A Study on Conservatism of Froude Scaling for Sloshing Model Tests

M. R. Karimi1,2,3, L. Brosset1, J.-M. Ghidaglia3, M. L. Kaminski2
1 Gaztransport & Technigaz, Saint-Rémy-lès-Chevreuse, France
2 Delft University of Technology, Delft, The Netherlands
3 École Normale Supérieure de Cachan, Cachan, France

ABSTRACT

Performing model tests is the most common way to study sloshing inside the tanks of LNG carriers. In practice model tests are usually performed in 3D and at scale 1 : 40. The measured pressures are then scaled based on feedback at sea and statistically post-treated to have an idea of real loads in LNG tanks and to predict the more severe loading cases. Apart from several different parameters that can influence the resultant pressures and loads such as properties of liquid and gas, the most important question would be how far these model tests are representative or at least conservative.

In order to study scaling biases of sloshing model tests, GTT performed model tests with three 2D model tanks representing a slice of the tanks of LNG carriers. In practice model tests are usually performed with water and air. At scale 1 : 10, 1 : 20, and 1 : 40. At scale 1 : 10 tests were performed with water and air. At scale 1 : 20 and 1 : 40, tests were performed with water and a solution of sodium polytungstate (SPT) (with a density of 1800 kg/m³) as liquid and different gases and gas mixtures. At all scales, partial fill level of 20% of the tank height was studied. For this comparison 2D irregular and Froude-similar excitations were imposed on the tanks at three scales with high accuracy corresponding to transverse sea conditions. At each scale, an array of pressure sensors was located on the vertical tank wall in the region impacted by the breaking waves. Simple and repetitive single impact waves (SIW) were also used to create more repetitive wave shapes for further deterministic studies. High speed cameras were placed in the vicinity of the impacted areas synchronized with the pressure measurement system. The goal was to capture the shape of the waves during the impacts for further observation.

It was observed that from a statistical point of view and at each scale, by keeping the same liquid, the pressures were reduced by using heavier ullage gases (with lower speed of sound). Also from a statistical point of view, keeping the same gas to liquid density ratio at model tests and scaling the measured pressures based on Froude similarity assumptions, always results in overall conservatism in pressure estimations at larger scales. A few local exceptions were observed which are worth studying further. Deterministic investigation of representativeness of the model tests needs an impact by impact study at different scales which would be the subject of future works.

KEYWORDS: Sloshing; model test; Froude; scaling; ullage gas; density ratio

INTRODUCTION

In a state of the art sloshing model test, tank geometry and fill level are scaled by a factor \( \lambda \) (as the geometrical scale) and tank motions are scaled by respecting the geometrical scale while time is scaled by factor \( \lambda^3 \) (found based on Froude similarity of the model test and full-scale). Gas-Liquid density ratio is also kept the same between the model test and full-scale according to Gervaise et al. (2009). In a more local scale other phenomena such as density ratio of gas and the liquid (Karimi and Brosset (2014) and Maillard and Brosset (2009)), speed of sound (compressibility) in both gas and liquid (Guilcher et al. (2012)), phase transition (Bogaert et al. (2010)), interactions between the liquid and the structure (Lugni et al. (2013)), and corrugations and raised edges (He et al. (2009)) become influential. Not taking those parameters into account may create biases in model tests results.

If all the local effects could have been scaled as well as the global effects the relation between the impact pressure at model scale and full scale could be found as \( p_F = \lambda^3 \frac{p_M}{\rho_M} \), where \( p_F \) is pressure measured at full-scale, \( p_M \) is measured pressure at model-scale, \( \rho_M \) is the density of liquid at full-scale and \( \rho_M \) stands for liquid density in model-scale. Braeuning et al. (2009) explains that in order to achieve this, compressibility of the liquid and gas should be scaled at model-scale and gas-liquid density ratio should also be the same at both scales. This ideal condition was called complete Froude scaling. In reality partial Froude scaling is achieved which will result in different scale factors for different phenomena (Bogaert et al. (2010)). Achieving complete Froude Scaling is not practically possible in model tests at much smaller scales and only the density ratio is kept the same between the two scales. In practice the measured pressures are scaled based on feedback at sea (Gervaise et al. (2009)) to have a clue about the pressures at full-scale and to be able to estimate more severe loading cases. Stochasticity of sloshing and limitations imposed by the number of sensors, distance between the sensors and the size of their sensing areas can also cause biases due to missing very local phenomena and the unavoidable averaging dictated by sensor sizes.

Two ways of studying the biases can be envisaged. On the one hand, studying the biases can be done deterministically if all the wave impacts at each model test can be measured by pressure sensors and captured visually by sensitive high-speed cameras. Then the effect of each biasing parameter can be studied on individual impacts (Karimi and Brosset...