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Effect of ullage gas on sloshing, Part II: Local effects of gas–liquid density ratio

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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, part I of this work 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 in the instants prior to the detection of any compressibility effects are referred to as local effects and are treated in the current paper (part II).

The test setup was identical to the one presented in Part I and consisted of two 2D model tanks representing transverse slices of tank 2 (out of 4) of a membrane LNG carrier with total capacity of 152000 m^3 at scales 1:20 and 1:40. Both model tests were performed at 20% fill level of the tank heights. Water was the main liquid that was used. In some tests at scale 1:20 a solution of sodium polytungstate (SPT) was also used which had a higher density compared to water. 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 *DR*s from 0.0002 to 0.0060 were utilized. Synchronized high-speed video cameras (@4000 fps) and arrays of piezo-electric PCB (112A21 and 112M361) pressure sensors (@40 kHz) monitored and measured impacts on the tank walls. In Part II of the study short and more regular tank motions which generated highly repeatable single impact waves (SIW) were used instead of long irregular tank motions which were considered in part I.

By comparing the single impact waves (SIW) generated by identical tank motions but with different *DR*s, it was observed that *DR* clearly modifies wave shapes prior to the moment of wave breaking. Larger *DR*s tend to slow down the wave front and delay breaking. It was also observed that larger *DR*s slightly slow down wave trough runup as well. Those effects would also lead to a mild shift of impact types by changing the *DR* (for example Flip-through to slosh or large gas-pocket to small gas-pocket impacts). By comparing single impact waves (SIW) generated by identical tank motions and the same *DR* but with different gas and liquid densities it was shown that keeping the same *DR* is essentially needed to keep the same impact geometry as recommended by the existing sloshing assessment methodologies. Free surface instabilities were also very similar for those waves generated with the same tank motions and similar *DR* but with different gases and liquids. Considering the reduction of wave kinetic energy by heavier[1] ullage gases as a relevant source of the statistical reduction of impact pressures and having in mind the mild shift of wave impact types caused by the change of *DR* it is still to be studied further why the heavier gas leads to smaller statistical pressures.

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[1] Throughout the paper the term *heavy gas* would refer to gases with higher density and the term *light gas* would refer to gases with lower density. This was thought to make the text easier to read (and write) compared to the terms *dense* and *less dense* although dense and less dense are more scientific. Nonetheless wherever needed, the value of *DR* is mentioned explicitly.

1. Introduction

1.1. General context of sloshing model tests and scaling issues

Sloshing model tests represent the basic tool for any sloshing assessment in LNG (liquefied natural gas) tanks of floating structures involving membrane containment systems. Among others, Gervaise et al. [1], Kuo et al. [2], ABS [3], BV [4], LR [5] and classification note No.30.9 from DNV [6] describe methodologies developed for such assessments. These methodologies have a lot in common. The model tank, built with smooth rigid walls generally made of transparent PMMA,[2] is partially filled with water and installed on the platform of a six degree-of-freedom sloshing rig, usually an accurate Stewart platform (hexapod). Many pressure sensors (usually 300 sensors in a typical GTT[3] sloshing study) acquiring at high frequency (>20 kHz) are arranged in rectangular arrays located in the tank areas where the most important wave impacts are expected to take place. The tests mimic at small scale all conditions that the floating structure is expected to experience during its life, covering different possible loading conditions, sea states, ship speeds, ship-wave incidences 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. Up-scaling the measured pressures is the crux of the problem as it involves large uncertainties.

Internal dimensions of model tanks are downscaled from the real internal tank geometry according to a geometric scale, λ, defined as the ratio of the dimensions at full-scale (prototype) and the dimensions at model-scale. This scale is recommended not to be less than 50 according to ABS [3], BV [4], LR [5] and DNV [6]. The geometrical scale of 40 is the scale adopted by GTT. The motions of the floating structure are calculated at real scale, usually by a 3D boundary element method (BEM) and downscaled according to Froude similarity before being applied by the sloshing rig to the model tank. This means that the time scale τ is the square root of the geometric scale ($\tau = \sqrt{\lambda}$). This does not mean that the flow inside the model tank is rigorously in similarity with the real flow for a given condition. Liquid and gas properties like density, compressibility, viscosity or surface tension at the interface may be involved during certain sequences of the flow. The liquid and the gas inside the model tank should therefore have their properties relevantly scaled with regard respectively to those of LNG and of natural gas (NG) in order to comply with all similarity laws involved or, in other words, in order that the small scale flow is described by the same dimensionless problem as the full scale flow. As in reality all these requirements cannot be simultaneously fulfilled, the similarity that is expected to be imposed by Froude-scaled excitations is necessarily biased.

According to the Vaschy–Buckingham theorem (π theorem) and considering the sloshing problem with a liquid surrounded by a gas inside a tank, the gas density (ρ_g^{ms} at model scale and ρ_g^{fs} at full sale) will necessarily intervene and a new dimensionless number is to be introduced combining the gas density with the liquid density. This dimensionless number could be the Atwood number $At = \frac{\rho_l-\rho_g}{\rho_l+\rho_g}$ but, as the liquid is much denser than the gas, it is preferred, as proposed for instance by Yung et al. [7], to introduce the density ratio $DR = \frac{\rho_g}{\rho_l}$.

Several authors studied the influence of DR on impact pressures during sloshing model tests statistically. Based on such tests performed in Marintek, Maillard and Brosset [8] for GTT or Yung et al. [7] for ExxonMobil observed a significant reduction of the statistical pressures when increasing the DR. They concluded that keeping the same DR at model test as at full scale ($DR \approx 0.004$) is a requirement and proposed to perform sloshing model tests with water and a right mixture of N_2 and SF_6 in order to meet this requirement. Ahn et al. [9] drew the same conclusions based on sloshing model tests performed in Seoul National University (SNU).

1.2. Context of the paper

In order to experimentally study scaling issues associated with sloshing and more specifically some biases brought to Froude similarity by improperly scaled gas properties, three model tanks have been built with internal dimensions representing those of a transverse slice of the tank 2[4] of a 152 000 m^3 LNG carrier (2D tank), respectively at scales 1:40, 1:20 and 1:10. Sloshing test campaigns have been carried out with the three tanks at the same filling ratio of 20% of the tank height and for Froude-similar forced excitations in the plane of the tank (3 DOF). Mostly the tests have been performed with water and different ullage gases providing a large range of gas–liquid density ratios (DR). Some tests at scale 1:20 have also been performed with a solution of Sodium Polytungstate (SPT) with a density of 1800 kg/m^3 with different gases. Whatever the scale, a high speed video camera was fixed to one side of the tank to capture the shape of the waves right before and during impacts. An array of pressure sensors was installed on the same side covering the impacted area. Additionally, a high definition(HD) camera also fixed to the tank recorded global deformations of free surface during the complete duration of the tests. As a result, these sloshing test campaigns allowed the study of the variability of the flow when accurately repeating the same conditions. Furthermore, the influence of liquid and gas properties, and the influence of scale, could also be studied.

This paper is the second of a series of four papers, gathering the most important results from these test campaigns. The first paper (Karimi et al. [10]) is based on the results at scales 1:40 and 1:20 for irregular excitations derived from calculated ship motions on a given sea state with a significant wave height of 6 m. It showed that, if a small tolerance (tolerance in terms of impact times) is introduced, impacts always happen at about the same instants when the same condition is repeated at a given scale regardless of the utilized ullage gas. When comparing similar sloshing model tests at two different scales with Froude-similar excitations, the impacts happen at Froude-similar instants. This observation is done regularly from the beginning up to the end of long sloshing model tests and does not deteriorate over time. The impacts that happen almost at the same instants (considering the accepted tolerance) regardless of scale or the utilized ullage gas, are referred to as *coincident impacts*. In between two successive impacts, when the wave front is far from the impact areas, the shape of the free surface repeats pretty well when repeating the same condition. This is also true when changing the gases for the range of DR studied. Nevertheless, the shape variations can still be clearly distinguished. The sources of variability seem to come firstly from free surface instabilities that develop just before the impacts during the gas escaping phase while the wave front approaches the wall and secondly from the fall of droplets after the splashing following wave impacts. Nevertheless, the perturbations brought by these different sources vanish quickly enough to prevent a progressive deterioration of the flow that would induce an increasing variability. In brief, the effective memory of the flow is short and the notion of a global flow complying with Froude similarity makes sense.

[2] Poly(methyl methacrylate) commonly known under the trademark **Plexiglas**.

[3] Gaztransport et Technigaz, Saint-Rémy-lès-Chevreuse, France.

[4] Among 4 LNG tanks.