eta,\zeta)\,dS \tag{6}$$

2.3 Numerical Evaluation of Velocity Potentials

A numerical approach is required to solve the integral Equation (6), as the kernel $\frac{\partial G}{\partial n}$ is complex and it does not permit any solution in closed form. The wetted surface of body is divided into l number of quadrilateral panels of area $\Delta s_l^m (l = 1........E_n)$ and the node points are considered at the centroid of each panel. The continuous formulation of the solution indicates that Equation (6) is to be satisfied at all points (x, y, z) on the immersed surface but in order to obtain a dicretized numerical solution it is necessary to relax this requirement and to apply the condition at only N control points and the location of the control points are chosen at the centroids of the panels. Consequently, discretization process allows Equation (6) to be replaced as

$$-\frac{1}{2}(\sigma_j^m)_l + \frac{1}{4\pi}\sum_{n=1}^{N}\sum_{k=1}^{E_n}\iint_{\Delta S_k^n}(\sigma_j^m)_k \frac{\partial G}{\partial n}(l,k)dS$$
$$= \begin{cases} \left(-\frac{\partial \phi_0}{\partial n}\right)_l & , \quad j = 7 \\ \left(n_j^m\right)_l & , \quad j = 1,2....6 \\ \text{(if panel } 'l' \text{ belongs to body } 'm') & \\ 0 & , \quad j = 1,2....6 \\ \text{(if panel } 'l' \text{ does not belong to body } 'm') & \end{cases} \tag{7}$$

2.4 Hydrodynamic Coefficients and Wave Exciting Forces and Moments

Once the velocity potentials have been determined, then the added-mass coefficients (a_{kj}^{mn}), the fluid damping coefficients (b_{kj}^{mn}) and the first order wave-exciting forces (F_k^m) can be calculated as follows:

$$a_{kj}^{mn} = -\Re e\left[\rho\iint_{S^m}\phi_j^n n_k^m dS\right] \tag{8}$$

$$b_{kj}^{mn} = -\Im m\left[\rho\omega\iint_{S^m}\phi_j^n n_k^m dS\right] \tag{9}$$

$$F_k^m = -\rho\zeta_a\omega^2 e^{-i\omega t}\iint_{S^m}(\phi_0 + \phi_7)n_k^m dS \tag{10}$$

For $m = n$, the added mass and damping coefficients are due to body's own motion, whereas for $m \neq n$, the coefficients are due to the motion of other bodies.

2.5 Equations of Motions in Frequency Domain

The equations of motion can be expressed by using the following matrix relationship:

$$(M + a)\ddot{X} + b\dot{X} + cX = F \tag{11}$$

where M is the inertia matrices, a is the added mass matrices, b is the fluid damping matrices, C is the hydrostatic stiffness matrices, F is the wave exciting force vector and X is the motion response vector. The above equations of motion are established at the centers of gravity of each body of the multi-body floating system. Since each body is assumed rigid and has six degrees of freedom, each matrix on the left-hand side of Equation (11) has a dimension of $(6N \times 6N)$ and X and F are $(6N \times 1)$ column vectors for N floating body system.

3. RESULTS AND DISCUSSION

3.1 Two Freely Floating Vertical Cylinders

The diameter and draft of each cylinder is 40.0 m and 10.0 m respectively and the gap between them is 20.0 m. The water depth is considered as 200.0 m. The wetted surface of each cylinder is divided into 234 panels. For 0° wave heading, Body 1 and Body 2 represent the lee side and weather side cylinder respectively as shown in Figure 1.

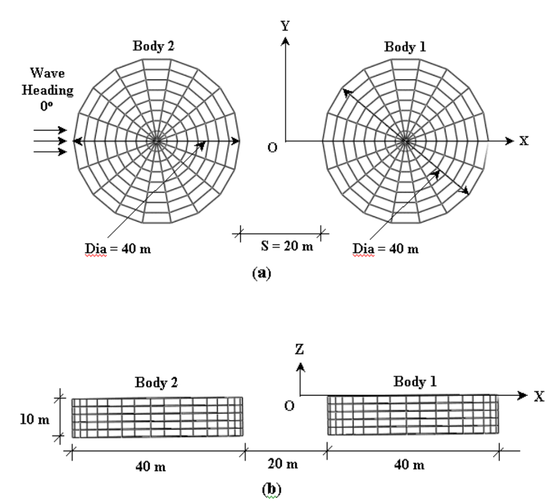

Figure 1. Two freely floating vertical cylinders.

The non-dimensional surge wave exciting forces on Body1 and Body2 are shown in Figure 2. Figure 3 presents the surge motion responses of Body1 and Body2. The results are plotted against ka, where k and a denote the wave number and radius of each cylinder respectively. Figure 2 and Figure 3 also make a comparison between the present results with the published results of Goo and Yoshida [7] and the agreement was found quite satisfactory.

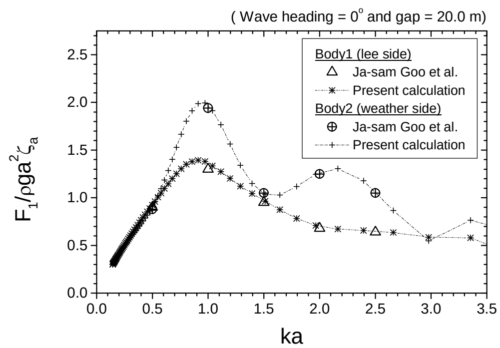

Figure 2. Surge wave exciting forces on two vertical floating cylinders.

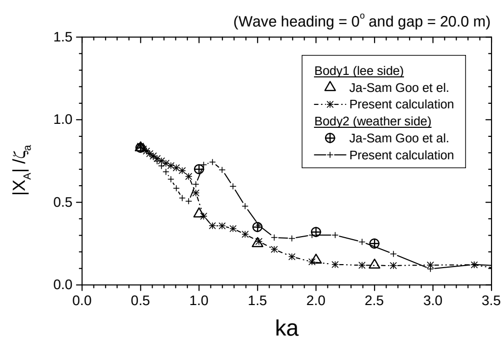

Figure 3. Surge motions of vertical floating cylinders

3.2 Two Freely Floating Rectangular Boxes

Two unequal-sized rectangular floating boxes are considered for the numerical analysis. The ratio of the volume of displacement between the smaller and the larger box is taken as 1:8. The length, breadth and draught of the smaller box are 109.70 m, 101.40 m and 30.0 m respectively and its C. G. is 0.20 m below M. W. L. Consequently, the length, breadth and draught of the larger box will be two times those of the smaller box. The dimension of the smaller box is similar to that of the box model considered by van Oortmerssen [3]. The water depth is considered as 100.0 m. The wetted surface of each box is divided into 300 panels as shown in Figure 4. In this paper, three different gap sizes between the two boxes are chosen i.e., 25m, 50m and 75m. On the other hand, the wave heading is taken as 0°, 180° and 270°.

Figure 5 and Figure 6 show the non-dimensional surge wave exciting forces against wave frequency for the smaller box at 0° and 180° wave heading respectively. The smaller body is located in the weather side for 0° wave heading, whereas it is positioned as lee side body for 180° wave heading. In Figure 5, the peak magnitude of the surge wave exciting force is amplified almost two times for a gap of 75 m when compared to an isolated box result. The peak magnitude shows a gradual increasing tendency as the gap is reduced to 50m and then to 25m. This amplification of peak magnitude may occur due to the radiated waves from the near-by larger body. It can be seen from the figure that the overall magnitude of wave exciting forces is higher than that of an isolated box result. For 180° wave heading, no amplification of peak magnitude is observed and the overall magnitude of the surge wave exciting forces on the smaller box is reduced considerably due to the shielding of the incident wave by the larger box.

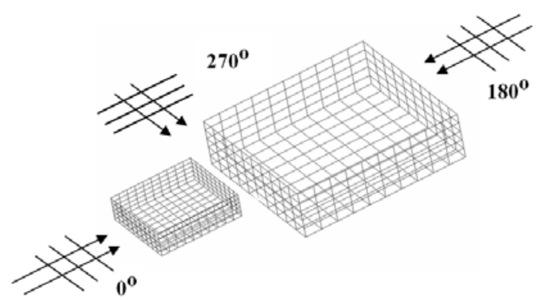

Figure 4. Mesh arrangement of wetted surface of two unequal-sized floating boxes.

Figure 7 shows the heave wave exciting forces on the smaller box for 0° wave heading. Since the smaller box is located in the weather side, the magnitude of heave exciting force is amplified initially followed by a sharp fall and afterwards it follows the isolated body result. Figure 8 and Figure 9 show the pitch wave exciting moments on the smaller box for 0° and 180° wave heading respectively. The overall tendency of pitch exciting moment is found similar to the surge exciting force results. For surge and pitch mode, when the gap is wider the period of trapped wave is getting longer meaning the gap effect will be located at a lower frequency than a narrower gap. Figure 10 and Figure 11 show the surge responses for the smaller box for 0º and 180º wave heading respectively. Initially, the motion response for both the wave heading is similar to an isolated box response.

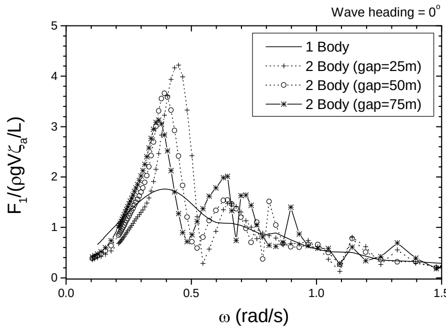

Figure 5. Surge wave exciting forces on smaller box

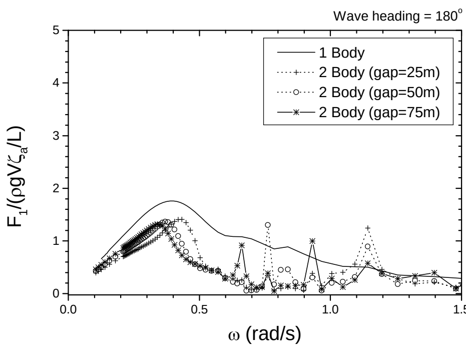

Figure 6. Surge wave exciting forces on smaller box

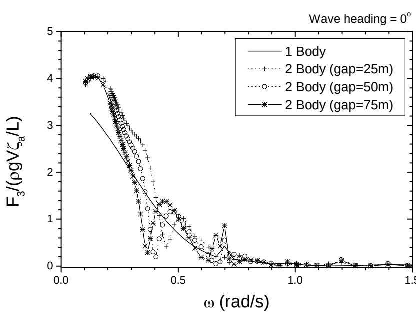

Figure 7. Heave wave exciting force on smaller box

It can be seen from both the figures that near 0.24 rad/s a sharp fluctuation occurs due to the formation of standing waves and afterwards the motion responses of the smaller box increases for lee side position and decreases for weather side position. Figure 12 and Figure 13 show the heave motion responses for smaller box for 0º and 180º wave heading respectively. The peak magnitude is amplified significantly with sharp and rapid fluctuations for weather side location of the smaller box. However the motion response reduces significantly for lee side position of the smaller box.

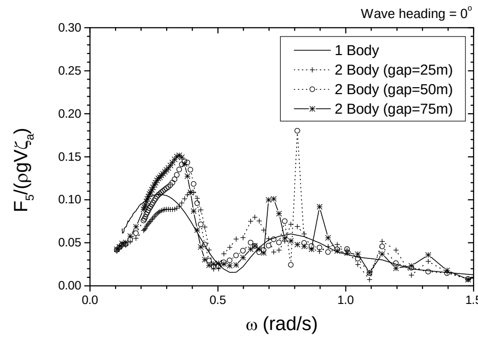

Figure 8.Pitch exciting moment on smaller box

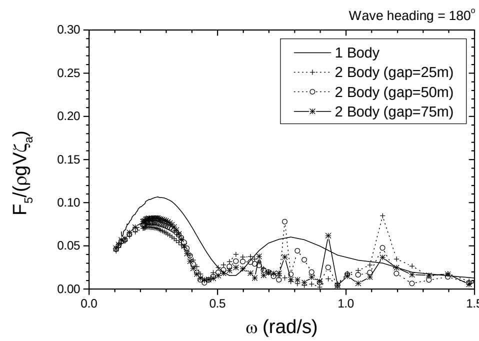

Figure 9. Pitch exciting moment on smaller box

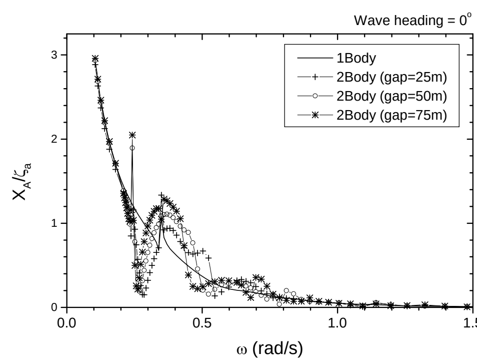

Figure 10. Surge motion response of smaller box

Due to coupling of surge, heave and pitch mode, fluctuation of motion responses is observed near 0.24 rad/s for all of these modes. Finally, Figure 15 shows the surge motion response of the smaller box for 270º wave heading. Although, the motion response in the surge mode is absent for an isolated body case, yet, due to asymmetric hydrodynamic forces to wave direction surge motion emerges for two box case.

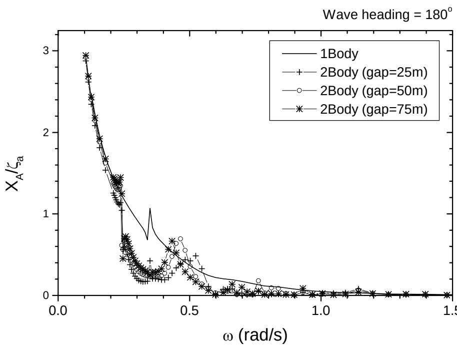

Figure 11. Surge motion response of smaller box

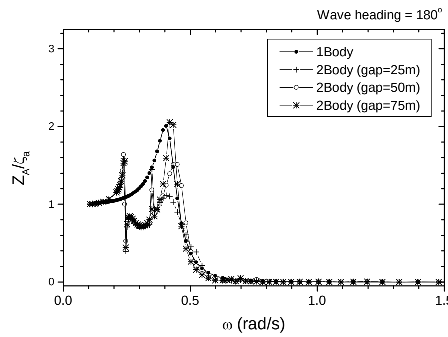

Figure 13. Heave motion response of smaller box

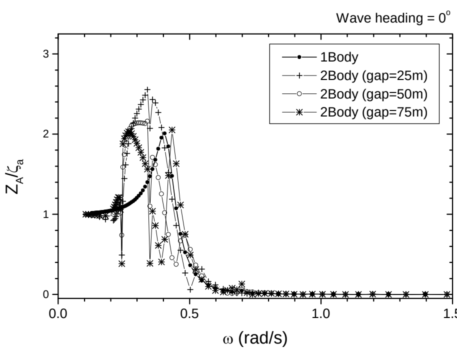

Figure 12. Heave motion response of smaller box

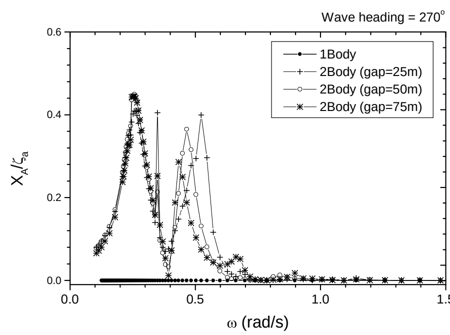

Figure 14.Surge motion response of smaller box

4. CONCLUSION

Using 3-D source distribution method, the hydrodynamic interaction for two unequal-sized freely floating rectangular boxes in regular waves is studied. Hydrodynamic interaction causes rapid changes in hydrodynamic loads and responses along the wave frequencies. The amplitude of motion responses and wave exciting forces for the smaller box can be increased or, reduced depending upon the wave heading. As the gap between the two bodies is shortened, the peak frequencies due to interaction move to higher frequencies. Therefore, hydrodynamic interaction should be taken into consideration to evaluate and design the safety and performance of a multi-body floating system.

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