ABSTRACT
The current demand of liquefied natural gas (LNG) from remote marine locations pushes the design of floating LNG (FLNG) liquefaction or regasification facilities, where LNG is transferred between shuttle carrier (LNGC) and terminal. Even if the tandem configuration is the primary choice for LNG transfer at rough offshore locations, side-by-side configurations would be the preferred option because of existing midship coupling manifolds on the present carrier fleet (no need for manifold modifications) as well as standard mooring systems and transfer-process-chains similar to oil-transfer. Therefore, the operation conditions at rough seas have to be improved to allow side-by-side LNG-transfer and to reduce offloading downtime.

Within the SOTLL-project, side-by-side LNG transfer up to $H_s = 3$ m is reached as a transfer limit using a new flexible pipe design, the advantages of sheltered areas at the leeside of the terminal barge and an optimized ship transfer position due to a flexible longitudinal offloading position. In addition to the evaluation of the hydrodynamic characteristics of this multibody system, one key aspect is the analysis of the exciting forces and motions due to wave amplification between the ships. In the gap between the hulls, the incoming wave field is amplified and changes dramatically. Depending on gap width, longitudinal offset, wave heading and length, large wave amplifications, standing waves and other resonance phenomena are observed which may result in high relative motions and increased forces of the entire mooring system. In this paper, the gap effects are investigated in detail with numerical approaches in frequency domain, validated by model tests at TU Berlin. A typical offloading scenario with barge and carrier is investigated for different gap sizes to identify suitable transfer configurations and ensure safe LNG offshore transfer up to $H_s = 3$ m.

INTRODUCTION
The importance of LNG (Liquefied Natural Gas) as a source of energy is continuously growing - large quantities of natural gas are located and produced at offshore locations. With rising distance of newly developed offshore gas fields to shore, the deployment of LNG tank ships is indispensable [1]. Until today,
no floating 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 combination with different offloading concepts. To face the problems during offloading operations in harsh offshore environment, the MPLS20\textsuperscript{3} system [3, 4] has been introduced to ensure safe LNG offloading up to $H_S = 5.5\, \text{m}$ in tandem configuration, using a mooring bay and flexible LNG-pipes. The only drawback comes along with additional investment in terms of manifold modification for already existing shuttle carriers, which have to be adapted for this transfer option. To serve the ocean going LNG fleet, which is equipped with LNG-transfer manifold at midship in most cases, a side-by-side solution would be advantageous.

Within the framework of the SOTLL\textsuperscript{2} project, a new side-by-side solution is investigated, identifying favourable transfer positions in terms of longitudinal and transversal offset, which use sheltered areas at the leeside of the terminal, resulting in lower relative motions to ensure safe offshore offloading up to $H_S = 3\, \text{m}$. Covering a large variety of transfer scenarios, four different types of ships are investigated in four different longitudinal positions at three different gap distances using four different turret positions.

The main focus is on the most common scenario, a generic terminal barge to carrier midship transfer, illustrated in Fig. 1 with main dimensions specified in Tab. 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Terminal</th>
<th>LNGC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length over all [m]</td>
<td>360</td>
<td>282</td>
</tr>
<tr>
<td>Breadth [m]</td>
<td>65</td>
<td>43.4</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 [m$^3$]</td>
<td>275,087</td>
<td>103,921</td>
</tr>
<tr>
<td>Loading Capacity [m$^3$]</td>
<td>280,000</td>
<td>134,000</td>
</tr>
</tbody>
</table>

To identify the influence of the gap width for the mentioned midship side-by-side scenario, two gap widths of $10\, \text{m}$ & $4\, \text{m}$ are analyzed numerically using WAMIT\textsuperscript{3} [5]. The results are validated by model tests at the seakeeping basin of TU Berlin.

The focus of this paper is laid on the complex problem describing the wave field between two ships, also known as gap effect. To face this resonance problem, the integration of damping lids is common usage and was introduced for WAMIT by Newman [6, 7], including generalized modes for the simulation of free surface patches in multibody interactions.

**Gap Effects**

The hydrodynamic problems, in particular the resonance effects between two side-by-side operating vessels, has been discussed and analysed for decades. Huijsman et al. [8] used a rigid lid along the gap to remove irregular frequencies. Chen [9] compared numerical calculations with damping lid and control surfaces for different vessel types with model tests. Pauw et al. [10] used adapted boundary conditions and semi permeable damping lids and suggested to tune the damping value $\varepsilon$, which reduces the vertical particle velocity, on basis of the second order drift forces. Bunnik et al. [11] enhanced the meshes used by Pauw, both using a symmetric setup validated by model test near the basin wall. Molin et al. [12] investigated rectangular barges, revealing the influence of the bilge shape. For calculating sloshing modes, the theoretical approach of Molin [13] is generally used. Fournier et al. [14] investigated a quite similar case (FSRU\textsuperscript{4}) as presented in this study (FLNG to LNGC) to investigate the influence of damping lids on surface elevation, body motion and forces. They also used WAMIT as the numerical approach, combined with HYDROSTAR calculations and model tests.

With the knowledge of this background and preliminary calculations according to Fournier et al. [14], a damping lid should be included in WAMIT between the vessels hulls. To estimate the relevant damping parameter for this lid, experimental investigations are made with focus on the wave propagation inside the gap. As mentioned, it is necessary to estimate the proper damping values for the implemented damping lid which influences body motions or second order drift forces. In this paper, the focus is laid on the wave propagation inside the gap, regarding wave height as well as regions of cancellation and amplification.

**PRELIMINARY SURVEY**

In general, at a side-by-side arrangement of a multibody system in head seas, the incoming waves are amplified as the LNGC bow acts as a funnel narrowing the initial intake width of $31.7\, \text{m}$ to the gap width of $10\, \text{m}$ (cf. Fig. 2). At the end of the gap, the width is increasing again, resulting in wave reflection (cf. Bunnik et al. [11]). In addition, the LNGC’s sway motion may induce a pumping effect or piston mode (cf. Molin [13]). As a consequence, depending on ship mooring and wave characteristics we observe propagating and standing wave patterns in the gap. It is

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\textsuperscript{1}Maritime Pipe Loading System 20\textsuperscript{7}
\textsuperscript{2}Sideways Offshore Transfer of LNG and LPG
\textsuperscript{3}Wave Analysis at Massachusetts Institute of Technology.

\textsuperscript{4}Floating Storage and Regasification Unit
also noted that the terminal motions in head seas in the relevant frequency range are negligible.

Thus, in a preliminary survey, the following studies are required:

- analysis of the motion behavior of the multibody system
- investigation of the wave propagation in the gap depending on the stiffness of the mooring lines

Motion characteristics of the multibody system

The motion behavior of the side-by-side scenario is numerically investigated in frequency domain using the panel code WAMIT, which has been modified by introducing experimentally determined viscous damping terms ($B_{44}$ and $B_{55}$).

The numerical models consist of a total number of 5768 panels for the terminal barge (blue) and 3376 panels for the LNGC (green). To adapt the free surface elevation inside the gap, a damping method has been developed in WAMIT using a damping lid (red lid between both hulls, cf. Fig. 4). The optional damping lid is 160 m long (which is about the length of the parallel midsection of the LNGC), consists of 320 panels and is located between both hulls at midship position. In our case and according to Newman [6], the wave field in the gap is described by 16 Tchebychev polynomials (for longitudinal direction) and two Fourier modes (for transversal direction). In total 32 new generalized modes can be used to describe the free surface elevation inside the gap.

Fig. 5 presents the results of the heave RAOs of the multibody system comparing the motion behavior of the arrangement with the terminal fixed or free floating, alternatively. Note that the terminal motion within the critical frequency range between 0.7 and 1 rad/s is negligible. In addition, the LNGC heave motions are nearly identical, i.e. independent of the terminal motion. As a consequence, it is decided to perform the following numerical and experimental investigations with a fixed terminal.
Influence of LNGC-mooring characteristics on the wave propagation inside the gap

The model tests (scale 1:100) are conducted in the seakeeping basin of the Ocean Engineering Division of the Technical University of Berlin (length 110 m, width 8 m, water depth 1 m). The electrically driven piston type wave maker is computer controlled and enables the generation of regular waves, deterministic irregular sea states with defined characteristics, tailored critical wave sequences as well as transient wave packages [15], which allows the evaluation of the spectral response within one short test run. The ship motions are measured with an optical tracking system, using LED-positions tracked by a five-camera-network in space and time. Wave elevation inside and outside the gap are registered by wave gauges.

As mentioned above, the terminal barge is fixed on trestles. The LNGC is attached to a spring-frame-construction fixed on the terminal barge (see Fig. 3 and Fig. 2, blue arms with springs), which enables an undisturbed investigation of the surface elevation in the gap. The stiffness of the springs refer to the mooring lines characteristics of the SOTLL mooring system. Note that heave, roll and pitch motions of the LNGC are nearly undisturbed. The surface elevation inside the gap is measured with a wave gauge array, consisting of ten probes, starting at +150 m every 30 m.

Alternatively, three stiffnesses have been investigated for the mooring array in a regular wave with the critical frequency of \( \omega = 0.81 \text{ rad/s} \). Fig. 6 present the results:

- At the standard stiffness \( c = 2.3E06 \text{ N/m} \), which follows from the elasticity of the SOTLL mooring lines, we observe the superposition of propagating and reflecting waves, influencing the wave propagation inside the gap.

![Figure 5](image1.png)

**FIGURE 5. HEAVE RAOS OF THE LNGC AND TERMINAL BARGE: FREE FLOATING TERMINAL BARGE (LEFT) AND FIXED TERMINAL BARGE (RIGHT).**

![Figure 6](image2.png)

**FIGURE 6. GAP SURFACE ELEVATION IN SPACIAL DOMAIN (DISPLAYING SUBSEQUENT TIME STEPS) FOR FIXED TERMINAL CONFIGURATION AND DIFFERENT MOORING STIFFNESSES (INCOMING REGULAR WAVE \( \zeta_a = 0.65 \text{ m} \)) AT A GAP WIDTH OF 10 m.**

![Figure 7](image3.png)

**FIGURE 7. ENVELOPES OF GAP SURFACE ELEVATION IN SPACIAL DOMAIN FOR FIXED TERMINAL CONFIGURATION AT A GAP WIDTH OF 10 m - NUMERICAL CALCULATIONS (RED) AND MODEL TESTS (BLUE), INDUCED BY AN INCOMING REGULAR WAVE (SHOWN IN BLACK).**

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enced by substantial pumping effects of the swaying LNGC, resulting in a standing wave system.

- Enhancing the stiffness to $c = 8.5E06 \text{ N/m}$, we observe a propagating wave pattern. The increased height simply follows from the funnel effect between the bow region and the gap. Wave reflection and pumping effects seem to be less significant.
- With infinite spring stiffness, i.e. an entirely fixed LNGC + FLNG scenario (pure diffraction), the wave system is similar to the former case, however, pumping and wave reflection are not significant.

In conclusion, the most critical scenario is observed if wave propagation and reflection occurs in combination with pumping effects.

**SYSTEMATIC INVESTIGATION OF GAP EFFECTS**

Using the standard spring stiffness and a gap width of 10 m, Fig. 7 shows the envelopes of the surface elevation for the wave frequencies $\omega = 0.765, 0.81, 0.84$ and 0.875 rad/s in spacial domain, illustrating a frequency dependent shape of amplifications and cancellations. Note that the amplifications, cancellations and knots of the surface shape fit very well to the numerical calculation without using any damping lid. Especially at the critical frequency ($\omega \approx 0.81 \text{ rad/s}$), WAMIT does not overestimate the surface elevation inside the gap. As a consequence, the following investigations will proceed without a numerical damping lid.

To analyse wave propagation inside the gap in frequency domain, Fig. 8 and Fig. 9 show the development of the surface
The numerical calculations are confirmed by model tests. Two major observations should be noticed in addition:

- As the gap effects represent resonant phenomena, wave package technique [15] is applicable but has to be handled with care, because the build-up of a stable wave pattern takes some time.
- Investigations with regular waves are recommended, as they excite these frequency depending phenomena in detail, especially if developing interactions inside the gap are being expected.

To benchmark the global quality of validation, Fig. 10 presents the surface elevation RAOs in spacial and frequency domain, starting with the numerical results (left) as well as the model test results gained by transient wave packages (middle) and by regular waves (right). Both experimental techniques are presented separately to show their potential of investigating these phenomena. With the help of transient wave packages, we can evaluate the surface elevation RAO for the whole frequency domain, using ten wave probes (grey, horizontal lines) as spacial sample points for the interpolation of the 3D-plot. Less sample points (due to a limited number of tests) are given using regular waves. In the vicinity of critical frequencies, both figures (model tests - middle and right) illustrate the characteristic amplifications ($\omega \approx 0.75 \text{ rad/s}$ at midship and
\[ \omega \approx 0.82 \text{ rad/s at } x \approx +90 \text{ m and } x \approx -60 \text{ m} \] and cancellations (\[ \omega \approx 0.82 \text{ rad/s at midship} \]) around critical frequencies. The experimental techniques are not able to catch effects like the pattern of continuous lines for higher frequencies (shown by the numerics, related to wave reflection at the gap exit and mentioned by Bunnik et al. \[11\]).

After validation of the numerical approach, we are able to analyse related, not-simplified scenarios. Fig. 11 presents the known numerical results for the (validated) terminal fixed configuration at 10 m gap width (left) as compared to the unrestricted scenarios (terminal free floating configuration at 10 m (middle) and 4 m (right) gap width) in spacial and frequency domain. Comparing fixed and free floating conditions (left and middle), amplifications and cancellations are similar with slightly smaller amplitudes for the free floating scenario. Comparing these cases with 10 m and 4 m gaps in the free floating configuration, the small gap increases the effects significantly, leading to enhanced and additional amplifications at higher frequencies. Also the characteristic pattern is extended towards higher frequencies.

CONCLUSIONS

The paper presents the innovative LNG Offshore transfer system SOTLL in side-by-side configuration. With flexible transfer pipes and optimized ship position at the terminal leeside, spectra with waves up to \[ H_{3} = 3 \text{ m} \] are still operational. The knowledge of gap effects including large amplifications, cancellations, superposition of reflected waves and other resonance phenomena is essential for the design and dimensioning of the mooring and transfer system.

As potential codes, which are used for the hydrodynamic analysis of the multibody systems, neglect viscous damping, the surface elevation in the gap and the resulting ship motions are said to be overestimated. Therefore, additional damping measures like ‘damping lids’ are common use to reduce the surface elevation between nearby offshore structures. To configure these lids, extensive model tests combined with numerical investigations have been conducted - with the surprising result that WAMIT - without damping lids - leads to excellent results.

Detailed studies illustrate the entire surface elevation in spacial and frequency domain for a large variety of transfer scenarios with different ship types, longitudinal positions, gap widths and turret positions. The result of this paper focuses on the most common scenario, a generic terminal barge to carrier midship transfer. However, any other configuration can also be analysed by this validated approach. As a next step, the analysis of forces and motions is envisaged - and it may be necessary to introduce locally adjustable damping devices.

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