

Model Scale Test vs. Full Scale Measurement: findings from the *Full Scale Measurement of Sloshing* project

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ABSTRACT

Model tests are widely used for the analysis of cargo sloshing in LNG tankers, and for design purposes. The complexity of the phenomena involved in LNG cargo sloshing impedes the application of simple scaling laws, and the transposition of model tests results to full scale remains an important issue.

A solution to enhance the representativeness of model tests is to refer to full scale measurements of sloshing. A first significant series of such measurements has recently been performed, followed by a model tests campaign reproducing the conditions corresponding to the full scale sloshing measurements.

KEY WORDS: LNG; sloshing; scaling; model tests; full scale.

INTRODUCTION

A Joint Industry Project (JIP) with BW Gas, Teekay, DSME, Lloyd's Register, DNV, Light Structures and GTT, dedicated to the Full Scale Measurement of sloshing, is currently providing an unprecedented insight into cargo sloshing in the tanks of LNG tankers. This first significant attempt to detect and measure sloshing impacts at full scale in operational conditions has been producing more than two years' worth of measurement data, thanks to the instrumentation installed in tank n°2 of a 148 000 m³ LNG Carrier, the LNG IMO, built by DSME and owned by BW Gas. Sloshing impacts are recorded at high fills, in the two forward corners of the tank ceiling.

Within the JIP, GTT has performed a first model tests campaign reproducing the conditions of the full scale sloshing measurements. The ship motions recorded on board the LNG IMO for a selection of voyages have been used as an input for the tests. A model of tank n°2 at scale 1/40 has been fitted with sensors at locations corresponding to the instrumented zones at full scale. Model tests, which are widely used as the best possible tool for sloshing design studies, can here for the first time be confronted with the reality they are aimed at representing.

The main results from the full scale measurements are briefly presented, and the basis for the selection of the periods to be simulated at model scale is explained. The preparation of the model tests, the test rig and the test plan are described, and results from the model test are provided and commented, with emphasis on the comparison with the full scale measurement results. Finally, the questions and challenges raised by the full scale / model scale analysis are briefly discussed.

FULL SCALE MEASUREMENTS

Two years on board the LNG IMO

The LNG IMO was launched at the end of 2008. During the very first loaded voyages, some elements of the measurement system had to be tuned or rectified, but soon the system provided continuous and accurate detection and recording of cargo sloshing in tank n°2. Table 1 gives a list of 15 loaded voyages for which full scale data was retrieved and analysed.

This database includes different routes, from Bonny (Nigeria) to Europe, South America and South East Asia. During these voyages, the ship sailed mainly in calm to moderate seas. No very severe conditions were encountered. Tank n°2 was always loaded to the maximum level (97.5% of tank height) at the departure from the Bonny terminal. Depending on the duration of the voyage, the arrival filling level could reach values as low as 92.5%H.

Table 1: list of loaded voyages

Voyage	Port		Date	
	departure	arrival	departure	arrival
7	Bonny	Yung-An	2009-09-22	2009-10-20
8	Bonny	Bilbao	2009-11-22	2009-12-04
9	Bonny	Altamira	2009-12-17	2010-01-03
10	Bonny	Bilbao	2010-01-22	2010-02-01
11	Bonny	Cartagena	2010-02-13	2010-02-23
12	Bonny	Montoir	2010-03-07	2010-03-21
13	Bonny	Montoir	2010-04-03	2010-04-14
14	Bonny	Montoir	2010-04-26	2010-05-09
15	Bonny	Montoir	2010-05-26	2010-06-06
16	Bonny	Montoir	2010-06-20	2010-06-28
17	Bonny	Bilbao	2010-07-17	2010-07-27
18	Bonny	Rio-de-Janeiro	2010-08-12	2010-08-23
19	Bonny	Altamira	2010-09-07	2010-09-23
20	Bonny	Incheon	2010-10-24	2010-11-17
21	Bonny	Shimizu	2011-01-04	2011-01-31

During these voyages, all the relevant parameters were continuously recorded. Thus all the sloshing measurements can be analysed with reference to the corresponding operational conditions.

The recordings can be classified as follows:

- Sloshing measurements
- Navigation parameters and ship loading conditions
- Environmental conditions

Instrumentation for on board sloshing measurement

The instrumentation dedicated to the measurement of sloshing impacts was installed in the two forward corners of the ceiling of tank n°2. It includes several sensors, mainly strain gauges, all of which are based on fibre optic Bragg gratings, and some of which have been specifically designed by Light Structures within the project. The instrumentation has been installed in tank n°2 by DSME and Light Structures during the building of the LNG IMO. Details of the instrumentation have been provided by Lund-Johansen *et al.* (2011).

Fig. 1 shows the location of the instrumented zones in tank n°2.

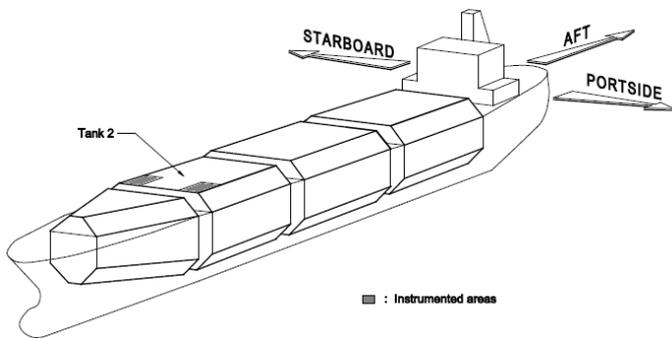


Fig. 1: location of instrumented zones on LNG IMO

Preliminary analysis of the data has shown that the best detection and measure of sloshing impacts were provided by the sensors labelled CSS1 to 4 and CSP1 to 4. These are strain gauges mounted beneath the cover plate of the primary insulation box located in the corner of the ceiling, respectively at starboard and portside.

The sampling frequency for these sensors is 20 kHz. Full rate recordings of the impacts are kept for analysis, as well as continuous, low rate data.

Fig. 2 shows the location of the strain gauges mounted at portside. The configuration at starboard is symmetrical.

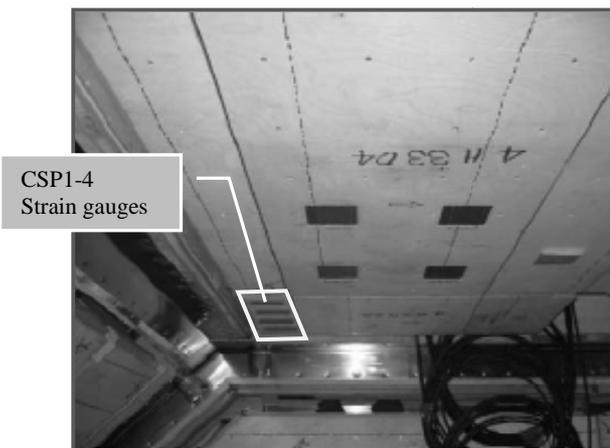


Fig. 2 : on board instrumentation portside corner

Because of the building principle of the box and of the configuration of the strain gauges, the following is considered, in a first level approach:

in either tank corner, the four gauges and the part of the cover plates on which they are installed constitute a single sensor, with a sensible surface of rectangular shape, and of dimensions 140 x 400 mm.

This assumption is also supported by the following observation: the analysis of the four strain gauge signals shows that all the strain gauges react simultaneously to a given load on the double cover plate (Fig. 3).

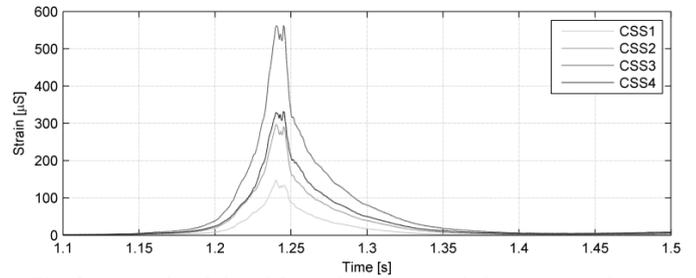


Fig. 3 : example of signal for an impact recorded on a corner box

Due to the detailed design and mounting principle of the primary box cover plate, the sensor measuring the highest strain value is sensor n°3 on either corner, as illustrated in Fig. 3. As a consequence, the sensors CSP3 and CSS3 were chosen as reference for the detection and measurement of sloshing impacts at portside and starboard respectively.

Loaded voyage n°20

Details are given here for one of the most significant periods of sloshing recorded on board the LNG IMO during the loaded voyages listed in Table 1: the period from 2010-10-24 12:00:00 to 2010-10-27 15:00:00, corresponding to the beginning of loaded voyage n°20.

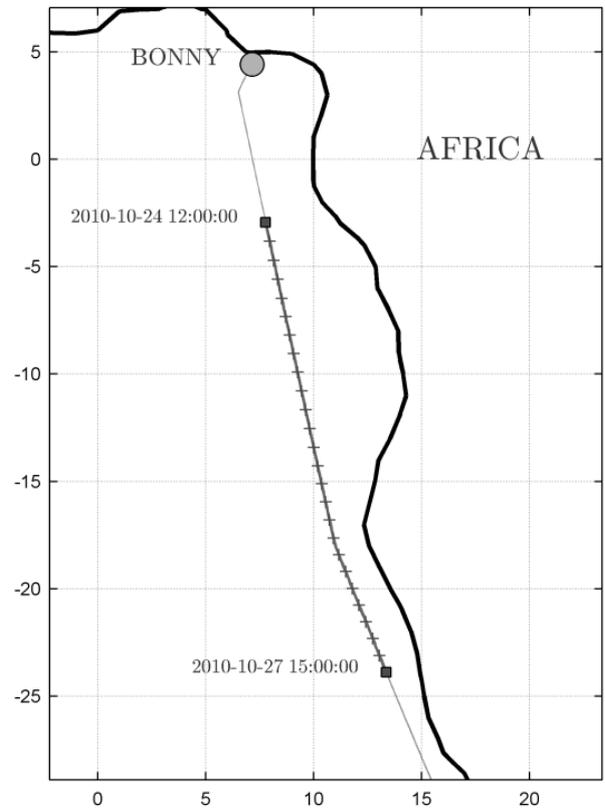


Fig. 4 : LNG IMO route at the beginning of voyage n°20

Operational and environmental conditions

During the selected period, the LNG IMO was sailing at 18 knots off the western African coast just after loading at Bonny (Nigeria). The filling level was about 97%H. The vessel encountered moderate to medium sea-states with significant wave heights estimated between 3m and 5m, and a mean peak period between 10 and 15 s. The waves were coming from the starboard head quarter. The wind was relatively moderate – average speed of 15 m/s – coming 40-50° off bow.

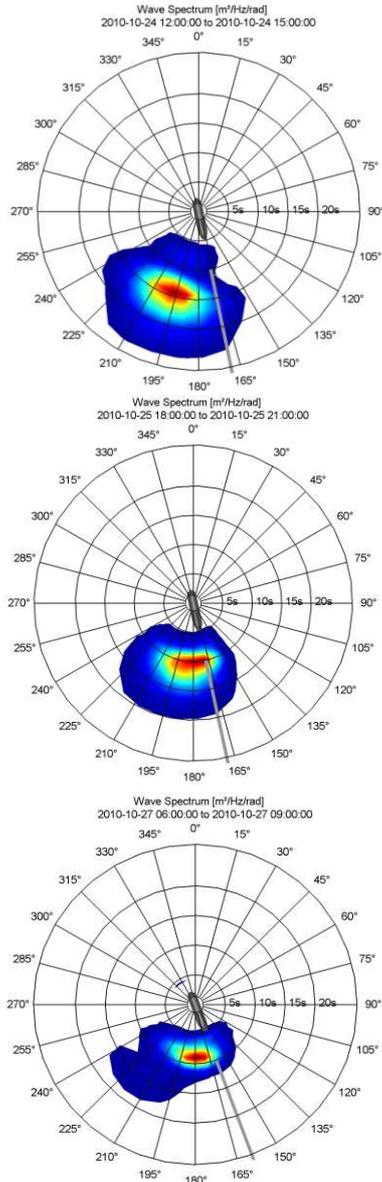


Fig. 5 : Wave spectra estimated by WaveX radar

Estimations of the sea states are provided by the WaveX radar system installed on board the LNG IMO. Wave spectra averaged over 3 hours are shown in Fig. 5 for the beginning, the middle and the end of the considered period. They show that during this period the vessel was sailing in globally stable conditions, with bow quartering swell from starboard. Changes are visible in the wave period at the beginning (from longer to shorter waves) and in the ship course at the end of the period.

The estimated wave heights are also shown (Fig. 6), indicating a maximum at almost 5 m around the middle of the period (2010/10/25, 15:00 to 21:00).

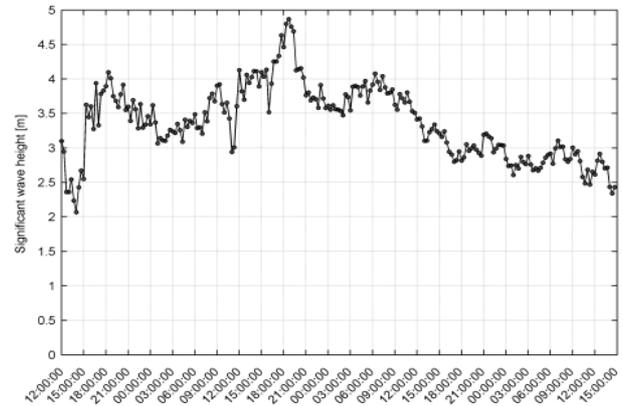


Fig. 6 : significant wave height estimated by WaveX radar

As the ship motions were continuously recorded by the Motions Response Unit installed on board, a statistical analysis of the motions can be done for the selected period. Fig. 7 presents the variation of the significant amplitude ($H_{1/3}$) for each degree of freedom, by steps of 3 hours. The motion amplitudes are calculated at the centre of tank n°2.

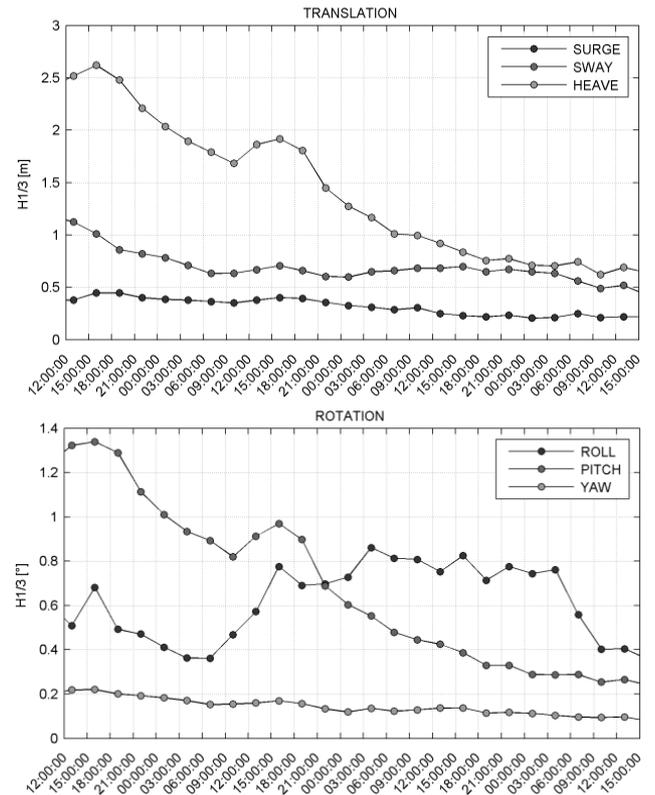


Fig. 7 : significant amplitude of ship motions during the considered period

Sloshing data recording

The results of sloshing measurements on both starboard and portside are presented in Fig. 8 for the considered period. It is observed that the

highest events rate (number of impacts per hour) on both sides was measured when the waves were highest.

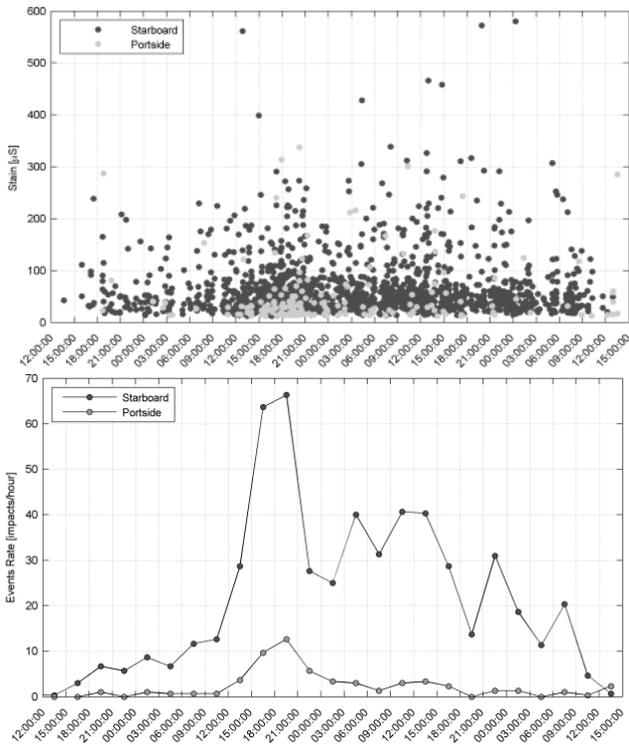


Fig. 8 : strain peaks and events rates at portside and starboard

MODEL TESTS SETUP AND PROCEDURE

The model tests campaign aimed to simulate at scale 1/40 the sloshing periods observed on board the LNG IMO. Several sloshing periods were identified and selected among the full scale measurements to be simulated with the GTT facilities.

This was the first ever series of model tests designed to reproduce situations observed and measured on board during standard commercial navigation, based on comprehensive on-board real time recordings.

The tests were performed with state-of-the-art tools and methods, using GTT's latest model tests methodology (Gervaise et al., 2009).

- The model tank was tank n°2 of the LNG IMO at scale 1/40.
- The hexapod test rig motions were derived from motion time histories recorded on board, by Froude scaling.
- The fluids in the tank were chosen in order to have a gas/liquid density ratio close to the one on board with LNG and its vapour.
- 180 pressure sensors were mounted on the corners of the model tank ceiling.

Model tests strategy

Full-scale database 3h-partition

It was decided to use a constant and handy time unit to describe the voyages from the departure port to the arrival port. Every day was thus divided into 3-hour sequences (00:00 to 03:00, 03:00 to 06:00 etc...). This arbitrary time basis is consistent with the usual definition of a sea-state, which assumes that a sea-state is more or less stable during 3 hours. It provides a simple and practical basis for the organization of the model tests and the analysis of results.

Full-scale sloshing period selection

A “sloshing” condition was identified as a condition producing at least 5 impacts per hour on CSS3. The selection criterion, applied to the mean impacts frequency for each 3-hour sequence, is thus described as:

$$ER_{CSS3} \geq 5 \text{ impacts/hour}$$

where ER means events rate. The definition of an impact is related to a strain threshold value of $12.5 \mu\text{S}$ at full-scale, on the CSS3 sensor. Using this criterion, the “sloshing sequences” were identified. Finally, successive “sloshing sequences” could be put together into “sloshing period” completed by starting and ending “no-sloshing sequences”. The analysis of the full-scale database ended with the selection of 210 sloshing sequences of 3 hours at full-scale which could be distributed in 22 sloshing periods.

The next step after the selection of the sequences to be simulated was to extract from the corresponding full scale data the information necessary to run a model test: time history of tank motions for the test rig, and tank filling level.

Ship motions processing

The motion generator used to perform the tests is a six-degree-of-freedom Stewart platform (hexapod, see Fig. 10), able to simulate the most severe motions of the LNG IMO with high accuracy.

All the time histories of the tank motions were derived from the motions recorded on board by the MRU mounted on the centre bulkhead at B-deck in the superstructure. To scale the full scale motions down to 1/40, the amplitude of translations was divided by 40, and the time was divided by $\sqrt{40}$ respecting the Froude similarity.

Low frequencies in yaw motion were filtered to cancel the yaw component corresponding to the course over ground, i.e. only yaw motions in the wave frequency range were kept. The roll and pitch motions on the other hand were not filtered: the low frequency components, corresponding to the static trim and list angles, were kept in the simulated motions.

In addition, to avoid too high accelerations at the starting and the ending of each run, the first and last minute of the time histories were multiplied by standard ramp signals.

The transposition of motions from the MRU position to the test rig reference point was directly performed by the test rig software (Fig. 9).

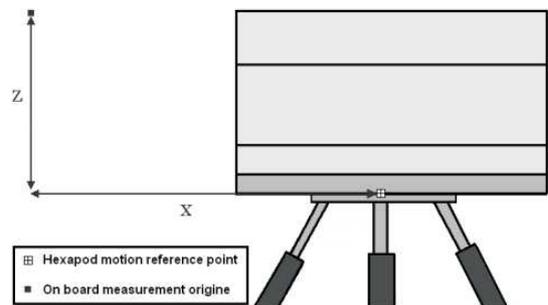


Fig. 9 : motion transposition

The use of the hexapod was automated so as to perform tests continuously. The tests were separated with pauses to let the free surface come to rest.



Fig. 10 : hexapod test rig

Tank filling level

The filling level in tank n°2 of the LNG IMO is continuously recorded by the CTS, based on a radar gauge located on the pump tower. The CTS is not specifically designed to measure the level in navigation conditions. The measurements are thus strongly affected by the movements of the liquid free surface in the tank.

Nevertheless, average values derived from the CTS readings appear to give a consistent estimate of the variation of the level in the tank over several days. Fig. 11 shows the evolution of the 30 minutes average and 3 hours average of tank n°2 liquid level measurements for the first sloshing period of voyage 20. The decrease of liquid level due to boil-off is clearly shown by the trend of the 3-hours average values.

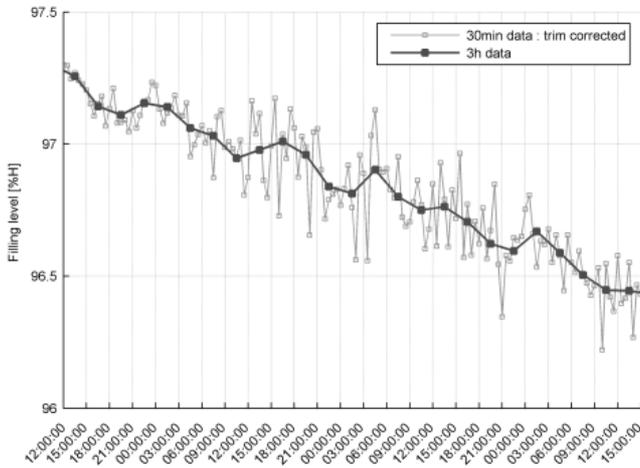


Fig. 11 : filling level measurement – sloshing period

The variability of the 30-min average values also gives an indication of the agitation of the liquid inside the tank during this period. As a reference, Fig. 12 shows the same readings, but for a calm period of the same loaded voyage.

Because the measurement is made at the location of the pump tower, i.e. close to the aft end of the tank, the filling level reading had to be corrected by taking into account the trim angle.

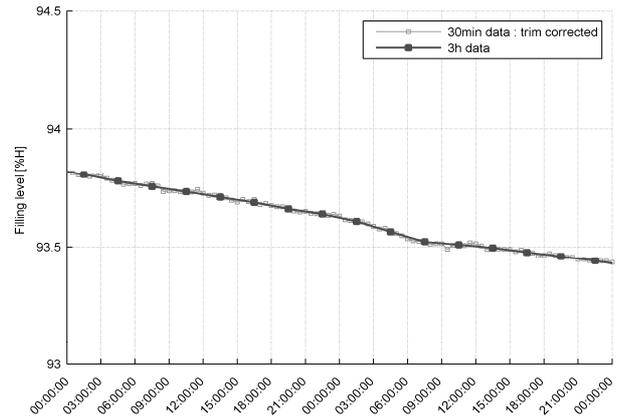


Fig. 12 : filling level measurement - no sloshing period

As the variation of filling level over the duration of a sloshing period (not more than 3 days) were not believed to have a significant influence on the model tests results, it was decided to round the readings to the next whole percentage of tank height (%H). The period in Fig. 11, for instance, was thus simulated with a model tank filling level of 97% H.

Fluid ratio densities inside tank

The model tests were performed at ambient conditions using a heavy gas mixture ($SF_6 - N_2$) as the ullage gas, and water as the liquid. The use of heavy gas instead of air allows the density ratio between liquid and gas in the tank at model scale (0.004) to be equivalent to the one at full scale, when being at ambient temperature.

$$\frac{\rho_{\text{Ullage Gas}}^{\text{Model Sc.}}}{\rho_{\text{water}}^{\text{Model Sc.}}} = \frac{\rho_{\text{Natural Gas Vapor}}^{\text{Full Sc.}}}{\rho_{\text{LNG}}^{\text{Full Sc.}}}$$

Maillard *et al* (2009) showed that respecting this density ratio allowed the model tests to be more representative.

Model Instrumentation

Model tank and instrumented areas

The model tank, made of PMMA, represented tank n°2 of the LNG Carrier LNG IMO at the scale 1/40. The PMMA is 50 mm thick, and can thus be considered as rigid with respect to the measured loads.

The pressure sensors were fitted inside stainless steel modules mounted in the openings of the model tank walls. The pressure sensors location had to be consistent with the full-scale sensors location in order to allow a comparison between model scale and full scale measurements. Hence, a particular care was given to ensure that the area instrumented in the model tests included the full-scale instrumented zones (Fig. 13).

Pressure acquisition

Pressures were measured with 180 pressure transducers of piezoelectric type, with a sensitive circular area of 5.5 mm diameter at model scale 1/40, (equivalent to 220 mm at full scale). The acquisition frequency was 20 kHz. The distance between two pressure sensors was 10 mm between axes. The axis of the closest sensor to the wall was located at 5 mm.

A pressure threshold of 50 mbar was defined as the minimum pressure which had to be up-crossed to consider an event occurred.

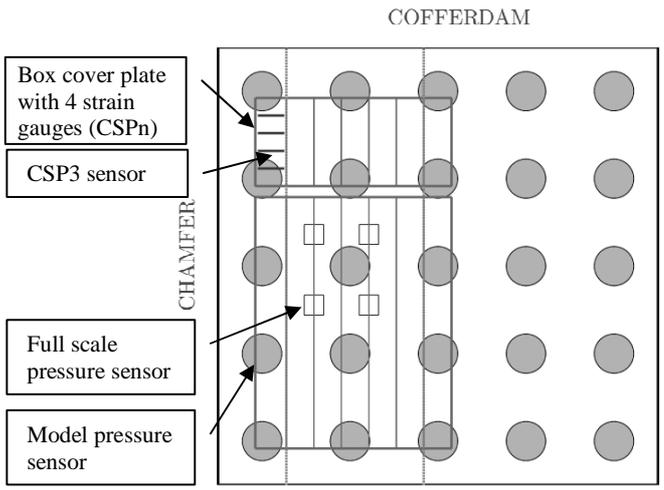


Fig. 13 : relative position between model scale and full scale instrumentations, portside corner

Model test real-time monitoring

A real time monitoring of the testing conditions was done to control their stability, and therefore the quality of the test results. The quality and precision of the motions simulated by the hexapod were real-time checked through an independent second hexapod located inside the first one (Fig. 10). These measurements were used to make sure that the motion time histories recorded on board were correctly simulated at model scale. The external temperature, the ullage pressure inside the tank, the temperature of water and ullage gas and the density of the ullage gas were continuously measured and checked in order to ensure the stability of the testing conditions. These parameters remained relatively stable all along the tests. This was necessary to ensure that the model scale density ratio between gas and liquid at ambient temperature was equal to the ratio at full-scale at cryogenic temperature.

In addition, every 10th run was dedicated to a control test using a reference motion sequence; variability of the events rate for a given group of sensor was quantified to ensure the stability of model tests conditions. Fig. 14 shows results of control tests proving a satisfying stability of testing conditions (variations of events rate within +/-10% around the mean value).

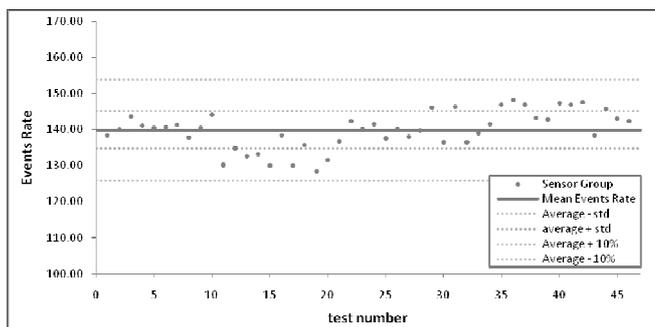


Fig. 14 : results of control tests on 97% H model tests

MODEL-SCALE & FULL-SCALE COMPARISONS

The results from the model tests are sloshing impact pressure peak samples, corresponding to the simulation of the 22 periods of sloshing

selected among the data recorded on board the LNG IMO. Each sloshing sequence was simulated 10 times, in order to produce large samples allowing to draw stable statistics.

A first, global observation based on the results was that the simulations were consistent with the measurements at full scale: for each period, the model test results showed the same global trend as the full scale data, i.e. a first sequence without impacts, then for the following sequences an increase of the number of impacts, then a decrease and again a last sequence with no impacts.

The full-scale data corresponding to the first period of loaded voyage n°20 were presented in the first section. The model test results corresponding to the same period are detailed hereafter and compared with the on board measurements.

The first value to be compared is the frequency of impacts – or events rate – expressed in terms of number of impacts per hour. This value is expected to be similar at full scale and model scale, because the model tests are designed to represent the full scale reality. Nevertheless, the comparison is not straightforward, because the counting of impacts has to be consistent between the on board measurements and the model tests.

How to count impacts coherently

The first difference for the definition of an impact, at model and full scale, is that the measured quantity is not the same: strain at full scale, pressure at model scale. Nevertheless, it can be assumed that the response of the cover plate (strain) is linear with regards to the pressure applied on the cover plate (Bogaert *et al.* 2010).

Furthermore, the same definition can be chosen for both measurements: an impact is counted when the signal up-crosses a given threshold.

Sensor location at model scale and full scale

As the impacts on the tank ceiling are very localized, the relative position of sensors at both scales is a critical parameter for the comparison of results.

The relative location of full-scale and model-scale sensors is shown in Fig. 15. This scheme indicates that the area of the primary box cover plate instrumented at full-scale is best represented by the two pressure sensors located in the ceiling corner along the chamfer on the model tank. The results from the CSS3 - respectively CSP3 - sensor are therefore compared to the results obtained with a combination of the corresponding two model scale sensors at starboard - respectively portside.

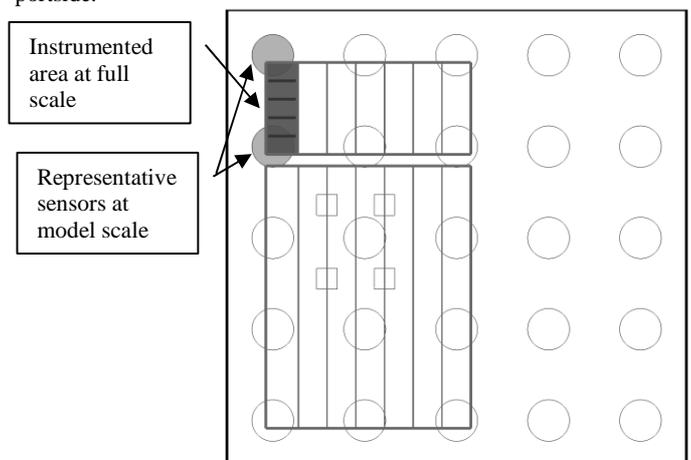


Fig. 15: relative location of sensors

Threshold considerations

The number of impacts counted at full scale and at model scale depends on the threshold value chosen in both cases for the signal of the strain gauges or the pressure sensors respectively. The data initially available corresponds to threshold values of 12.5 μ S and 50 mbar respectively at full scale and at model scale.

A preliminary analysis to compare these values was made, based on a simplified FEM analysis of the primary insulation box carrying the CSSn sensors. A uniform load was applied to the FEM on the double cover plate in cryogenic temperature. Using an estimated scaling factor based on the Froude number, it was found that the full-scale strain threshold was much lower than the strain value which would result from a uniform pressure on the cover plate corresponding to the model scale threshold value.

A similar observation can be made by comparing the total number of impacts recorded at both scales for the same period. For instance, during the first period of voyage n°20 described above, about 1640 impacts were recorded at full scale in the starboard corner of tank n°2.

The number of impacts recorded at model scale for the same period, averaged over the 10 repetitions run for each sequence, is about 420.

This can be commented as follows: the detection of sloshing impacts at full scale is very sensitive, and events of small amplitude can be detected as well as events producing significant response of the structure.

Nevertheless, to allow a comparison of the measurements on a consistent basis, an attempt was made to adjust this threshold difference, by considering that the total number of impacts should be the same at both scales over the period. This could be achieved by re-processing the full scale data with a strain threshold set at 70 μ S instead of 12.5 μ S.

Global flow comparison

Evolution of the events rate

Using this increased threshold value for the definition of an impact at full scale, the events rate comparison results as shown in Fig. 16. As each sequence has been simulated ten times at model scale, the variability of the results in terms of impacts counting can be estimated. This is illustrated in Fig. 16, which shows for each sequence three different values from the model tests results: the mean value of events rate (averaged over the 10 runs), and the mean value plus/minus the standard deviation.

Taking this variability into account, it appears that the comparison between the trends at full scale and model scale is globally satisfying. Nevertheless, for two 3-hour sloshing sequences – between 2010/10/25 15:00 and 2010/10/25 21:00 – a difference between full scale and model scale appears, which seems to be significantly beyond the expected effect of variability. Further analysis of the data is necessary to explain this observation.

Another illustration of the comparison between full scale and model scale for the same period is given in Fig. 17. The dots represent the results of impacts counting per sequence. The light grey surface represents the standard deviation associated to the model scale values. The dark grey band shows the ideal zone where the events rates are identical at full scale and model scale, taking into account the mean standard deviation on model scale results. As a consequence, it can be

considered that the intersection of the two areas defines the zone where model tests match the full-scale measurements.

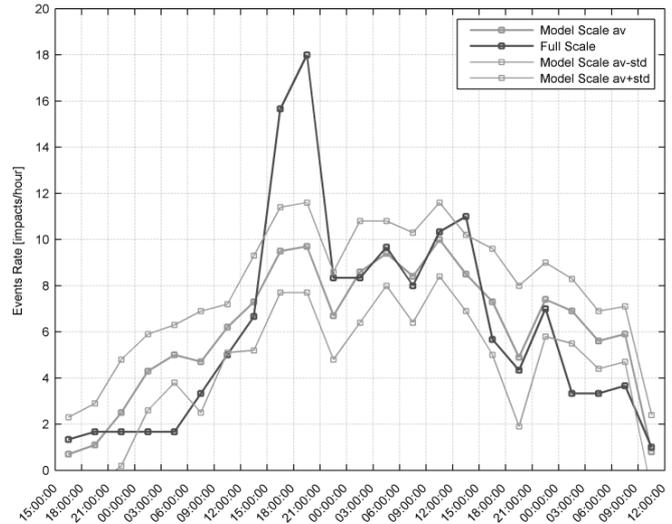


Fig. 16 : events rate during 1st period of voyage 20, full scale and model scale, starboard corner

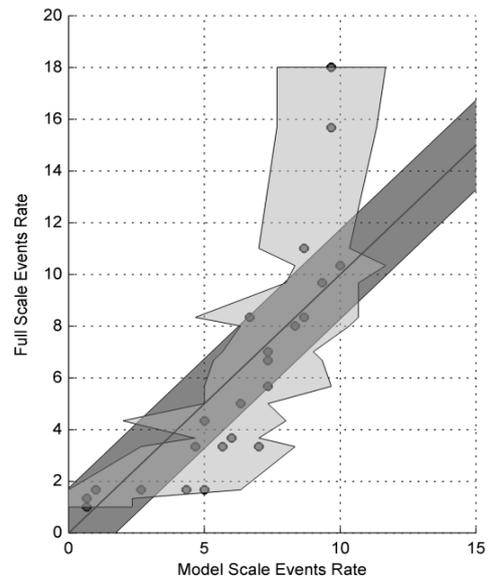


Fig. 17 : comparison of events rates, full scale versus model.

For most of the sequences, the model tests have satisfyingly represented the full scale measurements in terms of impact frequency. As the frequency of impacts is related to the motions of the liquid free surface, it can be concluded that the similarity of the global flow inside the tank at full scale and model scale is confirmed.

Nevertheless, two sequences show a significant deviation. Other sloshing periods, which are not presented in this paper, have also been analysed, and similar deviation between full scale and model scale have been observed for several sequences. This should be further analysed and explained.

Comparison between port side and starboard

During the selected sloshing period, the vessel sailed with an average static list angle of 0.52 degrees, and this angle induced a dissymmetry between both sides. This provides an additional way to check the global flow similarity, by comparing the number of impacts recorded at starboard and portside.

The comparison of the frequencies of impacts in both instrumented tank corners concluded that at full scale, the events rate at portside was 8% of the events rate at starboard. The same comparison was done with the model tests results, and a ratio of 10% was found.

This observation therefore confirms the relevance of model tests: with the same tank motions (including static list), the global flow at model scale resulted in roughly ten times more impacts at starboard than at portside, similarly to the measurements made at full scale. It also provides an illustration of the importance of static list as an input in sloshing studies.

Statistics: distributions and Weibull fit

The statistical distribution of the pressure peak samples obtained at full scale and model scale were also compared. For this comparison, a Weibull law was fitted to either sample.

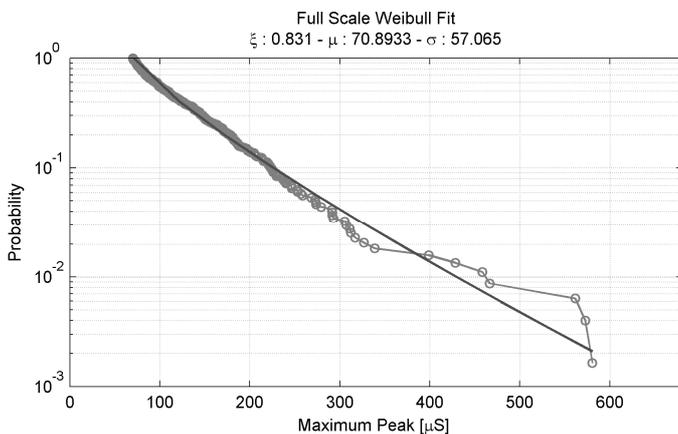


Fig. 18 : impact strain distribution at full-scale

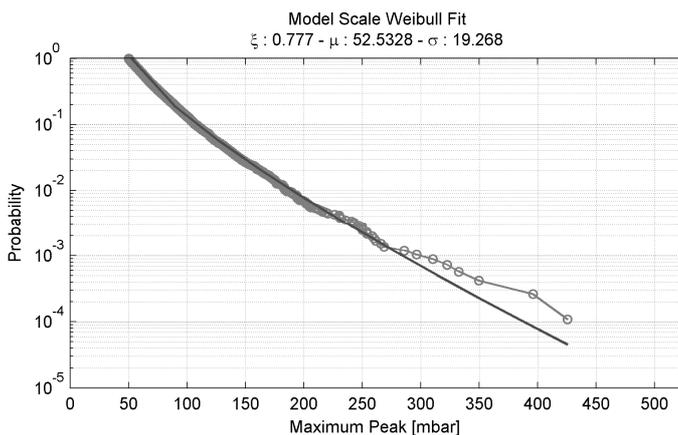


Fig. 19 : impact pressure distribution at model scale

The distribution at full-scale was based on the strain peak recordings on sensor CSS3 during the considered period, with a threshold set at 70 μ S. The distribution at model scale was built with the pressures

sample obtained with the 10 simulations of each sequence for the considered period (threshold set at 50 mbar).

The shape factors of the Weibull fits are in the same range on the considered period, which tends to show that the statistical behaviour of full scale strain values and model scale pressure values is similar.

CONCLUSION

A first comparison of sloshing impacts recordings at full scale and at model scale has been performed. For the model tests, the actual ship motions recorded at sea have been used as input for the simulation platform. This allows a direct comparison of full scale and model tests results, without the bias induced by the use of numerical sea-keeping analysis to produce tank motions.

The results of the model tests – at scale 1/40 – have shown a good correlation with the full scale measurements. The trend in terms of impact frequency over several days of navigation has been found fairly consistent, as well as the comparison between the measurements in both instrumented tank corners. This tends to confirm that experimental simulations of LNG sloshing at small scale provide a correct representation of the global flow inside the tanks, as expected according to theory.

Nevertheless, the good correlation between model tests results and full scale measurements needs to be confirmed for a wider range of conditions, which could be obtained by simulating in further model tests new sloshing periods recently measured by the on-board system. Furthermore, the full scale/model scale correlation has been analyzed globally on the considered sloshing period; a closer analysis of the results has shown that some sequences deviate from the global trend. This has also been observed for other periods not presented in this paper, and will need to be investigated and explained, e.g. by analyzing the recorded signals with a focus on the nature of the impacts.

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