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Analysis of Duplex Yoke Mooring System for Tandem Offloading of LNG

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ABSTRACT

The technology for transferring LNG between two floating vessels offshore is a crucial component in floating LNG facilities now in the planning stage. A duplex yoke mooring system and conventional boom-to-tanker LNG offloading arms were recently developed to carry out tandem offloading of LNG in open sea areas with significant wave heights up to 5.5 meters. This paper will present a methodology to evaluate the operability of the LNG offloading in severe environments. The relative motions between the FPSO and the carrier were predicted by a frequency-domain method. A series of model tests have been carried out. A good agreement between the predictions and measurements has verified and validated the analysis method and procedures. Berthing operations in seastates with a significant wave height of 3.5 meters were also conducted successfully. Therefore, it can be concluded that the technology of the duplex yoke mooring and boom-to-tanker loading arms is ready to be implemented for a safe and reliable transfer of LNG in harsh open sea environments for LNG facilities.

Keywords: Tandem offloading, LNG, FPSO, Duplex Yoke Mooring.

INTRODUCTION

Floating production, storage and offloading liquefied natural gas (LNG) facilities are being evaluated by the industry to meet the growing energy demand worldwide for environmental friendly, clean-burning LNG. Offshore transfer of LNG from one vessel to another in open sea and possible harsh environments is a technical and operational challenge, but side-by-side (SBS) transfer of liquid hydrocarbons and minus 48C° liquefied petroleum gas (LPG) is commonplace and is a proven practice in mild environments. Also well known is tandem (one vessel directly behind the other) transfer of oil through floating hose systems for floating production systems to oil tankers. However, transferring LNG at minus 160°C between two vessels is not common, and has not been done at all in a production capacity in any severe weather locations. SBS transfer of LNG with conventional loading arms has been proposed and studied for many years; and model testing and full size loading arm testing have been performed by FMC Loading Systems to prove those systems are satisfactory for moderate environments [1-3]. Vessel motion is the limiting factor in the severity of environment that these systems can successfully operate in, especially during the flange connection phase of the operation. One example of an exposed weather LNG terminal facility that experiences fairly constant wave frequency vessel motion is the Shell Brunei loading terminal [2]. This is a facility about 3km offshore, located on a jetty without a breakwater, where LNG was originally transferred through a tandem loading system consisting of multiple degree-of-freedom flexing LNG piping arrangement connected with cryogenic swivel joints. The original loading system served for over twenty years. The facility now operates with conventional FMC loading arms that utilize constant motion cryogenic swivel joints to load LNG.

The technology for transferring LNG between two floating vessels is a crucial component in floating LNG facilities. One of the primary applications for this technology is the floating hydrocarbon production unit for field developments where large quantities of gas are present. Unfortunately, many of the largest offshore gas fields are situated in areas of unfavorable weather, such as in the Timor Sea and offshore South Africa. The conventional side-by-side offloading with loading arms is limited by the seastates in which it can be operated. A significant downtime may be resulted in due to high frequency LNG offloading requirements. There are some in the industry that consider offshore LNG transfer technology to be a "blocking" technology, or at least one more hindrance to the progress of some major LNG projects. Although the general weather conditions at some promising offshore West Africa locations are not severe, a persistent sea swell is expected to cause undesirable vessel roll motions during LNG loading. An LNG transfer system that provides maximum operational availability and safety is needed as a part of commercial justification of several LNG production projects.

Berthing an LNG carrier to another floating vessel, and remaining moored there for 12 to 24 hours will require perfected berthing procedures and robust dependable equipment. A series of developments by FMC Energy Systems in the evolution of tandem vessel berthing and LNG transfer equipment has led to the system described in [1], a system ideally suited for environments such as West Africa and other locations where a tandem LNG transfer system is the preferred solution. The duplex yoke mooring system and conventional boom-to-tanker LNG offloading arms were recently developed to carry out tandem offloading of LNG offshore with higher seas states, up to 5.5 meters significant wave heights. The duplex yoke mooring system consists of a mooring yoke assembly with duplex axes and heavy weight. The mooring yoke assembly connects the bow of the carrier to the stern of the FPSO by two pendant linkages and allows the carrier to weathervane around the bow. The LNG will be transferred from the stern of the FPSO to the bow of the carrier with the boom-to-tanker (BTT) LNG loading arms.

Marine loading arms for handling LNG have been supplied by FMC Loading Systems for forty years. FMC SOFEC has provided offshore vessel mooring systems for over thirty years. Through this experience, an LNG offloading system using proven components from these two related technologies provides for LNG transfer rates up to 15,000 m3 LNG/hr in severe seastates. The new tandem mooring arrangement provides increased vessel safety and higher availability through increased vessel separation and by the methods of berthing the LNG carrier. Improved economics are achieved by the reduced need for large tug auxiliary vessels, and also by the reduced need for thrusters and DP controls on the LNG carrier.

Concepts for tandem offloading of LNG have been in development for over ten years by FMC Loading Systems. Model basin testing has been done in industry JIP studies [3]. A large-scale working model has been tested using vessel motion data from the model basin tests. The new yoke system that utilizes a duplex mooring yoke has been model basin tested for operation in harsh offshore environments.

The analysis of the tandem offloading system is very complex and challenging. There is no existing software capable of evaluating the two body motions accurately with a yoke mooring system due to the difficulty associated with the hydrodynamic interactions and wind and current disturbances between two bodies. The duplex yoke mooring between the two vessels makes it even more complicated. This paper will present a practical methodology to evaluate the operability of the LNG offloading in severe environments. The relative motions between FPSO and carrier were predicted by a frequency-domain method. A series of model tests have been carried out. A good agreement between the predictions and measurements has verified and validated the analysis method and procedures. Berthing operations in seastates with a significant wave height of 3.5 meters were also conducted successfully. Therefore, it can be concluded that the technology of the duplex yoke mooring and boom-to-tanker loading arms is ready to be implemented for a safe and reliable tandem offloading of LNG in harsh open sea environments for LNG production projects.

DEVELOPING LNG TANDEM OFFLOADING SYSTEM

The Shell Brunei LNG facility was the first boom-to-tanker system, and operated successfully for over twenty years. Although this loading system was mounted at the end of a jetty, not on a floating vessel, the system was required to connect with a moving vessel and load LNG while the vessel underwent wave frequency motion in its spread mooring. See Figure 1.

Figure 1 Shell Brunei LNG Loading Facility

All of the proposed BTT ship-to-ship LNG transfer systems utilize the piping pantograph as the flexible piping component that allows relative motion between the vessels. Constant motion cryogenic swivel joints and stainless steel pipe provide all required degrees of freedom of motion. Figure 2 illustrates the original BTT system concept. A carrier connection manifold system is required on the bow of each LNG carrier. Because the system used a nylon hawser to connect the vessels, large sway motions of the carrier required the crane boom to follow the motion of the carrier bow manifold. Otherwise the manifold travel could over-reach the physical limits of the pantograph, especially when combined with significant vertical motion.

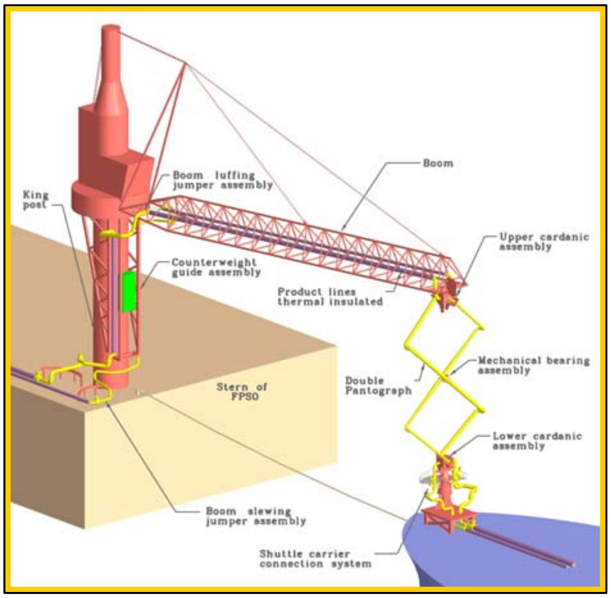

Figure 2 BTT for LNG FPSO

Three methods have been evaluated for berthing, or connecting, the LNG carrier to the LNG FPSO, see Figure 3. The original BTT system concept used a nylon hawser to connect the vessels, but this method has little resistance for side-to-side motions, and was limited to moderate sea states. A conventional soft yoke system was evaluated and found to allow about 36% of the hawser moored vessel motions, still excessive unless the pantograph boom follows the LNG carrier motion. A new yoke concept, the “duplex yoke” was developed to further minimize the lateral relative motion between the two vessels [1]. The LNG FPSO is secured to the seabed by an external or an internal turret single point mooring system, whereas a LNG carrier is connected to the stern of the FPSO by a duplex yoke tandem mooring system, which consists of a heavy ballast weight, linkage arms and a yoke as illustrated in Figures 4 and 5. The dual axes are equipped on the top and bottom of the weight. The mooring yoke assembly connects the bow of the carrier to the stern of the FPSO by two pendant linkages and allows the carrier to weathervane around the bow. The LNG will be transferred from the stern of the FPSO to the bow of the carrier with the boom-to-tanker LNG loading arms. This made it possible to keep the pantograph support boom stationary with respect to the FPSO because of the significant restriction of the relative motions between the FPSO and carrier by the duplex yoke mooring. For comparison, and with all other variables equal, the lateral motion allowed by the duplex yoke is only about ±10.5m relative to the FPSO. Figure 3 shows an illustration of comparative motions between the three methods.

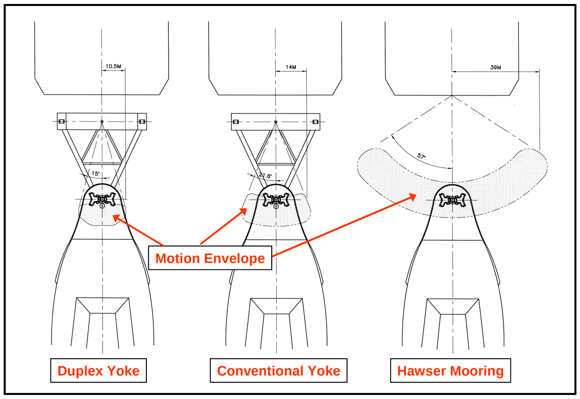

Figure 3 Motion Envelopes at LNG Carrier Manifold

Figure 4 Revolving Boom Tandem Loading System

The latest evolution of the revolving boom tandem offloading system is illustrated in Figures 4, 5, and 6. This concept retains the advantages of the stationary boom when in operation, that advantage being the boom does not follow the motions of the LNG carrier. In this case, the boom is locked in the outboard position and does not rotate while loading LNG. The rugged box construction of the boom safely allows for all required roll motions and side loads applied to the piping pantograph. However, the boom can be raised or lowered ± 4.5 meters to allow for large variations in draft of the two vessels.

Figure 5 Revolving Boom Tandem Offloading System

Figure 6 Tandem System in Parked Position

When the system is not loading an LNG carrier, the boom can be revolved around 180° to secure the boom onto a boom-rest. Then all necessary inspection and maintenance work is readily done on board the FPSO, as illustrated in Figure 6.

Concept improvements over the stationary boom concept include the following advantages:

- There are 16m (23%) added clearance between the two vessels
- Between vessel perpendiculars measures 75 meters
- The overall height of the structure above waterline is reduced 10m (15%)
- The boom height is adjustable ± 4.5 m, to provide for large variable draft difference between the two vessels
- Boom swings 180° to park piping pantograph onto service platform for improved safety and service access
- Because of the outboard location of the boom swing bearing, no additional deck space is required over the space previously needed for the stationary boom concept.

THEORETICAL ASSUMPTIONS AND SOLUTIONS

To analyze the tandem offloading system motions and response in random waves is very complex and challenge. There is no existing software capable of evaluating the two body motions accurately with a duplex yoke mooring system due to the difficulty associated with the hydrodynamic interactions and wind and current disturbances between two bodies. The duplex yoke mooring between the two vessels makes it even more complicated. Therefore, we made some basic assumptions to simplify the problems and try to find practical engineering solutions.

The assumption is that the phase differences between motions of two vessels would be evaluated based on the mean distance between the FPSO and LNG carrier and their yaw angles. The FLNG FPSO and carrier are then analyzed as a separated object and coupled with the phase differences. Based on our experiences with tandem offloading arrangement of a FPSO and a shuttle tanker, we believe this assumption will lead to reasonable good results since the distance between two bodies are quite big, typically lager than 70 meters.

The major limitations of the assumptions are that the interactions between two bodies and the FPSO shielding effects on the carrier are ignored. However, this will results in somewhat conservative results for collinear cases, since the shielding intends to reduce the strength of the wind, current and waves acting on the shuttle tanker. Since the shielding effects on the carrier are less important in crossed cases than the collinear cases, the accuracy of the predictions should be good for the crossed cases. The major benefits of the assumption is that the problems can be simplified to a single body motion analysis and use the existing proven technologies for design and analysis of the duplex yoke mooring system for LNG tandem offloading. Therefore, we can analyze the vessel global responses with mooring system in frequency domain, including the 1st and 2nd-order wave exciting forces and moments.

For the dynamic analysis of the tower yoke mooring system we utilized the results of our in-house state-of-the-art computer program SOFTYOKE^{TM}. This computer program simulates the highly nonlinear dynamics of a tower yoke moored vessel with tower, yoke, ballast and pendants. It has been designed to provide a complete, wave-basin-type simulation. It provides detailed tower yoke performance data for a particular vessel/mooring combination under specified water depth and environmental conditions. Physical tower yoke characteristics, including geometric dimensions, ballast weight and hydrodynamic properties of each element, can be specified.

The mooring load calculation is fully dynamic and utilizes a proprietary algorithm for the fast and efficient calculation of nonlinear dynamic loads. Long-period oscillations of the system are also characterized and contributions to long-period motions from low-frequency components of variable wind and wave-drift force are computed. The simulation comprises three distinct phases of calculation: "Static", "low-frequency" (typical periods of oscillation of one to four minutes) and "high-frequency" or "wave-frequency" (typical periods of oscillation of 3 to 20 seconds). Wind and current coefficients used in the analysis are based on the Oil Companies International Marine Forum (OCIMF) Prediction of Wind and Current Loads On VLCC's, 1994. Wave-drift force coefficients are computed using a proprietary analytical model (Seasoft). Utilizing the aforementioned coefficients, SOFTYOKE^{TM} determines the mean offsets and orientation of the vessel and the mean wind, wave and current loads acting on the vessel, which are all reported in a static equilibrium summary. After the mean loads and vessel offsets have been determined, a low-frequency dynamics analysis is then performed about the mean conditions. This phase of the analysis takes into account the assumed vessel characteristics, mooring system composition and environmental conditions in the calculation of system damping and low-frequency motions for surge, sway and yaw. Based on the low-frequency analysis of surge, sway and yaw, the significant, maximum and minimum pendant tensions and tower loads are developed.

Having computed system mean and low-frequency motions and loads, the final phase of the analysis involves computation of wave-frequency induced motions and loads. In the computation of wave-frequency mooring loads, both quasi-static loading (which are a function of static force-deflection properties) and nonlinear dynamic loading are accounted for. For the pendants and tower in the system, wave-frequency loads are computed at its mean plus significant low-frequency offset or mean plus maximum low-frequency offset.

For each design case, component loads and motions resulting from the computer analysis are typically combined using one or more of two methods:

1) Mean + <Sig> Low Frequency + <Max> Wave Frequency
2) Mean + <Max> Low Frequency + <Sig> Wave Frequency

These are recommended by the American Petroleum Institute (API). In essence, API suggests that both these methods be carried out to determine which produces the most severe motions and loads in order to have a conservative result. Method 1) prescribes that total motions and loads be determined by summing the mean system values imposed by the environment with the significant low-frequency system values, and then adding maximum wave-frequency values which have been determined around the significant low-frequency values. This method is normally used when wave-frequency motions and forces dominate. Method 2) prescribes that total motions and loads be determined by summing the mean system values imposed by the environment with the maximum low-frequency system values and then adding significant wave-frequency values which have been determined around the maximum low-frequency values. This method is normally used when low-frequency motions and forces dominate. For the purposes of the present design effort, maximum pendant tensions and tower assembly global design loads have been conservatively determined by the above methods.

HIGHER-ORDER BOUNDARY ELEMENT METHOD

In order to evaluate the first- and second-order wave excitations on the vessels, the higher-order boundary element method (HOBEM) will be utilized to solve the three-dimensional potential theory [4-9], which will be briefly describe here. Only the first-order wave-frequency problem will be discussed here.

The use of Green's theorem with ϕ and the free-surface Green function G leads to the following integral equation [10]:

$$c(\mathbf{p})\phi(\mathbf{p}) = \frac{1}{4\pi}\iint_{S_B}[G(\mathbf{p},\mathbf{q})\frac{\partial\phi(\mathbf{q})}{\partial n_q} - \phi(\mathbf{q})\frac{\partial G(\mathbf{p},\mathbf{q})}{\partial n_q}]dS \qquad (1)$$

where **p** and **q** represent field and source point vectors, respectively, and c(**p**) is a normalized solid angle at point **p** on the boundary surface S_B. Employing higher-order isoparametric elements, the body surface, velocity potential and its normal derivatives can be expressed by the higher-order shape functions on each element:

$$[x, y, z] = \sum_{j=1}^{s} N_j(\xi,\eta)[x_j, y_j, z_j] \qquad (2)$$

$$\phi(\mathbf{q}) = \sum_{j=1}^{s} N_j(\xi,\eta)\phi_j \, , \; \frac{\partial\phi(\mathbf{q})}{\partial n_q} = \sum_{j=1}^{s} N_j(\xi,\eta)(\frac{\partial\phi}{\partial n})_j \qquad (3)$$

where ϕ_j and $(\frac{\partial\phi}{\partial n})_j$ are the values at the j-th node and s denotes the number of the nodes on each element. For instance, the shape function for a quadrilateral quadratic element with 8-nodes can be expressed as (Zienkiewicz [11], 1977):

$$N_j(\xi,\eta) = \begin{cases} \frac{1}{4}(1+\xi_j\xi)(1+\eta_j\eta)(-1+\xi_j\xi+\eta_j\eta) & j = 1,3,5,7 \\ \frac{1}{2}(1+\xi_j\xi+\eta_j\eta)[1-(\eta_j\xi)^2-(\xi_j\eta)^2] & j = 2,4,6,8 \end{cases} \qquad (4)$$

Upon discretizing the body surface S_B with M higher-order elements and substituting Eqs. (3) and (4) in to Eq. (1), we obtain the following algebraic equation for the unknown ϕ_k:

$$\sum_{j=1}^{NOD} H_{ik}\phi_k = \sum_{j=1}^{NOD} D_{ik}\left(\frac{\partial\phi}{\partial n}\right)_k \qquad i = 1,2,...,NOD \qquad (5)$$

where,

$$H_{ik} = \sum_{e=1}^{M}\sum_{j=1}^{s}\delta_{kr}\hat{H}_{ij}^{(e)} + c_i\delta_{ik} \qquad (6)$$

$$D_{ik} = \sum_{e=1}^{M}\sum_{j=1}^{s}\delta_{kr}\hat{D}_{ij}^{(e)} \qquad (7)$$

and NOD is the total number of nodes on the body surface S_B. In Eqs. (6) and (7), δ_{kr} denotes Kronecker delta and r=NENN(j,e) is a connective matrix, which represents the correspondence between the local and global nodes.

The functions $\hat{H}_{ij}^{(e)}$ and $\hat{D}_{ij}^{(e)}$ are given by:

$$\hat{H}_{ij}^{(e)} = \frac{1}{4\pi}\iint_{\Gamma_e} \frac{\partial G(\mathbf{p},\mathbf{q})}{\partial n_q} N_j \, d\Gamma_q \qquad (8)$$

$$\hat{D}_{ij}^{(e)} = \frac{1}{4\pi}\iint_{\Gamma_e} G(\mathbf{p},\mathbf{q}) N_j \, d\Gamma_q \qquad (9)$$

where N_j is the j-th shape function and Γ_e the surface of each element. The full descriptions about the HOBEM and the formulae for evaluation of the first- and second-order wave forces can be found in Liu, et al [5-8, 10].

NUMERICAL AND MODEL TEST RESULTS

The tandem mooring shall be designed such that the integrity of the pantograph system is intact in any design conditions. Therefore, tandem offloading design criteria are

- The maximum allowable operating motion envelope of pantograph (relative motions between shuttle tanker & FPSO) in the maximum offloading storms is less than 12 meters
- LNG shall be offloaded to a carrier in severe storms
- The Connection/disconnection of the Carrier can be carried out in seastates up to ninety plus percent of probability of occurrence

The most offshore gas fields in the world are located in the areas with moderate environmental conditions, such as Indonesia, Malaysia, Persian Gulf and West Africa. Therefore, the maximum design conditions were chosen as the significant wave height of 5.5 meters. The wind and current were assumed to be at 45 and 90 degrees to the waves for the crossed cases. These design conditions are very close to the ones used for the LNG Offloading JIP by FMC Loading Systems in 1999 [3]. Actually, the 5.5 m waves are relatively severe for most geographical areas. The wave only case was chosen in order to eliminate any uncertainty associated with wind and current for a better correlation study with theoretical values. We also varied the peak period of the waves from 10.5 to 12 seconds for the crossed case to see sensitivity of the system responses. The environmental conditions for the study are listed in Table 1.

Table 1 Storm Environments for LNG Offloading

	Maximum Offloading Seastates			**Berthing**	
Cumulative Probability	**99.999%**			**99.40%**	
	Wave Only	Crossed 1	Crossed 2	Crossed	
Water Depth	64	64	64	64	m
Wave					
Wave Spectral Model	P-M	P-M	P-M	P-M	
Significant Wave Height	5.5	5.5	5.5	3.5	m
Peak Period	12	10.5	12	9.5	sec
Direction	180	180	180	180	deg
Wind					
Velocity		42.9	42.9	23.5	knots
Wind Spectral Model		API	API	API	
Direction		225	225	225	deg
Current					
Velocity		1.45	1.45	0.58	knots
Direction		270	270	270	deg

The capacities of the LNG FPSO and carrier were chosen as 240,000m^3 and 142,000m^3, respectively for the study. In order to validate the new LNG tandem offloading concept and verify the numerical procedures presented in the paper, a series of model tests have been conducted for LNG tandem offloading with the duplex yoke mooring system in the environmental conditions summarized in Table 1. The model tests were carried out based on the scale of 1:64 and the three-hours storms in prototype were modeled. The procedures of berthing the LNG carrier to the LNG FPSO were also carried out for the berthing seastates. The test set-ups are shown in Figures 7 and 8.

Figure 7 LNG tandem offloading model tests

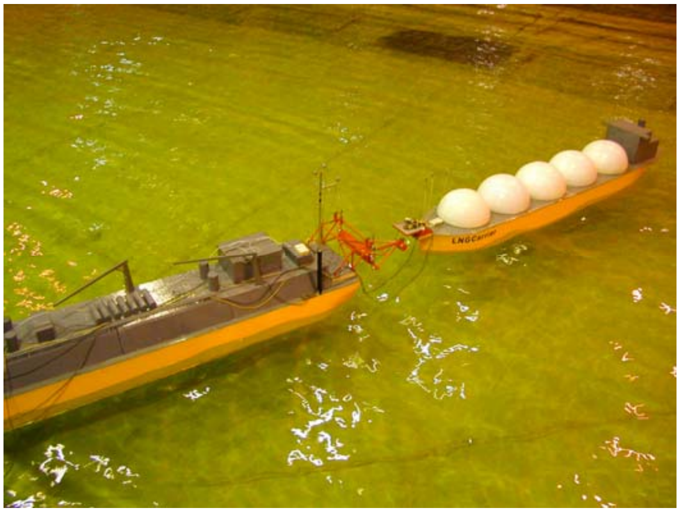

Figure 8 LNG carrier berthing operation tests

For the wave only case, the relative motions between the upper cardanic assembly on the LNG FPSO and the lower cardanic assembly on the LNG carrier (see Fig. 2.) were calculated based on the aforementioned method and procedures and the predicted results were found to be more conservative than the measured ones as expected, since the shielding of the FPSO on the carrier was not considered in the analysis. The measured sway motions are mainly induced by the fishtailing of the carrier, which is not modeled.

For the crossed 1 and 2 cases, good correlations between the model test results and predictions are observed. Since the broad sides of both FPSO and carrier are exposed to the wind, wave and current, the shielding effects of the FPSO on the carrier is limited. Thus the calculated low-frequency relative surge motions are slightly less than the test results. However, the relative sway motions are in better agreement. Particularly, the resultant relative xy motions, the motion envelopes are less than the targeted design value of 12 meters. They match well with the predictions. The measured significant relative vertical motions are in good agreement with the theoretical values as well. The measured and predicted resultant xyz motions are almost identical. The relative motions between the LNG FPSO and carrier are summarized in Table 2.

The relative x, y and z wave-frequency motion RAOs between the upper cardanic assembly on the LNG FPSO and the lower cardanic assembly on the LNG carrier (see Fig. 2) are presented in Figures 9 and 10. They are in very good agreement with our predictions.

The berthing operation tests were also performed successfully in the connection seastates with the significant wave height of 3.5 meters as presented in Table 1. The measured and predicted maximum hawser tensions are 265 and 262 metric tons, respectively.

CONCLUSIONS

Therefore, it can be concluded that the feasibility of the duplex yoke mooring system for LNG tandem offloading in open seas with significant wave height up to 5.5 meters has been confirmed. The tandem offloading system with the duplex yoke mooring system is robust and dependable equipment for the LNG transfer. The theoretical assumptions and predictions are verified and validated with good accuracy by the model test results. It is satisfactory that the simplified method proposed in the paper can generate reasonable good engineering approximations to such a complex problem. The model tests also confirmed the berthing operation procedures successfully. Thus, the technology of the duplex yoke mooring and boom-to-tanker loading arms is ready to be implemented for a safe and reliable transfer of LNG in harsh open sea environments for LNG facilities.

In the future, it is desired to develop a coupled analysis of multi-body motions with duplex yoke tandem offloading mooring system and time-domain analysis tools. It is also expected to conduct extensive model tests with different capacities of the LNG FPSO and carrier and different combinations of environmental conditions for a future LNG project.

Table 2 Relative Motions Between LNG FPSO and Carrier

		Theory	**Test**	**Theory**	**Test**	**Theory**	**Test**	
ENVIRONMENT		Wave Only		Crossed 1		Crossed 2		
Vessel Motions and Accelerations								
Surge Downstream	mean	-0.84	-0.13	-2.40	-2.94	-2.40	-2.88	m
stdv.	LF	1.12	0.70	1.31	1.30	1.32	1.76	m
max/min	LF	-4.26	-2.83	-6.47	-7.42	-6.51	-8.35	m
sig	WF	0.63	0.51	0.49	0.62	0.59	0.67	m
	Total	-4.89	-3.23	-6.96	-7.70	-7.10	-8.78	m
Surge Upstream	Total	3.21	2.60	2.16	2.26	2.30	2.09	m
Sway	mean		-0.43	0.68	0.29	0.67	0.38	m
stdv.	LF		1.02	2.40	2.36	2.44	1.64	m
max/min	LF		3.43	7.95	8.25	8.07	6.22	m
sig	WF		0.74	1.50	1.28	2.46	2.54	m
	min		-4.13	-8.09	-6.55	-9.19	-6.96	m
	max		4.25	9.45	10.07	10.53	8.03	m
Heave	sig	2.98	2.64	2.96	3.30	4.50	4.78	m
	max	5.54	4.84	5.49	5.96	8.37	9.99	m
xy	max	4.89	4.32	10.24	10.16	11.27	10.41	m
xyz	max	6.67	5.18	10.66	10.19	12.13	11.74	m

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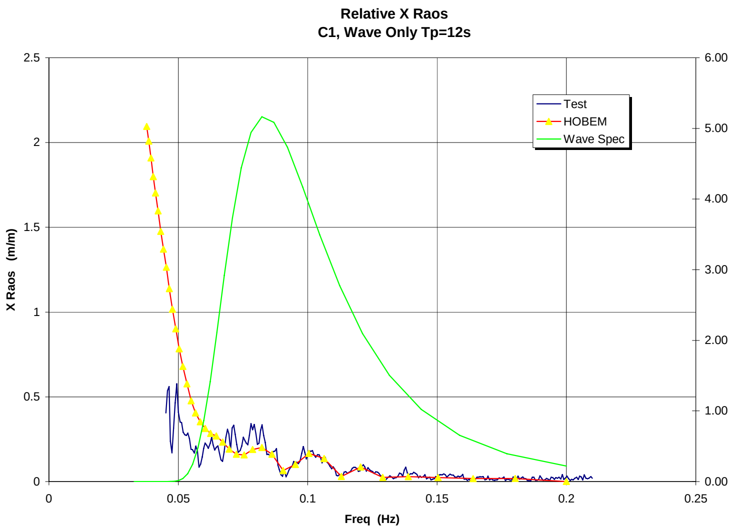


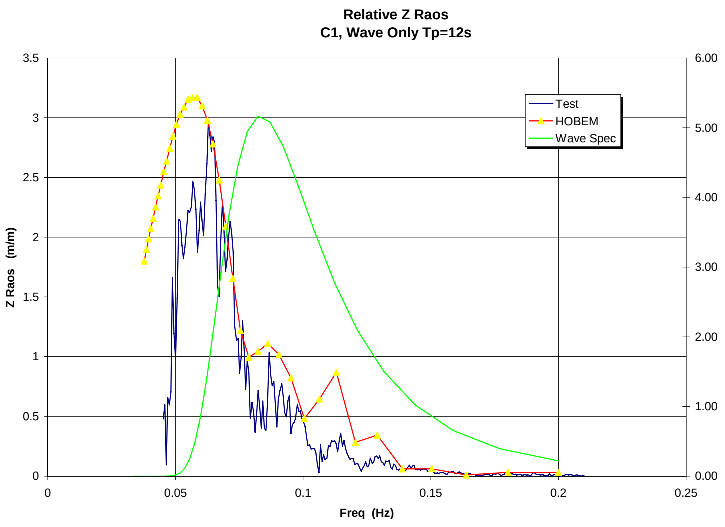
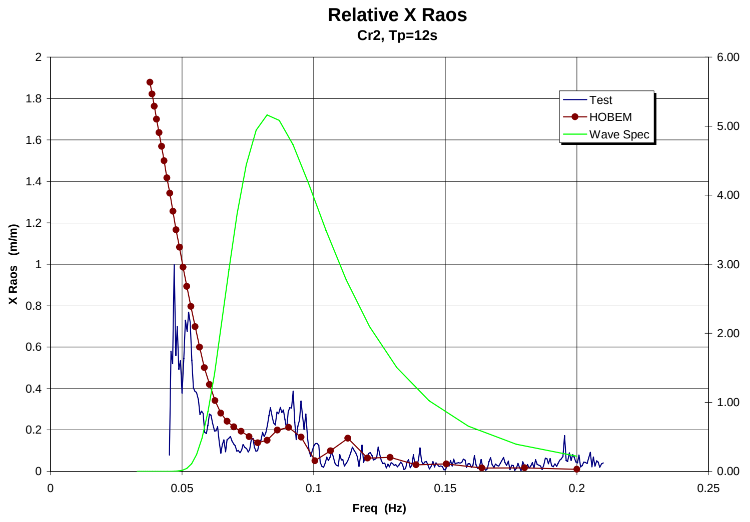
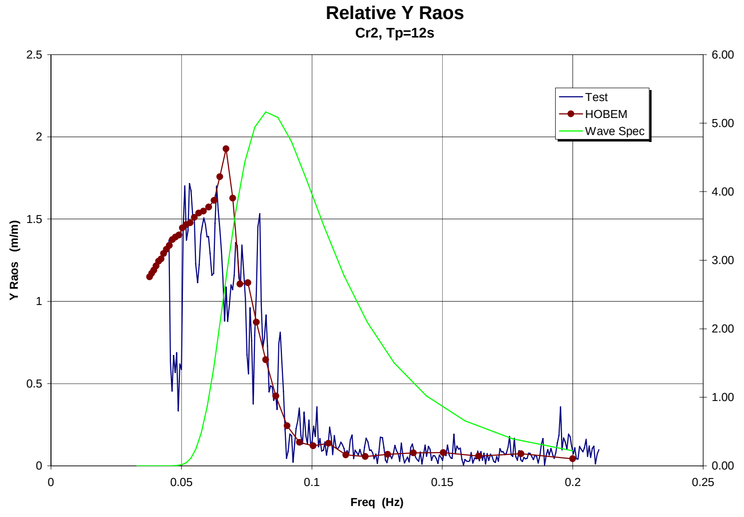


Figure 9 Relative X and Z-motion RAOs in wave only





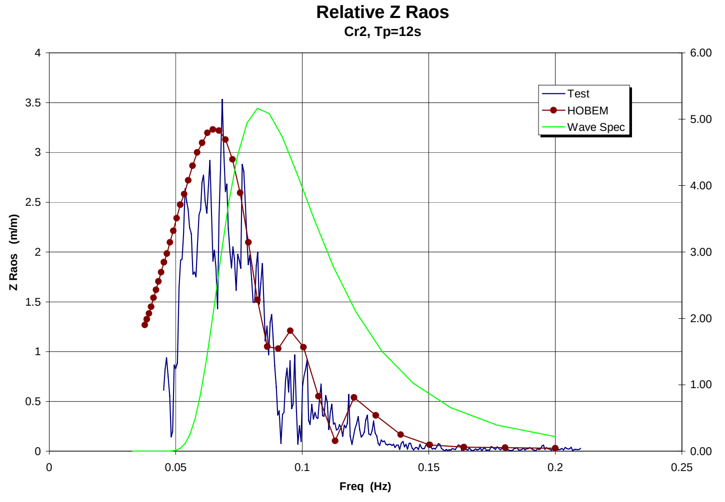


Figure 10 Relative X, Y and Z-motion RAOs in crossed-2 storm