

## ON HYDRODYNAMIC INTERACTION BETWEEN TWO RECTANGULAR BARGES FLOATING SIDE-BY-SIDE IN REGULAR WAVES

Mir Tareque Ali<sup>1</sup> and Yoshiyuki Inoue<sup>2</sup>

<sup>1</sup>Department of Naval Architecture and Marine Engineering, Bangladesh University of Engineering and Technology, Dhaka 1000, Bangladesh.

<sup>2</sup>Laboratory of Ocean System Design, Department of Environment and System Sciences, Yokohama National University, Yokohama 240-8501, Japan.

### ABSTRACT

This paper investigates the hydrodynamic interaction between two rectangular barges freely floating in each other's close vicinity. The physical aspect of hydrodynamic interaction is rather complicated and numerically sound scheme is highly recommended to study this complex phenomenon. In the present study, 3-D source-sink method has been adopted to determine the hydrodynamic coefficients and wave-exciting forces by taking into account the effect of hydrodynamic interactions among the different floating bodies and the coupled equations of motions are solved directly. A computer code has been developed using 3-D source-sink formulations. The validation of the code has been justified by comparing the present numerical results with that of the published ones for two freely floating vertical cylinders. To study the hydrodynamic interactions, numerical results for an isolated barge have been compared with those of two rectangular barges floating side-by-side in regular waves. The separation distance between the barges has been varied to examine the interaction effects for beam sea as well as for head sea conditions. Finally some conclusions have been drawn on the basis of the present analysis.

**Keywords:** Hydrodynamic interaction, Rectangular barges, 3-D source-sink method, Hydrodynamic coefficients, Wave-exciting forces.

### 1. INTRODUCTION

In recent years there have been significant increases in various offshore activities that involve two or more vessels floating freely in close vicinity. As a result, these floating structures experience considerable hydrodynamic interactions due to the action of wave exciting forces. Typical examples of multiple floating systems may include marine operations involving multiple vessels and platforms, offshore platforms supported by multiple columns, floating bridges, and LNG FPSO system.

The hydrodynamic analysis of a multi-body floating system is different from that of a single floating body. In the multi-body system, each floating body is situated in the diffracted wave field of other bodies. Therefore, the bodies will experience incident as well as scattered waves impinges upon them. When 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, when these waves arrive out of phase, then there will be a significant reduction of wave forces on multiple bodies compared to an isolated body. Moreover, each body will also experience radiated waves due to the

motion of other bodies. Hence, the hydrodynamic analysis of a multi-body system will be different from a single body analysis as a result of hydrodynamic interactions. The actual importance of interaction effect depends on the configuration of the multi-body system, which includes the size and shape of the floating bodies as well as the separation distances between them. It is therefore necessary to develop a numerically sound scheme in order to understand the hydrodynamic interaction phenomenon.

To study hydrodynamic interactions between multiple bodies, many researchers have used the 3-D source-sink method or, panel method. Faltinsen and Michelsen [1] used this method for direct numerical solution of wave effects on 3-D floating bodies. Van Oortmerssen [2] extended this method for two independent bodies of simple shapes. Inoue et al. [3] applied panel method to study the motion responses of an LNG FPSO system. Chakrabarti [4] used the multiple-scattering method in combination of panel method, to represent the interactions between different bodies. Lee and Newman [5] used panel method for more complex structure like MOB (Mobile Offshore bases). More recently, Ali and Khalil [6] applied the panel method to compute the

hydrodynamic interaction coefficients for freely floating multiple composite vertical cylinders in regular waves.

In this research work, the hydrodynamic interactions between two freely floating rectangular barges have been investigated. The 3-D source-sink method has been applied to compute the hydrodynamic coefficients and wave exciting forces and moments and the coupled equations of motions are solved directly. Based on the 3-D source-sink formulations, a computer code has been developed and the validation of the code has been justified by comparing the present results with that of the published ones for two freely floating vertical cylinders. Two freely floating rectangular barges have been considered to study the interaction effects for beam sea and head sea conditions. The separation distance i.e., gap between the barges has been varied and the numerical results are presented with an isolated barge results to illustrate the interactions.

## 2. MATHEMATICAL FORMULATION OF THE PROBLEM

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 are considered: one fixed to the bodies and another fixed to the space. In regular waves a linear potential  $\Phi$ , 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:

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

The wave circular frequency  $\omega$  can be written

$$\omega = \frac{2\pi}{T} \quad (2)$$

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

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

where  $\phi_0$  is the incident wave potential,  $\phi_7$  is the diffracted wave potential,  $\phi_j^m$  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  $\zeta_a$  is the incident wave amplitude. The incident wave potential can be expressed as

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

where  $\chi$  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.

### 2.1 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:

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

where  $(\xi, \eta, \zeta)$  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 Eq. (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:

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

### 2.2 Numerical Evaluation of Velocity Potentials

A numerical approach is required to solve the integral Eq. (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  $\Delta s_l^m$  ( $l = 1, \dots, E_n$ ) and the node points are considered at the centroid of each panel. The continuous formulation of the solution indicates that Eq. (6) is to be satisfied at all points  $(x, y, z)$  on the immersed surface but in order to obtain a discretized 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 Eq. (6) to be replaced as

$$-\frac{1}{2}(\sigma_j^m)_l + \frac{1}{4\pi} \sum_{n=1}^N \sum_{k=1}^{E_n} \iint_{\Delta S_k^n} (\sigma_j^m)_k \frac{\partial G}{\partial n}(l,k) dS$$

$$= \begin{cases} \left( -\frac{\partial \phi_0}{\partial n} \right)_l, & j = 7 \\ \left( n_j^m \right)_l, & j = 1,2,\dots,6 \\ 0, & j = 1,2,\dots,6 \end{cases}$$

(if panel 'l' belongs to body 'm')

(if panel 'l' does not belong to body 'm')

(7)

### 2.3 Hydrodynamic Coefficients and Wave Exciting Forces and Moments

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

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

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

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

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

### 2.4 Equations of Motions in Frequency Domain

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

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

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 Eq. (11) has a dimension of  $(12 \times 12)$  and  $X$  and  $F$  are  $(12 \times 1)$  column vectors for two floating body system. The elements of matrices and vectors in Eq. (11) are discussed in details by Ali [7].

## 3. RESULTS AND DISCUSSION

On the basis of above formulations, a computer code written in F77 has been developed considering double

precision variables. To justify the validity of the computer code, the numerical results are checked for two freely floating vertical cylinders. To study the interaction effects, a detailed computation is then conducted for two rectangular barges floating side-by-side in regular waves.

### 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 separation distance or, 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 as shown in Fig 1. For  $0^\circ$  wave-heading angle, body 1 and body 2 represent the lee side and weather side cylinder respectively.

The non-dimensional surge wave exciting forces on body 1 and body 2 are shown in Fig 2. To verify the accuracy of the present computations, the wave exciting forces are computed using diffraction potential as well as Haskind relationship. Fig 3 presents the surge motions of body 1 and body 2. The results are plotted against  $ka$ , where  $k$  and  $a$  denote the wave number and radius of each cylinder respectively. Fig 2 and 3 also depict comparisons between the present results with Goo and Yoshida [8] results and the agreement between both the results are found quite satisfactory.

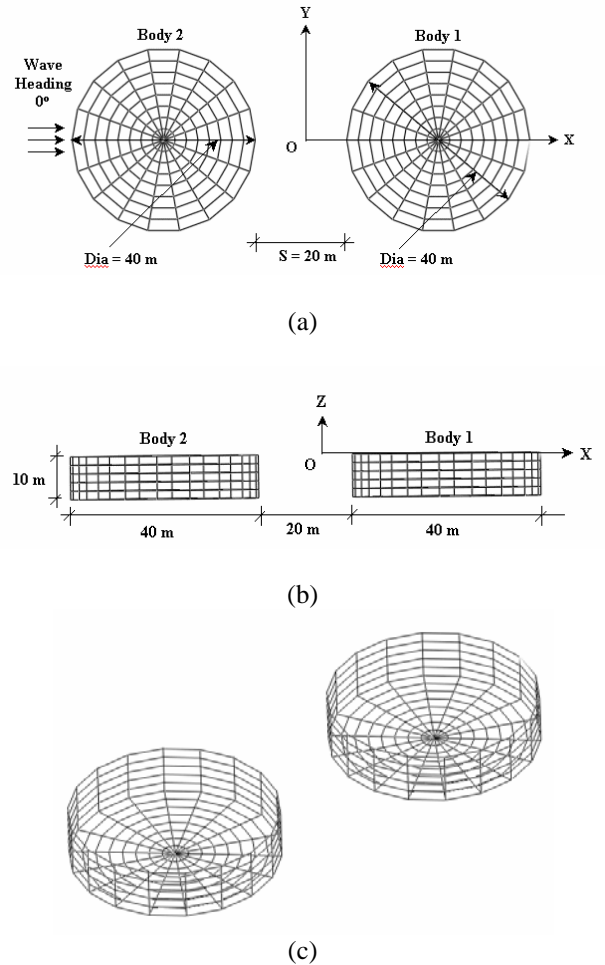


Fig 1. Mesh arrangements of the wetted surfaces of two floating vertical cylinders (a) Top view, (b) Side view and (3) 3-D view

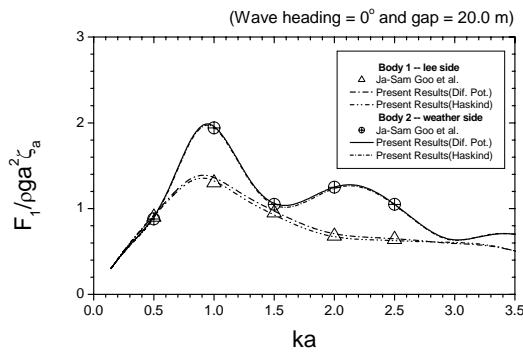


Fig 2. Surge wave exciting forces on floating cylinders

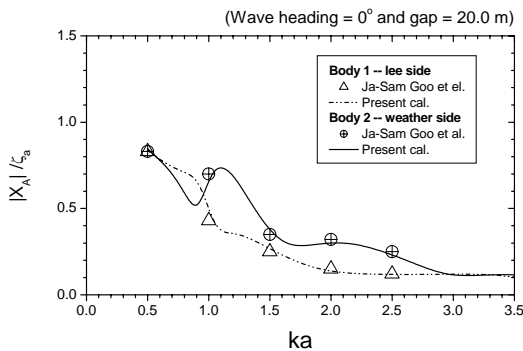


Fig 3. Surge motions of vertical floating cylinders

### 3.2 Two Freely Floating Rectangular Barges

The length, breadth and draft of each rectangular barge are 30.0m, 22.0m and 1.5m respectively. The barges are freely floated without any mooring facilities in 15.0m deep water. The wetted surface of each barge is divided into 348 panels. Fig 4 shows the arrangement of two barges and the discretization scheme. The separation distances or, gaps between adjacent long sides are varied to 4.0m, 8.0m and 12.0m.

Fig 5 and 6 show the non-dimensional surge and sway damping coefficients plotted against non-dimensional wave frequency ( $\omega(L/g)^{1/2}$ ), where  $L$  is the length of the barges. To investigate hydrodynamic interactions, the results for single body are depicted, also. As can be seen from the figures, the interaction in surge direction is very weak; however, it occurs in sway direction, strongly. The sharp peaks shown in Fig 6 are mainly attributed to locally resonated waves in confined fluid domain between the two barges. As the gaps become narrower, the peaks gradually move towards higher frequencies.

Non-dimensional sway wave-exciting forces on barge 1 (lee side) and barge 2 (weather side), for beam sea condition i.e.,  $90^\circ$  wave heading are presented in Figs 7 and 8 respectively. As evident from the figures, the magnitude of forces on barge 1 is very small compared to barge 2 and the force level of barge 2 is almost same in the case of a single barge. The sway wave-exciting forces are not affected significantly due to the variation of gaps between the barges. The appearance of sharp peaks may be due to the wave resonance in gaps between the barges.

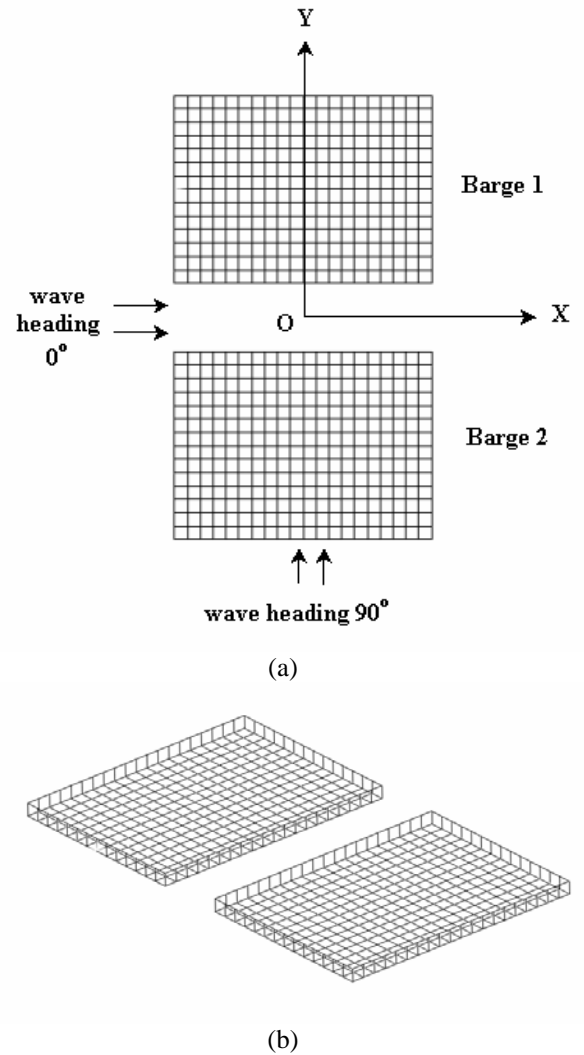


Fig 4. Mesh arrangements of the wetted surfaces of two rectangular floating barges

Non-dimensional roll wave-exciting moments on barge 1 and barge 2, for beam sea are presented in Figs 9 and 10 respectively. Similar to sway mode, the magnitude of roll moments on barge 1 is very small compared to barge 2 and the moment level of barge 2 is almost same in the case of a single barge. Moreover, the sway wave exciting moments are not affected significantly due to the variation of gaps.

For beam sea condition, Figs 11 and 12 show the sway responses of barge 1 and barge 2 respectively. It can be seen that the effect of hydrodynamic interactions are not so pronounced, as the gaps between the barges are varied. Figs 13 and 14 depict the roll responses for beam sea of barge 1 and barge 2 respectively. Due to the hydrodynamic interaction, the fluctuation in the responses can be seen according to wave frequencies. It can be seen from sway and roll responses that resonance occurs near  $\omega(L/g)^{1/2} = 2.0$ , when the gap between the two barges is 8.0m. Moreover, in some frequency bands, the roll responses are reduced for both the barges. Hence one can design the arrangement scheme to avoid resonance and minimize unfavorable responses through proper adjustment of gaps, in due consideration of main directions and frequencies of incident waves.

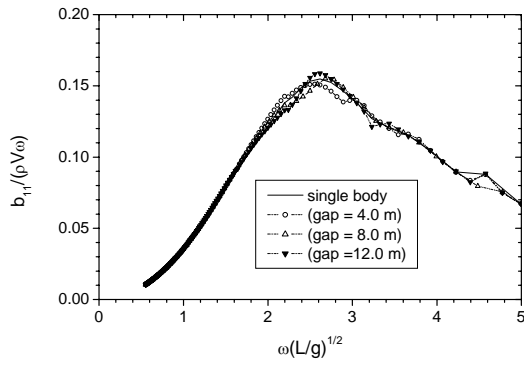


Fig 5. Surge damping coefficient of the barge

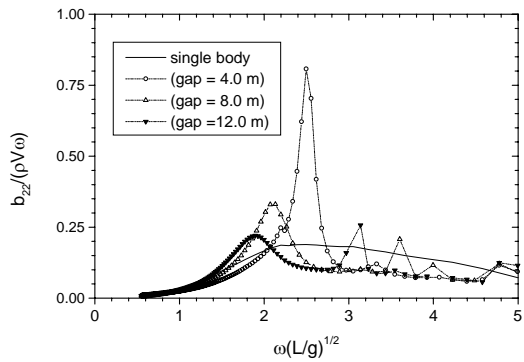


Fig 6. Sway damping coefficient of the barge

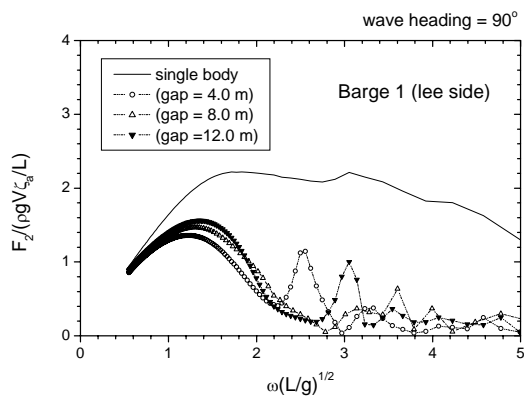


Fig 7. Sway wave-exciting force on lee side barge

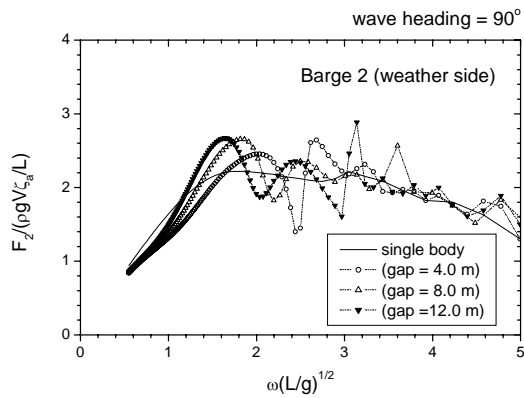


Fig 8. Sway wave-exciting force on weather side barge

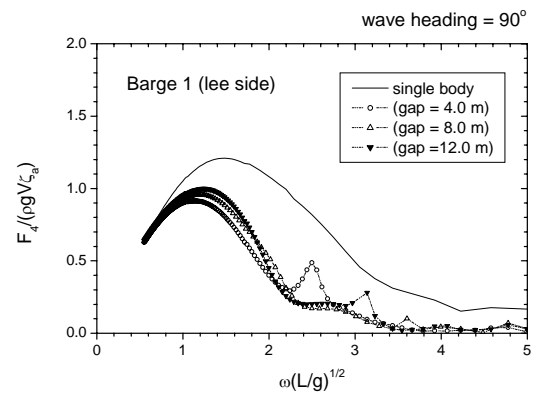


Fig 9. Roll wave-exciting moment on lee side barge

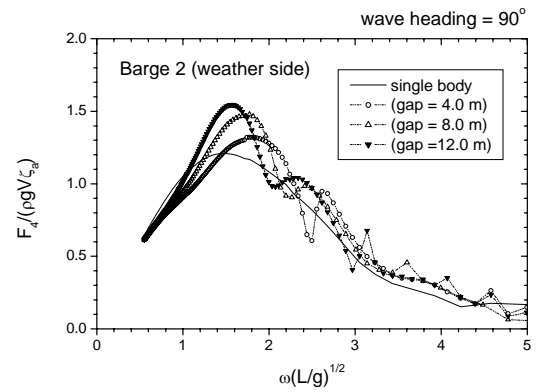


Fig 10. Roll wave-exciting moment on weather side barge

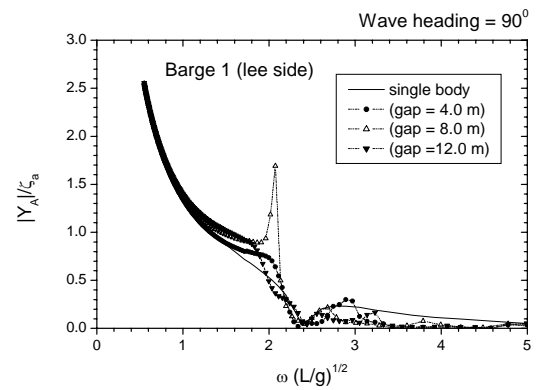


Fig 11. Sway motion response of lee side barge

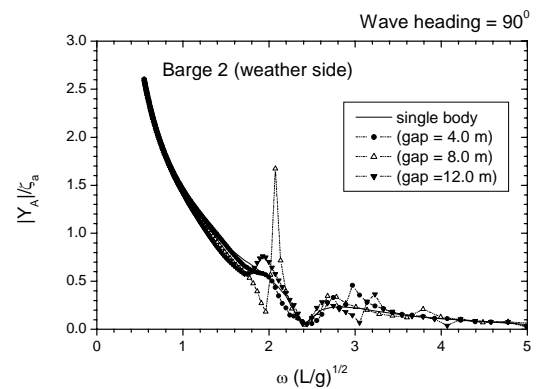


Fig 12. Sway motion response of weather side barge

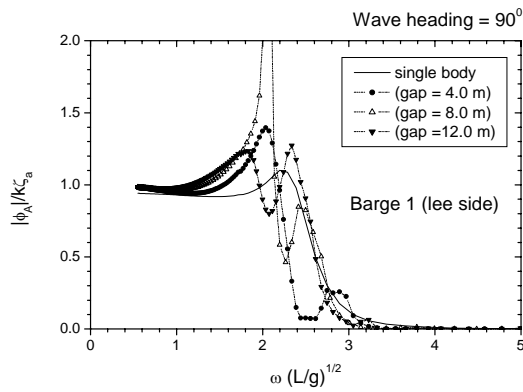


Fig 13. Roll motion response of lee side barge

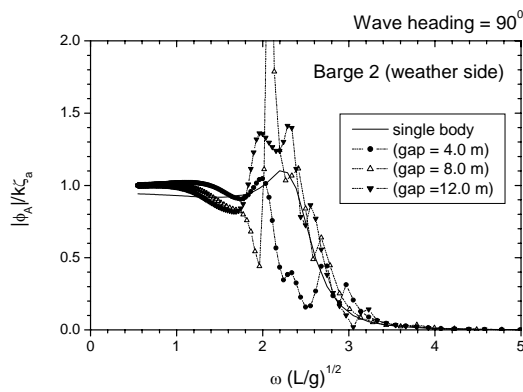


Fig 14. Roll motion response of weather side barge

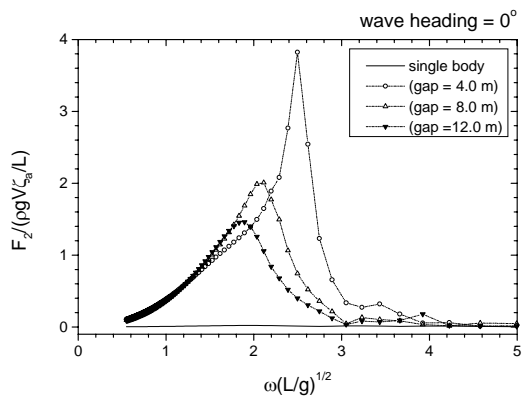


Fig 15. Sway wave-exciting force on barges

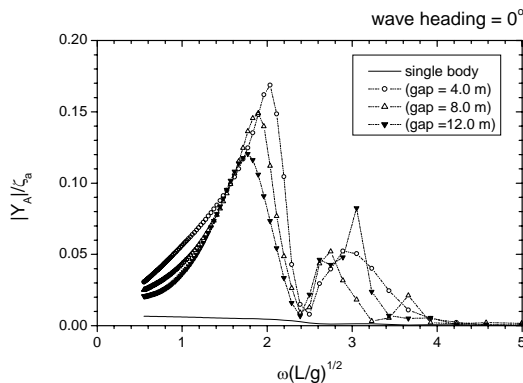


Fig 16. Sway motion response of barges

Figs 15 and 16 present the non-dimensional sway wave-exciting forces and sway responses for 0° wave heading angle. It is evident from the figures that for head sea condition, wave-exciting force and response for an isolated barge is absent in sway direction; however, they appear due to the presence of another body in the vicinity. As the gap is reduced, the peak gradually moves towards higher frequencies and magnitude of the peak is also increased at the same time.

#### 4. CONCLUSIONS

Using 3-D source-sink method, the hydrodynamic interaction on two freely floating rectangular barges in regular waves is studied. Hydrodynamic interaction causes rapid changes in hydrodynamic loads and responses along the wave frequencies. As each body is closer up together, 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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