EFFECTS ON SLOSHING PRESSURE
DUE TO THE COUPLING BETWEEN
SEAKEEPING AND TANK LIQUID MOTION

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INTRODUCTION

The influence of dynamic coupling due to the interactions between ship motions and tank liquid motion on the pressure levels on tank boundaries is here investigated by experimental means, using 6 d.o.f. test rig and 1/70 scaled tank model of standard LNG Carrier.

Vessel response, given as “traditional” non-coupled and “realistic” coupled motions are obtained by numerical calculations performed with Bureau Veritas hydrodynamic software HydroStar® in frequency domain, as shown in [1]. First the theoretical background of linear coupling in frequency domain is briefly summarized in the first part of this abstract. Then, the numerical results of coupled vessel response are validated trough the comparisons with basin model-test results using the vessels model with incorporated tanks filled with water [4].

Confidence in our validated model for numerical coupling permits further investigation of more realistic case corresponding to the expected partial filling operation of LNG Carrier in a site specific environmental conditions. For this configuration, sloshing effects induced by coupled and non-coupled vessel motion, introduced as the excitation to 6 d.o.f. small-scale model test rig, are presented in a comparative manner. Statistics of sloshing events recorded for coupled/non-coupled motions and for harmonic/random excitations are presented in this abstract and compared. For a lack of space, the figures of the random excitations results will be presented during the workshop. This work presents the initial stage in investigation of the consequence induced by coupled motion.

MOTION CALCULATIONS

Recent analyses on the dynamic coupling between liquid motions in ship’s tanks (sloshing) and rigid body motions of the ship (seakeeping) can be categorized in two groups: frequency domain ([1], [6]) and time domain approaches ([7][8]). The frequency domain approach is here considered. 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 part.

We consider the sloshing and seakeeping parts separately and after coordinates 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:

$$\left(-\omega^2\left(\left[\mathbf{M}_Q\right]+\left[\mathbf{A}_Q\right]\right)-i\omega\left[\mathbf{B}_Q\right]+\left[\mathbf{C}_Q\right]\right)\left\{\xi_Q\right\}=\left\{\mathbf{F}_Q^{DI}\right\} \qquad (1)$$

$\{\xi_Q\}$ - rigid body ship motions
$[\mathbf{M}_Q]$ - genuine mass matrix of the ship
$[\mathbf{A}_Q]$ - hydrodynamic added mass matrix
$[\mathbf{B}_Q]$ - hydrostatic damping matrix
$[\mathbf{C}_Q]$ - hydrostatic restoring matrix
$\{\mathbf{F}_Q^{DI}\}$ - 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 ε will be introduced). Then we transform the action (forces and moments) of the liquid motions 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:

$$\left(-\omega^2\left(\left[\mathbf{A}_T\right]+\left[\mathbf{A}_{TQ}\right]\right)+\left[\mathbf{C}_T\right]+\left[\mathbf{C}_Q\right]\right)\left\{\xi_Q\right\}=\left\{\mathbf{F}_Q^{DI}\right\} \qquad (2)$$

Coupling

We can now write the motion equation of the coupled system:

$$\left(-\omega^2\left(\left[\mathbf{M}_Q\right]+\left[\mathbf{A}_Q\right]+\left[\mathbf{A}_T\right]+\left[\mathbf{A}_{TQ}\right]\right)-i\omega\left[\mathbf{B}_Q\right]+\left(\left[\mathbf{C}_Q\right]+\left[\mathbf{C}_T\right]+\left[\mathbf{C}_{TQ}\right]\right)\right)\left\{\xi_Q\right\}=\left\{\mathbf{F}_Q^{DI}\right\} \qquad (3)$$

Numerical Results and Calibration of ε

The calibration of the above described parameter ε is performed through comparisons with experimental results [4]. The numerical calculations are performed with HydroStar. In the selected configuration, two separated prismatic LNG cargo tanks were modeled, located at the fore and aft parts of the vessel. Among the different configurations tested, the following one is of particular interest for our case.

The filling ratio is 30% of the height for the both tanks. The mesh used for our hydrodynamic computations is shown below:

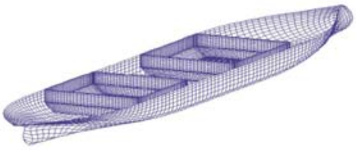

Fig. 1: Hydrodynamic mesh with two tanks filled at 30%H

RAO's in roll (β=90°) is presented for two values of the parameter ε (ε=0.02 and ε=0.1).

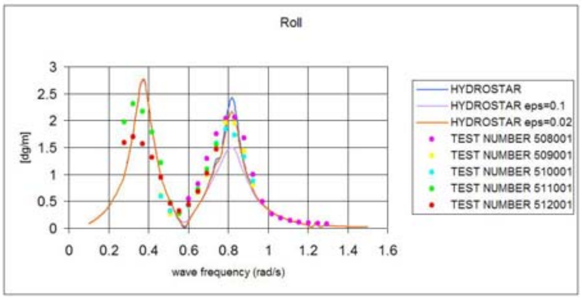

Fig. 2: Roll RAO for β=90°

For roll motion, we can observe the two characteristic peaks of a coupled system (ship + tanks). The first peak is associated with the motions of the ship and the second one with the liquid motions in the tanks. The value ε=0.02 gives the best results and will be considered hereafter.

APPLICATION TO A REALISTIC CASE

Environmental Conditions

Environmental conditions applied in this study corresponds to realistic site specific all-directions wave scatter diagram, with 5 m of maximum recorded significant wave height. Wave energy spectrum is generated according to JONSWAP model (derived for seas with limited fetch), with spectral peak parameter assumed 3.0.

Hydrodynamic Model

A LNG carrier with four tanks is here considered. The filling ratios are 90% of the height for the tanks (1) and (3) and 30% of the height for the tanks (2) and (4). The mesh used for the hydrodynamic computations is presented below:

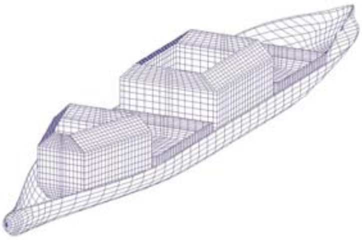

Fig. 3: Hydrodynamic mesh of the LNG Carrier filled at 90%H in tanks (1) & (3) and 30%H in tanks (2) & (4).

Non Coupled – Coupled Transfer Function

In this section, results of hydrodynamic computation are displayed in form of Response Amplitude Operators (RAOs). Moreover, we present the comparison of sway and roll (the most affected degree of freedom due to coupling) RAOs between non coupled and coupled motions. The motions affected by the coupling are the surge, sway, roll and yaw motions. Particularly, the roll motion is strongly affected with the presence of the two peaks described above instead of one peak in the case of the non coupled motion.

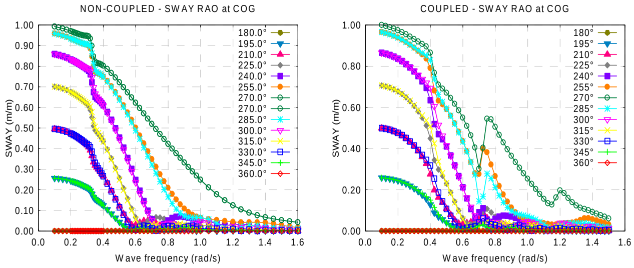

Fig. 4: RAO in Sway for Non Coupled / Coupled Motion

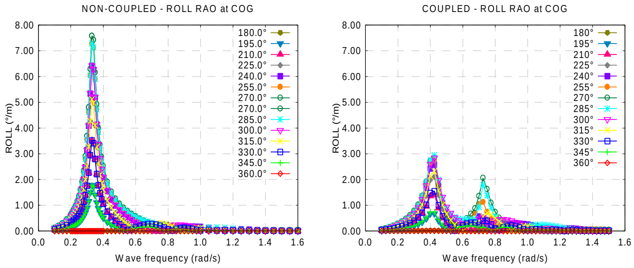

Fig. 5: RAO in Roll for Non Coupled / Coupled Motion

Then, spectral analysis has been performed for each combination of associated conditions (Hs, Tp, and heading) using JONSWAP spectrum for site-specific environmental conditions. The amplitudes of 1/10th significant level and response zero-crossing periods for non coupled and coupled motions are detailed. These figures highlight for sway and roll the operational case (Tp, heading) corresponding to the worst motions.

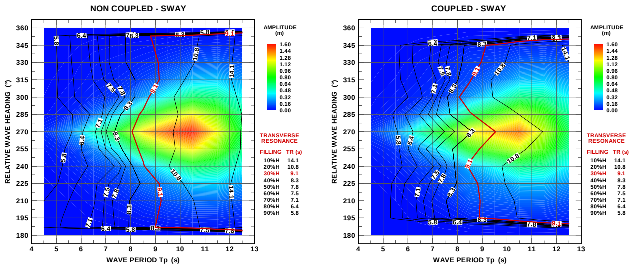

Fig. 6: Sway A1/10 & RTZ for Non Coupled / Coupled motion

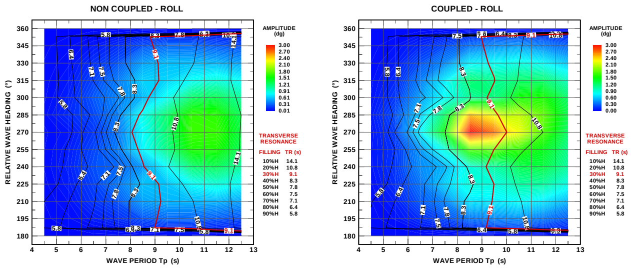

Fig. 7: Roll A1/10 & RTZ for Non Coupled / Coupled motion

MODEL TEST DESCRIPTION

Sloshing model test practice is based on the measurement of fluid impact pressure on the tank walls.

The model corresponds to the tank N°2 of BV reference vessel with standard cargo capacity of 138 000 m^3, scaled to 1/70 and made of a 20 mm thick Plexiglas®.

The impact pressures are measured by dynamic ICP® pressure sensors which natural frequency is above 100 kHz. Static pressure is not taken into account. A total of 54 points around the model could be used to locate the pressure sensors. A total of 16 pressure sensors is used for the tests. The sampling rate used is 20 KHz on each channel. The acquisition control program has been developed by Bureau Veritas. Several VBA® routines developed by Bureau Veritas are launched to:

(i) Extract for each channel, elementary statistics such as:
  - P_{max} : maximum of impact pressure
  - 10 Pmax : mean of the 10 higher impacts
  - $P_{1/10}$: mean of the tenth of the higher impacts
  - $P_{1/3}$: mean of the third of the higher impacts
  - N : number of impacts

(ii) Build graphic comparisons between selected tests.

Finally, statistical values of impact pressures are computed using statistical softwares (R® & Dataplot®), aimed to complete the assessment procedure from the impact pressure point of view.

EXPERIMENTAL RESULTS

Presentation of Results

In this section are detailed our experimental results concerning the pressure results for the tank No. (2) described above. The duration of the tests is 5-hours at full scale [5].

The Fig. 8 represents the two sensor configuration used during our experiments. On the left side, the sensors location for β=270° is represented. On the right side, the sensors location for the other headings considered here is represented.

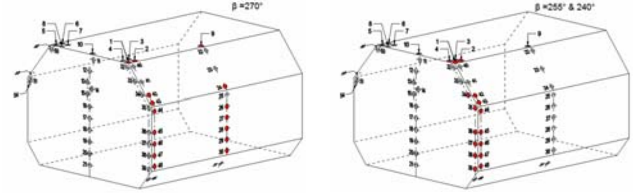

Fig. 8: Sensors Location for β =270° / other headings

First, we consider harmonic excitations obtained after spectral analysis for the case of zero forward speed. The pressure levels caused by non coupled and coupled motions are shown just below and can be compared.

For instance, the Fig. 9 shows the maximum pressure recorded among our pressure sensors for Non Coupled/Coupled motions. The Fig. 10 represents the highest average recorded among all the sensors of the ten highest pressure peaks (N.C./C. motions). The Fig. 11 shows the maximum number of impacts recorded among all the pressure sensors (N.C./C. motions). The Fig. 12 shows the statistical pressure associated at 3 hour-return period (named P_{stat} in the whole paper), calculated by the probability law which fits the best among Weibull-3 parameters, Log-Normal 3 parameters (N.C./C. motions). For each result, a unique scale is used, selected as the one giving the highest values between (non coupled, coupled) / (harmonic) excitations. Results for random excitations will be presented during the Workshop.

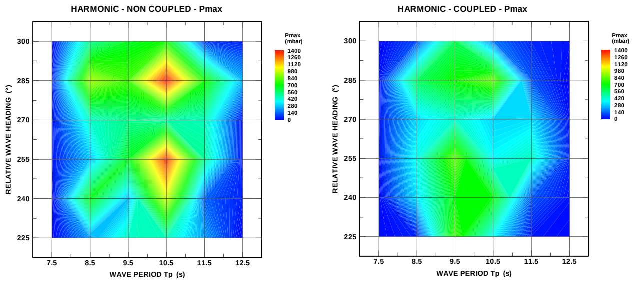

Fig. 9: Harmonic – Pmax : Non Coupled / Coupled

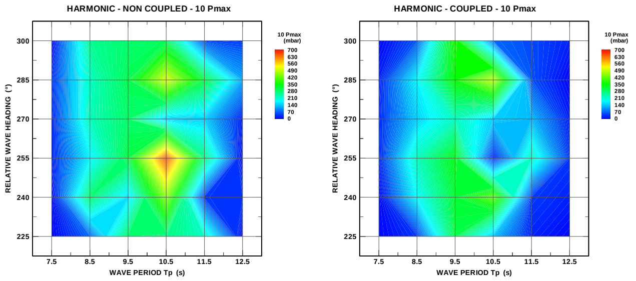

Fig. 10: Harmonic – 10 Pmax : Non Coupled / Coupled

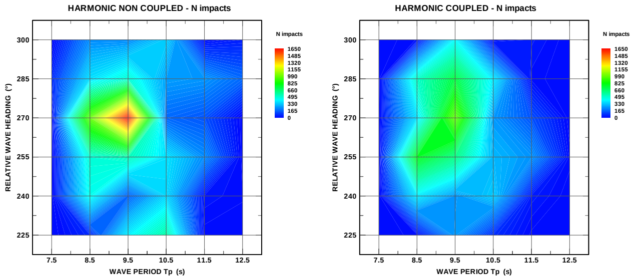

Fig. 11: Harmonic – N impacts : Non Coupled / Coupled

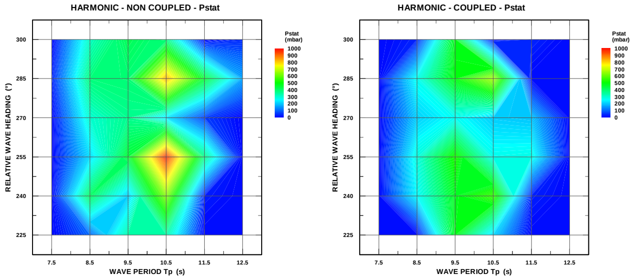

Fig. 12: Harmonic – Pstat : Non Coupled / Coupled

Overall Analysis: 5-hour Full-Scale Duration

Even if all headings have not been represented on the above graphs, the most prevailing cases are displayed. Indeed, the pressure levels for the headings (β=180°, 195°, 210°) are low compared to those detailed hereunder.

For the harmonic excitation, non-coupled motions represent the critical case for all kind of results considered (P_{max}, 10 P_{max}, number of impacts, P_{stat}).

Even if the most critical case is difficult to identify since it differs from the parameter studied (P_{max}, 10 P_{max}, number of impacts or P_{stat}), the 4 following cases appear to be the most relevant:

- (Tp, β)=(10.5 s, 285°)
- (Tp, β)=(9.5 s and 10.5s, 270°)
- (Tp, β)=(10.5 s, 255°)

Pressure levels for coupled motions are low compared with those obtained with non-coupled motions.

As it will be shown during the Workshop, concerning random excitations, the same tendency between non-coupled and coupled motions is observed. Indeed, non-coupled motions appear to be more critical in terms of pressure levels, except for the number of impacts.

Finally, for 5-hour full-scale duration analysis among all the hydrodynamic configurations (non-coupled/coupled; harmonic/random) considered, the most critical one appears to be the non-coupled motion with harmonic excitation.

Critical Cases: 30-hour Full-Scale Duration

Following these results, a focused analysis from five-hour to sixty-hour full scale has been carried out on four the most severe cases listed here above.

Our main concern was to assess statistical pressures P_{stat} using additional statistical distributions: Pareto and Generalized Extreme Value, selected threshold level, 95% confidence intervals, and the test duration required to collect sufficient size of the data sample allowing the convergence of statistical results.

In that regard, our observation is that 30-hours experiment is giving satisfactory steadiness of P_{stat} (for 3-hours return period) and confidence intervals. This test duration has been selected for all comparisons of critical cases using 4 statistical laws. This detailed analysis of 30-hours full scale leads to the same conclusions as 5-hour full scale cases elaborated here above.

CONCLUSION

The influence of dynamic coupling due to the interactions between ship motions and tank liquid motion on the pressure levels on tank boundaries is here investigated by experimental means, using 6 d.o.f. test rig and 1/70 scaled tank model of standard LNG Carrier.

Among all considered hydrodynamic configurations (non coupled/coupled; harmonic/random), the most critical one for the sloshing pressure appears to be non-coupled motion with harmonic excitation. This first conclusion of the study is very interesting since nowadays, due to the restricted computer resources, the major part of numerical calculations using CFD tools are performed with harmonic excitations. In addition, the state of the art of hydrodynamic computation is based on classical assumptions of rigid body motion without dynamic effects of free surfaces in tanks. Comparing sloshing effects induced by “traditional” sloshing excitation and the “realistic” one which is the random motion accounting for dynamic coupling with liquid motion in the tanks, it appears that currently used numerical model seems to be conservative, at least for the cases studied herein.

Further numerical sloshing analysis are envisaged to be carried in order to verify and confirm the observations from experimental study presented in this paper. For instance, the same kind of results will be presented at the Workshop for two partial fillings of 50%H instead of 30%H considered here.

Comparisons between these experimental results and numerical calculations will be presented at the Workshop.

In addition, due attention should be given to the statistical adjustment, particularly related to the proper selection of applicable statistical distribution and relevant acceptance criteria. Finally, it is to be underlined that conclusions drawn-out from this study should remain restricted only to the assumed operational case and any extrapolation to other configuration (as other filling or other tank capacity, for instance) may mislead to the erroneous recommendation.

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