Results of the First Sloshing Model Test Benchmark

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ABSTRACT

A benchmark on Sloshing Model Test (SMT) installations has been conducted between 2011 and 2012, involving nine participants. This benchmark was based on simple tank geometry, excitation conditions and measurement set-up together with basic fluids, so that the majority of the sloshing research community could take part. Results have been gathered from eight of the participants, for a varying number of the specified conditions, depending on the respective testing capacities.

Results are shown and discussed for seven of the fourteen initial excitation conditions. A way forward is proposed.

KEY WORDS: sloshing; LNG; benchmark; experimental; model test; hexapod, rectangular tank.

INTRODUCTION

During the 3rd sloshing symposium of ISOPE Conference (June 2011), a need was expressed to define reference test conditions to enable the comparison of experimental results from different testing facilities in the same way as has been done for years for model tests in towing tanks (especially in the framework of the International Towing Tank Conference, ITTC). GTT volunteered to organize such comparative tests: the first experimental benchmark on Sloshing Model Tests.

A specification was sent to the potential participants in September 2011 (see Gervaise, 2011). Fourteen test conditions at high filling levels have been proposed using a parallelepiped-shaped tank with one dimension much smaller than the two others (so-called 2D rectangular tank), in order to study two-dimensional liquid motions. Dynamic pressure measurements were asked for, with set-ups up to 72 sensors. The test fluids were simply water and air.

Nine participants answered positively to the call. Among them, results were received from Ecole Centrale de Marseille (ECM), Ecole Centrale de Nantes paired with Bureau Veritas (ECN-BV), Gaztransport et Technigaz (GTT), Marintek, Pusan National University (PNU), Universität Duisburg-Essen (UDE), Universidad Polytécnica de Madrid (UPM) and Universität Rostock (UR). GTT performed tests using their three testing installations, which are identified hereafter as GTT1, GTT2 and GTT3.

This paper presents the test conditions, the measurements, and the post-processing tools used to derive results that are summarized for seven, being chosen as the most significant, out of the fourteen conditions.

Due to the tight schedule for performing the tests, gathering all results and post-process the data, before writing this paper, it has not been possible yet to perform the in depth analysis that such results would deserve.

EXPERIMENTAL SET-UPS

The specification introduced testing conditions enabling the majority of the sloshing community to participate. The general objective was to compare the measurements obtained by each participant under the same conditions.

The benchmark tests were to be performed using a 2D rectangular tank, whose inner dimensions were 946 mm x 118 mm x 670 mm. These dimensions were supposed to be sufficiently small to be used by numerous participants and large enough to be representative of the most common scales used in Sloshing Model Tests.

The test fluids were water and air, the filling levels were chosen to obtain impacts on the ceiling of the tank. The liquid motions at high filling levels are commonly viewed as easier to master than those at lower filling levels.

Dynamic pressure recording on the ceiling was requested, at specified positions. However, a choice on the number of sensors to be used was allowed. Other measurements that could bring support for discussions were suggested.

Each participant has completed an ID form describing their facility and the way the benchmark tests were performed. The description included the sloshing motion rig, the tank, the sensors, their configuration and the data acquisition system used for the experimental benchmark. This section summarizes the results of this survey.

Test Rig

Each participant used their own sloshing motion rig(s) to perform the benchmark conditions, which require at least one horizontal and one vertical translation with one rotation. Characteristics of the different motion rigs used are presented in Table 1.

Table 1. Motion rig characteristics for each participant, the x axis being along the length of the tank, y along its width and z along its height.

Participant	Type	DOF			Precision		Independent measurement system
		Tx	Ry	Tz	T (mm)	R (°)	
ECM	hexapod	x	x	x			
ECN-BV	hexapod	x	x	x			
GTT1	hexapod	x	x	x	0.5	0.1	x
GTT2	hexapod	x	x	x	0.5	0.1	x
GTT3	hexapod	x	x	x	0.5	0.1	x
Marintek	cradle	x	x	x	0.1	0.05	x
PNU	hexapod	x	x	x			
UDE	hexapod	x	x	x	0.5	0.1	
UPM	other		x		-	0.07	
UR	cradle	x	x		0.1	0.5	x

Tank

The Benchmark tank's inner dimensions (946 mm x 118 mm x 670 mm) have been provided without margin of tolerance in the specification (Gervaise, 2011). The inner dimensions were to be checked by the participants and a precision was to be given. As shown in Table 2, all precision ranges are less than 1 mm.

University of Rostock used a tank of slightly smaller dimensions than specified so it could fit in their motion rig. Their results are presented after up-scaling to the right dimensions by Froude similarity.

GTT built two different tanks at the specified dimensions and shared them with some participants when it was convenient.

Table 2. Tank characteristics for each participant.

Participant	Tank dimensions (l x w x h in mm)	Precision (mm)	Particularity
ECM	From specifications	1	
ECN-BV	From specifications	1	Same tank as ECM
GTT1	From specifications	1	Same tank as ECM
GTT2	From specifications	1	Same tank as ECM
GTT3	From specifications	0.5	
Marintek	From specifications	0.5	Same tank as GTT3
PNU	From specifications		
UDE	From specifications	0.5	Same tank as GTT3
UPM	From specifications	0.1	
UR	700 x 87 x 496	0.5	Different scale (1:1.35)

Sensors

Six types of sensors have been used among the participants; their characteristics are given in Table 3 together with the acquisition frequency used for the tests.

Table 3. Sensor characteristics for each participant.

Participant	Type	Diameter (mm)	Acquisition frequency (kHz)
ECM	PCB 112A21	5.5	16.3 (harmonic)/ 25 (SIW)
ECN-BV	PCB 112A21	5.5	20
GTT1	PCB 112A21	5.5	20
GTT2	PCB 112A21	5.5	20
GTT3	PCB 112A21	5.5	50
Marintek	Kulite	~2.5	50
PNU	Kistler 211B5	5.5	20
UDE	Kulite XTM-190	3.8	50
UPM	Kulite XTL-190	~2.5	15
UR	PCB M106B	11	40

Sensor map

The complete specified configuration had 72 sensors divided in two rectangular arrays of 36, on each side of the ceiling, as shown in Figure 1.

A reduced configuration was also proposed with sensors 2-5, 8-11, 68-71 and 62-65 (a total of 16 sensors).

When having less than 16 sensors available, participants have defined their own sensors' map.

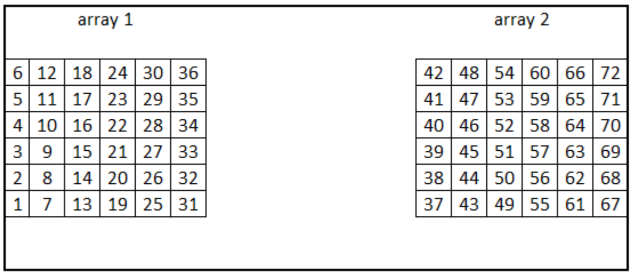

Figure 1. Specified sensor map and sensor numbering.

Each participant configuration is defined in Table 4. In order to summarize data, 4 areas have been defined:

- r1c1 : sensors 2-5
- r1c2 : sensors 8-11
- r2c1 : sensors 68-71
- r2c2 : sensors 62-65

r1 is the combination of r1c1 and r1c2, r2 of r2c1 and r2c2.

Due to a different scale, University of Rostock used a special configuration shown in Figure 2.

In order to be as fair as possible, comparisons are performed either using the reduced configuration or individual sensors.

More information about the different test setups can be found in the literature. For Ecole Centrale de Marseille (Molin, 2012), Bureau Veritas (Baudin, 2012), Gaztransport et Technigaz (Gervaise, 2009), Marintek (Graczyk, 2012), Pusan National University (Kim, 2009), Universidad Polytécnica de Madrid (Souto-Iglesias, 2011) and Universität Rostock (Schreier, 2009).

Table 4. Sensor configuration on each array for each participant, referring to the numbering defined in Figure 1. “-” indicates a continuous numbering.

Participant	Array 1	Array2
ECM	r1	r2
ECN-BV	r1	r2
GTT1	1-36	37-72
GTT2	1-36	37-72
GTT3	1-36	37-72
Marintek	1-36	37-72
PNU	1-36	37-72
UDE	8,10,15,17,20,22,27,29	45,47,50,52,57,59,62,64
UPM	1,4,6	67,70,72
UR	Defined in Figure 2	

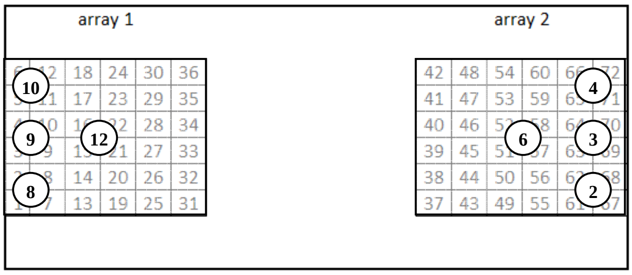

Figure 2. University of Rostock’s sensor map.

DISCUSSION ON THE CHOICE OF CONDITIONS

One of the objectives of the experimental Benchmark was to maximize the number of participants. As a result, the driving motions encompass only one or three Degrees of Freedom, and most of them only have one DoF. The diversity of excitations was aimed at covering a large screening at different high filling levels.

Harmonic Conditions (C01 to C08)

One Degree of Freedom harmonic motions (either translation or rotation) are, on a first approach, the simplest motions. They are easy to master and understand. 2500 periods were requested for each condition in order to insure a good statistical accuracy on pressures and events rate. A preliminary study at GTT had shown that for the selected conditions the events rate converged for 150 periods.

Nevertheless, such excitations can lead to unbalanced responses between symmetrical arrays depending on the excitation forcing. This is especially the case when the motion period is close to the resonance period. Motion periods varying around the resonance period of the fluid in the tank have been tested and eight conditions at high filling levels have been selected and proposed in the benchmark specifications.

Single Impact Wave (SIW) Conditions (C09 to C12)

Short excitations able to generate a single impact were proposed in order to test the repeatability of the measurements under the best conditions. A smooth motion combining a hyperbolic tangent and a sine were defined, creating a wave impact in a top corner of the tank.

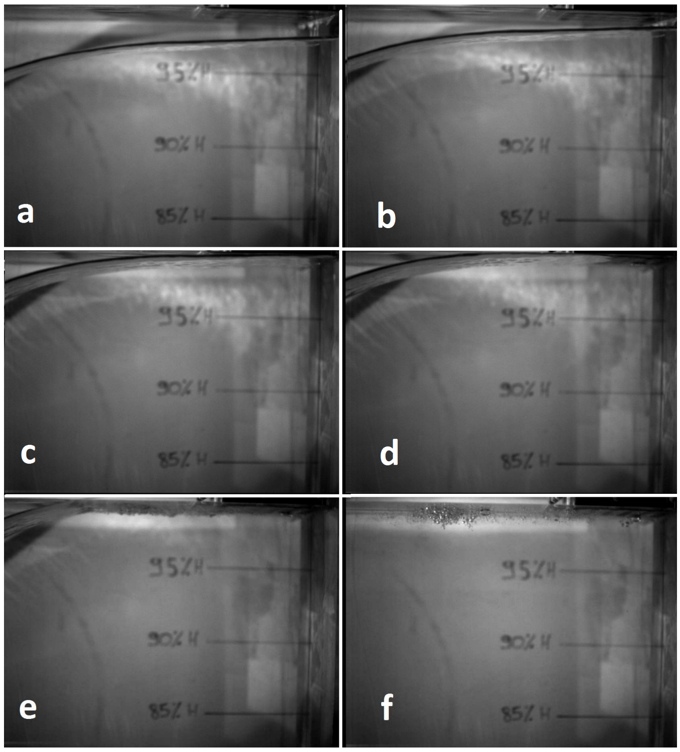

Figure 3. Snapshots from a high speed camera for a Single Impact Wave condition.

As shown in Figures 3.a~.f, the free surface is flat over the width of the tank, confirming a good bi-dimensional liquid motion behavior for this type of excitations.

Irregular Conditions (C13 and C14)

Irregular motions are the most representative of ship motions. This type of motion is commonly used by participants involved in sloshing assessments for new projects of LNG carriers by means of SMT. Irregular motions for conditions C13 and C14 have been derived from sea-keeping calculations on a LNG carrier by Froude scaling at scale 1:40.

Conditions summary

Table 5 summarizes all the conditions presented in this article with the post-processing duration used to analyze the data, depending on the number of repetitions gathered from each participant.

Table 5. Conditions post-processed in this article

Condition	Type	DoF	Period (s)	Amplitude (mm or °)	Post-processing duration
1	Harmonic	Tx	1.133	40	2000 periods
2	Harmonic	Tx	1.055	40	2000 periods
5	Harmonic	Ry	1.103	10	2000 periods
8	Harmonic	Ry	1.03	3	2000 periods
9	SIW	Tx	1.202	55	10 repetitions
13	Irregular	Tx	X	-	5 repetitions
14	Irregular	Tx-Ry-Tz	X	-	6 repetitions

Each participant performed tests for some or all of the specified conditions depending on their motion rig performance, the available testing time and the equipment. Furthermore, late or incomplete (at the time of writing) result delivery led to incomplete result samples. Due to these reasons, only GTT3 and PNU had data available for all the conditions.

POST-PROCESSING TOOLS

The specification encompasses test repetitions for each condition, so as to build sufficient statistical samples. The participants were requested to perform 5 repetitions of 500 periods for the harmonic conditions, 10 repetitions of one impact for the single impact wave conditions and 6 repetitions of about 47 minutes (5 hours full scale scaled down to 1:40 using a Froude similitude) for the irregular conditions. Out of those repetitions, the first 2000 periods for the harmonic conditions, the whole sample of 10 impacts for the SIW and at least 5 repetitions for the irregular conditions were used (see Table 5).

Sloshing Event

A sloshing event is determined by an exceeding of a pressure threshold ($P_{threshold}$) in a specific location of the tank. It lasts as long as one sensor is above the threshold. A given duration before the instant of the first up-crossing ($dt_{pre\text{-}crossing}$) and another one after the last down-crossing ($dt_{post\text{-}crossing}$) are set to take into account possible oscillations around the threshold. During an event's duration, the pressure increases from a low state to the observed maximum and then decreases to the low state.

If a single sensor is studied, a sensor event starts at a certain time $t_{start} = t_{crossing} - dt_{pre\text{-}crossing}$ before the pressure threshold is exceeded. It ends at t_{end}, a certain time after the pressure measured by the sensor has remained under $P_{threshold}$.

If a synchronized array of sensors is studied, then $t_{crossing}$ is defined as the instant the pressure measured by any sensor of the array exceeds for the first time the threshold. Then, t_{end} happens after the pressure measured by the last sensor of the array has remained below $P_{threshold}$ for a given time.

Using such definitions for t_{end}, the event duration $t_{event} = t_{end} - t_{start}$ depends on the impact type, the number of sensors and the duration above the threshold. The threshold was set at 5 kPa.

In order to encompass University of Rostock's larger scale and sensor size, GTT3 recordings have been further post-processed to derive area loads (150 and 200 mm^2 model area sizes) and University of Rostock's measurements scaled using a Froude similarity (x 1.35).

Analysis of the time pressure histories allows a fair comparison between events from different repetitions and different participants. To analyze the SIW conditions, a first selection is made on the channel which has recorded the highest pressure during a test, giving ten pressure signals for each participant coming from the ten repetitions. The average of the ten signals is computed and the pressure trace closest to the mean signal is selected to represent each participant. For the selected sensor, the maximum value of the pressure signal is recorded for all the repetitions. A mean and a standard deviation are computed. If the event shows pressure oscillations, then the second maximum on the pressure trace is also recorded and processed as for the first one. A FFT is performed to determine the pressure oscillation frequency, which is linked to the size of the gas pocket (Bogaert, 2010; Kimmoun, 2010).

Events Rate

The number of events recorded by a given sensor is calculated for each test. The Events Rate (ER) can be defined as a number of events per period or per a given duration (thus being an event frequency). For the harmonic conditions, the number of events is given per excitation period and is then representative of the number of events that were recorded over the number of events that could have happened. For the irregular conditions, the ER is given per minute.

The events rates are calculated for each individual sensor of the reduced configuration. Then the mean ER and the spatial standard deviation are computed for each sensor column. This provides information on the spatial behavior (most often the three-dimensional behavior) of each of the sensor columns.

Exceedance Probability

The exceedance probability is commonly used to define statistical characteristics and assess sloshing severity. It is here calculated using the order statistic medians (Filiben, 1975) for the sample of pressure peaks for the sensor having the highest ER on the reduced configuration. Exceedance probabilities for each participant are plotted over the post-processing duration defined in Table 5.

COMPARISON OF RESULTS

Harmonic Conditions

Due to the large amount of data gathered from each participant for all the conditions, only four representative harmonic conditions are presented in this article.

Condition C01 (80%H, Tx, amplitude 40 mm, period 1.133 s) represents a large translational excitation with a period equal to the theoretical resonance. Using a low threshold (5 kPa) and the definition of an event, C01 ER is close to 1 for most of the participants, i.e. the number of events on a considered sensor is close to the number of recorded periods as shown in Figure 4. Video recordings show the liquid similarly impacting one side of the ceiling after the other during one period.

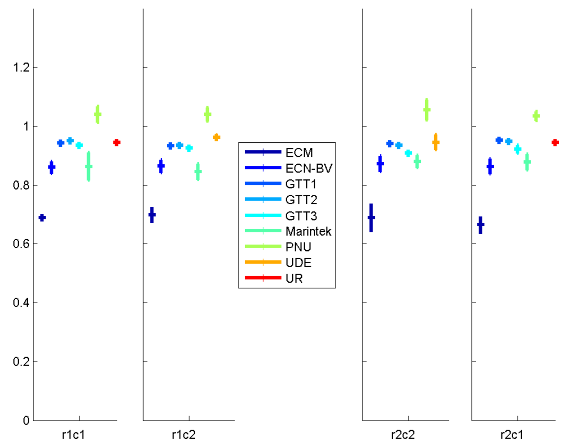

Figure 4. Mean ER and spatial standard deviation on several areas for C01 after 2000 periods.

Two behaviours are observed in Figure 4 when going from the columns close to the edges of the tank to the inner ones (r1c1 to r1c2 or r2c1 to r2c2): the mean ER either increases (ECN-BV, ECM, PNU) or decreases (GTT1, GTT2, GTT3, Marintek) with variations below 5%, which is not significant. For each participant, the ER spatial deviations are globally the same whatever the column that is observed. Whenever this is not the case, this would tend to show that some specific sensor(s) may have faced defects.

PNU and ECM are out of the group defined by the other participants. PNU's ER is above the other participants' and this observation is consistently performed throughout the whole condition set. Regarding ECM, their ERs are 0.75 times as large as the average of other participants excluding PNU. The authors do not have precise explanations for those observations. The causes have to be looked for in more detailed measurements.

Fig. 5 presents the exceedance probabilities for C01 after 2000 periods.

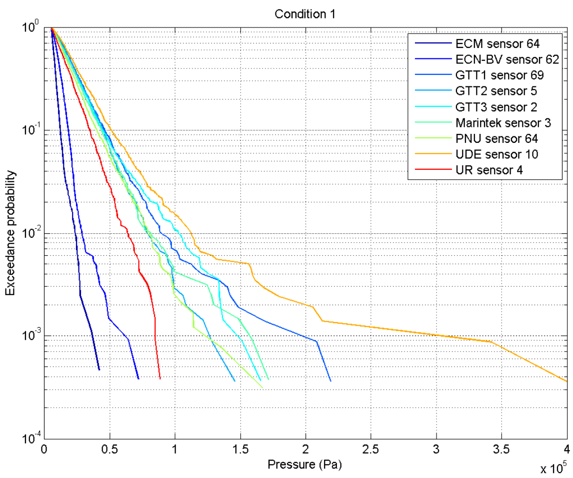

Figure 5. Exceedance probabilities for the sensor having the highest ER on the reduced configuration for C01 after 2000 periods.

Two difficulties arise when trying to compare the results obtained by the University of Rostock to the other participants: the test scale is smaller (dimensional ratio of 1:1.35) and the dynamic pressure sensors' sensitive surface is larger (11.05 mm diameter). In order to erase those differences, the results obtained by the University of Rostock are first scaled using a ratio of 1.35 obtained via a Froude similitude, and compared to results calculated over areas of 150 mm^2 and 200 mm^2. Those area sizes are on either sides of University of Rostock's pressure sensors' scaled sensitive surface (175 mm^2). Figure 6 presents the results obtained on GTT3 for the two mentioned areas compared to the University of Rostock's scaled measurements.

UR exceedance probability scaled at 1.35 is in between GTT3 – 150 mm^2 and GTT3 – 200 mm^2. As a consequence and according to Figure 5, GTT1, GTT2, GTT3, Marintek, PNU and UR have the same behavior for probabilities above 2.10^{-3}. At this probability level, 30% of dispersion on pressure values is observed between those participants. The observed dispersion at the tail of the curves is for the highest pressure values and the convergence of such points would have required more repetitions of this condition. For instance, exceedance probabilities computed with 4500 periods with additional tests from GTT, show a really good convergence till 3.10^{-3} and are within 30% at 10^{-3} as shown in Figure 7.

Obviously, the level of probability to compare results depends on the number of studied periods, and up to 2.10^{-3}, 2000 periods seems to be enough to allow fair comparisons for this condition. At this probability level, many of the participants converge to close results, although it is not the case for ECM, ECN-BV and UDE. As the trends shown by the probability of exceedance and/or the events rates obtained by those participants differ from the others', explanations should be provided.

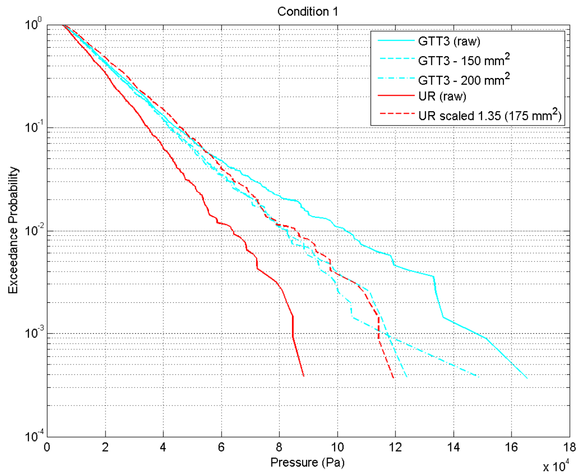

Figure 6. Exceedance probabilities for UR and GTT3 for different loaded area sizes for C01.

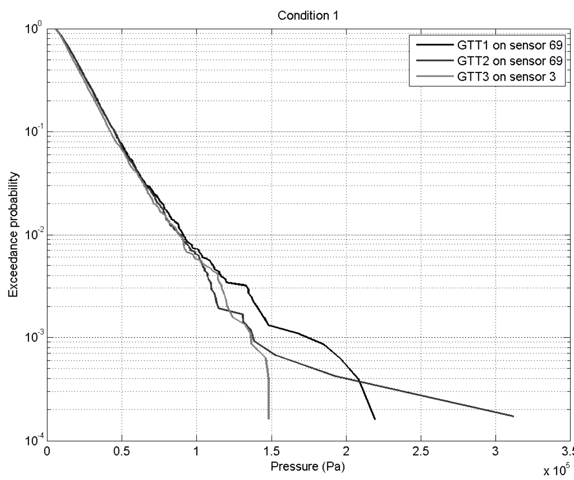

Figure 7. Exceedance probability for the sensor having the highest ER among the reduced configuration for C01 for GTT after 4500 periods.

Condition C02 (70%H, Tx, amplitude 40 mm, period 1.055 s) has a non-symmetric fluid response to a symmetric harmonic excitation. During one test of 500 periods, the fluid would almost always impact on the same panel, either r1 or r2, as illustrated in Figure 8, especially for GTT1 and GTT3 which have been only impacted on r1 along the five repetitions.

It can be observed that, for the majority of the participants, ERs on c1 and c2 are almost identical, and the ER gradient from one column to the other is very low on a given array. This is due to the fact that the impacts are mainly gas pockets, and no longitudinal gradient is observed. Actually, for participants using the complete sensor configuration, the ERs obtained for all sensors on the same side are almost identical. The large standard deviation shown by the results obtained by the University of Rostock on r2c1 is supposedly due to a defective sensor.

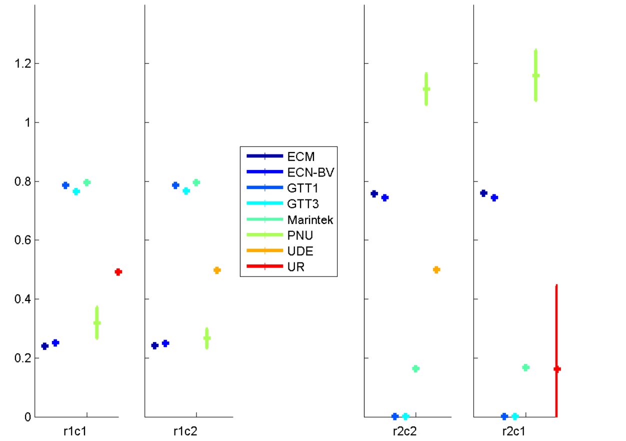

Figure 8. Mean ER and spatial standard deviation on several areas for C02 after 2000 periods.

This condition enhances a really sensitive and unstable mode. For instance, during one repetition at Marintek, a one-off small variation of the motion has been observed and switched the impacted panel from r1 to r2 as shown in Figure 9.

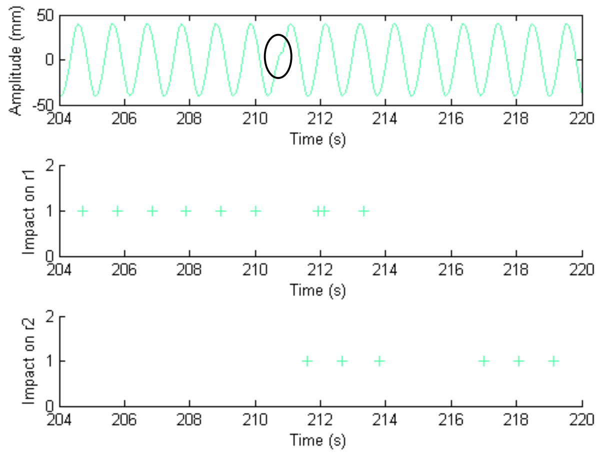

Figure 9. Marintek's recorded motion on C02 (repetition 3) with impacts on r1 and r2

In this non-symmetric condition, exceedance probabilities are still plotted on the sensor having the maximum ER. Results are shown in Figure 10.

UR results without any special treatment appear to be outside the group of curves formed by the others. Repeating the scaling as in C01, UR exceedance probability compared to GTT3 results with different membrane sizes are presented in Figure 11.

According to Figure 10 and Figure 11, two groups of participants are clearly separated. The first one includes UR, GTT3 and ECM and the second one ECN-BV, GTT1, Marintek and PNU. As explained previously, this really sensitive condition, enhancing a non-symmetric mode can be subject to motion variations regarding the command, tank imperfections and changes in environmental condition.

A motion study performed on GTT1 and GTT3, both belonging to different groups, shows no significant variations between repetitions regarding the input motion. Then, the tank used for GTT3 and Marintek is the same. Hence, motions and tank cannot explain the different behaviors observed in the exceedance probabilities. Only experimental and environmental conditions as, for example, the filling level, can be responsible for this difference. Nevertheless, the late result deliveries prevented us from analyzing these data.

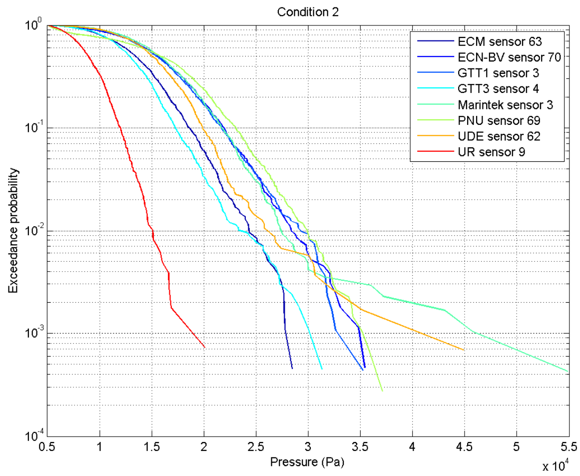

Figure 10. Exceedance probability for the sensor having the highest ER among the reduced configuration for C02 after 2000 periods.

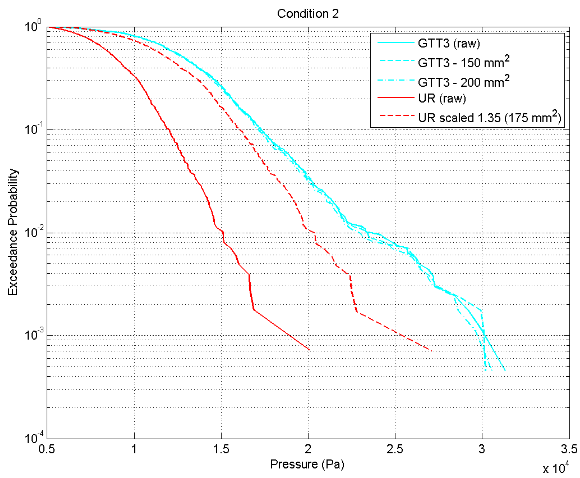

Figure 11. Exceedance probabilities for different loaded area sizes for C02.

Condition C05 (70%H, Ry, amplitude 10°, period 1.103 s) is a harmonic rotation with a center of rotation in the middle of the tank floor. This condition is close to the mechanical limits for most of the test rigs in terms of speed and acceleration, with a short period and a large pitch.

University of Madrid's ER is computed on one sensor on r1 and one on r2 which explains no spatial standard deviation is observed on those areas.

An ER gradient of about 5% is observed for almost all the participants from one column to the next one, tending to prove that the measured impacts are not large gas pockets. A thorough impact study on GTT3 confirmed this result and showed that most of the events present no or little pressure oscillation. When there are pressure oscillations, they happen after the maximum of the pressure, which is often due to a sharp rise (see Figure 13 for example).

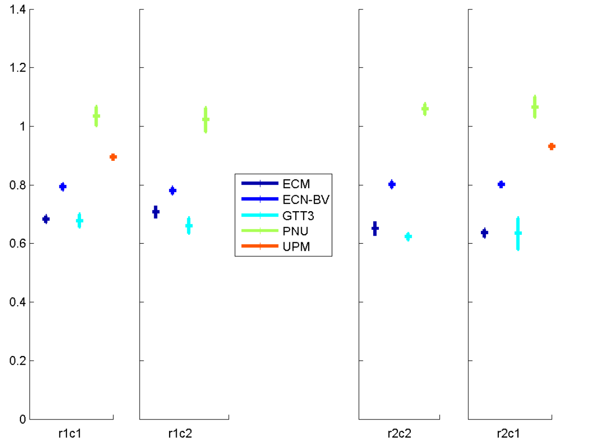

Figure 12. Mean ER and spatial standard deviation on several areas for C05 after 2000 periods.

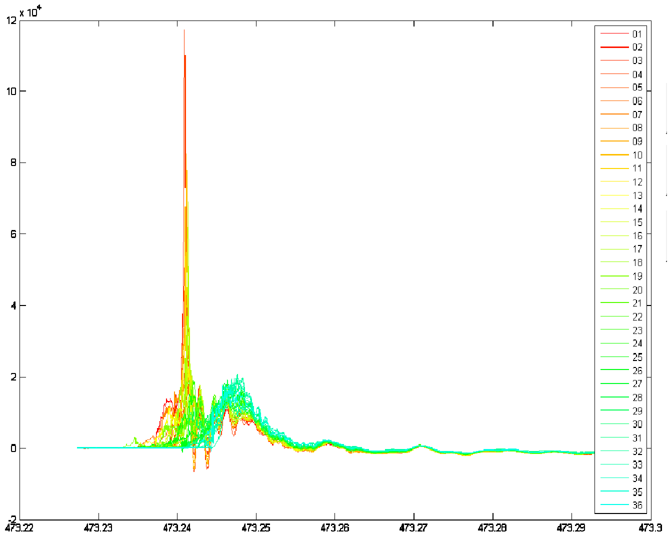

Figure 13. Pressure trace for GTT3, condition 05, test 01, strongest event on the complete impacted array.

Figure 14 shows the exceedance probability obtained by the different participants for condition C05.

The exceedance probabilities for this condition are scattered. Trend-wise, ECM and ECN-BV show the same behavior with pressure levels for a given probability lower than for the other participants, while PNU and UPM exhibit another behavior, with pressure levels for a given probability level larger than for the other participants. UPM's exceedance probability seems to reach a maximum around $4.5.10^4$ Pa. This behavior could be explained by the protective cap that is placed on top of the sensing patch on this type of Kulite sensor, as this cap cannot permit a good pressure transmission from the flow to the sensing patch when submitted to liquid pressure waves.

GTT3 shows a third behavior, with a more concave probability of exceedance. This may be due to the high acquisition frequency used.

C05 raised large differences between participants. This condition seems to be especially challenging for the test rigs and the sensors. Further investigations are needed to better explain those results.

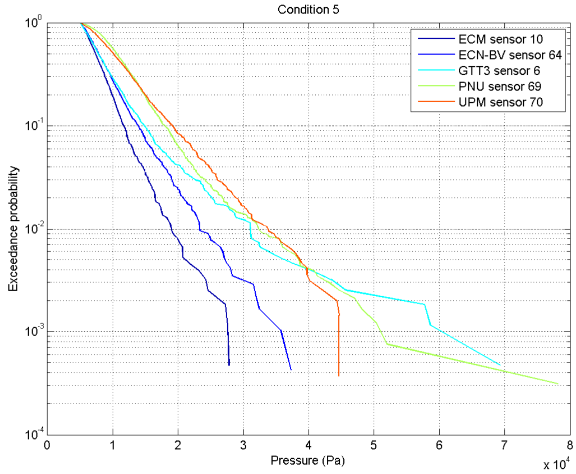

Figure 14. Exceedance probability for the sensor having the highest ER among the reduced configuration for C05 after 2000 periods.

Condition C08 (90%H, Ry, amplitude 3°, period 1.03 s) is a harmonic rotation with a center of rotation at the middle of the tank floor.

This condition has the weakest ERs recorded during the benchmark as shown in Figure 15.

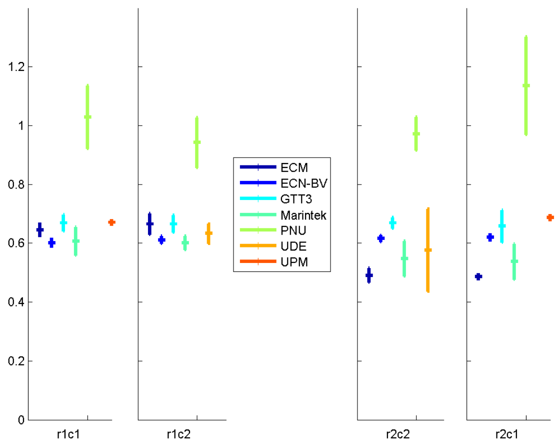

Figure 15. Mean ER and spatial standard deviation on several areas for C08 after 2000 periods.

As for C05, UPM's ERs are computed only on r1c1 and r2c1. A slight shift between arrays is observed for all the participants with spatial standard deviation on r2 for Marintek, questioning the 2D response of the flow. On each array, the ER is constant from one column to the other suggesting that most of the impacts are gas pockets covering the two columns. An impact study confirms this result for all the participants.

Figure 16 shows the exceedance probabilities obtained by all participants for condition C08.

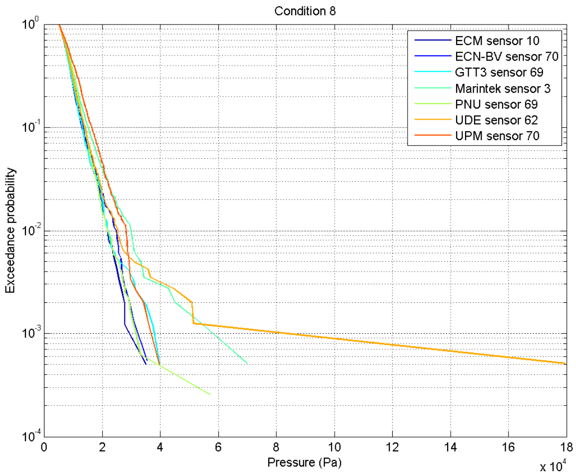

Figure 16. Exceedance probability for the sensor having the highest ER on the reduced configuration for C08 after 2000 periods.

ECM, ECN-BV, GTT3, PNU and UPM present similar behaviour. In this condition, and, certainly due to the type of impact, the protecting cap of UPM's sensors does not play a critical role. Marintek and UDE exhibit another behaviour, having recorded pressures much higher than the other participants.

This condition is interesting because the low events rate entails more difficulties to converge statistically than for the other conditions. It induces many gas pockets, which load the whole arrays.

Single Impact Waves

Condition C09 (70%H, Tx, amplitude 55 mm, period 1.202 s) is a single impact wave condition. Representative pressure histories are plotted according to the paragraph "post-processing tools" in Figure 17.

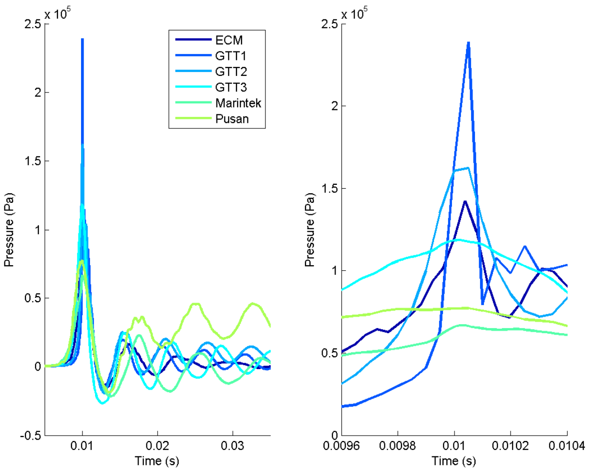

Figure 17. Pressure signatures for condition C09 as a function of time for several participants and several repetitions.

Although the maximum pressures recorded by the participants are different (in a ratio of almost 4), all the participants have reproduced the same gas pocket-type of impact. Pressure oscillations and high speed camera recordings show a gas pocket for this particular condition. As shown in Table 6, the volume of this air pocket seems to be globally conserved between participants as the pressure oscillation frequencies are within the same range.

Table 6. Characteristics of pressure signal for each participant

Participant	Repetitions	Gas pocket oscillation frequency (Hz)	Max. pressure		2nd max. pressure	
			Value (Pa)	std (%)	Value (Pa)	std (%)
ECM	9	145	1.31E+05	9.1	1.75E+04	13.5
GTT1	4	196	2.26E+05	5	2.34E+04	15.5
GTT2	5	184	1.82E+05	7.9	2.52E+04	10.3
GTT3	10	159	1.26E+05	7.7	2.57E+04	7.9
Marintek	10	124	6.41E+04	11.8	2.14E+04	27.1
PNU	10	137	8.40E+04	13.2	3.02E+04	79.6

Excluding GTT1 and GTT2, which do not have a sufficient number of tests (repetitions), GTT3 has the smallest relative standard deviation on repetitions on the first and second pressure maxima. This good repeatability may be due to the impact type, the high recording frequency used (50 kHz) or the removing of water drops sticking to the ceiling due to the surface tension. Those droplets have been observed to irregularly drop from the ceiling before the impact (UPM, GTT3), which perturbs the free surface and highly influences the pressure measurements.

The other Single Impact Waves Conditions show less repetitive results than condition C09 and are not displayed. Several causes can be highlighted.

The SIW excitations induce impacts on the two instrumented arrays, the first impact to be studied sometimes not having the largest amplitude. Some participants may have provided the measured pressure on the "wrong" array as there may have been confusion between the order of apparition of the events and their intensity. As the free surface must be unperturbed for these tests, only the first impact disregarding its amplitude is to be analyzed.

The pressure amplitude of the first impact may be too low to overrun the threshold and thus be analyzed. For some conditions, it is supposed that a small change in the excitation amplitude, frequency, the free surface shape at the beginning of the SIW motion or the liquid level, for example, can have a large influence on the dynamic pressure measurement.

Some recordings have shown drifts in the pressure signals, that do not appear to be pressure measurement, but could be electrical or thermal artifacts.

Those conditions are difficult to master, require a high precision in the test conditions, motion excitation and measurement as only one impact is measured and analyzed.

Irregular conditions

Condition C13 is driven by an irregular translation (Tx only) motion, has a filling level of 85% of the tank height with 6 repetitions of about 47 minutes excluding ramps. All the post-processed results are represented in 5 tests in order to include the maximum number of participants. ERs are defined for irregular conditions as the number of impacts per minute.

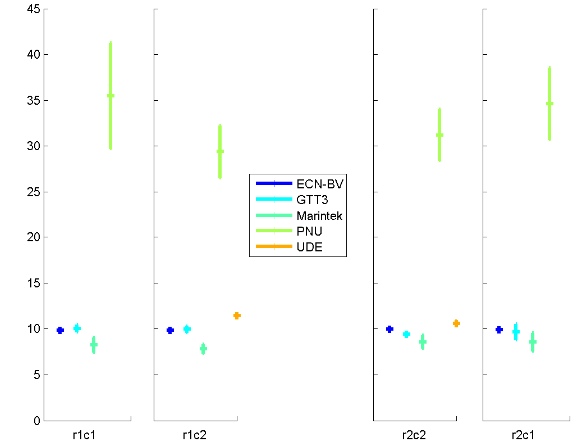

Figure 18. Mean ER and spatial standard deviation on several areas for C13 after 5 tests.

Figure 18 shows, again, the too large number of events recorded by PNU, and spatial deviation on GTT3, r2c1 and Marintek (all columns). This may be due to bad sensor behaviours (GTT3) or 3-D effects (Marintek).

The exceedance probabilities are plotted for the sensor showing the highest events rate on each of the two arrays, because the two arrays can exhibit different statistical behaviors. Figure 19 shows the results on array 1, whilst Figure 20 shows the results on array 2.

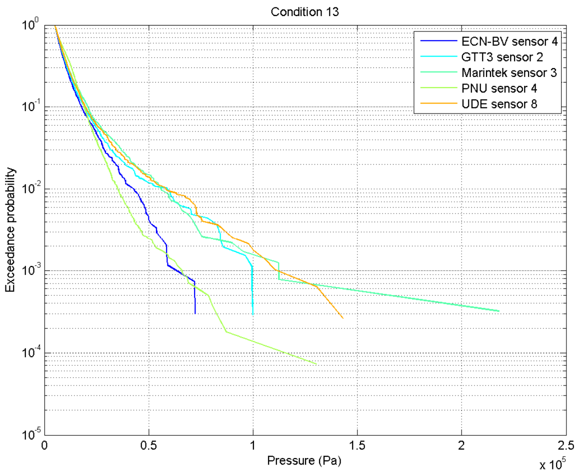

Figure 19. Exceedance probability for the sensor having the highest ER for C13 on r1 after 5 tests.

On array r2, all the participants follow the same trend. This is not the case on array r1, on which ECN-BV and PNU show lower pressures for a given probability level.

These asymmetries have not been investigated.

As C01, C13 shows a good convergence in terms of ERs and exceedance probabilities. Nevertheless, an investigation of the observed asymmetry and an acquisition frequency study (ECN-BV used an acquisition frequency of 20 kHz) are necessary to completely conclude on this condition.

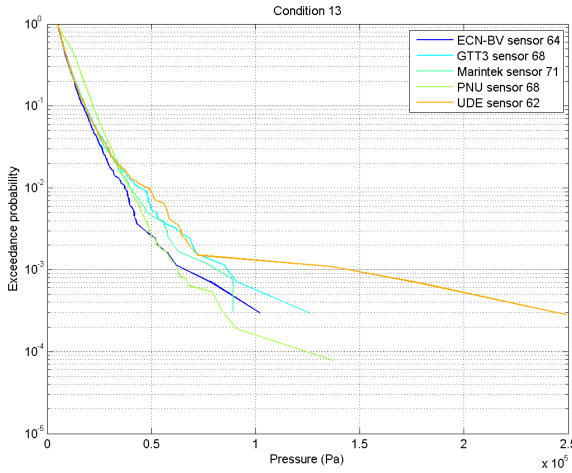

Figure 20. Exceedance probability for the sensor having the highest ER for C13 on r2 after 5 tests.

Condition C14 is an irregular motion at 85% of the tank height, with surge, heave and pitch, with 6 repetitions. As all the participants have performed the 6 repetitions of that condition, they have all been analyzed.

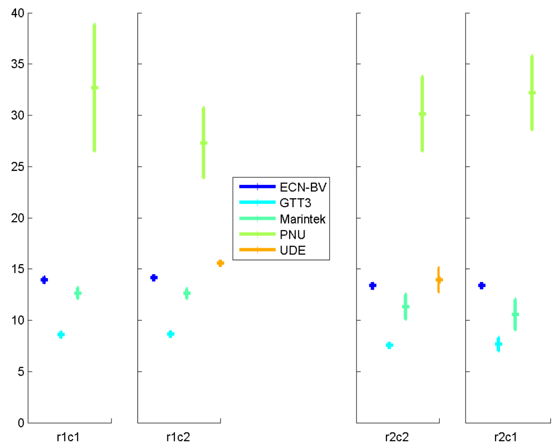

Figure 21. Mean ER and spatial standard deviation on several areas for C14 after 6 tests.

A large dispersion is observed among the participants on ERs for each area in Figure 21. This is the largest dispersion observed on all the benchmark conditions. Although it is difficult to generalize given the number of participants for this condition, there seems to be a group around 13 impacts per minute, with GTT3 and PNU outside of this trend.

This condition is slightly unsymmetrical as r2 presents a lower ER for all the participants except PNU. This non-symmetry is emphasized by the spatial deviation which is larger on r2 for GTT3, Marintek and UDE.

There is no or very little ER gradient from one column to the other whatever the observed array, again for all the participants except PNU. The study of the highest recorded pressures for GTT3 and Marintek (the only available at the time of writing), show complex impacts mixing ELP2 and ELP3 (Lafeber et al, 2012). The ELP3 behavior induced by bubbles or gas pockets is the most important at the end of the events, thus many of the sensors take part in these events, and the

ERs are very homogeneous on the first two columns of the given array.

Figure 22 and Figure 23 show the probabilities of exceedance for the sensor giving the maximum pressure on respectively array 1 and array 2.

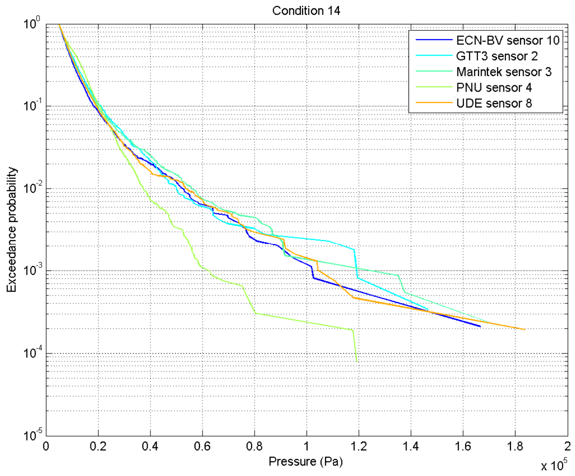

Figure 22. Exceedance probability for the sensor having the highest ER for C14 on r1 after 6 tests.

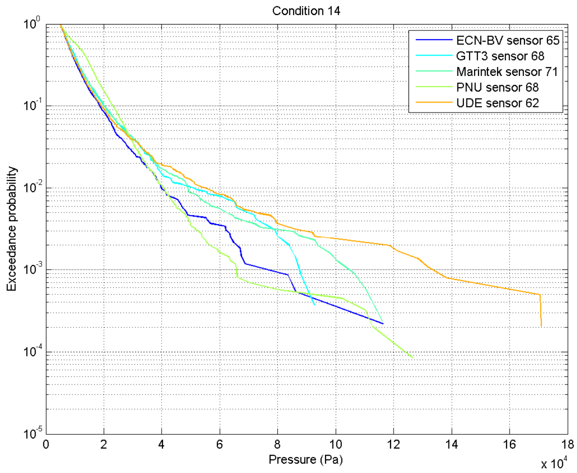

Figure 23. Exceedance probability for the sensor having the highest ER for C14 on r2 after 6 tests.

Even though large differences appear on ERs between participants, exceedance probabilities behave similarly. On r2, GTT3 and Marintek recorded higher pressure values than ECN, which may be explained by the acquisition frequency of 20 kHz for ECN and 50 kHz for the other participants. On this array and for these three participants, the tank may also play a role because GTT3 and Marintek have used the same tank.

Hence this condition seems to be discriminating on r2 on the acquisition frequency and/or the tank.

CONCLUSIONS

The first benchmark on Sloshing Model Tests was carried out during year 2011-2012 after a decision of the sloshing community, gathered for the third mini-symposium on Sloshing within ISOPE'2011 conference. This benchmark aimed at comparing the behaviour of the testing equipments used by laboratories working experimentally on sloshing.

Fourteen simple conditions have been specified for a 2D rectangular tank (one dimension much smaller than the other two) only for high filling levels (above 70% of the tank height). Different kinds of forced motions in the plane of the tank were imposed: harmonic motions (8), single wave impact (4) and irregular motions (2). Thirteen conditions were to be performed with only one degree of freedom (longitudinal translation or rotation around a perpendicular axis). Only one condition, one of the irregular excitations, was requested to be performed with three degrees of freedom.

A configuration of 72 pressure sensors split in two arrays in the corners of the ceiling was proposed. A simplified configuration, with only 16 sensors in two arrays, was also proposed for laboratories that did not own enough sensors.

The tests were expected to last from three to four days including the installment.

These simple requirements compared to what is currently used for any sloshing test campaign for a new project of LNG carrier, were intended to allow a maximum of laboratories to participate.

Nine laboratories participated to this benchmark. Eight of them could provide the data soon enough to have their results compiled in this paper.

The list of participants corresponds to almost the whole community involved in sloshing model tests, which by itself can be considered as a success. They range from universities with a 1 degree-of-freedom rig and a few sensors starting to deal with model tests, especially for academic research, to experimented laboratories with several hexapods and hundreds of sensors performing sloshing model tests regularly for the assessment of new projects of LNG carriers.

Most of the participants used the simplified configuration of pressure sensors or even less sensors and could not perform all the excitation conditions due to motion rig limitations. For the sake of clarity, only results related to 7 conditions (4 harmonic, 1 single wave impact and 2 irregular) were presented. They are representative and illustrate the main conclusions. Data from harmonic or irregular excitations were post-processed in order to compare the two most important types of statistical results for a sloshing assessment: the events rate (number of 'impacts' per a given duration) and curves of probability of pressure exceedance. Data from single wave impacts were simply used to compare the repeatability of the pressure results when impact conditions were almost perfectly repeated.

As many results were sent shortly before the writing of this article, the analysis of the results has not been carried out as far as it should be done. No result has been discarded for any condition as no evidence has been obtained for any mistake. Therefore the spreading of the results could sometime give a wrong impression.

Results from single wave impacts with one degree of freedom are rather good with most of the time a standard deviation smaller than 15% on the maximum pressure when the test is repeated ten times. This means that the ability of the participant's rigs to perform repeatedly a similar motion when driven by a given steering signal is good.

Statistical results from harmonic and irregular tests are of mixed quality:

- Events rates are reputed to be very stable and should normally be determined accurately with the number of repetitions proposed except with the tricky condition C02 leading to unsymmetrical liquid behaviour for a harmonic excitation. One participant has obviously much higher events rates than the average for all conditions. This could be due to a different definition of an event as the definition proposed could not lead to events rate larger than 1 for harmonic tests. However, this could not be proved. Even though these data were disregarded, the spreading of the results is still higher than expected for conditions C01, C02, C05 and C14, even for participants having the same type of pressure sensors.

- Probability of pressure exceedance curves are well known for being difficult to determine accurately. How to deal with this difficulty is at the heart of the job, where the experience intervenes. For both irregular tests, all curves are close for the high probability range (until 10^{-2}) and diverge afterwards. This seems to indicate non-converged results that could be improved by adding new repetitions of the tests, as it would be decided during a sloshing test campaign. For harmonic tests the discrepancies between the results start often from the root of the curves (high probability range) like for instance for tests C01, C02 and C05. This should be investigated further. As only irregular tests are used during a sloshing assessment of a LNG carrier, the spreading of the results for harmonic tests, is not so much worrying but deserves a relevant explanation.

First of all the analysis of these results should be carried out further in order to give relevant explanations to the strangest discrepancies. Every participant willing to continue the work will obtain all data, at least with the agreement of the others.

This first benchmark on sloshing model tests shows clearly how demanding sloshing experiments are. Results of sloshing model tests should not be considered naively as an exact reflect of the reality experienced within the tanks of LNG vessels: first of all they are only an experimental modeling of the reality that should be improved by constant R&D efforts for a better representativeness. Secondly, their reliability (repeatability of the statistical results in a given facility or comparison between two facilities) can only be achieved with much care. Experimental results should for instance not necessarily be considered as a reference for numerical validation.

The momentum gained with this collective work should not be stopped. This benchmark and the results obtained are considered as a photograph that could be used as the basis for the building of minimum requirements for sloshing tests good practices. A ad-hoc committee could be created, why not within ISOPE, in order to think about further analysis of the first benchmark, new possible benchmark tests and finally guidance for more reliable tests within the sloshing community, excluding any unrealistic objective related to a common methodology for sloshing assessment. The best way to keep such a process alive is to go forward step by step starting more complex tests only when having solved issues raised by simpler ones.

ACKNOWLEDGEMENTS

The authors wish to thank all the participants of the first benchmark on sloshing model tests and the organization of the ISOPE Conference who has supported this study.

The views expressed in the paper are those of the authors and do not necessarily represent the unanimous views of all the participants to this benchmark.

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