SLOSHING: FROM THEORY TO OFFSHORE OPERATIONS

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ABSTRACT

The current demand in liquefied natural gas (LNG) from remote marine locations drives the design of floating LNG (FLNG) liquefaction or regasification facilities, where LNG is transferred to shuttle carriers (LNGC). During the loading procedure, which takes about 18-24 hours for a standard sized LNGC, free fluid surfaces and varying filling levels occur inside the internal cargo tanks. This condition is critical since the seakeeping behavior of the LNGC — especially the roll motion — is strongly influenced and varying. In order to estimate and forecast the LNGC motions, numerical methods based on potential theory are the most efficient and appropriate method. The selected approach is validated by model tests at 30% water filling height inside four prismatic tanks. In-depth analyses, including force and moment measurements between tanks and hull, revealed a discrepancy between the analytical natural modes of a prismatic tank and the resonance frequencies for four prismatic tanks mounted to a LNGC hull. This effect is caused by the ratio of rigid to added mass of the system as well as the fact that the tanks are mounted to a standard hull shape featuring a longitudinal bow-stern asymmetry. In order to investigate this phenomenon systematically, surface elevations inside the tanks and natural modes for a symmetric cuboid hull are compared to results for a standard LNGC hull, both with the same main dimensions. The influence of the tank positions is also considered by comparing the original (longitudinally asymmetric) LNGC tank positions on the cuboid hull to an exactly symmetric arrangement.

FIGURE 1. MODEL TEST IMPRESSIONS OF RESONANT LIQUID MOTIONS INSIDE PRISMATIC TANKS ON A LNG CARRIER IN BEAM SEAS.

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INTRODUCTION

Due to its potentially dangerous impact, sloshing in marine applications is a field of extensive research work. Recently, Faltinsen compiled a book covering a wide range of issues related to marine sloshing [1]. A comprehensive review of existing approaches to the sloshing problem was published by Ibrahim [2]. Wave-induced vessel motions excite liquid motions inside large partially filled cargo tanks, as they are typical for cargo ships carrying oil, chemicals, liquid food, LNG or LPG. Unlike tanks for LNG transport, the large cargo tanks for LPG, oil, chemicals and liquid food transport are subdivided by bulkheads with openings to reduce the effective tank dimension for sloshing motions. LNG tanks are classified into non-freestanding tanks (membrane tanks, e.g. Technigaz Mark III and Gaz Transport NO96) and freestanding tanks (e.g. MOSS tanks or IHI SPB) and all types feature large, clean volumes without any subdividing internal structures like bulkheads and are particularly prone to violent sloshing effects. The influence of these sloshing motions is extremely strong for excitations in the vicinity of the first natural frequency of the tank. In general two major issues are caused by marine sloshing effects: structural problems due to high pressure on the tank walls and altered seakeeping behavior of the vessel due to the coupling of sloshing and ship motions.

The focus of the present investigations lies on the discrepancies between ‘idealized sloshing’ and sloshing occurring on vessels during offshore operations. ‘Idealized’ means sloshing as it is theoretically described and as it has been studied by several researchers under laboratory conditions, mostly with simplified symmetrical arrangements. Widely-known and recognized analyzes have been published by Molin, who proposed a linear modal approach (except for quadratic viscous roll damping and internal tank damping formulations) based on Principia’s code DIODORE to account for coupling effects between sloshing and ship motions. For validation purposes, a barge model was equipped with two rectangular tanks and was exposed to beam seas. Vessel motions as well as internal water motions were measured for altogether six different filling level combinations and wall roughnesses. Except for very low filling levels where nonlinear effects are dominant, good agreement of linear theory and model tests was achieved [3]. The first even sloshing mode, which was observed during experiments cannot be reproduced by linear theory since even modes are not directly coupled to the motion of the vessel. Further experiments with the same barge model included the systematical analysis of roof impact for flat and chamfered tank roof geometries with different airgaps and wave heights [4]. A general damping of sloshing effects on ship motions was observed for roof impacts, but varying airgaps lead to almost identical results despite for different roof impact intensities. For moderate sloshing and roof impact good agreement of linear theory and model tests was observed. The experimental results from these series were used as benchmark data for validation purposes — e.g. for a hybrid analysis method where the wave induced ship motions are determined by a linear tool which is coupled to MARIN’s CFD solver ComFLOW [5] as well as a linear potential theory method that takes into account coupling of internal free fluid surface effects and ship motions [6].

Another hybrid method for simulating the coupling process comprises a linear strip theory approach for calculating ship motions that is coupled to an adaptive nonlinear multimodal method as well as a linear method to predict internal sloshing with ‘2D model tests’ using a rectangular ship section equipped with two box-shaped internal tanks [7]. The model is allowed only to perform sway motions and is exposed to regular beam seas. It was found that for small to medium sloshing amplitudes linear theory shows good agreement with experiments while for stronger sloshing motions, the nonlinear multimodal method is capable of predicting associated shifting in the natural sloshing modes. In order to extend the applicability of the adaptive multimodal method for irregular waves, a convolution formulation with a retardation function is introduced to the coupled equations of motion [8].

Sloshing analyzes with LNG carriers (LNGC) have been conducted within the framework of the joint-industry project SALT (Seakeeping of structures Affected by Liquid Transient), where model tests with a moored FPSO and a free floating LNG carrier have been conducted. Published comparisons of roll motion RAOs obtained by the potential theory code DIODORE and model tests show good agreement, but some discrepancies for internal fluid surface elevations and resulting tank forces are evident [9].

Model tests results as well as experimental data have also been published by the consortium of the joint-industry project MPLS20 (Maritime Pipe Loading System 20”, [10]), where the motion behavior of an innovative offshore transfer system consisting of a turret-moored terminal barge and a shuttle carrier in tandem configuration was analyzed on basis of the potential theory code WAMIT (Wave Analysis at Massachusetts Institute of Technology) [11]. Further studies include the investigation of coupling effects between internal fluid motions and vessel motions, where LNGC motions obtained from model tests by applying the transient wave package technique show good agreement with linear potential theory results [12] as well as detailed analyzes of the relation between ship motions, internal fluid motions as well as forces and moments between tank and hull for selected wave frequencies [13].

Based on results and experiences published so far, a linear potential theory approach is considered to be adequate for analyzing the coupled seakeeping behavior of a LNGC with partially filled tanks. The surface elevations inside the internal tanks can also be calculated at least qualitatively, which is sufficient for the present study. Therefore, a method based on Newman’s proposal for considering internal tank effects with WAMIT is the basis for all following analyzes [14].

When detailed knowledge of the exact free surface contour
including air entrapment and resulting wall pressure is required, a RANSE-based method has to be applied. Peric [15, 16] was among the first to present an integrated method based on the commercial solver STAR-CCM that is capable to simulate the entire process at once: In a 3D simulation, the wave-induced motions of a LNG Carrier with partially filled tanks are calculated, taking account of the bidirectional coupling effects between free fluid motions in the cargo tanks and the vessel motions. In the same computational procedure, it is possible to obtain local pressures on the internal tank walls.

SETUP AND MOTIVATION

Within the framework of the research project MPLS20, model tests and numerical studies with a LNG carrier have been conducted. Testing configurations include solid filling conditions as well as partially filled cargo tanks. The standard case for validation purposes is 30% filling height in all four prismatic tanks. The knowledge gained through detailed evaluation of this data and continuous further work constitutes the basis for the joint-research project SOTLL (Sideways Offshore Transfer of LNG and LPG).

Setup

For experimental investigation, a glass-fibre reinforced plastic (GRP) model of a LNG carrier (see Fig. 2) is analysed at a model scale of 1:100 in the seakeeping basin of the Technical University of Berlin (TUB). The motions of the soft-moored model are precisely captured by an optical tracking system with individually pulsed infrared sensors. For detailed investigations of the internal tank fluid motions, each of the four tanks is equipped with three equally spaced wave gauges from the longitudinal tank centerline to the outer tank wall (see Fig. 2). The main dimensions of the LNGC and the prismatic tanks are listed in Fig. 2 and Fig. 3, respectively.

In order to analyze the coupling effects of the LNGC’s seakeeping behavior and the internal fluid motions in partially filled cargo tanks, transient wave package technique [17] is applied as a reliable method for global frequency domain studies. The numerical calculations are conducted in frequency domain and are based on the radiation-diffraction panel code WAMIT, which is a linear potential theory approach. Viscous damping is introduced to the numerical model by results from decay tests. The LNGC model is discretized by a total of 13,104 panels (submerged hull: 3,376 panels, tanks 4 × 2,432 panels).

Motivation

During the evaluation of the model test results for the LNGC in beam seas with 30% filling height in all four tanks, two phenomena are observed, that require further investigations. Fig. 4 shows the experimental LNGC roll motion RAO (red line) together with a tank gauge RAO (blue line) at the indicated reference point for (β = 90°) and 30% filling height. Three characteristic peaks can be observed: The lower frequency peak at ω = 0.32 rad/s is related to the hull resonance, the higher fre-

![Figure 2](image1.png)

FIGURE 2. 1:100 LNGC MODEL IN THE SEAKEEING BASIN OF TUB (TOP); SKETCH OF THE LNGC MODEL EQUIPMENT INCLUDING POSITIONS OF THE THREE INTERNAL TANK WAVE GAUGES (BOTTOM).

![Figure 3](image2.png)

FIGURE 3. NUMERICAL DISCRETIZATION OF THE LNGC’S PRISOMATIC TANK WITH CHARACTERISTIC DIMENSIONS.

![Figure 4](image3.png)

FIGURE 4. MEASURED LNGC ROLL MOTION RAO AND INTERNAL TANK GAUGE RAO AT REFERENCE POINT FOR A FILLING HEIGHT OF 30% AND β = 90°.
frequency peak at \( \omega = 0.90 \text{ rad/s} \) is caused by violent transverse sloshing of the internal fluid. The third peak at \( \omega = 0.74 \text{ rad/s} \) appears exclusively in the internal fluid motions but not in the roll motion results. According to [1], the theoretical first transverse sloshing mode for this case should be located at:

\[
\omega_{r1} = \sqrt{g \frac{\pi}{B_T} \tanh \left( \frac{\pi}{B_T} h \right)} = 0.72 \text{ rad/s} \quad (1)
\]

where the filling height inside the tank is denoted by \( h \).

From these findings, two questions arise:

1. Why is there no increased roll response at the theoretical first transverse sloshing mode of the investigated tank geometry (\( \omega = 0.72 \text{ rad/s} \)) but at \( \omega = 0.9 \text{ rad/s} \) instead? (The deviation between theoretical and measured sloshing resonance is denoted by \( \Delta \omega \) (see [13])?)

2. Why is there a clear peak in the internal fluid motions at \( \omega = 0.74 \text{ rad/s} \) that is not reflected in the roll motions or the theoretical sloshing mode?

It has been shown by [13], that the peak frequency shift \( \Delta \omega \) addressed by question 1 is accompanied by a phase shift between LNGC hull motions and internal liquid motions. Although strong transverse sloshing are present at \( \omega = 0.72 \text{ rad/s} \), no amplifying effect on the vessel motions can be observed. For higher frequencies (\( \omega > 0.8 \text{ rad/s} \)) internal liquid motions are in phase with the roll motion which leads to reciprocal amplification. However, this observation seems to be an effect of the third peak rather than a cause. As schematically illustrated in Fig. 5, the complete chain of cause and effect for the transverse sloshing peak shift can be broken down into three steps:

1. The matrix formulation of the underlying equation of motion

\[
s = -\omega^2 (A + M) + i\omega B + C = F_{ex}
\]

can be solved for the desired motion \( s \), by multiplying the external forces on the right-hand side by the inverse matrix of the internal forces (formulation in brackets on the left-hand side, in the following denoted by \( F_{int} \)). Hence, the roll motion \( s_4 \) can explicitly be determined by the expression

\[
s_4 = \sum_{j=1}^{6} f_{ex,j} \cdot f_{int,j_4}^{-1} .
\]

For the chosen LNGC geometry in beam seas (\( \beta = 90^\circ \)), the first, third and fifth term of Eq. (3) become zero and the sixth term is very small, so in this case the roll motion can be approximated by

\[
s_4 \approx f_{ex,2} \cdot f_{int,24}^{-1} + f_{ex,4} \cdot f_{int,44}^{-1} ,
\]

in other words by effects related to pure roll and sway-roll coupling. In box 1 of Fig. 5, these two components are visualized. It becomes clear that the the shifted peak at \( \omega = 0.9 \text{ rad/s} \) is related to the first term of Eq. (4), i.e. the sway-roll coupling. The decomposition of this term reveals that the shifting phenomenon is related to the inverse internal force component, which is further analysed in the next step.

2. The detailed investigation of the components of the inverse internal force \( f_{int,24}^{-1} \) reveals that the mass term is the source of the peak shift phenomenon. As shown in box 2 in Fig. 5, the peak of the added mass \( a_{24} \) (solid red line) is located at the predicted first transverse sloshing mode (\( \omega = 0.72 \text{ rad/s} \)). The inversion of both matrices leads to shifted discontinuities: the jump of the inverted added mass \( a_{24}^{-1} \) (dashed red line) is located at \( \omega = 1.16 \text{ rad/s} \) and of the inverted total mass \( [a + m]_{24}^{-1} \) (dashed blue line) at \( \omega = 0.9 \text{ rad/s} \). Since the inversion procedure obviously seems to be the key to the comprehension of the frequency shift, it is manually reconstructed in the subsequent step.

3. The inverse of the 6x6 mass matrix is determined according to Cramer’s rule:

\[
A^{-1} = \frac{1}{\text{det}(A)} \text{Ad} j(A) \quad (5)
\]

where \( \text{det}(A) \) is the determinant and \( \text{Ad} j(A) \) the adjugate matrix of \( A \), which can be calculated by the expression

\[
\text{Ad} j(A) = (-1)^{i+j} \text{det}(A^*_i) \quad (6)
\]

where the minor is denoted by \( \text{det}(A^*_i) \). The determinants of these sparse matrices can be calculated by applying Laplace expansion. For this particular case, the equation to determine element \( a_{24} \) of the inverted added mass matrix becomes

\[
a_{24}^{-1} = \frac{\text{det}(A^*_{24})}{\text{det}(A)}
\]

and the inverted total mass element is

\[
[a + m]_{24}^{-1} = \frac{\text{det}([A + M]^*_{24})}{\text{det}([A + M])}
\]

respectively. The procedure described above finally leads to an explicit expression for element \( a_{24} \) of the inverted added
FIGURE 5. SCHEME OF THE SYSTEMATICAL BACKTRACING OF THE FIRST TRANSVERSE SLOSHING PEAK SHIFT IN THREE STEPS

\[
\begin{align*}
\text{FIGURE 5}. & \quad \text{SCHEME OF THE SYSTEMATICAL BACKTRACING OF THE FIRST TRANSVERSE SLOSHING PEAK SHIFT IN THREE STEPS} \\
\text{Copyright © 2012 by ASME} & \\
\end{align*}
\]
The inverse total mass element can be expressed analogously. The discontinuities can finally be traced back to the peaks of absolute reciprocal value of the denominator of Eq. (9) — which is proven by the graph in box 3 in Fig. 5. Coupling of sway, roll and yaw motions are relevant influences. The magnitude of the phase shift is directly related to the ratio of rigid body mass (i.e. hull mass) to added mass: The lower the respective
rigid mass, the larger the peak shift $\Delta \omega$. For the added mass alone (equivalent to all rigid mass element equal zero, i.e. $M = 0$) the maximum shift is obtained, in this case $\Delta \omega = 0.44 \text{ rad/s}$, with a response peak at $\omega = 1.16 \text{ rad/s}$ instead of $0.72 \text{ rad/s}$.

The same effects have to be taken into account when LNGC seakeeping with internal liquids of different density is compared. It is common to conduct model tests with fresh water ($\rho = 998.2 \text{ kg/m}^3$) inside LNG tanks, but the obtained results cannot be directly transferred to full scale operations with LNG ($\rho = 435 \text{ kg/m}^3$). Due to the greater mass of the fresh water, the solid hull mass for the same vessel at constant draught has to be higher when the tanks are loaded with LNG instead. Consequently, the high-frequency peak of the internal LNG motions as well as the sloshing related roll motion peak will be closer to the theoretical first sloshing mode, i.e $\Delta \omega_{\text{H2O}} > \Delta \omega_{\text{LNG}}$.

**INTERNAL TANK SURFACE ELEVATIONS**

The three gauges mounted to each of the four prismatic tanks are referred to as G1 (located close to the tank side wall), G2 (halfway between the centerline an the tank side wall) and G3 (at the vessel’s centerline). Fig. 6 shows measured RAOs of the surface elevation of the internal fluid at each gauge location together with numerical results obtained by WAMIT. The comparison of results shows a good agreement. The linear numerical approach is capable to reproduce internal fluid motions qualitatively very well and over a wide range of frequencies also quantitatively to a satisfactory degree.

Inside each tank, the magnitude of fluid motion increases with increasing distance to the centerline of the arrangement, i.e. the highest elevations appear close to the tank side wall. From these local RAO measurements, it already becomes clear that the internal fluid in each tank responds differently to the excitations caused by the vessel moving in waves. The peak at $\omega = 0.74 \text{ rad/s}$ is more pronounced for the bow tank 1 and the stern tank 4 than for tanks 2 and 3.

In order to get a comprehensive impression of the internal fluid responses, the numerically obtained free surface deflections in tank 4 (refer to Fig. 6) are visualized in Fig. 8. The internal fluid motions at the hull resonance frequency $\omega = 0.32 \text{ rad/s}$ are shown in the left column, the response at $\omega = 0.74 \text{ rad/s}$ is shown in the center column and the right column contains resonant transverse sloshing at $\omega = 0.9 \text{ rad/s}$. For each frequency, one period of the respective fluid motion is represented by 3D images of a harmonic response oscillation at $\Phi = 0 \text{ rad}$ (response for wave crest at the ships centerline), $\Phi = \pi/2 \text{ rad}$ (zero down-crossing at ships centerline), $\Phi = \pi \text{ rad}$ (wave trough at ships centerline) and $\Phi = 3/2 \pi \text{ rad}$ (zero up-crossing at ships centerline) respectively. For orientation, the RAO of gauge G1 in tank 4 is shown at the top of the graphic. The position of the gauge is indicated by a vertical red line in each tank image.

For the hull resonance frequency at $\omega = 0.32 \text{ rad/s}$, the free surface inside tank 4 remains level and parallel to the surrounding still water level but inclines with respect to a ship-fixed observer. This phenomenon was already described by [12] to appear as if ‘the ship rolls around the internal fluid’.

At $\omega = 0.74 \text{ rad/s}$, strong sloshing occurs in tank 4. From the development over one period, it becomes clear that there is a moderate transverse component (see $\Phi = \pi/2 \text{ rad}$ and $\Phi = 3/2 \pi \text{ rad}$) but a strong longitudinal component (see $\Phi = 0 \text{ rad}$ and $\Phi = \pi \text{ rad}$). This asymmetric 3-D response is a surprising phenomenon since the incident wave angle is exactly $\beta = 90^\circ$. Due to the coupling of longitudinal sloshing and ship motions, a surge motion peak appears in the RAO (see Fig. 7).

Strong transverse fluid motions can be observed at $\omega = 0.9 \text{ rad/s}$. At this frequency, the surface elevations at the rear tank wall are constantly higher than at the front tank wall. The 3-D asymmetries that occur at $\omega = 0.74 \text{ rad/s}$ are further investigated by visualizing the response period for all four tanks in Fig. 9. Strong longitudinal sloshing (see $\Phi = 0 \text{ rad}$ and $\Phi = \pi \text{ rad}$) and minor transverse sloshing (see $\Phi = \pi/2 \text{ rad}$ and $\Phi = 3/2 \pi \text{ rad}$) is present in all four tanks. In particular the transverse component continuously decreases from tank 4 to tank 1 (refer to Fig. 6). Although the excitation is exactly symmetric (2-D), the response is asymmetric (3-D) and different in each tank.

In the following section, the causes for the observed internal fluid behavior are determined by successive elimination of all asymmetries in the system, i.e. the geometry and the mass distribution of the LNGC.

![FIGURE 7. EXPERIMENTAL SURGE MOTION RAO (RED LINE) AND INTERNAL SURFACE ELEVATION OF THE LNGC WITH 30% FILLING HEIGHT IN ALL FOUR TANKS IN BEAM SEAS ($\beta = 90^\circ$).](image-url)
FIGURE 8. SURFACE ELEVATION OF THE INTERNAL FLUID IN TANK 4 (STERN) FOR THE THREE SELECTED FREQUENCIES \( \omega = 0.32 \) rad/s (LEFT COLUMN), \( \omega = 0.74 \) rad/s (CENTER COLUMN) AND \( \omega = 0.9 \) rad/s (RIGHT COLUMN) FOR THE LNGC IN BEAM SEAS AT 30% FILLING HEIGHT. EACH COLUMN REPRESENTS THE HARMONIC OSCILLATING RESPONSE FOR EACH FREQUENCY IN FOUR STEPS (\( \Phi = 0 \) rad, \( \Phi = \pi/2 \) rad, \( \Phi = \pi \) rad AND \( \Phi = 3/2\pi \) rad), RESPECTIVELY.
FIGURE 9. SURFACE ELEVATION OF THE INTERNAL FLUID IN ALL FOUR TANKS FOR $\omega = 0.74$ rad/s FOR THE HARMONIC OSCILLATING RESPONSE IN FOUR STEPS ($\Phi = 0$ rad, $\Phi = \pi/2$ rad, $\Phi = \pi$ rad AND $\Phi = 3/2\pi$ rad): NOTE THAT 3D-SLOSHING EFFECTS ARE OBSERVED IN PURE BEAM SEAS ($\beta = 90^\circ$)!
FIGURE 10. MODIFICATION OF THE ORIGINAL LNGC GEOMETRY (1) IN TWO STEPS: REPLACEMENT OF THE HULL BY A RECTANGULAR BOX (2), CENTERING OF THE FOUR CARGO TANKS (3).

GEOMETRICAL VARIATION

The original geometry of the LNGC (geometry 1 in Fig. 10) is modified in two steps. At first, the original hull shape is replaced by a rectangular box of equal dimensions (LPP, B, T), where the new center of gravity of the hull alone is assumed to be located at the center of buoyancy of the box (geometry 2 in Fig. 10). In the second step, the four tanks are relocated from their original position (shifted towards the stern of the vessel) by ∆x = 5.5 m towards the bow so that the arrangement is symmetric with respect to the vessel’s center of buoyancy (geometry 3 in Fig. 10).

The influence of these variations on the internal fluid responses as well as the LNGC motions can be observed in all tanks and are shown exemplary for tank 4 (stern), Gauge 1 (tank side wall) in Fig. 11, where numerical results for 30% filling height in beam seas are shown. For the original LNGC arrangement (geometry 1), the surface elevation features the characteristic three peaks: The peak at ω = 0.32 rad/s is the hull resonance that also appears in the roll motion RAO, the peak at ω = 0.74 rad/s is the first longitudinal sloshing mode that leads to a surge response in beam seas and the third peak at ω = 0.9 rad/s is the first transverse sloshing mode that is coupled with the LNGC roll motion.

The substitution of the LNGC hull shape with a box-shaped hull of equal outer dimensions (geometry 2) leads to significant changes. Due to the different hull shape, displacement and mass distribution of the box-shaped hull, the hull resonance has shifted to 0.37 rad/s while the first transverse sloshing mode remains at 0.9 rad/s. Instead of a minimum of 1°/m, the roll motion now features a clear zero at ω = 0.43 rad/s. But most important, the fluid response peak at ω = 0.74 rad/s is now much less pronounced and therefore the surge motions are negligible. Hence, the asymmetry of the LNGC hull is a major cause for the three-dimensional fluid response.

FIGURE 11. COMPARISON OF NUMERICAL SURGE MOTION RAO, ROLL MOTION RAO AND SURFACE ELEVATION RAO (TANK 4, GAUGE 1) FOR THE ORIGINAL LNGC GEOMETRY (TOP), THE BOX-SHAPED HULL (CENTER) AND THE SYMMETRIC TANK ARRANGEMENT (BOTTOM).
The symmetrical arrangement of tanks mounted to the box-shaped hull (geometry 3) finally leads to an ideal response in beam seas. The longitudinal component of the internal fluid response together with the surge motion has completely vanished. Internal surface elevations as well as roll motions both now feature exclusively transverse effects — the roll hull resonance and the first transverse sloshing mode.

CONCLUSIONS

Experimental and numerical studies within the framework of the research project MPLS20 revealed a surprising phenomenon: For a standard LNGC with partially filled prismatic cargo tanks (filling height 30% in all four tanks) investigated in beam seas ($\beta = 90^\circ$), three peaks appear in internal fluid response RAO. It is shown that:

- The low frequency peak is related to the hull resonance of the roll motion.
- The high frequency peak is related to the first transverse sloshing mode of the tanks for 30% filling height, which is shifted towards higher frequencies by $\Delta \omega$. This effect is caused by the complex combination of the total masses due to motion coupling of sway, roll and yaw. The magnitude of $\Delta \omega$ depends on the the ratio of solid hull mass to added mass. The smaller the solid body mass, the larger the frequency deviation and vice versa. The same effect has to be taken into account when seakeeping with internal liquids of different density is compared. Since $\Delta \omega$ for fresh water is greater than for LNG, the results obtained by model tests cannot be directly transferred to full scale operations. Considering same vessel with identical draught, $\Delta \omega$ for LNG is always smaller as for fresh water filling.
- The third (intermediate) frequency peak is related to asymmetric effects that are investigated in detail.

Comparison of results obtained with the numerical approach and model test data shows that it is possible to reproduce the free surface elevations inside the tanks qualitatively excellent and also quantitatively to a sufficient extend by applying linear potential theory.

Comprehensive numerical analyses where the internal free surface elevation responses for the three frequencies are visualized through 3D-images at four instances of the harmonic oscillations. Asymmetries of the surface patterns inside each tank are observed and the response in each tank is also different. At the third (intermediate) frequency, strong longitudinal sloshing components are present, that even cause vessel motions (surge) perpendicular to the wave excitation.

In order to investigate the causes for these asymmetric effects, the original LNGC design is transformed into an exact symmetric arrangement in two steps:

- In the first step, the LNGC hull is replaced by a box-shaped hull of identical dimensions. This significantly reduces the longitudinal sloshing components and also the surge response.
- In the second step, the four tanks are centered on the box-shaped hull. All responses are now symmetric and no longitudinal effects are present.

Most of the studies published on sloshing so far consider idealized "2D" sloshing or do not mention asymmetric effects. But for offshore operations, such as loading procedures involving LNGCs that are moored to large floating terminal barges, and seagoing LNGCs with partially filled tanks, asymmetric 3D effects that cause responses perpendicular to the direction of excitation have to be taken into account as well in order to ensure safe operations.

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