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Dynamic analysis of three adjacent bodies in twin-barge floatover installation

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Abstract. Floatover technology has been widely used in offshore installation, which has many substantial advantages compared with the traditional derrick barge. During the topside offloading of a twin-barge floatover installation, the transport barge is side by side moored between two floatover barges. In this paper, the twin-barge model with the connecting hawsers and pneumatic fenders is established. Coupled dynamic analysis is carried out to investigate the motions of the barges under wind, wave and current environments. Particular attention is paid to the effects on system responses with different frictional performance of fender, axial stiffness of the hawsers and environmental conditions. The research results can be used for optimizing the parameters of the system and reducing the risk of topside offloading.

Keywords: twin-barge floatover; hawsers; pneumatic fenders; coupled dynamic analysis

1. Introduction

With the increasing need of the deep water oil and gas resources, more and more drilling and production platforms are widely used in offshore oil and gas production service. How to install these platforms safely and quickly has been the focus of the offshore industry. The installation of the topside is the main issues of the whole installation process. Until now, there are two major ways to install the topside of platform. One is traditional lift installation and another is floatover method.

The crane vessels (derrick barges) have been used to install an integrated deck onto a jacket structure for many years. As the integrated deck weight becomes larger and larger, the availability and capacity of such crane vessels restrict the application of lift installation. Furthermore, day rates of these crane vessels with large lift capacity are very high and these vessels are not available at all offshore locations. So floatover installation is becoming a preferred offshore topside installation method.

Various floatover technologies have been developed and successfully applied to the installations of integrated topsides onto fixed and floating platform substructures. The category of

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floatover technologies defines the major two methods: single barge scheme and twin barge scheme. The single barge scheme is widely used everywhere nowadays, but the design of the jacket frame structure have to meet the demand that a single barge can enter into. Besides this, the weight of topside increases gradually, so the single barge scheme is often limited by the draft of barges. In recent years, the twin-barge floatover has become the research focus in offshore topside installations.

In November 2006, the twin-barge floatover technology was applied to install the 3400Te Kikeh topsides onto the first-ever spar outside of the Gulf of Mexico for the first time in open waters (Edelson and Luo 2008). In this twin-barge floatover installation, the integrated deck is first loaded out onto a single transport barge and towed to the installation operation base. Two floatover barges are positioned either side of the transport barge, under the topside. The topside offload is completed by ballasting the transport barge out from beneath the topside, transferring the full topside load to the floatover barges, and is then removed. After this, the topside and floatover barges are made into a rigidly connected catamaran. At last, the catamaran is towed to the installation site and the topside load is transferred from the catamaran to Spar hull. In topside off loading operation, the transport barge is moored in close proximity between the two floatover barges, as shown in Fig. 1. The hydrodynamic coefficient of barges will present different dynamic characteristics with hydrodynamic interactions. The relative motions between these barges are concerned urgently by designers and operators.

The hydrodynamic interactions between multiple bodies have been reported by many researchers. 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 Ohkosu's theory to hydrodynamic interaction problem between two parallel structures in oblique waves. Fang and Chen (2001, 2002) used three-dimensional source distribution method to calculate the wave forces and motions of two bodies in waves. Inoue and Islam (1999, 2002) analyzed the motion responses of FPSO and the side-by-side moored LNG carrier; they developed a time domain method and discussed the discrepancies with the frequency domain. Choi and Hong (2002) applied higher-order boundary element model to analyze the hydrodynamic interactions of multi-body system.

Fig. 1 Transport barge and floatover barges in position

Kim and Ha (2002) used three-dimensional pulsating source distribution techniques to calculate the twelve coupled linear motion responses and relative motions of the barge and ship in oblique waves. Koo and Kim (2005) applied a multi-hull/mooring/hawser/fender coupled dynamic analysis program in time domain to simulate the multi-body system. They also compared the combined matrix method (CMM) and separated matrix method (SMM). They found that, when hydrodynamic interaction effects are expected to be smaller than mechanical coupling effects, the SMM can be an efficient way to solve the multi-body problem. Chitrapu and Mordfin (2007) analyzed the wave loads and vessel responses of two alongside vessels. An efficient time domain method is presented for evaluating the sea keeping and maneuvering performance of proximate vessels advancing with forward speed. Wong and Paton (2007) analyzed the effects of some parameters in FPSO and the side-by-side moored LNG carrier. In this study, variations between seasons, vessel conditions, the size of stern thrusters and the FPSO storage capacity were all investigated. Sun *et al*. (2008, 2012) used a quadratic boundary element method to solve the three-dimensional wave-structure interaction problem. The partial discontinuous elements have been adopted to remove the irregular frequencies in the calculations. As a result, corresponding meshes on the inner free surface are needed. Xu *et al*. (2012) used potential flow code WAMIT considering both low-order and higher-order boundary element method to analyze both multiple bodied system and single body. Corresponding model tests were also performed to compare with the numerical results.

The hydrodynamic interactions between multiple bodies have been studied by many researchers; however they mainly analyze the interactions between two bodies. The interactions between three bodies or more are rarely investigated. The hydrodynamics of three side-by-side bodies are more complex than for a single barge or two barges in waves for hydrodynamic interaction effect. In addition, the parameter analysis of hawser and fender is often neglected, the research work of multiple bodies needs to be further investigated. In this paper, time domain analysis is carried out to investigate the motion responses and mooring tensions by using the 3D potential theory. The objective of the present paper is to investigate the effects on responses of system indifferent frictional coefficient of fender, axial stiffness of hawser and environmental conditions.

2. Mathematical formulation

2.1 Equations of motion for the three floating bodies

Every floating body has six degrees of freedom. Under the assumption that the response are linear and harmonic, the eighteen linear coupled differential equations of motion for the three floating bodies can be written in the following form.

$$\sum_{j=1}^{18}[-\omega^2(M_{ij}+A_{ij})-i\omega B_{ij}+C_{ij}]\xi_j = F_i \qquad \textit{for } i=1,2,...,18 \tag{1}$$

Where M_{ij} is the generalized mass matrix for the three barges. A_{ij} and B_{ij} are the added mass and potential damping matrix respectively. C_{ij} is the restoring force matrix. ξ_j is the response motion in each of the six degree of freedom for each barge. F_i is the complex amplitude of the wave exciting force for the three barges.

2.2 Multi-body simulations

In the case of multi-body which are hydrodynamically and mechanically coupled, the equations mentioned above needs to be solved in a coupled matrix equation. In the case of 3-body system in this paper, the system has 18 degrees of freedom. All 3 bodies can be subject to wave-induced forces, hydrodynamic reaction forces and mechanical coupling effects. The equation of multi-body motion is given as follows (Hong 2005).

$$\begin{bmatrix} M^{11} & M^{12} & M^{12} \\ M^{21} & M^{22} & M^{23} \\ M^{31} & M^{32} & M^{33} \end{bmatrix} \times \begin{bmatrix} \ddot{X}^1 \\ \ddot{X}^2 \\ \ddot{X}^3 \end{bmatrix} + \begin{bmatrix} \int_0^t H^{11}(t-\tau)d\tau & \int_0^t H^{12}(t-\tau)d\tau & \int_0^t H^{13}(t-\tau)d\tau \\ \int_0^t H^{21}(t-\tau)d\tau & \int_0^t H^{22}(t-\tau)d\tau & \int_0^t H^{23}(t-\tau)d\tau \\ \int_0^t H^{31}(t-\tau)d\tau & \int_0^t H^{32}(t-\tau)d\tau & \int_0^t H^{33}(t-\tau)d\tau \end{bmatrix}$$
$$\times \begin{bmatrix} \dot{X}^1 \\ \dot{X}^2 \\ \dot{X}^3 \end{bmatrix} + \begin{bmatrix} C^{11} & C^{12} & C^{13} \\ C^{21} & C^{22} & C^{23} \\ C^{31} & C^{32} & C^{33} \end{bmatrix} \times \begin{bmatrix} X^1 \\ X^2 \\ X^3 \end{bmatrix} = \begin{bmatrix} F^1 \\ F^2 \\ F^3 \end{bmatrix} = f(x^1, \dot{x}^1, x^2, \dot{x}^2, x^3, \dot{x}^3, t) \tag{2}$$

Where M^{ij} = inertia and added inertia matrix of body *i* as a result of motion of body *j*.

H^{ij} = matrix of retardation functions of body *i* as a result of motions of body *j*.

C^{ij} = matrix of hydrostatic restoring forces of body *i*.

X^i = motion vector of body *i*.

F^i = vector of external forces on body *i*, including wave exciting forces and wave drift forces.

The inertia matrices, added inertia matrices and the matrices of the retardation functions are derived from multiple body diffraction analysis in the frequency domain. This implies that, the wave shielding of one body behind another body is taken into account.

3. Numerical simulation

3.1 Barges modeling

The numerical simulation model consists of three adjacent barges which are parallel positioned. Fig. 2 shows the front view of the arrangement of the three barges system. Barge B is the middle transport barge. The floatover barges A and C are positioned under topsides on both sides of the transportation barge. That is to say, the topside and the barge B can be considered as a rigid body and the topside doesn't contact with the floatover barges A and C before the topside offloading. The gap between the barge B and barges A or C is 1.5 m. The main parameters of the three barges are listed in Table 1 and the panel model of the barges is illustrated in Fig. 3.

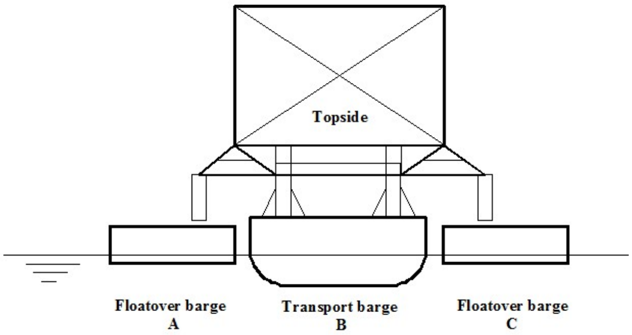

Fig. 2 The front view of the three barges system

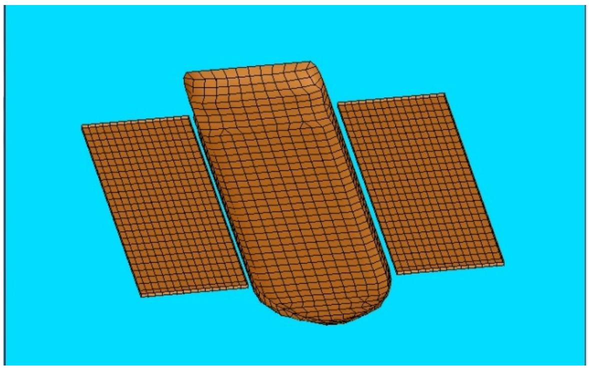

Fig. 3 Panel model of the three barges

Table1 Main parameters of the three barges

Designation	Symbol	Unit	Transport Barge	Floatover Barge
Length	L_{OA}	m	122.45	76
Breadth	B	m	30.5	24
Depth	D	m	7.6	4.9
Light Displacement	Δ	t	3636	1155
Light Draft	T	m	1.5	0.758
Full Load Displacement	Δ	t	18420	6487
Full Load Draft	T	m	5.96	3.8
Deadweight	DWT	t	14679	5332

3.2 Mooring system

The mooring system for the positioning of the three barges consists of 6 catenary mooring lines, 8 hawsers and 8 pneumatic fenders, as shown in Fig. 4. The catenary mooring lines which are used for positioning the middle transport barge B are made of chains. They are arranged at the stem and stern area and numbered as L1 to L6. The floatover barges A and C are positioned at both sides of the barge B with hawsers and pneumatic fenders. The hawser system consists of 8 identical steel ropes. Each floatover barge is connected with the transportion barge with 4 hawsers and 4 pneumatic fenders. The safe working load and maximum breaking load of the hawsers which are made of 44 mm steel wires is assessed to be 681 kN and 1238 kN, respectively. The 4 hawsers arrangement at each side of transportion barge consists of 1 stern line, 1 aft spring line, 1 fore spring line and 1 bow line. The hawsers are designated as A1 to A4 for barge A and C1 to C4 for barge B from aft to fore, respectively, as shown in Fig.4.

The pneumatic fender (ISO17357, 2002), which is filled with pressurized air inside the fender body, is often used as an energy-absorbing device and a spacer to keep a proper stand-off distance for ship-to-ship transfer operation. In this paper, the 8 pneumatic fenders of 1.5 m diameter have a maximum breaking load (MBL) of 1829 kN at 55% compression. The safe working load of the fenders is assumed to be 1005 kN. The fenders are numbered as F1 to F8, as shown in Fig. 4. The particulars of the mooring systems are listed in Table 2. For simplicity, the fender and the hawser are modeled as linear spring with the given EA (Table 2) in the present paper.

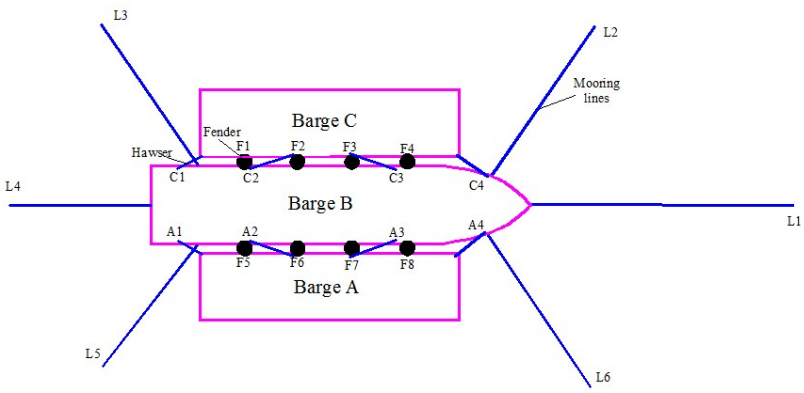

Fig. 4 Arrangement of the mooring systems

Table 2 Main particulars of mooring system, hawser and fender

Designation	Diameter/mm	Wet Weight/ kg·m^{-1}	EA/N	MBL/KN
chain	60.0	62.44	2.639E8	3144
Hawser	44.0	N/A	1.200E6	1238
Fender	150	N/A	2.217E6	1829

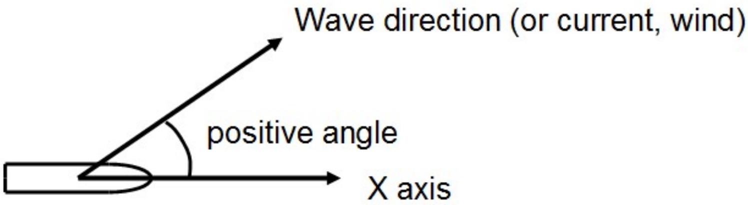

Fig. 5 The direction angles of environment loads

Table 3 Environment parameters

Wave	Wave spectrum	JONSWAP
	Hs/m	0.5
	Tp/s	5.0
	Gamma	3.0
	Direction/deg	180
Wind	Wind spectrum	API
	V/(m/s)	10.0
	Direction	180
Current	V/(m/s)	0.5
	Direction/deg	180

3.3 Environmental conditions

Numerical simulations are conducted for the case of side-by-side offloading operation in shallow water with wind, current and wave environmental conditions. The depth of water is 12 m. JONSWAP spectrum is used for representing the irregular wave. The API wind spectrum is used in this present simulation. Current velocity is assumed to be uniform with depth. As for the current and wind loading on the three barges, the standardized OCIMF data setsare considered in present study (OCIMF 1994). The direction angle of environment loads is defined as the angle between the positive x and the propagating direction, as shown in Fig. 5. The detailed environment parameters are listed in Table 3.

4. Results and discussions

The simulation is carried out by using the developed time domain coupled dynamic analysis computer program AQWA for the multi-body system. Total simulation time is 10000s. The time step interval is set to be 0.1s. AQWA uses combined matrix method to exactly accounts for all the hydrodynamic and mechanical Interactions, where all the hydrodynamic coefficients and mechanical coupling of hull and slender members are included in one large matrix.

In parameter analysis of fender and hawser, the collinear wind-wave-current environmental conditions from the head direction are studied here. Numerical simulations are carried out under the same environmental conditions. Due to the symmetry and simplicity, the relative motions and the hawser tensions between barge A and barge B are used as the analysisdata. It should be mentioned that the relative motions are computed as the COG of barge A motions minus the COG of barge B. And the 2nd-order slowly varying responses are also included in this analysis.

4.1 Sensitivity study for axial stiffness of hawser

In topside offloading operation, the twin barges are allowed to have small free motion in horizontal direction while restrained by hawsers assist. So the variation for axial stiffness of hawser may affect the relative motion between barges. In present paper, the axial stiffness of hawser is assessed as 1.0×10^6N, 1.2×10^6N and 1.4×10^6 N, respectively. The friction coefficient of fender is set to be 0.3.

Table 4 summarizes the statistics of the relative motions between barges A and B in the six motion modes for the three axial stiffness of hawser. From Table 4 we can see that the relative motions in horizontal directions are much larger than those in vertical direction. It is because of the small restoring force in horizontal plane. Due to the small gap, the hydrodynamic interactions between the three barges will be very strong. So the sway motion is pretty large. In almost every motion mode, the relative motions have a decrease tendency with the increase of axial stiffness of hawser and it is the most obvious in surge and sway mode. The reason may be that the environmental loads on system are from head direction.

Table 4 Relative motions between barge A and barge B in different axial stiffness of hawser

Relative motion		1.0×106N	1.2×106N	1.4×106N
Surge(m)	Mean	0.0047	0.0031	0.0014
	Max	0.2614	0.2064	0.1915
	Min	-0.2303	-0.1925	-0.1559
	RMS	0.0708	0.0551	0.0455
Sway(m)	Mean	0.1503	0.1141	0.0964
	Max	0.4663	0.3813	0.2983
	Min	-0.1882	-0.1865	-0.1975
	RMS	0.0697	0.0556	0.0447
Heave(m)	Mean	-0.0120	-0.0120	-0.0120
	Max	0.02992	0.03112	0.03115
	Min	-0.0515	-0.0515	-0.0547
	RMS	0.0108	0.0108	0.0109
Roll(deg)	Mean	0.0007	-0.0003	-0.0003
	Max	0.2893	0.2687	0.2463
	Min	-0.3274	-0.2690	-0.2074
	RMS	0.0921	0.0673	0.0548
Pitch(deg)	Mean	-0.0798	-0.0799	-0.0799
	Max	0.1165	0.1355	0.1285
	Min	-0.3153	-0.3070	-0.2953
	RMS	0.0569	0.0572	0.0568
Yaw(deg)	Mean	-0.0107	-0.0028	0.0011
	Max	1.221	1.037	0.8555
	Min	-1.334	-1.217	-0.8863
	RMS	0.3679	0.2885	0.2491

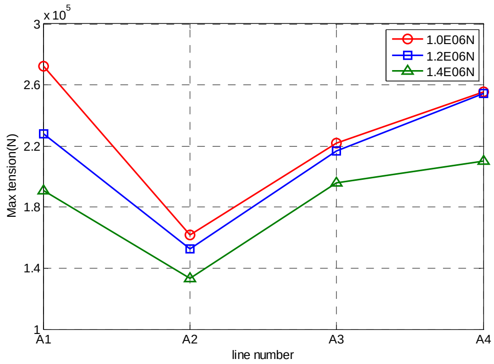

Fig. 6 The maximum tensions between barges A and B for different EA of hawser

Table 5 Relative motions between barges A and B for differentender friction

Relative motion		0.1	0.2	0.3
Surge(m)	Mean	0.0007	0.0028	0.0031
	Max	0.2884	0.2132	0.2064
	Min	-0.2858	-0.2378	-0.1925
	RMS	0.0857	0.0659	0.0551
Sway(m)	Mean	0.1474	0.1213	0.1145
	Max	0.4552	0.3694	0.3613
	Min	-0.1841	-0.1982	-0.1864
	RMS	0.0725	0.0600	0.0556
Heave(m)	Mean	-0.0120	-0.0120	-0.0120
	Max	0.0281	0.0294	0.0311
	Min	-0.0514	-0.0517	-0.0515
	RMS	0.0107	0.0108	0.0108
Roll(deg)	Mean	0.0007	0.0001	-0.0003
	Max	0.3015	0.2457	0.2687
	Min	-0.3108	0.2895	-0.2690
	RMS	0.0928	0.0744	0.0673
Pitch(deg)	Mean	0.0007	0.0028	0.0031
	Max	0.2884	0.2132	0.2064
	Min	-0.2858	-0.2378	-0.1925
	RMS	0.0857	0.0659	0.0551
Yaw(deg)	Mean	-0.0333	-0.0099	-0.0027
	Max	1.197	0.9783	1.037
	Min	-1.309	-1.116	-1.217
	RMS	0.3776	0.3093	0.2883

Fig. 6 shows the maximum tensions of four hawsers A1 to A4 for different axial stiffness of hawser. It can be seen from Fig. 6 that the maximum tensions will derease with the increase of axial stiffness of hawser, sharing the similar characteristics with the relative motions described above. The hawser of A1 which located in the stern of the barge is the most obvious in four hawsers. Furthermore, we can see that the most loaded hawser is located in the stern or bow of the barges.

4.2 Sensitivity study for friction coefficient of fender

As described above, the fenders are arranged at each side of the transportation barge. The pneumatic fender is considered as an effective factor to reduce impact and ship motion. Fender friction works best in situations when the friction force is smaller than other forces in the same direction. Friction will slow down the relative motion between the two structures, so it is necessary to analyze the friction performance of fender. In this paper, the friction force between barges is given by $F = \mu R$, where μ is the friction coefficient and R is the normal reaction. The friction coefficient of fender is respectively assessed as 0.1, 0.2 and 0.3 according to AQWA setting. The axial stiffness of hawser is set to be 1.2×10^6 N in the following study.

Table 5 summarizes the statistics of relative motions between barges A and B in the six motion modes for three different friction coefficient of fender. It can be seen from Table 5 that the relative motions in almost all modes have a decrease with the increase of friction coefficient of fender. It is also the most obvious in horizontal direction modes. However, there are some irregular data in roll and heave modes and the variation trend is not visible. This suggests that the fender friction has an inhibitory effect on the relative motions in topside offload operation obvious.

The Maximum and Root Mean Square tensions of the four hawsers A1 to A4 for different friction coefficient of fender are shown in Fig. 7. From Fig. 7 we can see that the maximum tensions of four hawsers have different variationtrend with the change of friction coefficient of fender. The line A1 appears a different trend comparing with other three lines. The reason may be related to its location. In addition, the hawsers of A1 and A4 in stern and bow of the barge are more sensitive for the variation of the parameters. This indicates that the friction performance of fender plays an important role in keeping the tension of hawser steady.

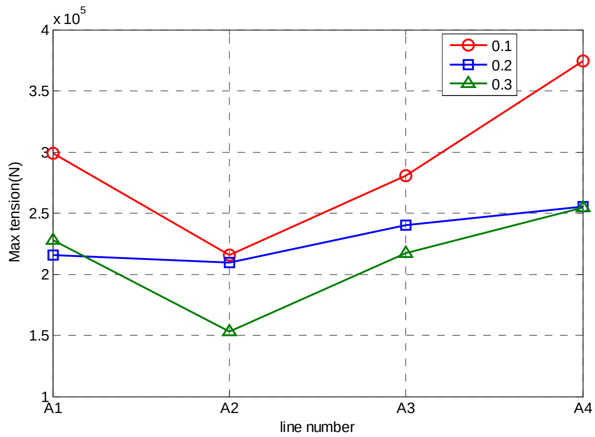

Fig. 7 The maximum tensions between barges A and B in different friction coefficient of fender

4.3 Sensitivity study for environmental conditions

Since the distance between the three barges is very small, the hydrodynamic interactions will be very complex in environmental conditions. So it is necessary to study the responses of system in different environmental conditions. For this analysis, the wind and current condition are listed in Table 3.

4.3.1 Sensitivity study for wave height

In this paper, the significant wave height is studied as the environment variable. The JONSWAP spectrum is used for the present study. Three significant wave heights with 0.5 m, 0.75 m and 1.0 m are under consideration.

According to the results studied above. The horizontal relative motions between barges are much larger than vertical relative motions. So only the maximum horizontal relative motions with different wave height are illustrated in Fig. 8. As we can see, the relative motion responses are become larger with the increase of wave height. The responses are very sensitive for the change of wave height. Fig. 9 shows the Maximum tensions of four hawsers A1 to A4 between barge A and barge B for different significant wave height. It can be seen that the maximum tensions of all four hawsers have an increase with the increase of wave height.

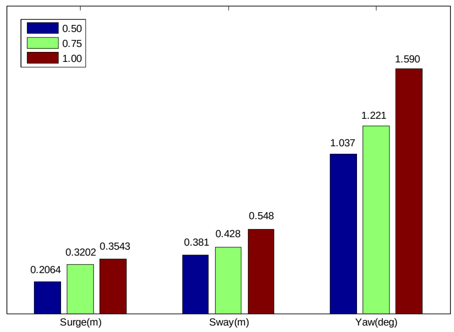

Fig. 8 The maximum horizontal relative motions with different significant wave heights

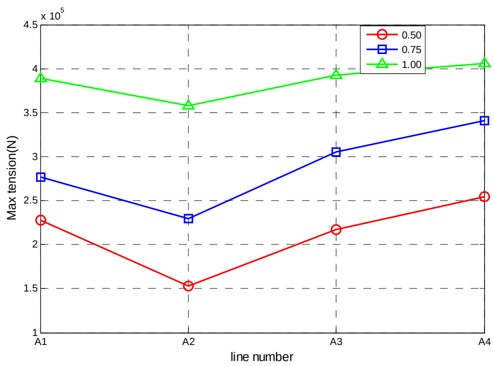

Fig. 9 The maximum tensions between barges A and B in different significant wave heights

4.3.2 Sensitivity study for wave angles

In topside offloading, the entire system will have different responses in different wave directions. Five wave angles with 0°, 45°, 90°, 135° and 180°are studied in the present paper. The responses are shown in Figs.10 and 11.

Figs. 10 and 11 shows the maximum horizontal relative motions and hawser tensions with different wave angles. It's clear that the maximum relative motions and hawser tensions are all occurred in wave angle of 90 deg. The system is the safest in wave angle of 0 deg. So the topside offloading operation should be avoided in the beam sea.

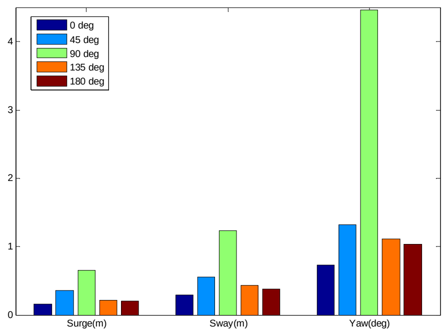

Fig. 10 The maximum horizontal relative motions with different wave angles

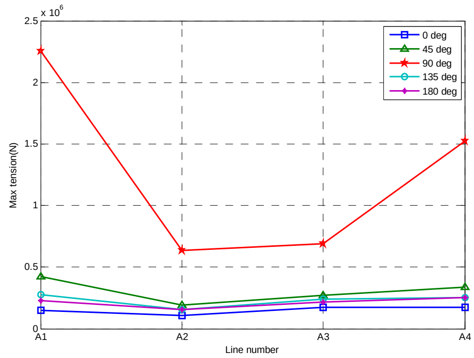

Fig. 11 The maximum tensions between barges A and B for different wave angles

5. Conclusions

The coupled side-by-side barge system with mooring lines, hawser lines and fenders is modelled and numerical simulation is conducted to investigate the motion responses. Several cases, including different axial stiffness of hawser, frictional performance of fender, wave heights and angles, are considered. The comparative study can be used for optimizing the parameters of the system and extending the operating limits. The following practical conclusions can be drawn:

- The relative motions in horizontal directions are much larger than those in vertical directions in side-by-side offloading operations. So it is the key to restrict the motions in horizontal directions.
- The increase of axial stiffness of hawser plays a great role in reducing the relative motions between barges and the hawser tensions. Thus it is important to select the axial stiffness of hawser reasonably for improving the safety in topside offloading.
- It can be seen that increasing the friction of fenders has an inhibitory effect on the relative motions and dynamic stability of hawsers. Some required measures must be taken to increase the friction of fender in practical project.
- The responses of system are very sensitive for the environmental conditions. So a relatively mild environment has to be chosen for the topside offloading.

Acknowledgments

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