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Effects of ullage gas and scale on sloshing loads

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ABSTRACT

Gas–liquid density ratio (DR) is a key dimensionless number in sloshing assessment methodologies of membrane containment systems for LNG tanks of floating structures. Earlier studies on the effect of DR were mainly statistical and effects of DR were usually mixed with those of gas compressibility and ullage gas pressure but attributed only to DR. In an attempt to separately study such effects, Karimi et al. (2015) [11] studied the effects of DR far from impact zones (global effects of gas–liquid density ratio) which proved to be small in the studied range of DR (0.0002 to 0.0060). The effects of DR near impact zones and before detection of any compressibility effects are referred to as local effects and correspond to modifications of wave shape before impact. They were treated in Karimi et al. (2016). This paper studies the influence of ullage gas at the same scale as well as scaling of sloshing loads at different scales.

The test setups were similar to those presented in Karimi et al. (2015) [11] and Karimi et al. (2016) and consisted of three 2D model tanks as transverse slices of tank 2 (out of 4) of a membrane LNG carrier with total capacity of 152000 m^3 at scales 1:10, 1:20 and 1:40. All model tests were performed at a fill level corresponding to 20% of the tank heights. Water as liquid and different ullage gases of helium (He), air, two mixtures of sulfur hexafluoride (SF_6) and nitrogen (N_2), and pure SF_6, all at atmospheric pressure with a range of DRs from 0.0002 to 0.0060 were used. Synchronized High-speed video cameras (@4000 fps) and arrays of piezo-electric PCB pressure sensors (@40 kHz) monitored and measured impacts on the tank walls. The study was mainly based on the definition of *Impact ID* based on impact coincidence.

The results are presented at 4 main stages. First, in the same way that sloshing loads measured in irregular model tests are treated in the current methodologies, the measured pressure peaks are studied as statistical samples. Next by the notion of impact ID, the effect of change of ullage gas at the same scale is verified. Thirdly with the same notion of impact ID, impacts are tracked down through three scales to verify scaling. At last dominant impact IDs are introduced. It is shown that the most severe impacts are generated by only a few dominant IDs.

1. Introduction

When stored in tanks equipped with membrane containment systems as those proposed by GTT,[1] liquefied natural gas (LNG) remains in a state close to a thermodynamic equilibrium with its vapor at atmospheric pressure (the gas pressure is intentionally kept slightly above the atmospheric pressure), corresponding to a temperature of −163 °C. Any new project of a floating structure storing or transporting LNG in membrane tanks is assessed for sloshing loads by means of sloshing model tests. A model tank made of smooth rigid walls of PMMA,[2] reproducing the inner dimensions of the real tank at a smaller geometrical scale $1 : \lambda$ (usually $\lambda = 40$), is placed on the platform of a 6 degree of freedom (DOF) motion rig. The tank is filled with water and a heavy gas. As the density of water is more than twice the density of LNG, a density scale $1 : \mu$ (μ is defined as ρ_{LNG}/ρ_{water}) is to be introduced in the dimensional analysis. The heavy gas is made of a mixture

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1 Gaztransport&Technigaz.

2 Polymethyl methacrylate commonly known under the trademark **Plexiglas**.

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of sulfur hexafluoride (SF_6) and nitrogen (N_2) tuned in order to match the same gas-to-liquid density ratio (DR) as in a real tank with natural gas and LNG. The motions of the floating structure are calculated at scale 1 usually by means of a classical boundary element method (BEM) taking into account the possible speed of the ship (usually under the approximation of the encounter frequency) and the coupling between the floating structure and the cargo motions. These motions are imposed by the rig to the model tank after having been down-scaled. As the gravity is the same at both scales, all forced accelerations at small scale must be the same as at full scale, which imposes a time scale $1 : \tau$ related to the geometric scale by $\tau = \sqrt{\lambda}$. Many pressure sensors (typically 300 sensors for every sloshing test campaign) acquiring at high frequency (>20 kHz) are regularly arranged in rectangular arrays located in the most exposed areas of the tank. The tests mimic at small scale all conditions that the floating structure is expected to experience during its life, screening different possible loading conditions, sea states, ship speeds, wave incidences with regard to the floating structure and fill levels in the studied tank. Samples of pressure peaks are gathered in order to enable long term statistics and, after a scaling process, derive design loads at a suitably low probability. Among others, ABS [1], BV [2], LR [3], DNV [4], Gervaise et al. [5] and Kuo et al. [6] describe methodologies developed for such sloshing assessments based on sloshing model tests.

For large scale LNG ships decades of experience are available. This feedback enabled GTT to tune experimental scale factors from sloshing model tests performed in conditions for which sloshing incidents occurred (indentations of plywood boxes of NO96 containment system, permanent deformations of the stainless steel membrane corrugations of Mark III containment system). For less classical tank or ship designs when almost no feedback is available, as for tanks of LNG as a fuel that can be used for any kind of commercial ship or for small scale applications in general, a scaling based on dimensional analysis is applied: $P^{fs} = \frac{\mu\lambda^2}{\tau^2} \times P^{ms} = \mu \times \lambda \times P^{ms}$, where P is the pressure and ^{fs} and ^{ms} stand respectively for full scale and model scale.

This pressure scaling derived from the three fundamental scales $(1/\lambda, 1/\mu, 1/\tau)$ would be perfectly accurate if liquid and gas flows during sloshing model tests were in complete similarity with respective liquid and gas flows at full scale. This would be the case if at both scales these flows were entirely described by the simplest approximation of the problem represented by incompressible Euler equations. Under this assumption only the density of the different fluids matters. A common dimensionless form of this simplified problem can then be used at both scales exhibiting a single dimensionless number, DR.

The reality is more complex and the sloshing model test as described above must be considered as an approximation of reality. Firstly, there are phenomena in LNG tanks that are not modeled at model tests (see for instance [7,8] about the Sloshel JIP which was done to improve the understanding of some of those phenomena). For instance phase change occurs at full scale between LNG and its vapor, especially driven by the quick local gas compression or expansion, which might modify the impact loads but is not taken into account at model scale. Secondly, other properties of the fluids than densities are involved, especially during impacts, which cannot be scaled adequately at model scale biasing their influence on the flow with regard to full scale.

The liquid compressibility is involved at every contact point between the liquid and the wall when there is a normal velocity of the liquid particle with regard to the wall (impact). A pressure wave is then emitted from this point propagating through the liquid at the speed of sound which is possibly significantly reduced due to the presence of bubbles. The gas compressibility is involved in two different situations. Firstly, while the gas escapes in between an approaching wave and the wall. At first, the gas flow is incompressible as the gas escapes at a sufficient rate to keep the same density in the remaining available space in between the wave and the wall. As this space is getting smaller and smaller, the gas is forced to accelerate. Significant fractions of Mach number can be reached. When the gas cannot escape sufficiently quickly any longer, its density and therefore its pressure increases. Secondly, while the gas is entrapped in a cavity, it must comply with the space provided by the much denser liquid. Its compressibility acts like a non-linear spring inducing oscillations of the cavity volume and pressure and modifying back the liquid flow. Under a higher level of approximation taking care of both the liquid and the gas compressibility additionally to their density, the common dimensionless form of the problem at both scales would now exhibit two additional dimensionless numbers, M_L and M_G, respectively the Mach number within the liquid and within the gas.

Furthermore, the liquid and gas viscosities and the surface tension at the interface are also involved at both scales. They are directly related to phenomena generating local perturbations of the global flow which do not repeat well when accurately repeating the same sloshing conditions at a given scale. These phenomena are (1) the development of free surface instabilities, especially generated by the shearing gas flow in between a wave and a wall just before any impact; (2) the fall of droplets onto the free surface after any impact splashing and (3) the generation of bubbles into the liquid. They are the sources of the local variability of the flow that causes the well-known local variability of impact pressure measurements. The problem should thus be modeled with a higher level of approximation at both scales adding Reynolds numbers, Re_L and Re_G respectively in liquid and gas, and Weber number We to the already long list of dimensionless numbers governing the common dimensionless problem.

A perfect similarity between gas and liquid flows at both scales would therefore require not only that the time scale imposed by the forced motions is the square root of the geometrical scale but also the equality of all mentioned dimensionless numbers at small and full scales. Each of these equalities imposes a direct down-scaling of the corresponding fluid property from full scale to model scale. Among them, only DR is really kept the same at both scales with the right choice of the gas density inside the model tank. None of the other properties can adequately be down-scaled from the values at full scale. For instance, the liquid and gas are much too stiff at small scale; the surface tension at the gas–liquid interface is also much higher at small scale than in the reality, leading to less fragmentation during the development of free surface instabilities or during splashing after impact and proportionally larger bubbles. Therefore, as these phenomena are the main causes of the variability of the flow, statistics carried out from the measured pressure peaks at model scale do not necessarily well represent statistics that would reflect the variability of the pressures at full scale.

Eventually, all these issues raise questions about the relevance of sloshing model tests. Nevertheless to address these concerns, comparisons between full scale measurements on board a 148 300 m^3 membrane LNG carrier and sloshing model tests mimicking the conditions for which sloshing was experienced on board, showed that despite all the mentioned issues, sloshing model tests remain conservative on a long-term basis, which is the most important conclusion from a design perspective. The study was performed within the Full Scale Measurement (FSM) JIP led by DNV and described in [9,10]. More precisely, statistical distributions representative of the ship operational profile over four years of measurements proved to be more conservative when built from model tests than from full scale measurements. Comparison of the design pressure defined at a probability 10^{-3} per year showed a safety margin for both curves. However, the