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Prediction of Motion Responses between Two Offshore Floating Structures in Waves

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Abstract

In this paper, the motion responses with hydrodynamic interaction effect between two offshore floating structures in various heading waves are studied by using a linearized three-dimensional potential theory. Numerical calculations using three-dimensional pulsating source distribution techniques have been carried out for twelve coupled linear motion responses and relative motions of the barge and the ship in oblique waves. The computational results give a good correlation with the experimental results and also with other numerical results. As a result, the present computational tool can be used effectively to predict the motion responses of multiple offshore floating structures in waves.

Keywords: two floating structures, hydrodynamic interaction, coupled motions

1 Introduction

Recently, offshore offloading operations take place in many locations throughout the world. In general, many offshore operations involve the use of two or more floating structures which are positioned closely to transfer oil or gas during offloading so that they affect each other's motion responses through hydrodynamic interaction in waves. Consequently the large motions between two floating bodies, which would cause the damage of offloading system and the collision. Because of these serious problems during offloading operations, it is very important to study the motion behaviors between two floating bodies due to the hydrodynamic effect.

There are a few authors research about application of motion responses of multiple floating structures in waves. Ohkusu(1974) analyzed the motions of a ship in the neighborhood of a large moored two-dimensional floating structure by strip theory. Kodan(1984) extended Ohkusu's theory to hydrodynamic interaction between two parallel structures in oblique waves by strip method. Van Oortmerssen(1979) and Loken(1981) used the three-dimensional linear diffraction theory to solve this problem. Fang and Kim(1986) analyzed the motions of two longitudinally parallel barges by strip method. Fang and Chen(2001) used three-dimensional source distribution method to predict the relative motion and wave elevation between two bodies in waves.

In this paper, a motion program has been developed for the multiple floating structure problem based on the single floating structure problem(Chun et al 1990, Kim 1997) using three-dimensional linearized potential theory and three-dimensional source distribution technique.

In order to validate the developed calculation program, the comparisons are performed for Kodan(1984)'s experimental and 2-D results, Fang and Kim(1986)'s 2-D results and Fang and Chen(2001)'s 3-D results, respectively. Also, to find the separation effect between two bodies, we considered the various position arrangements for a side-by-side and a tandem offloading.

2 Theoretical background and mathematical formulation

To describe the motions responses between two bodies in waves, we consider 3 sets of right-handed orthogonal coordinate systems as shown in Figure 1. $O-XYZ$ is the space fixed coordinate system. $O_A-X_AY_AZ_A$ and $O_B-X_BY_BZ_B$ are the oscillatory coordinate systems fixed with respect to ship A and B, respectively. The $O-XY$ plane coincides with the undisturbed free surface, the X-axis in the direction of the body's forward and the Z-axis vertically upward. Oscillatory coordinate systems $O_A-X_AY_AZ_A$ and $O_B-X_BY_BZ_B$ are used to describe the body motion in six degrees of freedom with complex amplitudes $\xi_i(i=1,2,...12)$. Here $i=1,2,3,4,5,6$ represent surge, sway, heave, roll, pitch and yaw for ship A, respectively and $i=7,8,9,10,11,12$ represent surge, sway, heave, roll, pitch and yaw for ship B, respectively as shown in Figure 1.

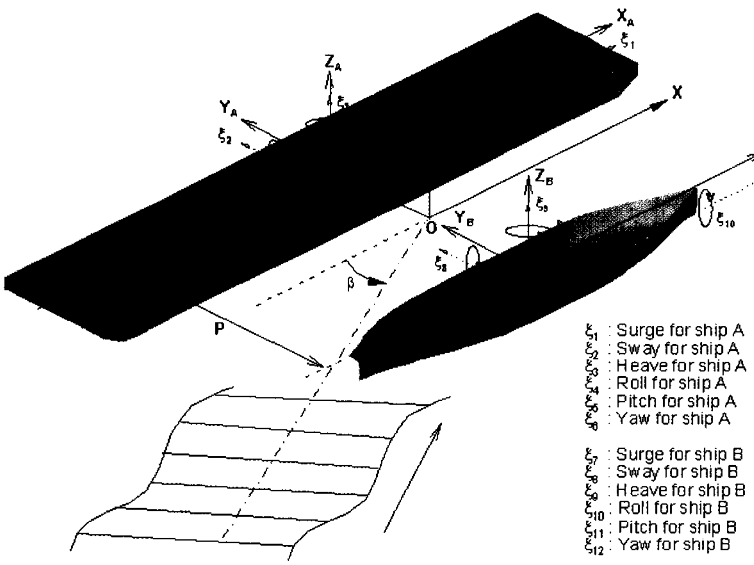

Figure 1: Definition of co-ordinate system

The total unsteady potential for a sinusoidal wave excitation with encounter frequency, ω_e, can be expressed as

$$\phi(x,y,z,t)=[\phi_I(x,y,z)+\phi_D(x,y,z)+\sum_{i=1}^{12}\xi_i\phi_i]e^{-i\omega_e t} \tag{1}$$

where $\phi_I(x,y,z)$ is the incident wave potential representing the incident waves; $\phi_D(x,y,z)$ is the diffraction potential representing the disturbance of the incident waves diffracted from the body; $\phi_i(i=1,2,...12)$ are the radiation potentials due to oscillations of the two bodies in calm water with unit amplitude. The incident wave potential was given as follow

$$\phi_I = -\frac{ig\zeta_a}{w_o} e^{kz} e^{i(kx\cos\beta + ky\sin\beta)} e^{-i\omega_e t} \tag{2}$$

where ω_o is the wave frequency, ζ_a is the wave amplitude, k is the incident wave number, $k = {\omega_o}^2/g$, and β is an arbitrary heading angles(180^o for head sea).

The individual potentials have to satisfy in the fluid domain, on the free surface, the submerged body surface, the sea bed and a suitable far-field radiation condition at infinity.

Laplace equation

$$\nabla^2\phi = 0 \qquad \text{in the fluid domain} \tag{3}$$

Linear free surface condition

$$-{\omega_e}^2\phi + g\frac{\partial}{\partial z}\phi = 0 \qquad \text{on } z = 0 \tag{4}$$

Body boundary condition for diffraction potentials

$$\frac{\partial}{\partial n}(\phi_I + \phi_D) = 0 \qquad \text{on ship A and ship B} \tag{5}$$

Body boundary condition for radiation potentials

$$\frac{\partial}{\partial n}\phi_i = -i\omega_e n_i \quad (i = 1, 2, ...6) \quad \text{on ship A} \tag{6a}$$

$$\frac{\partial}{\partial n}\phi_i = 0 \quad (i = 7, 8, ...12) \quad \text{on ship B} \tag{6b}$$

$$\frac{\partial}{\partial n}\phi_i = 0 \quad (i = 1, 2, ...6) \quad \text{on ship A} \tag{7a}$$

$$\frac{\partial}{\partial n}\phi_i = -i\omega_e n_i \quad (i = 7, 8, ...12) \quad \text{on ship B} \tag{7b}$$

where,

$$\begin{aligned} (n_1, n_2, n_3) &= \overrightarrow{n} && \text{on ship A} \\ (n_4, n_5, n_6) &= \overrightarrow{r} \times \overrightarrow{n} && \text{on ship A} \\ (n_7, n_8, n_9) &= \overrightarrow{n} && \text{on ship B} \\ (n_{10}, n_{11}, n_{12}) &= \overrightarrow{r} \times \overrightarrow{n} && \text{on ship B} \end{aligned}$$

with $\overrightarrow{n}$ is the outward unit normal vector on ship A and ship B and $\overrightarrow{r}$ is the position vector with respect to the origin of the reference frame on ship A and ship B.

Sea bed condition

$$\frac{\partial}{\partial n}\phi = 0 \qquad \text{for} \quad z \rightarrow -\infty \tag{8}$$

Radiation condition at infinity

$$\lim_{kr\to\infty} \sqrt{kr}(\frac{\partial\phi}{\partial n} - ik\phi) = 0 \qquad \text{at} \quad \text{kr} \to \infty \tag{9}$$

The wave exciting force F_i can be divided into the incident wave part, $F_i{}^I$, and the diffraction part, $F_i{}^D$.

$$F_i = F_i{}^I + F_i{}^D = -i\rho\omega_e \iint_{S_A+S_B} (\phi_I + \phi_D) n_i ds \tag{10}$$

The motion induced force is

$$E_i = -i\rho\omega_e \iint_{S_A+S_B} \sum_{j=1}^{12} \xi_j \phi_j n_i ds = \sum_{j=1}^{12} T_{ij}\xi_j \tag{11}$$

where,

$$T_{ij} = \omega_e{}^2 A_{ij} - i\omega_e B_{ij} \tag{12}$$

The terms A_{ij} and B_{ij} are added mass and damping coefficients, respectively.

$$A_{ij} = \frac{\rho}{\omega_e}\text{Im}[\iint_{S_A+S_B} \phi_j n_i ds] \tag{13}$$

$$B_{ij} = -\rho\text{Re}[\iint_{S_A+S_B} \phi_j n_i ds] \tag{14}$$

Under the assumption that the responses are linear and harmonic, the twelve linear coupled differential equations of motion for two floating bodies can be written in the following form

$$\sum_{j=1}^{12} [-\omega_e{}^2(M_{ij} + A_{ij}) - i\omega_e B_{ij} + C_{ij}]\xi_j = F_i \qquad \text{for} \quad \text{i} = 1, 2, ...12 \tag{15}$$

where, M_{ij} is the generalized mass matrix for the ship A and ship B, C_{ij} is the restoring force matrix for ship A and ship B, respectively, ξ_j is the complex amplitude of the response motion in each of the six degree of freedom for each body, and F_i is the complex amplitude of the wave exciting force for ship A and ship B.

3 Numerical procedure

The diffraction and radiation potential can be represented by the distribution with the density on the surface S_A and S_B.

$$\iint_{S_A+S_B} \sigma(Q)G(P,Q)ds(Q) = 4\pi\phi(P) \qquad \text{for} \quad \text{P} \quad \text{inside} \quad \text{fluid} \tag{16}$$

The unknown source density σ can be found by imposing the body boundary conditions and it gives

$$\frac{1}{2}\sigma(P) + \frac{1}{4\pi}\iint_{S_A+S_B}\sigma(Q)\frac{G(P,Q)}{\partial n}ds(Q) = V_n \qquad \text{for P body surface} \qquad (17)$$

where, V_n is the normal component of the velocity on the body surface and is given in (5), (6) and (7). In order to calculate the Green's function more efficiently, Telste and Noblesse(1986)'s techniques have been used in this program.

4 Relative motion between two floating bodies

The longitudinal, horizontal and vertical relative motion between ship A and ship B at any position can be expressed as three components,

$$\frac{L_R}{\zeta_a} = \frac{1}{\zeta_a}[(\xi_1 + z_A\xi_5 - y_A\xi_6) - (\xi_7 + z_B\xi_{11} - y_B\xi_{12})] \qquad (18)$$

$$\frac{H_R}{\zeta_a} = \frac{1}{\zeta_a}[(\xi_2 + x_A\xi_6 + z_A\xi_4) - (\xi_8 + x_B\xi_{12} + z_B\xi_{10})] \qquad (19)$$

$$\frac{V_R}{\zeta_a} = \frac{1}{\zeta_a}[(\xi_3 - x_A\xi_5 + y_A\xi_4) - (\xi_9 - x_B\xi_{11} + y_B\xi_{10})] \qquad (20)$$

where, (x_A, y_A, z_A) and (x_B, y_B, z_B) are the coordinates of the position with respect to each body frame system; see Figure 1.

5 Numerical result and discussion

The Numerical calculations of motion response and relative motion have been carried out for Kodan(1984)'s rectangular barge and conventional ship model with zero speed. The principal particulars of a barge and a ship model are given in Table 1. The distance between barge and ship from each body's center of gravity is $1.2m$, i.e., P=$1.2m$(see Figure 1). The longitudinal centers of barge and ship are positioned same.

In order to validate the developed calculation program, the comparisons are performed for Kodan(1984)'s experimental and 2-D strip theory numerical results, Fang and Kim(1986)'s 2-D strip theory numerical results and Fang and Chen(2001)'s 3-D potential theory numerical results, respectively.

The numerical calculated results of motion response and relative motion in waves are presented in Figure 2 through Figure 25.

5.1 Motion behaviors between barge and ship

Figure 2 and 3 show the sway amplitude for ship at 45^o and -45^o heading waves. The heave amplitudes for a ship at 45^o and -45^o heading waves are shown in Figure 4 and 5. Due to the

Table 1: Principal particulars of models

Items	Unit	Barge(Left)	Ship(Right)
Length	m	3.125	2.088
Breadth	m	0.600	0.369
Draft	m	0.113	0.131
Displacement	m^3	0.203	0.081
Waterplane area	m^2	1.875	0.685
GM_T	m	0.223	0.074
GM_L	m	7.184	2.523
KG	m	0.106	0.080
K_{xx}	m	0.118	0.097
K_{yy}	m	0.751	0.506
K_{zz}	m	0.760	0.480
The distance between the centers of two model, P=1.2m			

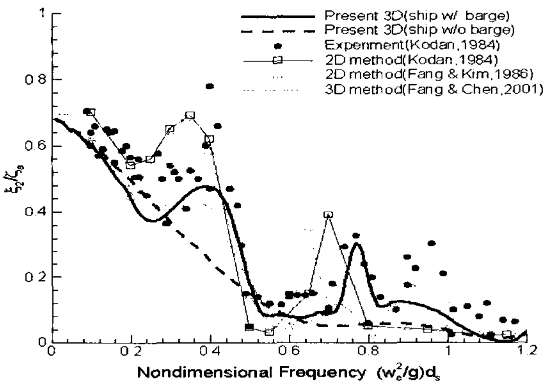

Figure 2: Sway amplitude for ship at β=45^o

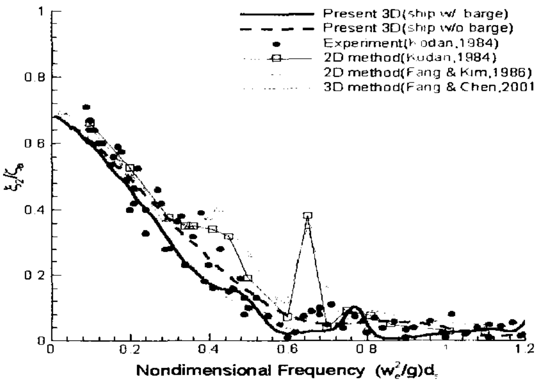

Figure 3: Sway amplitude for ship at β=-45^o

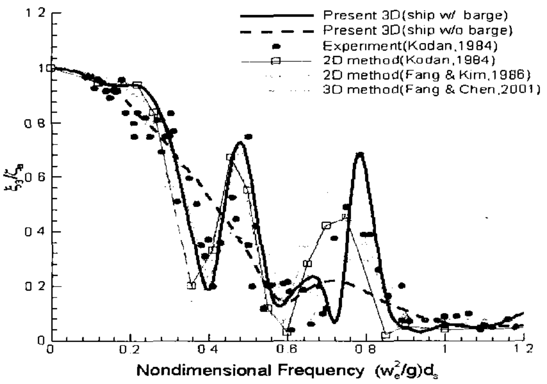

Figure 4: Heave amplitude for ship at β=45^o

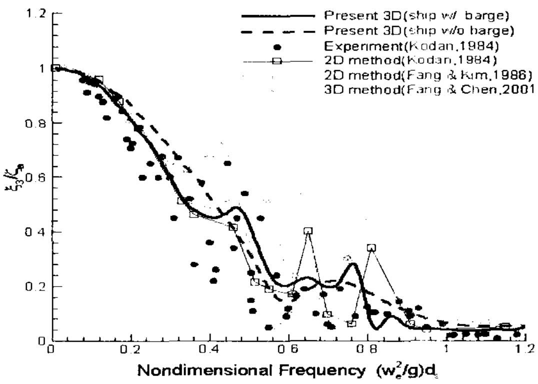

Figure 5: Heave amplitude for ship at β=-45^o

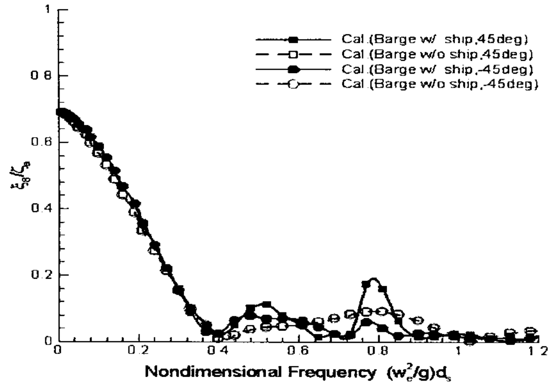

Figure 6: Sway amplitude for barge

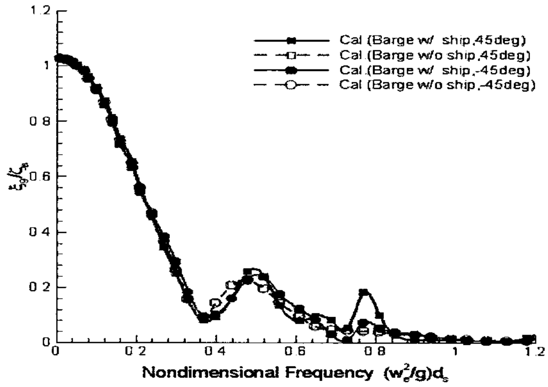

Figure 7: Heave amplitude for barge

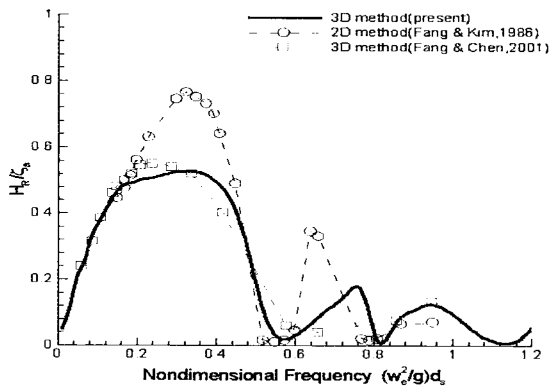

Figure 8: Horizontal relative motion at β=45^o

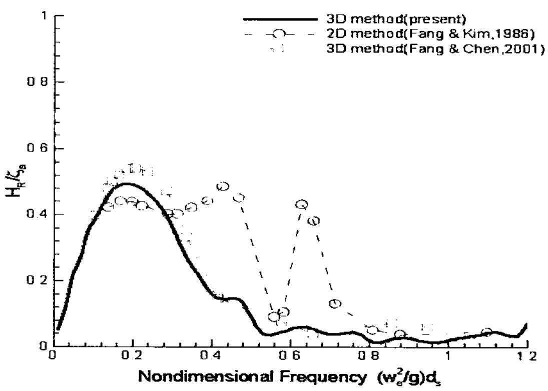

Figure 9: Horizontal relative motion at β=-45^o

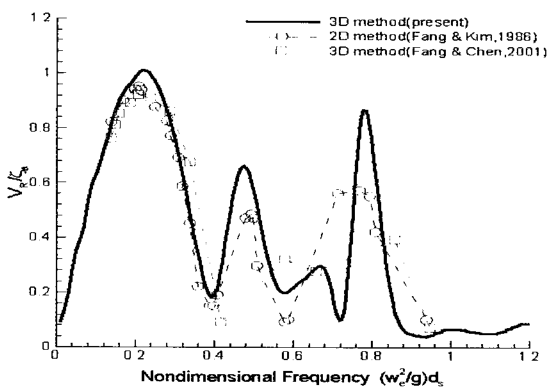

Figure 10: Vertical relative motion at β=45^o

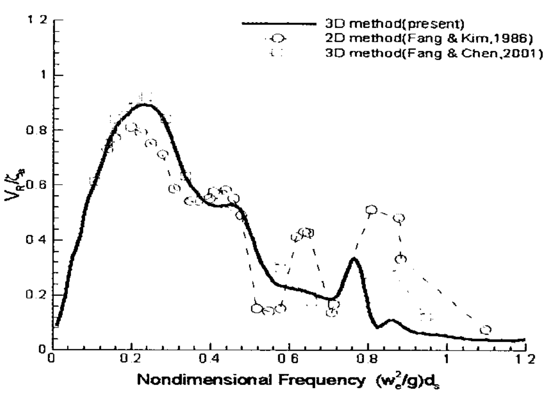

Figure 11: Vertical relative motion at β=-45^o

hydrodynamic interaction effect between barge and ship, the ship motion responses with barge are quite different from the responses of a single ship without barge. All the motion responses of the ship with barge are smaller on the leeside than on the weather side because of the sheltering effect.

Figure 6 and 7 show the sway and the heave amplitude for barge at 45^o and -45^o heading waves, respectively. Unlike the ship's case, the motion responses of barge with ship are the same as the motion responses of single barge without ship except several frequencies, which causes the hydrodynamic interaction effect between barge and ship. In general, the present 3-D results are much closer to the experimental result than other numerical results specially heave motion response.

5.2 Relative motions between barge and ship

Figure 8 and 9 show the horizontal relative motion amplitudes at 45^o and -45^o heading waves. The calculation positions for the relative motion are each body's center of gravity, i.e., $(x_A, y_A, z_A) = (0,0,0)$, $(x_B, y_B, z_B) = (0,0,0)$.

Figure 10 and 11 show the vertical relative motion amplitude at 45^o and -45^o heading waves. For comparison of the present 3-D relative motion results, Fang and Kim(1986)'s 2-D results and Fang and Chen(2001)'s 3-D results are used. As we can see, the present 3-D results have the same behavior as Fang and Chen(2001)'s 3-D results except the high frequency, which caused the difference of heave motion responses in those regions.

5.3 The separation distance effect between barge and ship

In order to find the effect of the separation distance between barge and ship on the motion responses, we considered the various position arrangements for a side-by-side offloading and a tandem offloading which given in Figure 12 and 13. For a side-by-side offloading, we considered the distance between the centers of two model, P=1.200m, 0.900m and 0.600m, respectively. For a tandem offloading, we considered the distance between the centers of two model, P=6.250m, 4.690m and 3.125m, respectively.

The sway, heave and pitch amplitudes for ship and barge in side-by-side offloading at $\pm 45^o$ heading waves are shown in Figure 14 through Figure 19, respectively. Due to the hydrodynamic interaction effect between ship and barge, the ship motion responses with barge are quite different from the responses of a single ship without barge. All the motion responses of the ship with barge are smaller on the leeside than on the weather side because of the sheltering effect due to presence of barge. The motion responses of ship are decrease and the peak frequencies are shifted the high frequency region due to the standing wave between two floating structures as the separation distance decrease. Unlike the ship's case, the motion responses of barge with ship are the same as the motion responses of single barge without ship except several frequencies, which causes the hydrodynamic interaction effect between barge and ship.

The sway, heave and pitch amplitudes for ship and barge in tandem offloading at $\pm 45^o$ heading waves are shown in Figure 20 through Figure 25, respectively. Due to the hydrodynamic interaction effect between ship and barge, the heave and pitch motion responses of ship with barge are some different from the responses of a single ship without barge except sway motion responses. In case of tandem offloading, the horizontal motions are the same behaviors with single body motion response; however, the vertical motions are affected by neighborhood floating structure. Like the

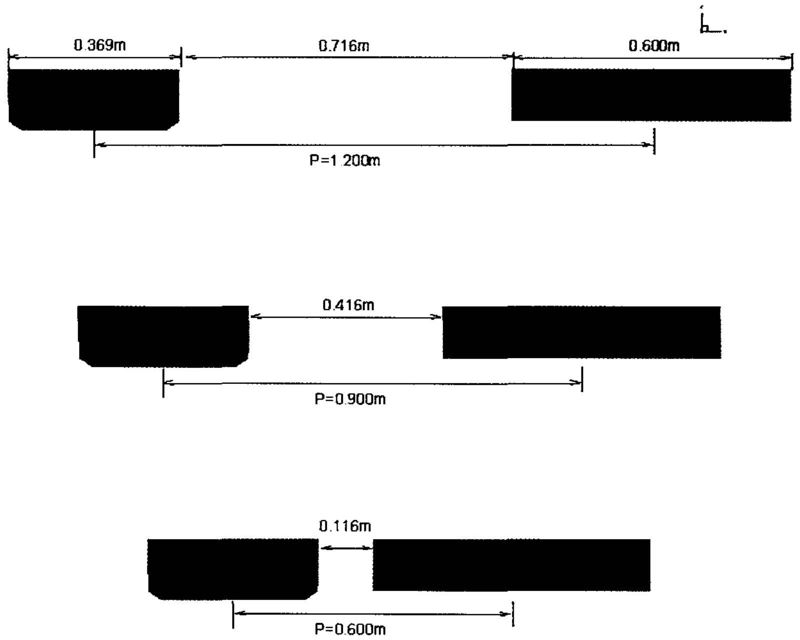

Figure 12: Various position arrangements for side-by-side offloading

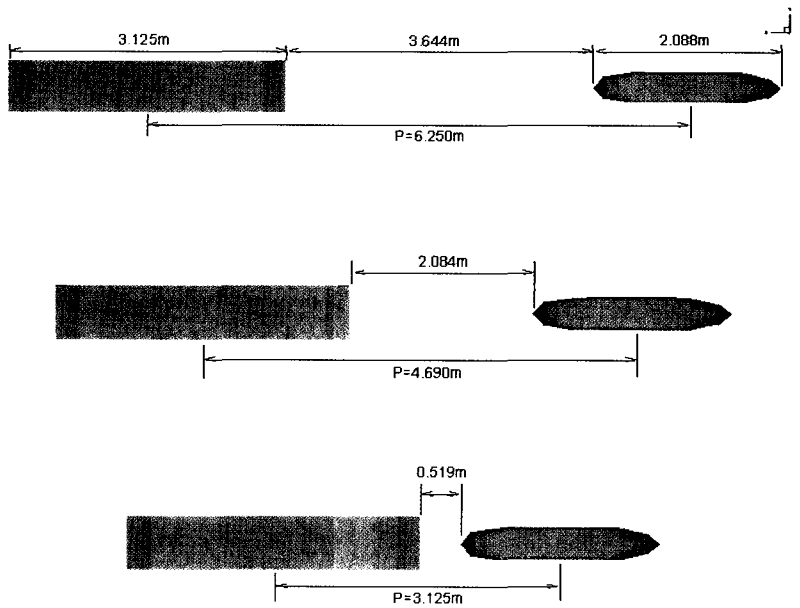

Figure 13: Various position arrangements for tandem offloading

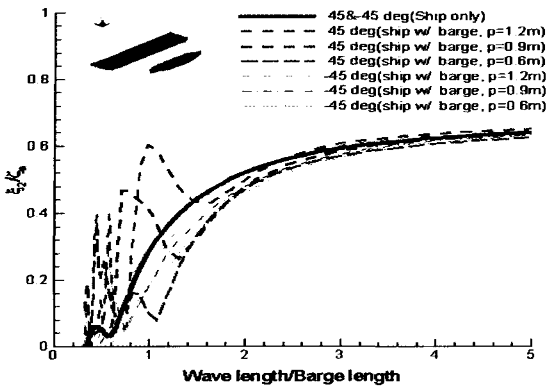

Figure 14: Sway amplitude for ship

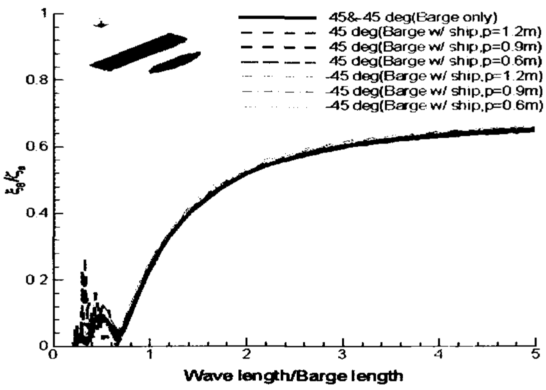

Figure 15: Sway amplitude for barge

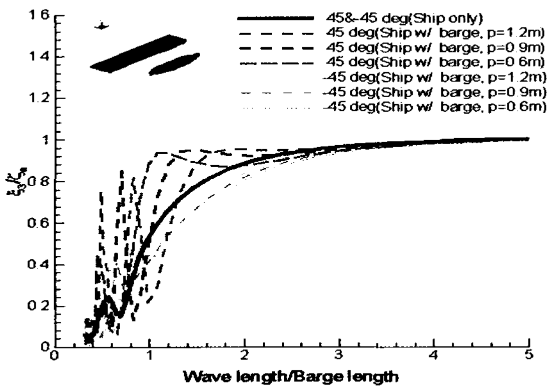

Figure 16: Heave amplitude for ship

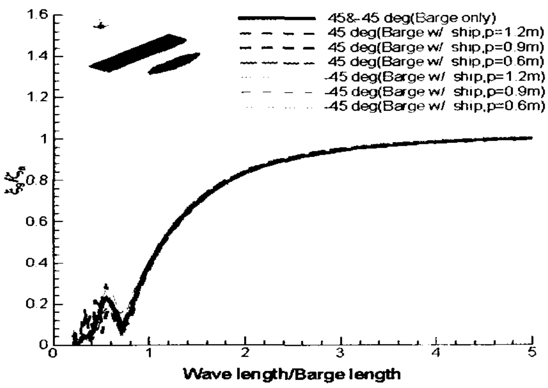

Figure 17: Heave amplitude for barge

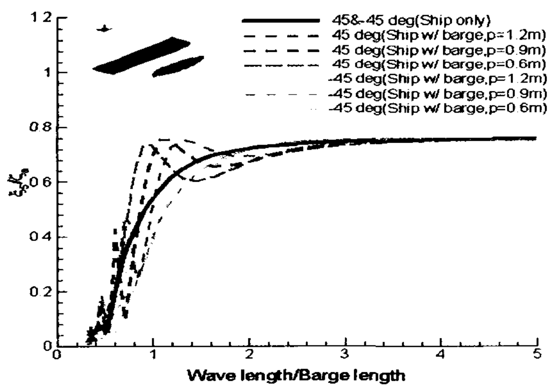

Figure 18: Pitch amplitude for ship

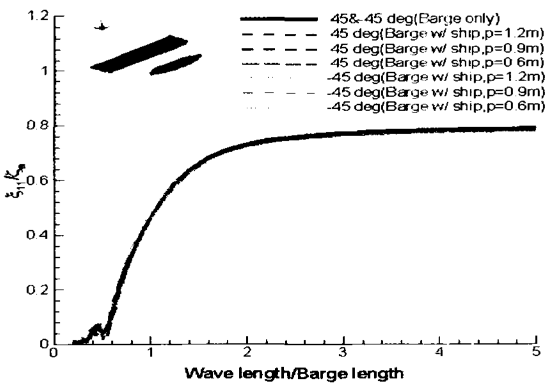

Figure 19: Pitch amplitude for barge

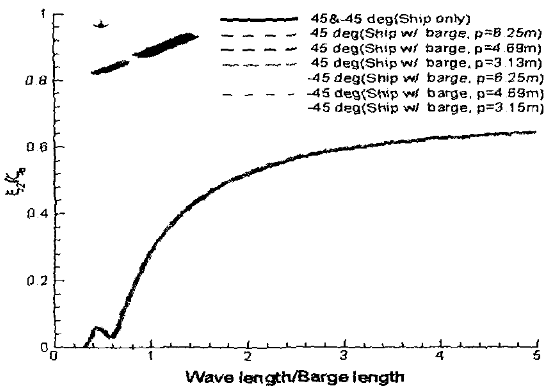

Figure 20: Sway amplitude for ship

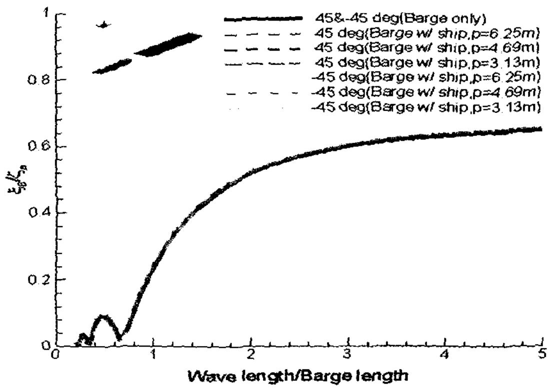

Figure 21: Sway amplitude for barge

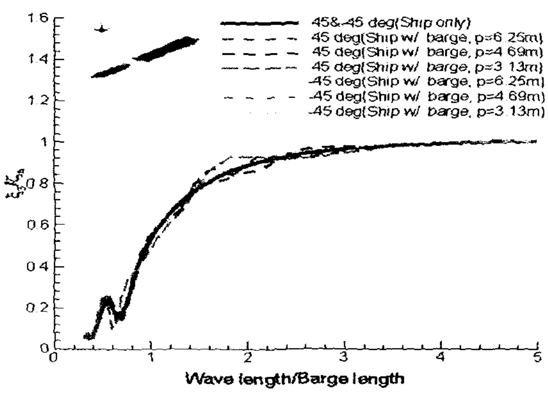

Figure 22: Heave amplitude for ship

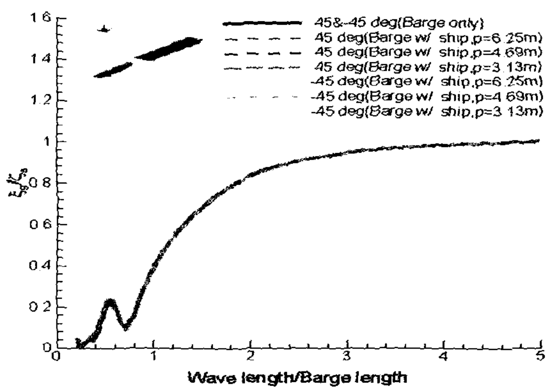

Figure 23: Heave amplitude for barge

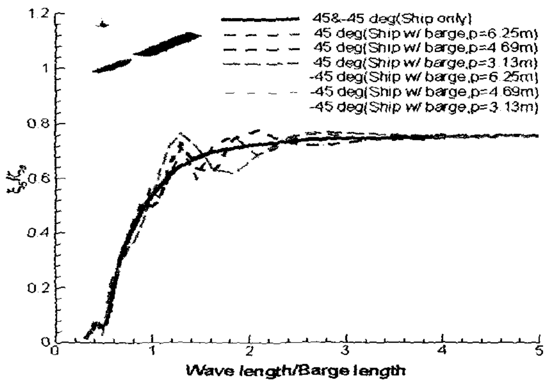

Figure 24: Pitch amplitude for ship

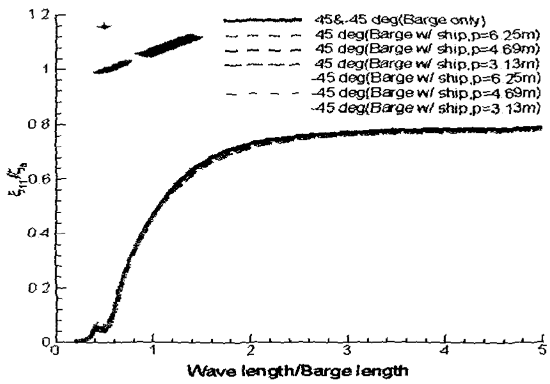

Figure 25: Pitch amplitude for barge

side-by-side offloading case, the motion responses of ship in tandem offloading are decrease and the peak frequencies are shifted the high frequency region as the separation distance decrease.

From the computational results it can be concluded that the hydrodynamic interaction effect of presence of neighborhood floating structures during offloading can be quite significant in the view point of seakeeping because they affect each other's motion responses through hydrodynamic interaction in waves. Consequently the unnecessary large motions between two floating bodies, which would causes the damage of offloading system and the collision between two bodies.

As a result, the optimum separation distance of these multiple floating structures during offloading should be carefully designed to avoid resonance motion response, dangerous damage and collision.

6 Conclusion

In this present paper, a numerical prediction is described on the coupled motion responses of between two offshore floating structures including the hydrodynamic interaction effect in oblique waves. The numerical calculation results give a good correlation with the experimental results and also with other numerical results. The motion responses between two floating bodies due to hydrodynamic interaction effect can be quite significant phenomena during offloading. Thus, the optimum separation distance of these multiple floating structures during offloading should be carefully designed to avoid the unnecessary large motions between two floating bodies. The present developed numerical calculation program can be used effectively to predict the motion responses and relative motions of multiple floating structures in various waves.

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