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Experimental investigation on dynamic responses of FLNG connection system during side-by-side offloading operation

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Abstract

This paper presents an experimental investigation on dynamic responses of the connection system in the FLNG (Floating Liquefied Natural Gas) system during side-by-side offloading operations. A typical side-by-side connection system for an FLNG and LNG (Liquefied Natural Gas) carrier that includes 16 hawsers and 6 fenders is adopted. Three typical irregular wave cases are used in the model test. Relationships between relative vessel motion and the load born by the connection system are obtained, and features of dynamic connection system responses are summarized based on the analysis results. The results show that hawsers and fenders at different locations are sensitive to different motion patterns; loads on connection systems have distinct dynamic properties, and snap loading crucial to the safety of offloading processes can be induced. Moreover, for partially filled conditions, sloshing effects on vessel motion and on the connection system are examined. FLNG and LNGC are subjected to large low frequency responses in side-by-side configurations due to hydrodynamic interactions and sloshing effects. Furthermore, sensitivity analyses of the connection system relative to wave amplitudes and directions are conducted. According to our sensitivity studies, high wave amplitudes can excite pronounced relative motions and large loads on the connection system; heading and oblique waves significantly affect spring hawsers in mid-ship areas and breast hawsers in bow and stern areas; and positive sheltering effects can be obtained when FLNG occupies the weather side.

Keywords: FLNG; side-by-side offloading; connection system; relative motion; sloshing effect

1 Introduction

With growing demands for oil and natural gas, floating liquefied natural gas (FLNG) systems have been proposed as a means of exploiting offshore nature gas. Compared to underwater pipelines installed in gas fields, FLNG system is more economical and efficient, especially for scattered, remote and deepwater gas fields. Offloading LNG from FLNG to LNG carriers is rather challenging and should be conducted with great care. Generally speaking, FLNG vessel and LNG carrier can be in tandem or side-by-side configuration during offloading operation. In tandem configuration, hydrodynamic interaction between vessels is relatively weak, but the flow lines have to overcome extremely low temperature. Such configuration also calls for more cargo flexible pipelines, as the relative motions between vessels are much more pronounced, especially

for relative surge, sway and yaw motion [1][2]. In side-by-side offloading operation, FLNG vessel and LNG carrier are connected in close proximity with more hawsers and fenders. This arrangement can reduce distance and relative motions to some extent while providing conveniences for offloading operation. However, hydrodynamic interaction significantly affects vessel motion. Changing vessel fill levels during offloading operations and sloshing in liquid tanks [3][4] also contribute to the complexities of coupling effects in FLNG system.

Connection system including hawsers and fenders plays a crucial role in restricting relative motions between vessels within a certain range. Thus, vessel collisions, offloading arm cracks and other potential risks can be mitigated. In reliable connection system, hawsers should have proper length and stiffness to restrict relative vessel motion and avoid breakage. Attention should also be paid to load distributions on each hawser to ensure that no hawser becomes overloaded. In this respect, an optimized arrangement of hawsers and fenders is desirable in consideration of safety and economic efficiency levels of offloading operations.

Hydrodynamic characteristics of side-by-side moored vessels are essential to the safety of offloading operation. Considerable research on multiple floating vessels in side-by-side configuration has been conducted. Extensive analytical and numerical accomplishments were reviewed in [5]. As this system is highly complex, assumptions and simplifications are adopted to obtain acceptable numerical simulation results. Linear free surface is often used when addressing hydrodynamic coefficients of large floating bodies and have been proven to be efficient [6]. However, linear surface tends to overestimate water velocity levels in areas close to vessels. To obtain more realistic simulation results, rigid wall conditions have been adopted on the free surface between vessels [7]. Rather than using artificial lid, Chen [8] employed an authentic equation of “perfect” fluid that accounts for energy dissipation by introducing damping force. Moreover, viscous effects become apparent in small gaps between vessels. In generating better simulation results, artificial damping terms have been used to account for flow resistance [9].

Because connection system features are highly complex, normal numerical calculation methods are unlikely to predict extreme conditions accurately. In connection systems, tension force levels are typically assumed to be quasi-static in numerical simulations. During coupling computation processes, tension on hawsers is proportional to the relative displacement between vessels and is then transmitted to the hull [10][11]. However, this evaluation may be inaccurate for several aspects that have not been accounted for. First, inertia and damping terms related to hawsers are ignored. Second, snap loading can be induced when hawsers translate from a slack state to a taut state. Several different numerical [12][13] and analytical [14] methods have been applied in pursuit of dynamic solutions, but such methods can only be used for conditions that do not involve obvious impulsive properties. Experimental research conducted by Dracos [15] shows that snap loading can significantly amplify the maximum tension amplitude and that it is nonlinear with the excitation amplitude. Mamoun [16] studied LNG side-by-side offloading from a Floating Storage and Regasification Unit (FSRU) to an LNG carrier through a benchmark study. However, he found no agreement between extreme loads on hawsers after comparing calculation results of three numerical programs. Similar discrepancies between experimental and numerical results have been identified by Zhao [2], noting difficulties associated with fully reproducing transient snap loading mechanisms. Furthermore, coupling effects of hawsers in two floating platforms were fully taken into consideration by Koo [17]. However, obtaining accurate impulsive properties of forces on connection system is difficult. At present, accurate predictions of snap loading

mechanisms that involve the use of analytical or numerical methods remain limited to simplified models. Therefore, experimental research should be recognized as an effective approach that is of paramount importance to the evaluation of connection system safety levels.

Experimental methods are currently some of the most advanced and reliable techniques available for solving complex hydrodynamic problems (e.g., side-by-side offloading scenarios). Some experimental studies on connection systems have been conducted. Inoue [18] compared numerical and experimental results of parallel-connected FPSO and LNG carriers in waves. Hong [19] carried out model tests on multiple bodies wherein only two hawsers and two fenders were installed between FPSO and LNG carrier. An FPSO model was moored by horizontal mooring lines and was subjected to regular waves. A similar model test and numerical simulation was also presented by Buchner [20]. These model tests mainly focus on hydrodynamic interactions and relative motion patterns between vessels or on coupling with mooring lines and risers [21]. Less attention has been paid to connection systems, and very limited results exist for the loads on connection system in real working conditions. Valk [22] presented a classical design of a connection system arrangement in a side-by-side configuration consisting of spring and breast lines. Features of different arrangement models were presented. Lee [23] conducted experimental and numerical studies on offloading performance levels of the Hyundai LNG-FPSO. Hawsers in this arrangement had 4×3 breast lines and 2×2 spring lines. Offloading availability estimations were presented based on global performance results. Zhao [24] conducted numerical and experimental research on FLNG system in side-by-side configuration. In his research, a simplified connection system was adopted, but no detailed discussions on connection system were presented. In the studies described above, systematic research on connection system is not adequately conducted, and more experimental research that illustrates dynamic response characteristics of side-by-side FLNG connection system is needed.

In this paper, an experimental investigation on dynamic connection system responses is presented. The main purpose of this study is to identify properties of load distribution in a classical connection system and factors related to load distribution. A model test of a FLNG system with 16 hawsers and 6 fenders in side-by-side configuration is carried out. Loads born by hawsers and fenders are analyzed over time and frequency domain to determine the relationship between load distribution and relative motions. Dynamic response properties, including transient snap loading responses of hawsers, are presented. In reference to vessels that occupy partially filled conditions, sloshing effects on vessel motion and connection system are discussed. Comparisons between connection system performance levels in different sea conditions reveal effects of wave direction and amplitude patterns. Conclusions are drawn based on the analysis results, which can be used to guide further studies and connection system design.

2 FLNG system description

The conceptual FLNG system used in this study was designed by the China National Offshore Oil Corporation (CNOOC) and by the Marine Design and Research Institute of China. This FLNG system is designed to be positioned in the South China Sea at a water depth of 1,500 m. A model test was conducted at a model scale of 1:60 in the Deepwater Offshore Basin at Shanghai Jiao Tong University. The basin is 50 meters long, 40 meters wide and 10 meters in depth and is equipped with advanced testing and measuring facilities.

2.1 Vessels

The FLNG vessel is equipped with 10 identical LNG tanks that are double-row arranged and the LNG carrier has four LNG tanks. Figs. 1 and 2 show the configurations of the FLNG and LNG carrier, respectively. Wave probes are installed in liquid tanks to capture free surface elevation. For FLNG, wave probes in a tank located in the third row and portside are presented in Fig. 3. In this study, three typical fill levels of the FLNG system in offloading operation are considered. For FLNG, fully loaded, 50% loaded and 10% loaded fill levels are used, and for the LNG carrier, ballasting, 50% loaded and full fill levels are used. The major parameters of the FLNG vessel and LNG carrier are listed in Tables 1 and 2.

In the measurement of vessels' motions, global coordinate system and vessel-fixed coordinate system are defined for each vessel. The two coordinate systems coincide with each other in initial condition and locate in the gravity center of vessels with x-axis pointing bow, y-axis pointing port side and z-axis pointing upward. Based on global and vessel-fixed coordinate systems, six degree motions of each vessel are obtained. The relative motions between vessels are defined as the motions of LNG carrier relative to FLNG vessel's motion, which means large relative motions are induced when two vessels move apart from each other. The relative motions are regarded as zero in the initial condition.

Fig. 1. General FLNG structure

Fig. 2. General LNG carrier structure

Fig. 3. Wave probes installed in liquid tanks in the third row and portside of the FLNG

Table 1. General FLNG parameters

Designation	Unit	Fill level A (fully loaded)	Fill level B (50% loaded)	Fill level C (10% loaded)
Overall length	m	340	340	340
Breadth, B	m	61	61	61
Depth, D	m	37	37	37
Draft, T	m	17.844	15.599	14.261
Displacement	t	323251	278805	252826
Center of gravity above the base, KG	m	23.977	22.265	23.147
Center of gravity midship, LCG	m	-5.613	-4.075	-0.562
Roll gravity radius, Kxx	m	21.749	23.750	25.891
Pitch gravity radius, Kyy	m	87.963	85.778	85.179
Yaw gravity radius, Kzz	m	88.730	86.645	86.124

Table 2. General LNG carrier parameters

Designation	unit	Fill level A (fully loaded)	Fill level B (50% loaded)	Fill level C (10% loaded)
Overall length	m	291	291	291
Breadth, B	m	45.8	45.8	45.8
Depth, D	m	26.5	26.5	26.5
Draft, T	m	9.646	9.688	11.717
Displacement	t	99100.5	99546.3	122671
Center of gravity above the base, KG	m	12.059	12.298	16.501
Center of gravity midship, LCG	m	0.036	0.392	-0.68
Pitch gravity radius, Kyy	m	70.229	65.702	65.92

2.2 Mooring system

The mooring system of the FLNG system includes an inner turret that supports free vessel rotation around it and 15 mooring lines. Mooring lines are divided into 3 groups; each group includes 5 lines positioned 5 degrees apart. Each mooring line has 3 segments with a total length of 3,351 m. Table 3 presents information on the mooring lines. The pre-tension force acting on each mooring line is 5,000 kN.

The FLNG system was designed to function in the site at a water depth of 1,500 m. Based on a model scale of 1:60, the dimensions of the water basin are not large enough to support such a mooring system in the consideration of both depth and artificial seabed size. In this case, mooring system truncation is necessary, and this has been proven to be effective when conducting ultra-deep water model tests. Main criteria like coupling between vessel and mooring system, restoring forces, representative tension characteristics for each mooring line are considered in mooring system truncation [25][26]. In the premise of maximizing the use of basin space, the mooring system was truncated at a water depth of 350 m in the prototype in this study. The parameters of the truncated mooring lines are listed in Table 4. Because the truncating system is not the main focus of this study, it is not described in detail.

Table 3. The configuration of mooring lines in the prototype

	Length (m)	Diameter (mm)	Weight in air (kg/m)	Submerged weight (kg/m)	Breaking loads (kN)	Axial stiffness (kN)
Chain	100	146.05	427.10	371.58	18908	1607180
Wire rope	1859	139.7	102.40	81.40	19186	1822670
Chain	1392	146.05	427.10	371.58	18908	1607180

Table 4. Configuration of truncated mooring lines at a 350 m water depth

	Length (m)	Submerged weight (kg/m)	Axial stiffness (kN)
Chain	100	371.58	50636.5
Wire rope	304.7	1484.17	78576.7
Chain	430.8	909.93	128084.7

2.3 Connection system

The typical connection system adopted in this study includes 16 hawsers and 6 fenders, as shown in Fig. 4. Hawsers include 8 spring lines, 5 bow lines and 3 stern lines that can be regarded as breast lines. This type of design has been widely adopted in side-by-side offloading operations, and spring and breast lines are mainly responsible for relative longitudinal and lateral motions, respectively. Hawsers are divided into 4 groups based on their locations for the convenience in analysis. Groups 1 through 4 include hawsers 1#–5#, hawsers 6#–9#, hawsers 10#–13#, and hawsers 14#–16#, respectively. Table 5 shows the locations of hawsers in the FLNG and LNG carrier and the stiffness of each hawser. Each hawser is 72 mm in diameter with a minimum breaking load of 3469.2 kN and has a pre-tension of 350kN in the initial state.

6 fenders are fixed to FLNG and are positioned in the parallel middle body of the vessel. The locations of the fenders are shown in Table 6. The react force of the fender reaches a peak value of 5,690 kN under 60% length deformation. The original length of the fender is 10.5 m long when it's not been compressed. The react force of fender has nonlinear properties when it's under compression, as indicated by the dashed line shown in Fig. 5. For simplicity, a piecewise linear spring is used in the model test to simulate this nonlinear property. The two parts of the piecewise spring have stiffness levels of 0.49 kg/cm and 0.175 kg/cm. In the initial condition, gap between vessels is smaller than fender lengths, and fender react forces are balanced by pre-tension forces in hawsers.

Fig. 4. Side-by-side FLNG system configuration

Table 5. Hawser locations and stiffness levels

Hawser		Location in the FLNG			Location in the LNG carrier			Stiffness (kN/m)
Group	Number	X (m) From mid-ship	Y (m)	Z (m)	X (m) From mid-ship	Y (m)	Z (m)	
1	1#	167.3	-17.2	42.5	145.4	3.4	27.0	2413.8
	2#	156.8	-24.7	42.5	136.2	10.8	27.0	3252.4
	3#	155.6	-25.3	42.5	134.2	11.9	27.0	3306.8
	4#	141.1	-29.5	42.5	116.3	19.2	27.0	3626.8
	5#	139.9	-29.7	42.5	114.5	19.8	27.0	3585.3
2	6#	67.3	-30.5	37.5	98.9	22.4	27.0	3294.3
	7#	61.6	-30.5	37.5	95.6	22.7	27.0	3086.4
	8#	21.2	-30.5	37.5	90.3	22.9	27.0	1584.6
	9#	16.2	-30.5	37.5	84.9	22.9	27.0	1594.7
3	10#	-16.2	-30.5	37.5	-84.9	22.9	27.0	1594.9
	11#	-21.2	-30.5	37.5	-103.3	22.9	27.0	1338.5
	12#	-61.6	-30.5	37.5	-109.7	22.9	27.0	2243.5
	13#	-67.3	-30.5	37.5	-114.5	22.9	27.0	2282.8
4	14#	-154.4	-30.5	37.5	-144.5	-4.7	21.5	2983.5
	15#	-160.3	-30.5	37.5	-144.5	-6.6	21.5	2720.4
	16#	-162.5	-30.5	37.5	-144.5	-8.0	21.5	2592.8

Fig. 5. Fender deformation properties

Table 6. Fender locations in the FLNG

Fender number	X (m) (From mid-ship)	Y (m)	Z (m)
1	64	30.5	16.65
2	42	30.5	16.65
3	20	30.5	16.65
4	-20	30.5	16.65
5	-42	30.5	16.65
6	-64	30.5	16.65

3 Definitions of sea conditions

We aim to find inherent regularities in the connection system under wave conditions rather

than determining the validity of the FLNG system. Given this perspective, wind and current levels were not taken into consideration to simplify the test and analysis. Wave amplitudes and directions are the main concern of this study, as they seriously affect hydrodynamic interactions. Random waves are described by the three-parameter Jonswap spectrum. Table 7 shows three irregular waves with different significant wave amplitudes (H_s), peak periods (T_p) and wave directions. Compared to sea condition 1, sea condition 2 presents the same wave direction but a higher wave amplitude. Sea conditions 3 and 4 present the highest wave amplitude (135- and 225-degree wave directions corresponding to the FLNG and LNG carrier on the weather side, respectively). Severe conditions with H_s levels higher than 3 m were not studied, as they were considered too extreme for the side-by-side offloading operation [21]. Vessel models were also tested in band-limited white noise waves (Fig. 6) to examine hydrodynamic interaction effects under different wave directions.

Fig. 6. Power spectrum density levels of a band-limited white noise wave

Table 7. Sea condition parameters

	H_s (m)	T_p (s)	Wave direction
Sea condition 1	2	7.5	180 deg
Sea condition 2	2.5	8.25	180 deg
Sea condition 3	3	9	135 deg
Sea condition 4	3	9	225 deg
White noise wave 1	3	5-25	180 deg
White noise wave 2	3	5-25	135 deg
White noise wave 3	3	5-25	225 deg

4 Results and discussion

4.1. Connection system load properties

In this section, effects of relative motions between vessels on the connection system are studied, and dynamic properties of loads on the connection system are discussed. As the liquid tank was partially filled for the majority of the offloading period, test results for fill level B and sea condition 1 are used as representative results. The statistical results of the loads on 16 hawsers and on 6 fenders are summarized in Table 8. The Max, Min and Mean in the table stand for maximum, minimum and mean value of the data measured. Std stands for standard deviation that reflects the fluctuation in time domain.

In the interest of conducting a convenient analysis, relative motions in the longitudinal and lateral directions of vessels are adopted rather than vessel surge and sway motions. Relative motions in the longitudinal and lateral directions are determined based on equation (1). In equation (1), $\mathbf{d}_0$ is the initial vector displacement between the CoG (center of gravity) of two vessels, and γ is the average value of yaw angles between two vessels.

$$\begin{bmatrix} d_{longitudinal} \\ d_{lateral} \end{bmatrix} = \begin{bmatrix} \cos \gamma & -\sin \gamma \\ \sin \gamma & \cos \gamma \end{bmatrix} (\mathbf{d}_0 + \begin{pmatrix} surge_{LNGC} \\ sway_{LNGC} \end{pmatrix}) - \begin{pmatrix} surge_{FLNG} \\ sway_{FLNG} \end{pmatrix} \quad (1)$$

The deforming length of hawser l can be calculated from:

$$l = \|\mathbf{x}_{FLNG} - \mathbf{x}_{LNGC}\| - l_0 \quad (2)$$

where l_0 is the length of a hawser in the initial condition and $\mathbf{x}_{FLNG}$ $\mathbf{x}_{LNGC}$ are motion histories of hawser locations in the FLNG and LNG carrier, respectively, which can be calculated from:

$$\mathbf{x} = \mathbf{x}_0 + \mathbf{x} + \mathbf{k}_0 \mathbf{r} \quad (3)$$

$$\mathbf{k}_0 = \begin{bmatrix} \cos \beta \cos \gamma & -\cos \beta \sin \gamma & \sin \beta \\ \sin \alpha \sin \beta \cos \gamma + \cos \alpha \sin \gamma & -\sin \alpha \sin \beta \sin \gamma + \cos \alpha \cos \gamma & -\sin \alpha \cos \beta \\ -\cos \alpha \sin \beta \cos \gamma + \sin \alpha \sin \gamma & \cos \alpha \sin \beta \sin \gamma + \sin \alpha \cos \gamma & \cos \alpha \cos \beta \end{bmatrix} \quad (4)$$

where $\mathbf{x}_0$ is a hawser's initial location in global coordinates and $\mathbf{x}$ is the transitional motion of vessel, $\mathbf{k}_0$ is the matrix that decided by the rotatory motion histories of vessel and $\mathbf{r}$ is the displacement vector from a vessel's CoG to a hawser's location, α , β and γ are the pitch, roll and yaw motion angle of vessel. Relative motion patters between vessels are defined as the motion of LNG carrier relative to FLNG vessel.

Loads on hawsers are closely related to relative motion patterns between vessels and to their locations. Hawsers of the same group always share similar load time histories, as they are close in proximity and present similar direction disposal features, which are shown in Fig. 7. In the following discussion, representative hawsers in each group are selected without a loss of generality. First, loads on the breast hawsers in groups 1 and 4 are sensitive to relative yaw and lateral motion patterns. As shown in Fig. 8, hawser 16# presents similar peak frequencies as those of relative yaw motion. A similar phenomenon is found between loads on hawser 3# and relative lateral motion pattern shown in Fig. 9. This finding can be attributed to the fact that these hawsers are installed in bow and stern areas, and their direction disposal patterns mostly move in lateral direction. Both relative lateral and yaw motion patterns can cause considerable lateral displacement in bow and stern areas and then exert loads on these hawsers. Fig. 9 also shows that hawsers in these two groups are affected by relative pitch motion pattern. However, designing specific hawsers that restrict relative pitch motion is unnecessary, as pitch motion pattern in vessels are always less violent under significant restoring forces. The same can be concluded for heave motion. Second, unlike breast hawsers, spring hawsers in groups 2 and 3 are mainly sensitive to relative longitudinal motion, as their direction disposal patterns reflect the longitudinal directions of vessels. Fig. 10 shows that spectra of hawser 9# and relative longitudinal motion are consistent in terms of peak frequencies. As hawsers in groups 2 and 3 have opposite restriction effects on relative longitudinal motion for their differences in direction, hawsers in these two groups experience similar load histories but in opposite phases, as shown in Fig. 11. Moreover, loads on all of the hawsers are also affected by relative roll motion between vessels, as indicated in Fig. 12. This result is attributable to the fact that hawsers are installed in broadside areas, and

relative roll motion can result in relative displacement between the two ends of hawsers.

For fenders, relative lateral and relative roll motion patterns between vessels account for compression on fenders, and relative yaw motion has evident effects on fenders close to the bow and stern. Because fenders can only be suppressed in the horizontal plane, relative pitch and relative heave motion contribute little to loads on fenders. Fig. 8 shows the effects of relative yaw motion on fender 1#. The statistical results shown in Table 8 prove that mid-ship area fenders tend to share similar load properties and fenders on either side are subjected to large maximum loads caused by relative yaw motion pattern.

Fig. 7. Time histories of loads on hawsers

Fig. 8. Spectra of relative yaw motion and loads on hawser 16# and fender 1#

Fig. 9. Spectra of loads on hawser 3# and relative lateral motion and relative pitch motion patterns

Fig. 10. Spectra of relative longitudinal motion and loads on hawser 9#

Fig. 11. Time histories of loads on hawsers 8# and 11#

Fig. 12. Spectra of loads on hawsers 3# and 9# and relative roll motion pattern

Table 8. Statistical results of loads on the connection system under fill level B and sea condition 1

	Unit	Max	Min	Mean	Std
Hawser 1#	kN	960.8	66.5	306.5	138.7

Hawser 2#	kN	933.5	69.6	281.7	128.1
Hawser 3#	kN	1117.8	52.3	334.2	173.3
Hawser 4#	kN	1034.3	87.2	345.0	136.7
Hawser 5#	kN	1138.0	100.6	403.5	145.4
Hawser 6#	kN	2013.3	61.7	480.1	334.6
Hawser 7#	kN	1309.4	105.7	487.7	137.0
Hawser 8#	kN	1283.2	125.0	392.7	110.7
Hawser 9#	kN	1039.6	145.0	394.0	124.4
Hawser 10#	kN	1495.1	75.6	513.5	242.4
Hawser 11#	kN	1003.4	111.5	356.7	130.0
Hawser 12#	kN	1069.6	83.0	291.5	114.7
Hawser 13#	kN	1339.3	74.9	290.5	165.4
Hawser 14#	kN	1296.9	74.9	484.9	212.5
Hawser 15#	kN	1288.8	87.2	431.3	215.8
Hawser 16#	kN	1096.2	81.2	269.6	135.4
Fender 1#	kN	543.3	276.7	408.4	29.9
Fender 2#	kN	499.3	270.6	397.5	26.0
Fender 3#	kN	509.4	294.7	406.3	25.9
Fender 4#	kN	548	269.1	395.4	26.4
Fender 5#	kN	532.7	284.5	404.8	24.7
Fender 6#	kN	641.3	230.9	410.8	42.8

During the offloading operation, hawsers respond dynamically to relative displacement between vessels and have obvious nonlinearities. Snap loading can be induced when hawsers are subjected to a sudden event of significant relative displacement. Table 8 shows that the maximum loads on hawsers far exceed corresponding mean loads, and large standard derivative values indicate dramatic load variations. For example, hawser 6# presents the largest maximum load value of 2013.3 kN and a standard deviation value of 334.6 kN. From the time history of loads on hawser 6# shown in Fig. 13, strong impulsive properties are easily observable. Relative to the time history of the deforming length of hawser 6#, this impulsive phenomenon exerts much larger loads on the hawser than those loads obtained via the corresponding quasi-static analysis.

Moreover, loads on hawsers can differ sharply for small differences in relative motions and some unexpected phenomena were found. The parallel hawsers in group 2 show different sustained loads within one snap loading course. For example, hawsers 7# and 6# should be subjected to similar levels of relative displacement, as these two hawsers are positioned parallel and close to one another. As shown in Fig. 13, the load on hawser 7# presents a similar time history tendency as the deforming length of hawser 6#, exhibiting a lower response feature rather than an impulsive response property as that in hawser 6#. This difference may be attributable to

the order of load bearing. Although hawsers 6# and 7# are close to one another, hawser 6# is closer to the bow and presents a larger angle with these vessels than those of hawser 7# due to the curved shape of the LNGC bow area. Therefore, hawser 6# will endure loads transferred from the relative yaw motion before hawser 7# does. Furthermore, hawser 6# can be viewed as a buffer to hawser 7#, reducing the load on 7# but increasing the load on 6#. This order of load bearing is not conducive to the side-by-side offloading operation, as it causes the load to be unequally distributed within the connection system. Conversely, load histories on hawser 12# and 13# are more synchronized, as shown in Fig. 14. These two hawsers are roughly symmetrically arranged with hawsers 6# and 7# in relation to mid-ship and will experience similar levels of relative longitudinal displacement with hawsers 6# and 7#. Because hawsers 12# and 13# are parallel, they are subjected to relative displacement almost simultaneously, and in turn extreme snap loading processes like those found in hawser 6# are avoided. Consequently, parallel arrangements of neighboring hawsers efficiently reduce extreme high snap loading processes. Furthermore, the effects of load bearing orders must be considered when designing parallel hawser in bow areas.

Loads on fenders are highly stable and equally disposed with limited impulsive response levels. Table 8 shows that the maximum loads on the fenders are much lower than the designed peak value (5690 kN), as illustrated in Fig. 5. This finding indicates that the stiffness of fenders can guarantee enough resistance and can thus prevent serious deformations and impulsive loads, which are also proved by small standard derivative values in Table 8. As a result, collisions between the FLNG and LNGC can be avoided during the offload operation.

Fig. 13. Time history of loads on hawsers 6# and 7# and deforming lengths of hawser 6#

Fig. 14. Time histories of loads on hawsers 12# and 13#

4.2 Influence of sloshing effects on dynamic responses

Fill levels of both FLNG and LNG carriers change during offloading operations. Sloshing effect variations in tanks have unexpected effects on vessel motion patterns and on connection system loads. Of the three fill levels, vessels subjected to the most serious sloshing effects in fill level B for all of the liquid tanks are 50% full. In this section, test cases in sea condition 1 are chosen to examine sloshing effects on the connection system.

Liquid sloshing in tanks clearly affects vessel roll motions. For a single vessel, sloshing in tanks tends to reduce roll motion responses. However, this tendency may not always be true for side-by-side configuration conditions. Fig. 15 presents roll motion spectrums of FLNG and LNG carrier with three fill levels. The single vessel tests show that the roll motion responses of both FLNG and LNG carrier are smaller for fill level B than those for fill levels A and C. Natural frequencies of vessels in fill level B also have a decrease for damping effects of sloshing in tanks. However, Fig. 15 also shows that for fill level B, when both of FLNG and LNG carrier are 50% full, roll motion of both FLNG and LNG carrier present larger amplitudes in side-by-side configuration condition than those in single vessel condition, especially in the low frequency zone. This phenomenon shows that 50% filled liquid tanks can reduce roll motions in single vessels but can also augment low frequency roll motion responses in side-by-side configuration. For 50% full vessels, sloshing in tanks can increase roll damping levels and can counteract roll motions of the vessels, as confirmed by sloshing results in fill level B for side-by-side configuration. Fig. 16 shows that the sloshing history in wave probe 2# has obvious phase shift with the roll motion history of FLNG. The time history of free surface elevation presents pronounced wave frequency and low frequency properties, which due to sloshing are determined not only by vessel motion frequencies but also by the natural frequency of liquid tanks [27]. Such inconsistencies between sloshing and vessel roll motion pattern reduce roll motion responses under fill level B. In side-by-side configuration, vessel roll motions are affected by hydrodynamic interactions and sloshing effects. Due to hydrodynamic interactions, the low frequency roll motion responses of both FLNG and LNG carrier under side-by-side configuration conditions are more significant than those of single vessel conditions under fill levels A and C. This phenomenon is more evident for vessels under fill level B, especially for LNG carrier that with larger liquid weight ratio. It reveals that coupling between sloshing and ship motion may also contribute to the higher responses in low frequency.

Sloshing in tanks also generates complex relative roll motion patterns between vessels. Comparisons between the time histories of two vessel roll motion patterns of fill levels A and B are shown in Fig. 17. For fill level A, two vessels largely present consistent roll motion phase patterns, as no sloshing forces with a shift difference are induced. For fill level B, sloshing in tanks is no more consistent with the vessel roll motion phase, complicating roll motion patterns and causing an evident phase shift between motion histories of FLNG and LNG carrier. The statistical results shown in Table 9 demonstrate that vessels present most pronounced relative roll motion patterns under fill level B, and relative roll motion patterns contribute to large loads on spring hawsers in groups 2 and 3, as shown in Fig. 18. Moreover, Figs. 15 and 17 show that LNG carrier roll motion pattern is more heavily affected by inner tank sloshing than those of FLNG. This result is partly attributable to the fact that FLNG has a large mid-ship section coefficient that enables it to achieve better roll motion performance. In addition, tanks are positioned in two rows

in FLNG, which can reduce static moment caused by sloshing effects on roll motion to one quarter. Finally, weights of liquids in tanks account for 20.3% and 49.1% of the total displacement in FLNG and LNG carrier, respectively. As a result, LNG carrier is more sensitive to sloshing effects in tanks.

Besides roll motion, yaw motion of FLNG system is also affected by sloshing effects, as it can bring lateral excitation to liquid tanks. Due to damping effects of sloshing in tanks, Table 10 shows that FLNG system presents the lowest degree of yaw motion under fill level B. The large yaw angle found in fill levels A and C lead to increased loads on breast hawsers in the bow and stern and to large loads on fenders, as shown in Fig. 18.

Fig. 15. Roll motion spectra in white noise wave 1 under three fill levels

Fig. 16. Time histories of FLNG roll motion and free surface elevation in probe 2# under fill level B

Fig. 17. Roll motion time histories of vessels under fill levels A and B

Fig. 18. Maximum load on hawsers and fenders under sea condition 1

Table 9. Statistical results of relative roll motion for three fill levels under sea condition 1

Case	Unit	Max	Min	Mean	Std
Fill level A	deg	0.187	-0.493	-0.113	0.080
Fill level B	deg	0.353	-0.795	-0.115	0.151
Fill level C	deg	0.400	-0.399	0.017	0.082

Table 10. Statistical results of yaw motion for three fill levels under sea condition 1

Case		Unit	Max	Min	Mean	Std
Fill level A	FLNG	deg	1.742	-1.418	0.202	0.752
	LNGC	deg	1.951	-1.545	0.201	0.793
Fill level B	FLNG	deg	0.041	-2.579	-1.538	0.571
	LNGC	deg	0.092	-2.593	-1.548	0.576
Fill level C	FLNG	deg	7.461	-5.519	1.892	3.792
	LNGC	deg	7.281	-4.736	1.889	3.520

4.3 Sensitivity to sea conditions

Both wave amplitude and direction are closely related to vessel motions that are excited during offloading operations. Sea conditions under which offloading operations can be conducted safely are heavily restricted. In this section, effects of wave amplitudes and directions are analyzed through comparisons between connection system performance levels under different wave conditions. Fill level B is selected as a representative fill level.

First, connection system sensitivities to wave amplitudes are examined by comparing the results of sea conditions 1 and 2, as these two sea conditions differ only in wave amplitudes. In sea condition 2, significant wave amplitude increase to 2.5 m, and the maximum loads on hawsers shown in Fig. 19 increase accordingly. Loads on spring hawsers in groups 2 and 3 show the most rapid increase, especially for loads on hawser 8#, which increase by more than 65%. Loads on breast hawsers in groups 1 and 4 and on fenders increase slightly, with the largest increase of 16.2% appearing in hawser 3#. This finding can be attributed to the fact that wave amplitude increases in a heading sea leads to more violent longitudinal motion patterns and has limited effects on relative lateral and yaw motions. The data in Table 11 show that relative longitudinal motion significantly increases under sea condition 2. In addition, vessel yaw angles remain rather small under heading wave conditions, as shown in Table 12. Based on the analysis results shown in chapter 4.1, pitch and heave motions are not listed, as they have little effects on loads on the connection system.

Wave direction effects on the connection system were also examined. Both hydrodynamic interaction and sheltering effects on FLNG system change with wave direction variations. In sea conditions 3 and 4, FLNG occupies the weather and lee sides, respectively. Relative to sea condition 2, sea condition 3 causes dramatic increases in maximum loads on breast hawsers in groups 1 and 4 and on all of the fenders. This pronounced increase can be attributed to the average yaw angle of the FLNG system of roughly -24 degrees under the oblique wave condition, as shown in Table 12. In turn, high relative yaw and relative lateral motion levels are excited, inducing dramatic increasing trends in loads on the connection system. The statistical results shown in Table 11 clearly illustrate that relative yaw and lateral motion levels fluctuate considerably under sea condition 3. Such violent relative yaw motion pattern account for high maximum loads not only on hawsers in groups 1 and 4 but also on fenders close to the bow and stern. Nevertheless, the oblique wave-induced relative lateral and yaw motion patterns have less significant effects on spring hawsers in groups 2 and 3, as longitudinal wave forces on vessels also decline for the yaw angle. As a result, when FLNG occupies the weather side, oblique waves do not generate high loads on spring hawsers in groups 2 and 3. However, when FLNG occupies the lee side under sea condition 4, spring hawsers are also subjected to high loads, and maximum loads on hawsers reach 3222.8 kN in hawser 6#. This high loading occurs because changes in hydrodynamic interactions between vessels have negative sheltering effects. Spectral results of vessel roll motion patterns in white noise waves 2 and 3 are presented in Fig. 20 and serve as a good illustration of sheltering effects. The LNG carrier has more significant response when it occupies the weather side instead of the lee side. For this reason, relative motion levels between vessels increase under sea condition 4, as shown in Table 11. High relative roll and longitudinal motion levels place more loads on the spring hawsers. Therefore, placing FLNG on the weather

side is more reasonable during offloading operations, and positive sheltering effects on LNG carriers can thus be achieved to reduce loads on the connection system. In addition, it can be seen from Fig. 19 that loads on breast lines are less sensitive to shielding effects and no much differences can be found between loads on these hawsers in sea condition 3 and 4. That's because the relative yaw motion, as presented in Table 11, is slightly affected by the shielding effects for the weathervaning characteristic of FLNG system.

The analysis presented above clearly shows that positive sheltering effects can allow a connection system to endure more violent sea conditions. Under heading waves, maximum loads on hawsers increase from 2013.3 kN to 2610.0 kN when H_s increases from 2 m to 2.5 m and the loads distribution becomes rather uneven. Due to positive sheltering effects, maximum loads on hawsers only slightly increase to 2672.2 kN under sea condition 3. Similarly, uneven distributions of loads on hawsers under sea condition 2 can be refined by using positive sheltering effects, and a safety factor that is greater than the present value (1.33) can be expected.

Fig. 19. Maximum value of loads on hawsers and fenders

Fig. 20. Roll motion spectrums in white noise waves 2 and 3

Table 11. Statistical results of major relative motion patterns under four sea conditions

Sea condition	Designation	Unit	Max	Min	Mean	Std
1	Rel. longitudinal	m	0.352	-0.398	0.016	0.079
	Rel. lateral	m	0.353	-0.369	0.017	0.090
	Rel. roll	deg	0.795	-0.352	0.114	0.149
	Rel. yaw	deg	0.167	-0.154	-0.010	0.036
2	Rel. longitudinal	m	0.501	-0.559	-0.002	0.130
	Rel. lateral	m	0.331	-0.502	-0.033	0.102

	Rel. roll	deg	1.285	-0.457	0.139	0.200
	Rel. yaw	deg	0.200	-0.204	-0.002	0.044
3	Rel. longitudinal	m	0.487	-0.884	-0.213	0.159
	Rel. lateral	m	0.424	-0.840	-0.217	0.166
	Rel. roll	deg	1.690	-1.005	0.124	0.345
	Rel. yaw	deg	0.357	-0.404	-0.018	0.090
4	Rel. longitudinal	m	0.800	-0.700	0.020	0.180
	Rel. lateral	m	0.440	-0.830	-0.239	0.070
	Rel. roll	deg	2.028	-1.735	0.157	0.375
	Rel. yaw	deg	0.586	-0.318	0.114	0.120

Table 12. Statistical results of vessel yaw motion patterns under four sea conditions

Sea condition	Designation	Unit	Max	Min	Mean	Std
1	FLNG	deg	0.041	-2.579	-1.538	0.571
	LNGC	deg	0.092	-2.593	-1.548	0.576
2	FLNG	deg	4.275	-3.068	0.167	1.427
	LNGC	deg	4.295	-3.078	0.166	1.427
3	FLNG	deg	-10.331	-31.464	-23.973	2.996
	LNGC	deg	-10.325	-31.521	-23.990	2.988
4	FLNG	deg	74.3686	41.2894	57.8257	5.0424
	LNGC	deg	74.5225	41.2407	57.9405	5.0671

5 Conclusions

For an FLNG system in a side-by-side offloading operation, predictions of connection system loads are of great importance. Forces acting on fenders and hawsers are affected by several factors, including fill levels, sea conditions, and their locations on vessels. This experimental study summarizes dynamic response properties of connection systems. Dynamic properties of connection systems under different fill level and sea conditions are obtained, and the following conclusions can be drawn.

- 1) Spring hawsers are sensitive to relative longitudinal motion, and breast hawsers are more sensitive to relative lateral motion and yaw motion. Hawsers respond dynamically and snap loadings that are much more pronounced than the corresponding static responses can be induced, placing high demands on connection systems.
- 2) Loads on fenders are affected by relative lateral and relative roll motion patterns between vessels, fenders adjacent to bows and sterns that are subject to large loads caused by relative yaw motion pattern.
- 3) For the 50% full condition, vessel relative roll and yaw motions are obviously affected by sloshing in tanks. In addition, vessels are subjected to significant low frequency responses in side-by-side configurations due to hydrodynamic interactions between vessels.
- 4) Spring hawsers in mid-ship areas and breast hawsers in bow and stern areas are sensitive to heading and oblique waves, respectively. Fenders are more sensitive to oblique waves, which

can induce apparent relative lateral motion. When FLNG occupies the weather side, sheltering effects positively contribute to loads on the connection system.

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