Large scale LNG Sloshing Model Tests

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ABSTRACT

The motion of the LNG fluid inside gas carriers is normally restricted by the loading condition of the vessel, ie either the vessel is operated at near empty condition or at fully loaded condition. In this way resonance or sloshing effects of the fluid on the ship’s hull are limited. However nowadays the LNG carriers are considered to be operating at intermediate loading conditions as well. Subsequently they will be sailing with partially filled LNG tanks. In this condition the LNG fluid is more likely to be induced into resonance due to wave action and roll motions. This resonance or sloshing behavior of the LNG fluid will lead to high impact pressures on the thermally insolated ship’s hull.

Due to the different physical properties of the LNG fluid with respect to water in terms of density and viscosity, little is known on the behavior of the LNG fluid in resonance condition. Day to day practice in retrieving sloshing loading data is based on relatively small scale model tests, eg 1:20 or 1:30. A disadvantage here is that any air pressure effects are not modeled. Therefore hydro-elastic phenomena cannot be modeled at this scale. A way around is to reduce the ambient air pressure when doing scaled model tests. This by itself is not trivial to do. In this paper however we will describe a study of model test experiments on a large scale 2-D section (scale 1:10) of an LNG carrier in various loading conditions without depressurization.

Using High speed video observations the wave front formed by the bore of the LNG in resonance is related to measured impacts on the tank hull. Also loading on a hydro-elastic panel as part of the hull, with the correctly scaled structural properties, is measured. Significant influence of the stiffness on the pressure pulse was observed.

Key words: Large scale Oscillation Tests, Sloshing.

INTRODUCTION

Sloshing is a phenomenon of great engineering importance in the fields of naval architecture, ocean engineering and civil engineering. Severe sloshing can occur in a large oil storage tank, a reservoir and a fuel tank. Especially, an excessive sloshing motion in an LNG tanker can rupture the pipeline in a tank and in addition to that, the tank itself. The results of several research programs to investigate sloshing in Liquid Natural Gas (LNG) Carriers are presented in Abramson et al.(1974). In the study, the history of sloshing-related problems in LNG carriers is discussed including a list of recorded tank damages for LNG sloshing when the filling height is low and high relative to the tank length. In both cases impact loads occur and induce extremely high pressures. Class societies, containment system designers and ship operators have conducted thorough studies of these damages. In every instance the sloshing of the cargo was identified as the cause of the damage, Shin et al (2003). Simple but effective plans were proposed to counter the sloshing impact in the fully loaded condition. The height of the chamfer at the topside was increased and the insulation box at the tank top was reinforced to withstand the sloshing impact in the fully-loaded condition.

There are a considerable number of investigations on the sloshing problem, both numerically as well as experimentally, the early ones from Chester (1968) and Chester and Bones (1968). For the case of small amplitude excited motions, Faltinsen (2002), Huijsmans et al (2004) and Yamamoto et al (1995) showed results of oscillation experiments where the computed impact pressures were compared with measured results.

A very steep wave front like a hydraulic jump has been observed in experiments. The bore traveled back and forth between the tank walls (Hill 2003). Many applications are given to the 2-D sloshing problem whereas nowadays 3–D geometries can be modeled as well. The violent sloshing problem is determined through a highly non–linear free surface motion. In these gravity driven flows viscosity effects generally play a minor role. However in the case of liquid LNG, the fluid properties are not so clear. The top layer of the LNG fluid consists of liquid LNG with a rich content of gas bubbles. So the density viscosity and vapour pressure may play a vital role. The presence of bubbles makes potential flow type of modeling inadequate. To overcome these kinds of deficiencies of potential flow solvers Volume of Fluid Solvers are used nowadays, Wemmenhove (2005). The LNG tank in this study is a closed tank top. In this paper the main results presented, are on the measurement of the impact pressures and wave heights due to a rolling motion of the tank from experiments at model scale. Besides the VoF method, Smooth Particle Hydrodynamics (SPH) are applied as well to the sloshing problem, Nam and Kim (2006). Hydro-elastic effects on cargo tanks have been studied by Lee et al (1999) and Xiong et al (2006). When the waves are overturning and hitting the water surface, air bubbles may be present in the fluid. In this
case, a direct numerical solution based on potential flow with the non-linear free surface conditions would break down.

Weemkenhove (2007) is presently working on an extension of the VOF method for a second (air) phase, including compressibility. The test results are being used to validate this method.

SLOSHING TESTS

Test set-up and instrumentation

A 2D slice of an LNG containment system was build at scale 1:10. The reason for this choice of scale was to try to have as realistic as possible interaction effects between gas and fluid. Going to an even larger scale was practically not possible due to the limitations in the dimensions and weight of the tank. The containment system was based on the type of tank used in a No96 LNG carrier (prismatic tank). The main dimensions of the containment system (model scale values) are given in Figure 2 and Table 1.

The objective of the tests was to provide validation material for a 2-phase VOF method (Wemmenhove, 2005). In this VOF method, only rigid geometries can be modeled. Therefore, the model was built as rigid as possible to avoid interaction effects between impact forces and structural response of the containment system. The containment system was made of stainless steel and supported by stiffeners. The walls were made smooth (no insulation was modeled). The front and backside of the containment system were made from thick perspex to allow visualization of the fluid flow during the tests. Figure 3 shows the containment system under construction in the model workshop.

Table 1: Main dimensions LNG containment system (model scale).

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>2.697 m</td>
</tr>
<tr>
<td>B1</td>
<td>1.948 m</td>
</tr>
<tr>
<td>C1</td>
<td>0.438 m</td>
</tr>
<tr>
<td>C2</td>
<td>0.838 m</td>
</tr>
<tr>
<td>B2</td>
<td>1.948 m</td>
</tr>
<tr>
<td>B3</td>
<td>1.948 m</td>
</tr>
<tr>
<td>B4</td>
<td>1.948 m</td>
</tr>
</tbody>
</table>

Hydro-elastic effects were modeled by placing 6 measurement panels in the sidewalls containing pressure transducers. Two types of measurement panels were modeled:
1. Stiff panels with minimal hydro-elastic effects
2. Flexible panels to study hydro-elastic effects

Figure 4 shows the details of one of the (stiff) measurement panels, having a natural frequency of approximately 3000 Hz. The flexible panel was built such that it had a natural frequency of approximately 400 Hz.

The containment system was oscillated on a large oscillator capable of generating combined sway and roll motions of the containment system. Figure 5 shows the containment system mounted on the oscillator.
The tests were carried out with water and air at atmospheric pressure. During the tests the following items were measured:

- Pressures in the panels.
- Water height in the containment system (12 locations).
- Motions and accelerations of the containment system.

A data acquisition system was connected to the containment system measuring at high-frequency (10 kHz) to capture also the short (fast) impacts. Furthermore, video recordings were made with a high-speed camera operating at 100 or 200 Hz. The recordings were synchronized with the other measurements by measuring the start pulse of the camera. Digital camera recordings were made of the total setup.

**Test program**

The test program consisted of the following variations:

- Filling rates of 10, 25, 70 and 95 percent.
- Regular and irregular motions
- Sway only, roll only and combined sway and roll motions.

Depending on the filling rate, different measurement panels were instrumented and the high-speed camera was focused on a different part of the containment system. The high-speed camera was connected to the model.

The roll motions of the LNG carrier were obtained using theoretical roll and sway Response Amplitude Operators valid for beam seas. The following (full scale) input spectra were used:

<table>
<thead>
<tr>
<th>Hs [m]</th>
<th>Tp [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. 3.0</td>
<td>10.6</td>
</tr>
<tr>
<td>2. 8.1</td>
<td>10.6</td>
</tr>
<tr>
<td>3. 11.1</td>
<td>13.4</td>
</tr>
<tr>
<td>4. 12.1</td>
<td>16.2</td>
</tr>
</tbody>
</table>

The time traces of the sway and roll motions were generated with a random phase model and were input to the control software of the oscillator.

**Results**

Unless indicated otherwise, the results discussed in this section are related to the stiff panel and for non-depressurised conditions.

**10% filling rate**

The fluid flow at 10% filling rate is characterized by:

1. Bores that develop in the containment system due to shallow water effects.
2. Air captured during impacts on the vertical sidewalls.

Figure 6 shows a snapshot of a digital camera recording of a typical bore, using an irregular motion. Figure 7 shows a high-speed camera image of the flow at 10% filling rate just prior to impact, with entrapped air.

The results show that for regular motion tests, there is a large spreading in the measured peak pressures. In these tests, the containment system was oscillated with a periodic motion, with subsequent periods showing no visual difference in the measured motions. Figure 8 shows the measured sway motion (10 periodic events plotted on top of each other). Figure 9 shows the measured impact pressure in these 10 successive events:
Due to inertial effects, the imported motions were not completely sinusoidal.

It can be seen that the peak pressure varies between 100 and 550 hPa. The total test lasted 20 minutes, meaning that approximately 400 of these impacts were generated. These peak pressures were collected and used to generate a probability density function, shown in Figure 10. This shows again the large amount of spreading in the peak pressure.

Figure 9: Spreading in peak pressure 10 successive regular impacts.

Figure 10: Probability density function of peak pressure P07 in regular sloshing test, 10% filling rate, stiff panel.

Figure 11: Integrated pressure pulse.
Instead of looking at the peak pressures, it is also possible to look at the pressure integrated over the duration of the impact as shown in Figure 11. This is also a more relevant parameter for the structural response of the containment system. Figure 12 shows the probability density function of the integrated impact pressure:

Figure 12: Probability density function of integrated pressure pulse P07 in regular sloshing test, 10% filling rate, stiff panel.

The spreading in this parameter is much smaller.

The test was repeated (identical motions), but the stiff panel in the containment system sidewall was replaced with a flexible one (400 Hz natural frequency instead of 3000 Hz). Figures 13 and 14 show the probability density function of the peak pressure and the integrated impact pressure.

Figure 13: Probability density function of peak pressure P07 in regular sloshing test, 10% filling rate, flexible panel.

The peak pressure distribution is very similar to the distribution derived from the test with the stiff panel. However, the integrated pressure pulse is significantly lower (about 10%).

At 25% filling rate the water level is such that shallow water effects are less noticeable. The mean water level is such that the oblique lower corners of the containment system are fully submerged. Therefore, the impacts are now directly hitting the vertical wall of the containment system causing high impacts and significant run-up (sometimes even up to the ceiling of the containment system). Figure 15 shows high-speed camera images just prior to, and of a typical, relatively severe impact on the container system wall. The red arrow indicates the position of a pressure measurement. There is 0.05 s between the 2 images.

Figure 14: Probability density function of integrated pressure pulse P07 in regular sloshing test, 10% filling rate, flexible panel.

Figure 15: High-speed camera images at 25% filling rate. Photo 12286 (left) and photo 12291 (right).

Figure 16 relates these images to the pressure measurement and the water height measurement close to the wall of the containment system (6 cm distance). This Figure shows that the synchronization of the high-speed camera images with the measurements gives very good insight in the physics of the impact and is therefore very useful in validating numerical simulations of these types of sloshing events.

At a 70% filling rate, the wave run-up on the walls is high enough to hit the ceiling of the containment system regularly. The upper chamfer changes the direction of the flow such that a water jet shoots along the ceiling and even hits the opposite wall, where it mixes with the local
flow. This is shown in the 4 snapshots in Figure 17:

![Figure 17: Images digital camera of regular test at 70% filling rate.](image)

Figure 16: Images high-speed camera related to pressure and water height measurement at 25% filling rate.

Figure 17: Images digital camera of regular test at 70% filling rate.

Figure 18: Pressure at ceiling, 70% filling rate.

Figure 19: Images high-speed camera of regular test at 95% filling rate showing large bubble clouds.

**CONCLUSIONS**

Large scale oscillation tests (1:10) with a 2D section of an LNG containment system were successfully performed at various filling rates (10, 25, 70 and 95%). The tests were carried out to obtain validation material for a Volume of Fluid (VoF) method, extended for 2-phase flow. The tests showed some very interesting physics of sloshing such as:

- Shallow water bores
- Run-up against the vertical walls of the containment system
- Impacts on the ceiling of the containment system
- Captured air during impacts
- Heavy mixing of water and air

These effects were captured accurately by means of a large number of
measurement devices, including pressure transducers, water height sensors, motion and acceleration sensors and cameras (including high speed). Significant effects of the stiffness of the panel are observed. This leads to the conclusion that hydro-elastic effects cannot be disregarded. The results of the tests are being used to validate a VoF method extended with 2-phase flow and compressibility.

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REFERENCES


Dong Yeon Lee, Hang Shoon Choi: Study on sloshing in cargo tanks including hydroelastic effects, Journal of Marine Science and Technology Vol 4, No. 1, 1999


