ABSTRACT
The current demand in liquefied natural gas (LNG) encouraged the design of various concepts for floating LNG (FLNG) liquefaction or regasification facilities. With increasing transport distance, e.g. from remote marine locations to the onshore gas supply net, gas pipelines become uneconomic compared to shuttle carriers for LNG (LNGC). Due to its high energy density, offshore transfer from processing terminals to carriers and from carriers back to receiving terminals has to be analyzed in detail. During the transfer period, free fluid surfaces occurring in the cargo tanks of the LNGC are leading to a significant decrease of the initial intact stability and altered motion behavior. This paper focusses on the influence of resonant tank sloshing on the LNGC’s roll and surge motions. Analyses of transverse and longitudinal sloshing yield a surprising phenomenon: the frequency shift \( \Delta \omega \) between the theoretical natural frequency of the tank alone and the respective motion peak for a vessel with four tanks mounted to the hull. Force measurements between tank and hull reveal a peak at the tank’s natural frequency that causes strong liquid motions with related forces and moments on the hull but no increased vessel motions. Additional investigations comprise the offloading situation with a multi-body arrangement of LNGC and a FLNG (the MPLS20 system) in tandem and briefly also in side-by-side configuration. The slow drift motions on the turret-moored FLNG are exemplarily investigated in head seas.

INTRODUCTION
For several decades, natural gas was merely a byproduct of oil production. Today, its importance as energy source is continuously growing. Large quantities of natural gas are produced from offshore locations, with associated problems of transportation to further onshore processing. Especially for remote marine gas fields, the deployment of LNG (Liquefied Natural Gas) tank ships is a more economic alternative than pipelines - with increasing significance (see [1]). Until today, no floating offshore liquefaction facilities are operating, but investments are increasing and the progress of several projects is considerable [2]. All concepts feature large turret moored terminal barges. In July 2009, Shell Gas & Power Developments BV signed a contract with Technip and Samsung Heavy Industries, forming a consortium to develop, construct and install several floating liquefaction terminals (referred to as FLNG terminals in the following) within the next 15 years [3]. An impression of the 480 m long and 75 m wide terminal vessel, which is designed for side-by-side offloading is shown in Fig. 1 (left).
The first application for this concept will be off the coast of Western Australia, where Shell’s "Prelude" and "Concerto" gas fields are situated. Founded in 2006, Flex LNG is specialized in developing solutions for offshore LNG production. In cooperation with Samsung Heavy Industries, the "Flex LNG Producer" (LNGP) was developed (see Fig. 1, right). This 336 m long and 50 m wide liquefaction terminal vessel is moored and connected to the gas field via a turret buoy system designed by APL AS. Shuttle carriers can be loaded either in side-by-side or in tandem configuration. LNGP1 will be the first of three ordered vessels of this type to be completed, and is scheduled to operate in the "Bilabri" gas field off the Nigerian coast [4]. In contrast to current long-term planning of liquefaction facilities, there is already some progress observable in floating LNG reception facilities. The first realized solution is the "Energy Bridge" principle, developed by the Texas based company Excelerate Energy. Currently, a total of eight Energy Bridge Regasification Vessels (EBRV) is in operation. The concept is suitable for both ship-to-shore transfer (GasPort) and offshore transfer (Gateway). In both cases, a conventional LNG carrier is moored side-by-side to an EBRV which regasifies the LNG. In case of GasPorts, shore-based loading arms transfer the gas into the downstream delivery infrastructure, while for offshore Gateways, cone-shaped STL buoys (Submerged Turret Loading, see Fig. 2, left) are applied to transfer the gas via pipelines to the onshore infrastructure [5].

The second type of marine LNG reception facilities that are already operating is "Adriatic LNG", built by Aker Solutions for Exxon Mobil. Since 2008, conventional LNG carriers are calling at this GBS terminal (Gravity Based Structure), situated 15 km off Porto Levante in the Adriatic Sea (see Fig. 2, right). LNG is transferred in side-by-side configuration to the GBS, where the regasification process takes place. Subsequently, the gas is transferred to the Italian mainland via pipelines.

The design and motion capabilities of cryogenic transfer systems is the limiting parameter for the operational range of the entire FLNG system. The two transfer configurations — tandem and side-by-side — are characterized by specific transfer technologies. For side-by-side transfer, FMC Technologies’ rigid "Marine Loading Arms" are currently state-of-the-art. They have been designed to handle relative motion amplitudes between the two vessels of 1.0 m in longitudinal, 2.0 m in transversal and 1.2 m in vertical direction. Due to these limitations, side-by-side transfer with rigid loading arms is currently possible only for calm waters to moderate sea states. In tandem configuration, the coupling points for the cryogenic transfer system are typically located at the bow of the carrier and the stern of the terminal, instead of amidships as for the side-by-side configuration. Since this implies larger relative motions that have to be handled, aerial or floating flexible pipes instead of rigid arms have to be used. Dutch Bluewater developed a cryogenic transfer pipe of 8” to 16” inner diameter for aerial applications, but so far only a prototype was built. The OCT consortium (Offshore Cryogenic Transfer), led by Norwegian Framo Engineering, also developed an offshore transfer system for LNG in tandem configuration — which is not in operation until today [6]. In order to develop a safe and efficient offshore LNG transfer system that exceeds the capabilities of the state-of-the-art technologies, the research project MPLS20 (Maritime Pipe Loading System 20”) was funded by the German Federal Ministry of Economics and Technology.

In the framework of the joint research project MPLS20, an innovative offshore transfer system between a turret moored terminal barge and a shuttle carrier in tandem configuration is developed and analysed [7, 8]. Brugg Pipe Systems has designed a corrugated transfer pipe of 16” inner diameter for cryogenic LNG loading/offloading — which is significantly exceeding currently existing pipe diameters and hence transfer rates. The work of Nexans focuses on the manufacturing technology of the vacuum insulated transfer pipes. IMPaC Offshore Engineering is in authority of the approach and handling system and Technical University Berlin has conducted model tests as well as numerical simulations in order to analyse the hydrodynamic characteristics of the multi-body arrangement. The focus lies on the tandem configuration with cursory investigations of the side-by-side arrangement.

The proposed transfer system consists of a generic FLNG terminal design with the new "Mooring Bay" concept, a modified standard LNG carrier (LNGC) and the approach and handling system for the developed 16” transfer pipes (see Fig. 3).
The FLNG (for main dimensions see Tab. 1) features a wave flattening bow and provides a cargo loading capacity of up to 280,000 m³ LNG in five independent SPB tanks (Self-supporting, Prismatic, IMO Type B) which are sloshing-proof and offer a flat deck. The LNGC (for main dimensions see Tab. 1) is equipped with four membrane tanks and is slightly modified compared to today’s standards, as one additional and specially designed receiving manifold is placed at the deck bow area. This bow manifold completely enters the "Mooring Bay" at the aft end of the terminal when the LNGC is moored for cargo transfer, significantly reducing the free span lengths of the transfer pipes compared to crude oil transfer techniques. The distance between the bow of the LNGC and the stern of the FLNG is 10 m in this configuration.

The mooring system features the patented "Mooring Bay", built of the two "Mooring Wings" which are fixed to the FLNG terminal’s aft end at starboard and portside, respectively. The mooring arrangement for the LNGC is symmetrical with six mooring lines, each operated by load adequate winches and heave compensation systems.

In the following sections, the hydrodynamic challenges of FLNG concepts, i.e. tank sloshing and its influence on ship motions as well as mooring investigations, are exemplarily depicted for the MPLS20 system.

**TABLE 1. MAIN DIMENSIONS OF THE MPLS20 VESSELS**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FLNG</th>
<th>LNGC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length over all [m]</td>
<td>360 (+ 40 &quot;Mooring Bay&quot;)</td>
<td>282</td>
</tr>
<tr>
<td>Breadth [m]</td>
<td>65</td>
<td>42</td>
</tr>
<tr>
<td>Draught [m]</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Height [m]</td>
<td>33</td>
<td>26</td>
</tr>
<tr>
<td>Displacement [m³]</td>
<td>275,087</td>
<td>103,921</td>
</tr>
<tr>
<td>Loading Capacity [m³]</td>
<td>280,000</td>
<td>152,000</td>
</tr>
<tr>
<td>Roll Rad. of Gyr. [m]</td>
<td>21.81</td>
<td>14.41</td>
</tr>
<tr>
<td>Pitch Rad. of Gyr. [m]</td>
<td>88.76</td>
<td>81.10</td>
</tr>
<tr>
<td>Yaw Rad. of Gyr. [m]</td>
<td>92.36</td>
<td>81.81</td>
</tr>
</tbody>
</table>

**SLOSHING**

Offshore offloading procedures for hazardous cargo such as highly explosive LNG require detailed knowledge of the system hydrodynamics in order to ensure safe operations. During the transfer period, which typically takes about 18-24 hours, free fluid surfaces occur in the cargo tanks of the LNGC. This leads to a significant decrease of the initial intact stability and altered motion behavior as shown by [9–14]. While the FLNG unit is equipped with sloshing-proof SPB tanks, the LNGC selected for the investigations features standard prismatic tanks without internal partitions. This type of tank is prone to resonant free surface motions that are induced by the ship moving in waves.

Fig. 4 shows a comparison between the LNGC surge ($\beta = 180^\circ$) and roll ($\beta = 90^\circ$) RAOS for the solid filling case (please note that the model is not equipped with bilge keels) and tanks with 30% filling height ($h/H_T = 0.3$). It can be deduced, that the low-frequency peak of the roll motion ($\omega = 0.2$ rad/s) is related to the hull resonance, since no fluid motions inside the tanks can be observed, i.e. the ship is rolling and the fluid surface remains in a horizontal plane parallel to the water surface in the basin. In contrast to this, the high-frequency roll motion peak ($\omega = 0.86$ rad/s) is clearly related to strong transverse sloshing inside the tanks. The same applies to the surge motion peak ($\omega = 0.74$ rad/s), which is related to moderate lon-
TABLE 2. CHARACTERISTIC DIMENSIONS OF THE LNGC’S PRISMATIC TANKS

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length $L_T$</td>
<td>38.3</td>
</tr>
<tr>
<td>Breach $B_T$</td>
<td>35.8</td>
</tr>
<tr>
<td>Height $H_T$</td>
<td>26.1</td>
</tr>
<tr>
<td>$\delta_1$</td>
<td>4.65</td>
</tr>
<tr>
<td>$\delta_2$</td>
<td>5.0</td>
</tr>
<tr>
<td>Volume $m^3$</td>
<td>37,960</td>
</tr>
</tbody>
</table>

In order to assess the problem comprehensively, one prismatic tank alone — as illustrated in Fig. 5 and described in Tab. 2 — is investigated analytically and numerically at first. The numerical calculations are conducted in frequency domain, and are based on the specially adapted radiation-diffraction panel code WAMIT (Wave Analysis at Massachusetts Institute of Technology, [16], which is a potential theory approach [17], [18]. This numerical method has been validated successfully by model tests at a scale of 1:100 in the seakeeping basin of TU Berlin [15]. Transient wave package technique has been applied to determine the respective RAOs in the seakeeping basin of TU Berlin [15].

According to [19], the natural transverse sloshing frequency of the $i^{th}$ mode for a rectangular tank is given by the expression

$$\omega_{r,i} = \sqrt{\frac{g}{B_T} \tanh \left( \frac{\pi i}{B_T} h \right)}$$

where the respective filling height inside the tank is denoted by $h$. The natural frequency is not dependent on the density of the fluid inside the tank. For prismatic tanks with chamfered bottom, [19] proposed a correction factor:

$$\frac{\omega_{r,i}^2}{\omega_{r,i}^2} = 1 - \frac{\delta_1 \delta_2^{-1} \sinh \left( \frac{\pi i}{B_T} \right) - \delta_2 \delta_1^{-1} \sinh \left( \frac{\pi i}{B_T} \right)}{\pi i \sinh \left( \frac{2 \pi i h}{B_T} \right)}$$

This correction factor, denoted as $\omega_{r,i}^2$, is applied to the natural frequency of the $i^{th}$ mode for prismatic tanks. For filling levels of 20% to 70%, the resonant frequencies are strongly shifting with altered liquid depths. In very "shallow liquid conditions" ($h/B_T < 0.1$ and $h/L_T < 0.1$), hydraulic jumps may occur inside the tank. For solid filling (i.e. filling height 100%), the maximum ratio is $h/B_T = 0.73$ and $h/L_T = 0.68$, respectively, due to the dimensions of the LNGC’s tanks. As shown in Fig. 6, the WAMIT calculations for $\beta = 90^\circ$ with the tank alone reveal a very good agreement with results based on Eqs. (1) and (2), within a filling range from 20% to 70%, where the first natural tank frequency follows a hyperbola approaching $\omega = 0.93$ rad/s with increasing filling height. For filling levels

FIGURE 5. NUMERICAL DISCRETIZATION OF THE LNGC’S PRISMATIC TANK WITH CHARACTERISTIC DIMENSIONS

FIGURE 6. TANK RESONANCE FREQUENCIES ACCORDING TO [19] COMPARED TO WAMIT RESULTS
within the top chamfer region, i.e. more than 70%, strong deviations occur, since these geometrical features are not covered by Faltinsen’s approach. The bottom chamfer region on the other hand — i.e. less than 20% filling height — is taken into account by Eq. (2). Nevertheless, results from both approaches should be considered with care in this domain, since the effect of the tank bottom falling dry at low filling heights and resonant liquid motions is neglected. Due to the different characteristic length, the hyperbolic curve for the longitudinal frequencies approaches \( \omega = 0.9 \text{ rad/s} \). Since Faltinsen’s formula is not explicitly valid for this case, slight deviations between analytical and numerical results can be observed throughout the entire frequency range (for \( \beta = 180^\circ \)).

Comparing the frequency of the sloshing-related roll motion peak for 30% filling height (\( \omega = 0.86 \text{ rad/s} \), see Fig. 4, right) to the analytical transverse sloshing frequency of the tank alone for 30% filling height (\( \omega = 0.72 \text{ rad/s} \), see Fig. 6), reveals a significant deviation, in the following denoted by \( \Delta \omega \). Obviously, there are no amplified roll motions at the theoretical natural frequency, while strong motions occur in a higher frequency range. In order to fully comprehend this phenomenon, the calculated roll motion for 30% filling height is correlated to roll moments, measured between the LNGC hull and the foremost and sternmost tank, respectively (see Fig. 7): Although the results for both tanks show different characteristics in frequency domain, the stern as well as the bow roll moment feature three peaks. Two of those are already known from the roll motion analysis — the LNGC hull resonance at \( \omega = 0.2 \text{ rad/s} \) and the sloshing-related peak at \( \omega = 0.86 \text{ rad/s} \). The third peak is of intermediate frequency and appears in the vicinity of the analytical natural frequency but differs slightly for both tanks. Since the magnitude of this peak is in the order of \( 2 \times 10^8 \text{ kNm per meter wave amplitude} \), it should be considered for structural analysis of LNGC hull designs. Further clarification follows from numerical investigations of the surface elevation inside the bow and stern tank at the reference points indicated in Fig. 8. The comparison of the roll moments with the related surface elevations reveals the cause for the third peak: Strong liquid motions. With the sloshing motion results, the causes for the two roll motion peaks can also be verified:

- At the hull resonance frequency (\( \omega = 0.2 \text{ rad/s} \)), no liquid motions are observed. Roll motions and moments are significant.
- At the sloshing-related peak (\( \omega = 0.86 \text{ rad/s} \)), extremely high fluid motions in the tanks as well as high roll motions and moments are observed.
- At the intermediate (third) peak (\( \omega \approx 0.72 \text{ rad/s} \)), transverse fluid motions (sloshing) as well as roll moments are significant; however there is no effect on the roll motion of the vessel.

The reason for this phenomenon is illustrated in Fig. 8 (bottom) showing the phase angles of the hull’s roll motion as well as of the surface elevation at the reference points 1 and 2. Again, deviations between results for the stern and the bow tank occur in the vicinity of the natural frequency. From the combination of the results for the surface elevation and the respective phase angles in Fig. 8, it can be deduced that - probably due to the LNGC hull’s longitudinal asymmetry - the liquid motions inside all cargo tanks are slightly different in magnitude and phase. It also becomes clear that in the range of approx. \( \omega \approx 0.8 \text{ rad/s} \) a phase shift between hull motion and liquid motion causes the effect of the shift of the peak frequency by \( \Delta \omega \). The analytical natural transverse frequency at \( \omega = 0.72 \text{ rad/s} \) lies within this range, where internal fluid motions have no amplifying effect on the ship motions. For frequencies \( \omega \approx 0.8 \text{ rad/s} \), liquid cargo motions for all tanks are in phase with the roll motion of the vessel, i.e. their effects are superimposing each other. This leads to a rather stretched peak region with the highest magnitude at \( \omega = 0.86 \text{ rad/s} \). Comprehensive numerical simulations with fresh water (\( \rho = 998.2 \text{ kg/m}^3 \)) as well as LNG (\( \rho = 435 \text{ kg/m}^3 \)) and the complete range of filling heights are conducted to generalize the resonant behavior and findings for the standard case with 30% filling height. In the upper part of Fig. 9, “transverse” results (\( \beta = 90^\circ \)) are presented while the lower part illustrates “longitudinal” results (\( \beta = 180^\circ \)). In both parts, the solid lines represent the resonance frequencies for one tank alone (as already shown in Fig. 8 together with results from Faltinsen’s for-

![Figure 7](image-url)
FIGURE 8. COMPARISON OF MEASURED ROLL MOMENTS AND CALCULATED SURFACE ELEVATIONS AT THE INDICATED REFERENCE POINTS FOR THE BOW TANK (TOP LEFT) AND THE STERN TANK (CENTER LEFT) AS WELL AS PHASE ANGLES OF THE SURFACE ELEVATIONS AND THE ROLL MOTION OF THE HULL (BOTTOM LEFT) FOR 30% FILLING HEIGHT IN ALL FOUR TANKS AND $\beta = 90^\circ$
FIGURE 9. RESONANT PHENOMENA INSIDE THE PRISMATIC TANK IN TRANSVERSE (TOP) AND LONGITUDINAL DIRECTION (BOTTOM) VALID FOR STERN AS WELL AS BOW TANKS
mulae, which are denoted by asterisk symbols. These data of one single "free" tank are compared to the effect of four hull-mounted equally filled tanks on the LNGC’s motions in waves. Numerical results with LNG are represented by dashed lines; dash-dotted lines show fresh water frequencies. Note that motion peaks are shifted towards higher frequencies for increasing densities of the liquid cargo. The deviation $\Delta \omega$ remains approximately constant in the transverse direction while it increases with increasing filling height in the longitudinal direction. $\Delta \omega$ between LNG filled tanks onboard the LNGC and a tank alone is marked by light grey regions in Fig. 9. Model test motion data (for 10%, 20% and 30% fresh water filling height in all four tanks mounted to the LNGC’s hull) are indicated by rhombuses, which agree well with the respective calculations. Please note that the experimental filling height values are slightly differing from the numerical values.

MOORING ANALYSIS

As illustrated in Fig. 10, the turret mooring system of the MPLS20 FLNG terminal consists of 12 identical mooring lines assembled in four groups of three lines, each of which is made of four segments with the characteristics given in Tab. 3. The center lines of the groups are arranged at an angular distance of 90° and the angular distance between each line within a group is 15°. The turret is located 192.5 m from the terminal’s center of gravity in $x$-direction in the center plane ($y = 0$). The water depth is 100 m, whereas the distance of the fairleads to the sea bed is considered to be 121 m (see Fig. 10). The first step of the mooring analysis is the investigation of the behavior of a single line. The mooring analysis, that is presented in the following is concerned with the FLNG alone, i.e. without having the LNGC connected to it. In Fig. 11, the static configuration of a single mooring line in the two-dimensional plane under various pretension forces in the range of $0.87E06 \text{ N} \leq T_P \leq 2.96E06 \text{ N} —$ applied at the fairlead — is presented. For three different pretension levels $T_P$, various external loads $F_{ex,H}$ are applied on the 12 turret lines. The resulting horizontal excursions of the vessel in $x$-direction are shown in Fig. 12 (left).

The stiffness of the mooring system in the horizontal plane $k_{xx}$ in dependency of the three selected pretension levels and the imposed external horizontal force is depicted in Fig. 12 (right). It can be observed that for a wide range of external loading, the stiffness of the mooring system remains almost constant. This range depends on the pretension level. With the determination of the mooring system’s stiffness, the complete system of governing equations that describe the static equilibrium of the extensible lines is solved for each line separately using the 4th order Runge-Kutta method for non-linear ordinary differential equations. The results are then properly superimposed to predict the final balancing position of the moored FLNG under specified loading conditions exemplarily in $x$-direction (surge drift motion) using

<table>
<thead>
<tr>
<th>Composition</th>
<th>Seg.1</th>
<th>Seg.2</th>
<th>Seg.3</th>
<th>Seg.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length, $L$ [m]</td>
<td>900</td>
<td>100</td>
<td>150</td>
<td>50</td>
</tr>
<tr>
<td>Diameter, $D_{eq}$ [m]</td>
<td>0.184</td>
<td>0.25</td>
<td>0.087</td>
<td>0.13</td>
</tr>
<tr>
<td>Mass in air, $m$ [kg/m]</td>
<td>370</td>
<td>686</td>
<td>33.4</td>
<td>185</td>
</tr>
<tr>
<td>Add. mass, $m_a$ [kg/m]</td>
<td>27.27</td>
<td>50.3</td>
<td>6.1</td>
<td>13.6</td>
</tr>
<tr>
<td>Sub. weight, $w$ [N/m]</td>
<td>3157.8</td>
<td>5854.8</td>
<td>267.8</td>
<td>1579</td>
</tr>
<tr>
<td>Elasticity, $EA$ [N]</td>
<td>5.58E9</td>
<td>10.33E9</td>
<td>1.01E9</td>
<td>2.79E9</td>
</tr>
</tbody>
</table>

FIGURE 11. STATIC CONFIGURATION OF A SINGLE LINE IN THE 2D PLANE FOR VARIOUS PRETENSION FORCES $T_P$ APPLIED AT THE FAIRLEAD

TABLE 3. CHARACTERISTICS OF THE MOORING LINE SEGMENTS (NUMBERED FROM BOTTOM TO TOP)
For the evaluation of the structure’s mean excursion \( \bar{x}_0 \), the mean wave forces \( F_{x0}^{(2)} \) in irregular seas are required together with the mooring system’s stiffness, given in Fig. 12 (right). Wind and current effects have not been considered in this exemplary calculation. The slowly-varying vessel motions then are obtained by accounting for the mooring system’s restoring characteristics around the mean equilibrium position of the FLNG and the associated spectra of the low-frequency excitations [22]:

\[
F_{x0}^{(2)} = 2 \int_0^\infty S_\zeta(\omega) \frac{F_{x0}^{(2)}(\omega)}{\zeta^2_{a}} \, d\omega
\]  

(3)

A JONSWAP spectrum \( S_\zeta(\omega) \) with \( H_s = 5.5 \, \text{m} \), \( T_0 = 10 \, \text{s} \) and \( \gamma = 3.3 \) is considered as the basis of the investigations. The mean drift forces \( F_{x0}^{(2)}/\zeta^2_{a} \) in regular waves have been calculated using the potential theory solver WAMIT and the momentum conservation principle. The results for head seas (\( \beta = 180^\circ \)) — and for comparative reasons also for beam seas (\( \beta = 90^\circ \)) — are presented in Fig. 13. Note that the mean drift forces are normalized by the fluid density \( \rho \), the gravitational acceleration \( g \), the squared wave amplitude \( \zeta_a \) and the respective characteristic length \( L_x \) (i.e. the breadth of the FLNG, and \( L_x = 400 \, \text{m} \), i.e. the vessel’s length). These two forces and the given environmental conditions, the mean wave drift loads of \( F_{x0}^{(2)} = 1.2535 \times 10^5 \, \text{N} \) for head seas, and exemplarily also \( F_{x0}^{(2)} = 1.5216 \times 10^5 \, \text{N} \) for beam seas, are determined.

For the following calculations, head seas (\( \beta = 180^\circ \)) are considered exclusively. The mean excursions for the mean drift force, defined by \( \bar{x}_0^{(2)} = F_{x0}^{(2)}/k_{xx} \) with the associated stiffness coefficients \( k_{xx} \) for the three pretension levels are given in Tab. 4.

The slowly-varying response spectrum of the terminal’s motion in irregular seas is given by the relation [22]:

\[
S_\epsilon(\mu) = S_F(\mu) \frac{1}{k_{xx}^2 \left\{ 1 - \left( \frac{\mu}{\mu_{\text{crit}}} \right)^2 \right\}^2 + \left( 2 b \frac{\mu}{\mu_{\text{crit}}} \right)^2 }
\]

(4)

where \( S_F(\mu) \) is the spectrum of the slowly-varying second-order wave forces exerted on the structure, which by assuming New-

![FIGURE 12. HORIZONTAL TURRET’S EXCURSION VERSUS HORIZONTAL EXCITING FORCE FOR THREE PRETENSION LEVELS (LEFT); MOORING SYSTEM’S STIFFNESS COEFFICIENT IN THE HORIZONTAL DIRECTION DEPENDING ON THE PRETENSION LEVEL AND THE EXTERNAL FORCE (RIGHT) ESE]

<table>
<thead>
<tr>
<th>Pretension ( T_P ) [N]</th>
<th>Stiffness ( k_{xx} ) [N/m]</th>
<th>Mean exc. ( \bar{x}_0^{(2)} ) [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2E06</td>
<td>3.77E05</td>
<td>1.20</td>
</tr>
<tr>
<td>0.3E06</td>
<td>3.99E05</td>
<td>0.90</td>
</tr>
<tr>
<td>0.4E06</td>
<td>4.22E05</td>
<td>0.71</td>
</tr>
</tbody>
</table>

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man’s approximation [23] is given by [24]:

\[
S_F(\mu) = 8 \int_0^\infty S_\zeta(\omega) S_\zeta(\omega + \mu) \frac{F_{\mu}^{(2)}(\omega + \mu/2)}{\Omega^2} d\omega
\]  

(5)

\(F_{\mu}^{(2)}(\omega + \mu/2)\) is the mean drift force on the structure in x-direction, \(\mu_0 = \sqrt{k_{xx}/(m + a_{xx})}\) is the natural frequency of the horizontal motion component due to the presence of the mooring system, with \(a_{xx}\) being the added mass of the FLNG terminal in x-direction, and \(b\) the non-dimensional critical damping coefficient defined by the relation \(\beta_{xx} = 2b\mu_0(m + a_{xx})\). Its calculation presumes the evaluation of the three main damping components besides radiation damping: Damping related to the friction on the wetted part of the structure, to the second-order wave drift and mooring-induced damping. In the present analysis, critical damping is assumed to be \(b = 0.2\).

Fig. 14 (left) shows the spectrum of the slow-drift excitation on the FLNG in head seas (\(\beta = 180^\circ\)), evaluated according to Eq. (5), while in Fig. 14 (right), the corresponding spectra for the slow-drift surge responses are given with respect to the three pretension levels. With the root mean square of these spectra

\[
\bar{x}_{RMS} = \sqrt{\int_0^\infty S_\mu(\mu)d\mu}
\]

(6)

the significant \(\bar{x}_s = 2\bar{x}_{RMS}\), and maximum \(\bar{x}_{max} = 1.86\bar{x}\), expected slow surge drift amplitudes can be calculated by spectral analysis methods. The results of this analysis are shown in Tab. 5, in dependency of the pretension level in the mooring system. Based on the pretension in the lines, the turret-moored FLNG’s significant surge drift amplitudes are in the range of 1.72 m to 1.88 m, with associated maximum surge drift amplitudes of 3.19 m to 3.49 m.

**TABLE 5. SIGNIFICANT AND MAXIMUM SLOW-DRIFT EXCURSIONS OF THE TERMINAL IN SURGE DIRECTION**

<table>
<thead>
<tr>
<th>Pretension (T_P) [N]</th>
<th>Sign. exc. (\bar{x}_s) [m]</th>
<th>Max. exc. (\bar{x}_{max}) [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2E06</td>
<td>1.88</td>
<td>3.49</td>
</tr>
<tr>
<td>0.3E06</td>
<td>1.79</td>
<td>3.34</td>
</tr>
<tr>
<td>0.4E06</td>
<td>1.72</td>
<td>3.19</td>
</tr>
</tbody>
</table>

**PERSPECTIVES**

The previous investigations are exclusively related to the MPLS20 offshore LNG transfer system, i.e. fixed design and operation parameters. In order to widen the basis of investigations, an alternative tank type as well as the side-by-side loading configuration is exemplarily analyzed in the following subsections.

**Tank Type Variation**

Apart from prismatic tanks (such as the membrane types GT96 and TGZ Mark III by the French companies Gaz Transport & Technigaz), many LNGC’s are equipped with spherical tanks (or "MOSS" tanks - developed by the Norwegian company Moss Maritime). The advantage of this type of tank is its self-supporting capability, but the drawbacks are higher fabrication costs compared to equivolumetric membrane type tanks as well as the less efficient utilization of the LNGC hull shape and thus more void space between cargo tanks and ballast tanks.

With the successfully validated potential theory approach, the LNGC’s motion characteristics are now exemplarily analyzed with four spherical tanks \((V_T = 37,960 \text{ m}^3, \text{ diameter } D_T = 41.7 \text{ m})\) as illustrated in Fig. 15. Comparing the surge and roll motions of the LNGC hull described in Tab. 2) equipped with equivolumetric prismatic and spherical tanks (filling volume

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**FIGURE 15. VISUALIZATION OF THE LNGC HULL DISCRETIZATION WITH SPHERICAL TANKS**
9,800 m$^3$ per tank, 30% filling height) reveals differences in the tank resonance behavior. The surge motion RAO (see Fig. 16, left) peak that is related to longitudinal tank sloshing is significantly shifted towards higher frequencies and also lower in magnitude compared to the resonance peak for prismatic tanks. A similar tendency can be observed for the roll motion RAO (see Fig. 16, right), where the low-frequency hull resonance peak appears at the same wave frequency for both cases, while the high-frequency transverse tank sloshing peak is shifted and decreased in magnitude.

Although further studies are necessary to draw general conclusions, this exemplary analysis already suggests the spherical tank’s advantages considering liquid sloshing coupled with ship motions.

**Side-by-Side Configuration**

The majority of planned offshore LNG transfer systems (see Fig. 1) are designed for side-by-side configuration loading procedures, although offshore transfer operations are limited to significant waves heights of $H_s = 3$ m, whereas tandem offloading is feasible in sea states up to $H_s = 5.5$ m. Due to manufacturing restrictions, today the maximum fender size sets the distance between FLNG and LNGC to 4 m. Due to manufacturing restrictions, today the maximum fender size sets the distance between FLNG and LNGC to 4 m. Nevertheless, for exemplary numerical analyses, a gap width of 10 m between the two hulls is chosen. The coupling points for the transfer pipes are located at the side of the vessels’ decks at the center of gravity in $x$-direction. The obvious advantage of this arrangement becomes clear from Fig. 17. Due to the very low influence of the pitch motion at this position, the magnitudes of the relative motions in the vertical direction are significantly decreased. The drawback of this arrangement is increased relative rotatory motions with resulting torsion on the cryogenic pipes.

For two floating bodies in side-by-side configuration, resonant wave motions inside the gap between the side walls have to be taken into account [25–28]. The assessment of this effect is critical for the design of the mooring arrangement between the two vessels. The surface elevation between FLNG and LNGC (at the location indicated by the red line in Fig. 18, bottom) for a gap width of 10 m related to the incident wave is shown in Fig. 18 (top). In the frequency range $0 < \omega < 0.6$ rad/s, the wave elevation in the gap is slightly lower than the surrounding sea. For $0.7 \text{ rad/s} < \omega < 0.85$ rad/s, strong amplifications occur, leading to waves more than 3.5 higher than the incident waves.

At $\omega = 0.8$ rad/s, the surface elevation is calculated numerically for different locations and time steps along the length of the gap. As illustrated by Fig. 18 (bottom), the wave gauge position meets the antinode of the central standing wave — a few meters to the left or right or at a node, the RAO would be completely different. Therefore, the wave field forming inside the gap has to be analyzed in detail with respect to the location and the times, frequency domain analyses alone are not sufficient. Model test series will show whether the potential theory approach overestimates the amplification effects inside the gap. Further investigations should also focus on the determination of the wave elevation in the gap depending on the relative position of the vessels (gap width and length as well as longitudinally shifted arrangements) excitation frequency, water depth and draught. Future work also includes investigation with different classes of LNGCs, the consideration of the FLNGs turret mooring with respect to second order forces and motions and the implementation of this data and experience into an assistance system for offshore LNG transfer.

**CONCLUSIONS**

The resonance frequency of fluid moving inside a prismatic tank is dependent on the filling height. Surprisingly, the respective resonance frequencies for a single “free” tank do not match
the sloshing-related motion peaks of a vessel with the same tank mounted to the hull. However, measurements and numerical calculations reveal high surface elevations inside the tanks as well as high forces and moments between tanks and the hull in the very vicinity of the "free" tank’s natural frequencies. Results for the foremost and the sternmost tank are slightly differing. Systematical investigations with different filling heights as well as liquids of different density show a difference factor Δω, which increases with denser liquids. In transverse direction, Δω remains approximately constant while it continuously grows with increasing filling heights in the longitudinal direction. The physical explanation for this phenomenon is discovered by comparing the free surface elevations inside the tanks to the motions of the vessel: the liquid motion characteristics inside each tank are slightly different and the respective phase angle reveals a phase shift between fluid and hull motions at the tank’s natural frequencies, which becomes zero in the proximity of the sloshing related motion peak, i.e. the liquid and the vessel are moving in phase, superimposing each other at this point. An exemplarily analysis of the FLNG’s turret mooring design in head seas yields significant slow drift motions of 1.72 m to 1.88 m and maximum slow drift motions of 3.19 m to 3.49 m, depending on the pretension level of the mooring lines.

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