Experimental and Numerical Investigations of the Global Forces Exerted by Fluid Motions on LNGC Prismatic Tanks Boundaries

Nicolas Moirod, Eric Baudin, Thomas Gazzola and Louis Diebold
Bureau Veritas, Marine Division, Research Department
Neuilly-sur-Seine Cdx, France

ABSTRACT

This paper presents experimental and numerical investigations on global forces exerted by fluid motions on LNGC prismatic tanks boundaries that contribute to improve the prediction of the dynamic seakeeping/sloshing coupling through efficient numerical tools.

KEY WORDS: LNG Terminals, sloshing model tests, CFD (computational fluid dynamics), partial fillings sloshing, coupling seakeeping/sloshing.

1 – INTRODUCTION

The paper deals with researches of Bureau Veritas that aim at improving methodology and procedures for the analysis of hydrodynamic and sloshing responses of LNG vessels operating as LNG terminals in wide range of operational conditions. This paper contributes to a better understanding of global effects of fluid flows during sloshing events and their induced influence on ship motions.

In the current methodology of Bureau Veritas, partial fillings (when allowed) have to be investigated in details for severe sea-states conditions that can be faced by any specific LNG carrier operating as LNG terminal. Events at sea have demonstrated that low partial fillings generate the most critical sloshing cases for which coupling effects have a great influence.

Seakeeping/sloshing coupling effect can be studied by the help of model tests’ campaign involving the construction of the model of the ship with its cargo filled of liquid in a wave basin. This is typically what was done by the past for roll response enquiry [5]. But this type of useful experiments is expensive, time-consuming and linked to specific ship or a specific scenario.

Ship motion and induced cargo tank liquid motion are driven by liquid global forces on tank boundaries and hydrodynamic ship motion response. Ship motion response can be easily calculated on one side thanks to a validated seakeeping code based on linear potential theory (HydroStar©) while inner tank global forces can be evaluated with CFD calculations on the other side. The ultimate purpose being to numerically couple ship motion response with inner tank liquid motions, the first step is to demonstrate the accuracy of the results obtained with CFD that can help in calibrating input data for time domain seakeeping simulations.

The experimental campaign consists in measuring global forces exerted on a 3D tank model filled with liquid and submitted to pure sway motions generated by an hexapod on which a weighing device is mounted. All the tests are then reproduced using CFD codes (OpenFOAM and Flow3D). In the meantime, hydrodynamic calculation on the tank is also performed using linear potential theory. Added mass and damping obtained with CFD, seakeeping codes and experiments are compared and this helps in calibrating the damping coefficient to use within linear potential flow model for sloshing.

The validation of CFD, which was successfully started with the roll motion of an academic quasi-2D tank model during the MARSTRUCT project [1] is completed here with the comparison of global forces, added mass and damping data of sway motions of a 3D tank model.

All fillings levels are to be investigated but as low partial fillings remain the most critical, results shown in this paper are mainly focused on 20% of the height (20%H) filling level; the complete validation being on-going.

2 – METHODES

2 - 1 Model Test Campaign

Description

Sloshing model tests are based on the measurements of the global efforts exerted on tank (Empty tank+ fluid).

The model used corresponds to the tank N°2 of BV reference vessel with standard cargo capacity of 138 000 m³, scaled to 1 to 70 and made of a 20 mm thick Plexiglas®. Motions are generated using Froude scaling.

The test rig used for the model tests is a six-degree-of-freedom platform called hexapod. This model is a mistral type from...
SYMETRIE. The specifications of this rig allow us to generate motion within the specified limits. The table below provides the details:

<table>
<thead>
<tr>
<th>Motion</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surge</td>
<td>+/- 465 mm</td>
</tr>
<tr>
<td>Sway</td>
<td>+/- 465 mm</td>
</tr>
<tr>
<td>Heave</td>
<td>+/- 300 mm</td>
</tr>
<tr>
<td>Pitch</td>
<td>+/- 30°</td>
</tr>
<tr>
<td>Roll</td>
<td>+/- 30°</td>
</tr>
<tr>
<td>Yaw</td>
<td>+/- 45°</td>
</tr>
</tbody>
</table>

Tab. 1: Motion limits of the hexapod

The maximum load to be tested is 1000 kg still weight and 1000daN of dynamic forces in case of moving masses such as for sloshing tests. The dynamic performances of the actuators reveal a maximum velocity range of 600mm/s and the precision is +/- 1mm for the translation motions and +/- 0.1° for the rotations.

The weighing device is composed of a dynamometer based on 4 piezo-resistive 3D transducers (Kistler 9251A) located between 2 adjusted plates made of Aluminium4G. One of the plate is bolted on a stiff steel base which itself is placed on Hexapod during experiments.

Only pure sway motion is applied on tank during this campaign.

- 7 filling ratios are investigated (7.5%H – 10%H – 20%H – 30%H – 50%H – 70%H – 95%H)
- 4 amplitudes of sway motion are tested (0.5m; 1.0m; 1.5m and 2.0m – full-scale(FS))
- For each case, a minimum of 15 periods are tested in an accurate interval around theoretical resonance period.
- Test duration is 150 s (largely enough to get accurate Y- forces response in the steady state of each specific case )
- A video is recorded for each case for further free-surface comparison
- A total of 530 tests are recorded

Intervals of periods associated to each filling ratio are displayed on the following graph:

\[ F = \sum_{i} a_i \cos(n \omega t) + \sum_{i} b_i \sin(n \omega t) \]  

where the input motion has the following expression:

\[ Y = Y_0 \cos(\omega t) \]

The analysis is focused on both raw time series and first harmonic of the signal. The contribution of the empty tank is easily removed knowing exactly the mass and the input motion. Then added mass, damping and phase shift are deduced from each simulation.

Thus:

\[ A = a_1 \quad \text{- Added mass} \]
\[ D = b_1 \quad \text{- Damping} \]
\[ \Delta \psi = \psi_m - \psi_f \quad \text{- Phase shift} \]
\[ \psi_m ; \psi_f \quad \text{- Phase of input motion ; Phase of liquid forces} \]

\[ F_{acc}^w ; F_{vel}^w \quad \text{- Liquid force in phase with acceleration ; in frozen} \]
\[ F_{acc}^f ; F_{vel}^f \quad \text{- Liquid force in phase with velocity ; in frozen} \]

\[ A = \frac{F_{acc}^w}{F_{acc}^f} \quad (3) \]
\[ D = \frac{F_{acc}^f}{F_{acc}^w} \quad (4) \]

\[ \Delta \psi = \psi_m - \psi_f \]

Model test results

A typical set of results obtained from model tests is shown hereunder:

\[ F = F_{acc}^w + F_{vel}^w \quad (1) \]

\[ F = F_{acc}^f + F_{vel}^f \quad (2) \]

Fluid flow video recording and forces measuring is the basis of the output from model tests. From forces, adimensionalized added mass, damping and associated phase shift are deduced.
The set of results for added mass, damping and associated phase shift is presented on figures 8 to 13 for 20%H filling level and for 4 amplitudes of motion from 0.5m(FS) to 2m(FS).

Figures 18&19 show times series of global fluid forces Fy for two chosen frequencies, and an amplitude of 21.43mm (corresponding to 1.5m full scale). The two codes give similar results in term of global forces magnitude and phase shift from input motion.

2 - 2 CFD Calculations

Description of the solvers used

FLOW3D is a commercial CFD software from Flow Science based on Navier-Stokes equations (mass and momentum conservation), Volume of Fluid (VOF) modelling technique and Finite Volume discretization. Each cell of VOF mesh is filled with either liquid or gas and a free surface presence is defined by the corresponding fraction of fluid as the filling rate of cell by the liquid phase.

OpenFOAM is an open source parallel CFD toolbox that can of course simulate complex fluid flows (large Eddy simulations, Reynolds-averaged Navier-Stokes, compressible models...), but also flows involving chemical reactions or heat transfer. OpenFOAM comes with lots of different pre-build solvers and meshing and visualisation tools and uses finite volume numeric method to solve systems of partial differential equations ascribed on any 3D unstructured mesh of polyhedral cells. The fluid flow solvers are developed within a robust, implicit, pressure-velocity, iterative solution. OpenFOAM is available freely under the GNU General Public License (GPL). This license gives to the user the freedom to run, copy, distribute, study, change and improve the software. Access to the source code is a precondition for this.

Mesures

The two meshes used for 20%H filling level are presented on figures 14&15 hereunder. A Cartesian mesh is used in Flow3d whereas a structured hexahedral mesh is used in OpenFOAM.

Free surface flows

An example of free surface instant capture from the two solvers is presented hereunder:

Note that one shouldn’t pay attention to colours in CFD pictures since focus is made on the shape of the free surface. Flow3D fluid velocity field colours do not match OpenFOAM pressure field colours.
One can notice the influence of motion amplitude on added mass and damping (figures 20 to 23). There is no shift in period but magnitude is significantly changed.

Due to the numbers of runs to perform and non-negligible CPU time consuming, CFD simulations for other filling levels are still on going. At the end it will constitute a complete database of 7 filling levels ready to compare with experiments.

2 - 3 Linear Frequency Domain Model - HydroSTAR®

Within the frequency domain approach, the problem is formulated under the classical assumptions of linear potential theory and Boundary Integral Equations method is used to solve both sloshing and seakeeping hydrodynamic parts. The two parts are considered separately and after coordinate’s transformation for the sloshing problem, the motion equation of the coupled system is written.

Seakeeping

In the classical linear rigid body seakeeping analysis we end up with the motion equation in the form:

\[
( - \omega^2 ( [M_Q] + [A_T] ) - i \omega [B_Q] + [C_Q] ) \{ \xi_Q \} = \{ F_Q^{DI} \} \quad (6)
\]

- rigid body ship motions
- genuine mass matrix of the ship
- hydrodynamic added mass matrix
- hydrostatic damping matrix
- hydrostatic restoring matrix

\{ F_Q^{DI} \} - hydrodynamic excitation force

where subscript “Q” indicates that quantity is written with respect to the global reference point Q.

Sloshing

The linear case is considered here. Similar to the seakeeping part, an interior boundary value problem is formulated for the potentials associated with six degrees of freedom of the tank. The final result gives the added mass matrix associated with each tank motion (in the local frame of the tank). Note, that since the linear theory is assumed, no damping can be generated by the liquid motions in the tank (an artificial damping \( \varepsilon \) is introduced). Then the action (forces and moments) of the liquid motions is transformed from the local (tank) coordinate system to the global (ship) coordinate system. The sloshing has the following motion equation form in the ship’s frame:

\[
( - \omega^2 ( [A_T] + [A_TQ] ) + [C_Q] ) \{ \xi_Q \} = \{ F_Q^{DI} \} \quad (7)
\]

Coupling

The motion equation of the coupled system can now be written:

\[
( - \omega^2 ( [M_Q] + [A_Q] + [B_Q] + [C_Q] - i \omega \{ B_Q \} + \{ C_Q \} + \{ C_{TQ} \}) \{ \xi_Q \} = \{ F_Q^{DI} \} \quad (8)
\]

Damping of the sloshing motion

The damping of sloshing motion is taken into account in order to avoid the violent resonant motions in the tank. (For more details, see Ref[3] “Dynamic coupling of seakeeping and sloshing” Malenica, Zalar, Chen ISOPE:2003):

With the linear potential sloshing model, the intention is not to model the sloshing phenomena in the tank, but just to evaluate correctly the most important part of sloshing dynamics which influences the ship global behaviour. As the model used is potential and linear, the damping is treated only approximately. The basic idea is to modify the body boundary condition on the tank boundaries:

\[
\frac{\partial \varphi}{\partial n} = i \varepsilon \kappa \varphi + v_n \quad (9)
\]

The consequence of this new body boundary condition (9) is that the resulting potential becomes complex with the imaginary part giving the damping matrix. Numerically, potential remains the same and only the Boundary Integral Equation changes.

This implies that the boundary layer is the only source of dissipation. Note, that the free surface condition can also be modified in a similar manner. Finally, the most important, is to obtain accurate ship motion response, especially after calibration of the parameter \( \varepsilon \). Wherever the energy is dissipated, the final effect on ship motions is the same, provided accurately calculated added mass.

Numerical Results and Calibration of \( \varepsilon \) (first results)

The above described parameter \( \varepsilon \) was calibrated by the past using SALT JIP results and its comparisons with experimental results [5]. The numerical calculations were performed with HydroStar©.

In this model test campaign, a set of two separated prismatic LNG cargo tanks were modelled, located at the fore and aft parts of the vessel.

Among all configurations, the example case presented hereunder shows a filling ratio of 30% of the height for the both tanks. Hydrodynamic mesh and associated Roll is presented on figures 24 & 25 below:
In the figure 25, RAOs in roll (β=90°) is presented for two values of the parameter ε (ε=0.02 and ε=0.1). The first peak is associated with the motions of the ship and the second one with the internal liquid motions in the tanks. The value ε=0.02 gives the best results.

Continue investigating on ε parameter with 138k LNGC case

The tested configurations presented here correspond to hydrodynamic computations of 138k LNGC on which the specific Tank N°2 is modeled and filled from 7.5%H to 95%H exactly as in model test. As only pure sway motions are applied on tank during model tests, attention is focused only on hydrodynamic motion response in sway.

The Figures 28&29 below show different hydrodynamic meshes used for respectively 20%H and 70%H filling level in tank.

A set of 15 simulations by filling level with ε values from 1% to 15 % have been performed as shown on figures 30 to 33 hereunder:

3 – RESULTS

The aim of these investigations remains the ultimate coupling between a seakeeping code in time domain and a CFD code for inner tanks liquid motions. The validation of the time domain model for the seakeeping part is explained in [7], [8] & [9]. The validation of CFD codes have been started first during MARSTRUCT project with a quasi-2D tank in roll and continue here with the 3D tank in sway during a dedicated model test campaign.

3 – 1 Quasi2D-Sloshing Case

CFD validation relies on the accurate calculations of the sloshing-induced forces and moments by the CFD code as illustrated hereafter. With this aim, a set of quasi 2D experimental cases [1] & [3] were carried out with pressure and global torque (exerted by the fluid – water – on the tank boundaries) measurements [1].

Free surfaces, pressures and global torques calculated with FLOW3D and OpenFOAM are in very good agreement compared with experiments’ measurements as illustrated on following figures (Figures 34 to 39).
A good accordance between the first harmonic of the measured global torque and this one calculated with CFD is shown on Fig. 39. Pressures magnitudes are also investigated (see figure 38) and give a very good correlation with a classical slight over-prediction due to the VOF method.

### 3 – 2 Validation of CFD Codes for Low Partial Fillings

This dedicated sloshing model test campaign aim at validating CFD codes threw the comparison of free surfaces, global-forces time history, as for 2D-case; but not only: Added Mass and Damping are also investigated and compared with CFD in a first step, and compared with hydrodynamic computations in a second step, calibrating at the same time the right value of the $\varepsilon$ parameter.

The results presented here are based on a tank filled at 20%H considering that the prior investigations concerns low partial fillings.

**Free surface comparison**

Free surface comparison shown hereafter concerns 20%H filling level in tank excited with a 1m (full scale) amplitude and a chosen sway motion period.
Epsilon is varying from 3% to 7% for the considered range of amplitudes. This result will improve seakeeping analysis that take into account one or several tanks in low partial fillings.

### 3 - 3 Validation of CFD Codes for Other Fillings

All the work done for 20%H filling level is being repeated for all filling levels considered:

- Very low fillings (7.5%H & 10%H) post treatment is on going
- Very high filling (95%H) post-treatment is on-going.
- 30%H & 50%H partial fillings post treatment will be presented at the conference.

First results for High partial fillings (70%H) concerns only free surface capturing and first Y-forces time series comparison and are presented hereafter:

#### Free surface comparison

<table>
<thead>
<tr>
<th>Model test</th>
<th>OpenFOAM</th>
<th>Flow3D</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Fig. 50" /></td>
<td><img src="image" alt="Fig. 51" /></td>
<td></td>
</tr>
</tbody>
</table>

#### Y-force time history comparison

| ![Fig. 52](image) |
| ![Fig. 52](image) |

The first results show a good agreement with experiments.

### 4 - Conclusion

The proposed paper deals with Bureau Veritas investigations on global forces exerted by fluid motions on LNGC prismatic tanks boundaries that contribute to improve the prediction of the dynamic seakeeping/sloshing coupling through efficient numerical tools.

In the current methodology of Bureau Veritas, the analysis of hydrodynamic and sloshing responses of LNG vessels operating as LNG terminals in wide range of operational conditions make a particular attention to low partial fillings for which coupling effects have a great influence. Seakeeping analyses are performed thanks to hydrodynamic calculations in frequency domain taking into account the inner tank sloshing motions. Then, severe selected sea-states conditions are generated from seakeeping analysis and coupled motions applied in
CFD sloshing simulations. The fully coupled method using hydrodynamic calculations in time domain and CFD sloshing simulations is under development and needs more validations.

This paper presents a preliminary investigation in which CFD codes are validated through a quasi-2D roll motion academic case. This means global forces calculated with CFD are in a very good agreement with experiments. In addition, this paper shows the extension in 3D of this validation, by the comparison of global forces, added mass and damping results obtained with CFD and those obtained during a dedicated sloshing model test campaign. The validation of CFD codes presented here tends for 20%H filling level that is taken as a reference for low partial fillings.

Once it is demonstrated that CFD can generate accurate liquid motions forces in tank for low partial fillings, it can be easily used for the calibration of artificial damping parameter $\varepsilon$ to use in a seakeeping calculation that considers linear potential flow model for sloshing.

The ongoing work concerns the following validations of CFD codes for very low filling levels and high filling levels. And a further sloshing model test campaign will certainly study 3D roll motions and imposed irregular motions, which will be reproduced numerically.

At the end, the aim of these overall investigations on global forces in many configurations is to directly couple seakeeping and sloshing in time domain with the help of the two efficient numerical tools: potential theory code (HydroStar©) and CFD code.

ACKNOWLEDGEMENTS

The Quasi-2D sloshing experiments and the associated numerical calculations (section 2) were performed in the scope of the project MARSTRUCT, Network of Excellence on Marine Structures which has been financed by the EU through the GROWTH Program under contract TNE3-CT-2003-506141.

The 3D sloshing model test campaigns (section 4) were performed in Ecole Centrale de Nantes (ECN).

The authors are grateful to Filip Andreski for his contribution to the preliminary validation of solvers.

REFERENCES


