IMPACT OF SLOSHING ON FLNG

(Dynamic Responses, Impact Loads and Proposed Solution)

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Offshore offloading of LNG from a floating terminal vessel to a floating LNGC is an intricate and challenging process. LNG is an extremely hazardous cargo, largely because of its high energy density, hence, to guarantee safe transfer operations, detailed knowledge on all involved hydro-dynamic effects is required. (Sprenger, 2012). This includes:

- Structural loads on tank walls caused by sloshing effects in partially filled tanks,
- Modified seakeeping behavior of the LNGC caused by sloshing in partially filled tanks and
- Modified seakeeping behavior due to multi-body effects.

Sloshing

Floating vessels (FLNGs, in this case) experience continuous cargo loading and offloading, so, slack tanks (tanks that are not full) cannot be avoided. The natural pitching and rolling movements of the vessel at sea and the liquid free surface effects can cause the liquid to move within the tank. This movement could become substantial enough to create high impact pressure on the tank surface. This effect, called “sloshing” can cause structural damage or premature engine shutdown. Sloshing promotes different types of motion of the free surface of the liquid contained in the tanks, including simple planar, non-planar, rotational, irregular beating, symmetric, asymmetric, quasi-periodic and chaotic motion. (Muslim, Kamil, & Mohammed, 2018)

Sloshing phenomena with respect to free fluid surfaces in moving containers poses a problem that is prominent not only in marine applications. Extensive research projects on sloshing in aircraft and rocket fuel tanks has been published since the 1960s. NASA researchers have conducted much studies on the influence of free fluid surfaces in fuel tanks on the dynamic stability of rockets. Interestingly, in marine applications, sloshing may even be desired where specially designed antiroll tanks on ships act as liquid damping systems that help in reducing roll motion amplitudes.

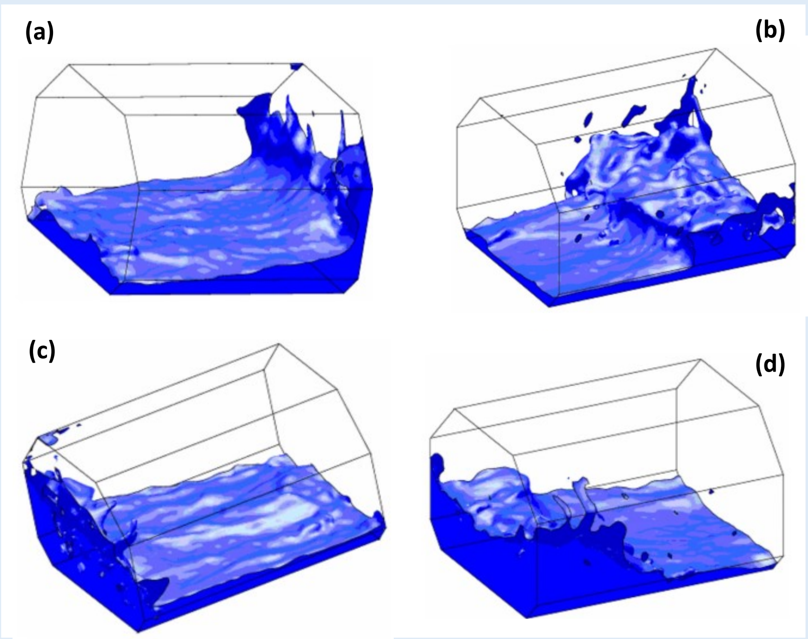


Figure: Free surface shapes after 3/4 of the eight oscillation period and after full, 1/4 and 1/2 of the ninth oscillation period. (from top to bottom, respectively)

Source: (Zorn, Moctar, & Schellin, 2009)

The sloshing motion in an LNG tank at the low-filling level is quite different from that experienced at high filling levels. Even in a low or non-zero environment, where the slosh frequencies are very low and the torques exerted on the vehicles may not be great, slosh occurs due to long-term liquid motions which give rise to amplitudes thus resulting in failure.

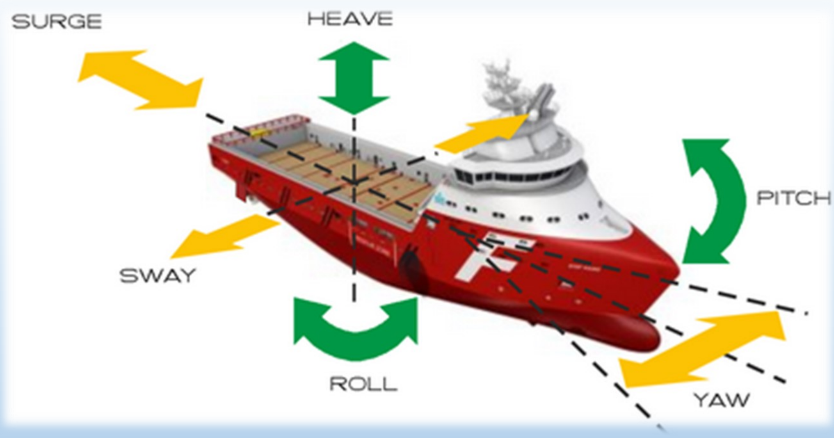
Similar systems are installed in very tall buildings to decrease wind-induced oscillations. (Sprenger, 2012).

Sloshing however will:

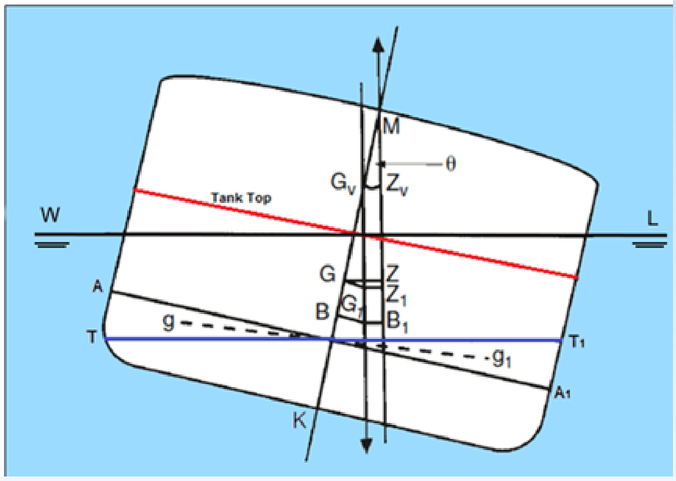
- Impact loads on containers and load structure response of the internal wall surface
- Induce a considerable moment to influence motions of FLNG/carriers.

Free surface effect usually occurs with partially filled tanks/compartments. When this slosh wave reaches the side of the tank, part of the fluid's energy is transferred to the wall of the tank. If the period of this slosh happens to be close to the vessel's motion response or a harmonic of the ship's response, then its stability can be jeopardized in an instant. There are six degrees of freedom (6DoF) which a typical floating vessel will experience at sea. They are:

- **Surge** – forward/backward in the X - direction
- **Heave** – Up/down in the Z direction
- **Sway** – Left/right in the Y direction
- **Yaw** – Normal axis (Z direction)
- **Pitch** – Transverse axis (Y direction)
- **Roll** – longitudinal axis (X direction)



When any partially filled tank or compartment moves due to a ship's rolling and pitching motions, the stability of the ship reduces. This happens because when the ship is inclined, the liquid in the tank shifts to the lower side of the tank. Also, FLNG has a higher centre of gravity due to the low density of LNG and larger waterline areas. This further affects its stability because if we recall, the higher the COG of an object is, the less stable it is and the more likely the object is to topple over if it is tilted. Momentum of large volumes of moving



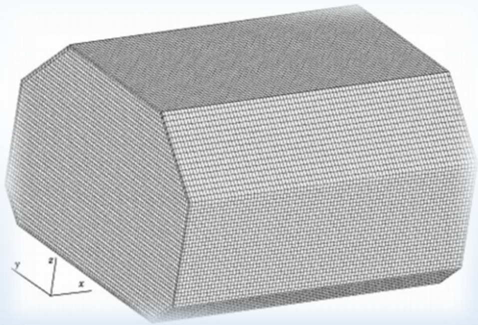
liquids cause significant dynamic forces, which act against the righting effect.

This figure above from (Chakraborty, 2019) gives a fantastic illustration of the free surface effect. In the figure, the ship tank extends from the bottom to the tank top (shown in red), and is only partially filled. It shows the free surface of liquid in the tank move from AA to TT_1 as the ship changes its position from being upright to one inclined to a certain angle of heel (say 'theta' ϴ). The volume of the liquid within the wedge between points 'A' and 'T' shifts to the lower side between the points A_1 and T_1. The centre of buoyancy shifts from 'B' to 'B_1' and the COG too shifts too from 'G' to 'G_1'.

The effect of this shift of liquid is such that the resultant weight of the entire system acts through a virtual point which is much higher than the actual centre of gravity of the ship. This virtual centre of gravity 'G_V' is obtained by extending a vertical line from the new centre of gravity 'G_1' to the centerline of the ship. So, the resultant KG increases, therefore reducing the metacentric height of the ship. The new metacentric height with free surface effect is now 'G_VM', and the new righting lever is 'G_VZ_V', both of which are significantly less than the original values (without free surface effect). It is this reduction in the metacentric height, or rise in the COG of the ship due to free surface effect, that reduces the stability of the ship or may even render it unstable. (Chakraborty, 2019)

Once an FLNG facility is in operation, moving decks may present major challenges on the operability and efficiency of process equipment with two-phase flow. As such, process equipment that is sensitive to vessel movement should be located close to the floating vessel's center line to reduce the forces exacted by movement in the six degrees of freedom. Certain properties unique to LNG such as, low temperature, compressibility of entrapped gas, hydrodynamic interaction between liquid and containment system and dynamic material characteristics, challenge the vessel's strength and may require additional reinforcement of critical areas. These areas include the insulation system, tank structure or the pump tower which serves as the cargo handling connection to the hull and the base support structure.

LNG tanks are classified into **non-freestanding tanks** (membrane tanks, e.g. *Technigaz Mark III* and *Gaz Transport NO96*) and **freestanding tanks** (independent containment systems e.g. *MOSS* tanks or *IHI SPB*). Sloshing affects membrane constructed tanks while Independent containment systems - are not subject to the same sloshing impact. (Muslim, Kamil, & Mohammed, 2018). Partial loading at any tank filling level is Inherent in the design of Moss design tanks, giving them distinct advantages over membrane containment systems, when handling spot trading and offshore loading or unloading. Due to safety regulations, no welding is allowed on the internal tank barriers which have to withstand extreme temperatures and pressure. Therefore, all LNG tank types feature large, clean volumes without any subdividing internal structures like bulkheads and are particularly prone to violent sloshing effects.



The Linear Theory of Liquid Sloshing

The linear theory of liquid sloshing is appropriate for determining the natural frequencies and wave height of the free surface. This theory is also useful for determining the liquid velocity, hydrodynamic pressure, forces and moments as long as the free surface maintains a planar shape with a nodal displacement that remains perpendicular to the line of excitation. The amplitude of slosh, in general, depends on the magnitude and frequency of the tank motion, liquid-fill depth, liquid properties and tank geometry. The ship's motions excite sloshing, which in return affects the ship motions. The sloshing induced roll moment on the vessel will cause roll damping by appropriately selecting the highest natural sloshing period close to the roll natural period. If the fluid viscosity is considered, then Navier-Stokes equations would be employed to estimate the thickness of the fluid participating in the tank motion. (Skejic & Faltinsen, 2007)

Current experimental and numerical studies show that even at the milder sea states, the sloshing load at the filling level near 30% of tank height can be as high as

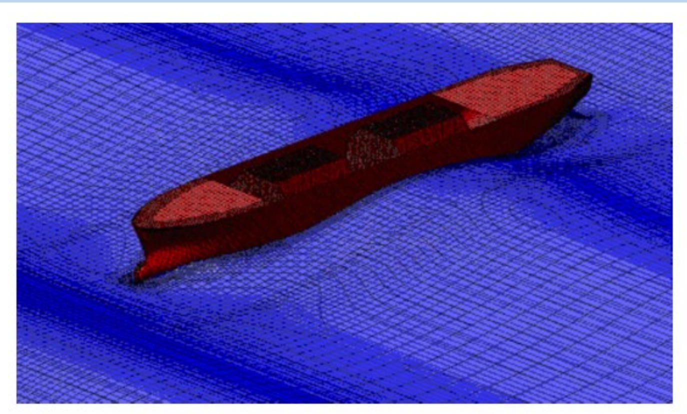


Figure: Geometry of LNG ship and grids on free surface, hull and tank walls (Zorn, Moctar, & Schellin, 2009)

the sloshing load at the high filling level. To worsen things, the sloshing pressure at this low filling level has wider impact area and longer duration. (Jingxia Yue, 2020) investigated the sloshing impact load on the tank wall for various loading conditions and sea states using a numerical approach. They mathematically modelled the transient motion of LNG carrier using impulse response function (IRF) and wave exciting force calculated from the three-dimensional frequency-domain panel method. With regards to the relative motion of both vessels, LNGC has more severe motion responses than the FRSU.

Proposed Solution

The liquid behaviour in tanks is normally represented by the fluid dynamic methods such as the boundary element method, finite difference method, particle method, etc. and is coupled with the floating body motion. We intend to provide rational explanations and solutions to the influence of liquid sloshing on the FLNG motion using Experimental and Numerical methods, which in extension, are simple motion calculation methods considering liquid sloshing and also Computational Fluid Dynamics (CFD)-based numerical calculation method. Consequently, it is possible to simulate accurately the complex phenomena of floating body motion influenced by sloshing using numerical calculation, however, at the same time such a highly elaborate numerical calculation can become an opaque process and the correctness of the calculation results would be difficult to verify.

Verification method

The most reliable verification method is the comparison of results from experiments conducted on a model, nevertheless, it is time consuming and expensive. An alternative verification method would be to confirm whether the major characteristic indicator, say, the natural period or the period corresponding to the peak response, is close to the one predicted by other methods. Though this method only provides partial reliability, it can be done easily. Another benefit of this method is that it is possible to identify the fundamental mechanism of the phenomenon of interest. (Nakashima, Nishimoto, & Arai, 2017)

Experimental and Numerical Methods

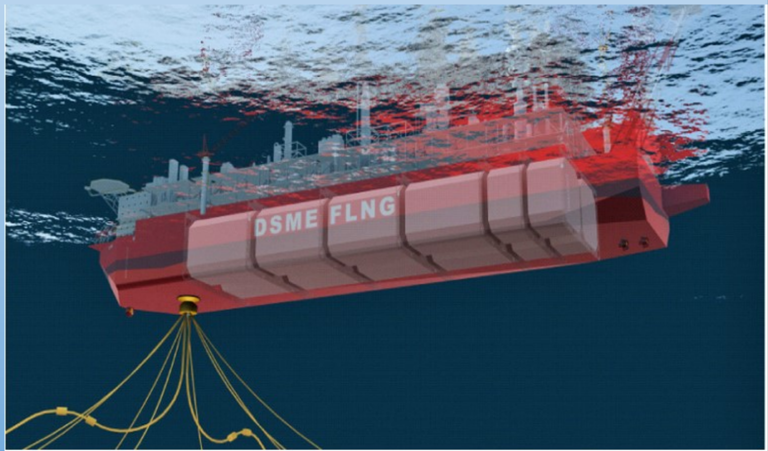
The two codes which would be used to verify and validate results obtained with two packages implementing the same theoretical formulation are WAMIT (Wave Analysis at Massachusetts Institute of Technology) and AQWA. (Dinoi, 2016)

WAMIT

WAMIT is a radiation/diffraction program, based on a three-dimensional panel method, developed for the analysis of the interaction of surface waves with offshore structures. The flow is assumed to be ideal and time-harmonic. Although this method is very expensive, it is highly essential to study the hydrodynamic relationship between the bodies and to assess the effects of the tank walls on the resonant gap zone of interest. It allows calculations in both higher order and low order methods. Numerically, WAMIT will allow the consideration of the higher order method, with the advantage of obtaining a faster convergence which could imply smaller computational time than AQWA solver; mainly when symmetries in the numerical model would be considered in order to simulate the tank walls. (Dinoi, 2016)

AQWA

AQWA is a 3D panel code developed by ANSYS applied for the investigation of the wave, wind and current on floating and fixed offshore structures. It is a BEM (Boundary Element Method) code that calculates the seakeeping problem in frequency and time domain (using the frequency domain output), considering first and second order effects. The time domain module allows to consider irregular wave, current effects, wind and mooring dynamics. (Dinoi, 2016)



Motion calculation method

The effect of lateral sloshing, which is dynamic in nature, is mainly due to a horizontal oscillation of centre of liquid mass relative to the tank. This can be well represented by a mechanical model. The mechanical model of sloshing was originally developed in the mid-1960s and used to represent the coupling effects with the spacecraft motion for predicting and controlling the spacecraft behaviour and stability. (Nakashima, Nishimoto, & Arai, 2017) Similar mechanical model can also be used to represent the coupling effects with the floating body motion as shown below.

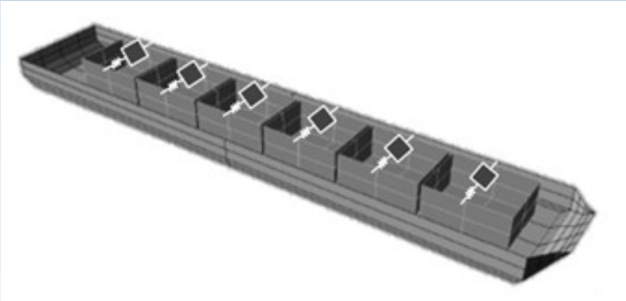


Figure: Mechanical Model Application for FLNG (Nakashima, Nishimoto, & Arai, 2017)

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