Repeatability and Two-Dimensionality of Model Scale Sloshing Impacts

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ABSTRACT

Canonical test cases for sloshing wave impact problems are presented and discussed. In these cases the experimental setup has been simplified seeking the highest feasible repeatability; a rectangular tank subjected to harmonic roll motion has been the tested configuration. Both lateral and roof impacts have been studied, since both cases are relevant in sloshing assessment and show specific dynamics. An analysis of the impact pressure of the first four impact events is provided in all cases. It has been found that not in all cases a Gaussian fitting of each individual peak is feasible. The tests have been conducted with both water and oil in order to obtain high and moderate Reynolds number data; the latter may be useful as simpler test cases to assess the capabilities of CFD codes in simulating sloshing impacts. The repeatability of impact pressure values increases dramatically when using oil. In addition, a study of the two-dimensionality of the problem using a tank configuration that can be adjusted to 4 different thicknesses has been carried out. Though the kinematics of the free surface does not change significantly in some of the cases, the impact pressure values of the first impact events changes substantially from the small to the large aspect ratios thus meaning that attention has to be paid to this issue when reference data is used for validation of 2D and 3D CFD codes.

KEY WORDS: Impact pressure, repeatability, two-dimensionality, statistical description.

INTRODUCTION

The state of the art sloshing assessment procedures for LNG vessels and floating production and storage units are based on risk assessment techniques (DNV, 2006; LRS, 2009; Gervaise et al., 2009; Kuo et al., 2009; Diebold, 2010). In such procedures, the statistical characterization of the sloshing loads relies on data obtained from experimental campaigns. Due to the extra costs that derive from these campaigns, a mid-term goal of designers is to characterize the sloshing loads using CFD technologies.

A widely known attempt to establish the current capabilities of CFD codes to achieve this target emerged from the Special 1st "Sloshing Dynamics" Symposium at ISOPE-2009 Conference, in which a benchmark test case was proposed to all participants(Kim et al., 2009). Contributions were presented using commercial codes (Godderidge et al., 2009) and meshless methods(Rafiee et al., 2009). Although this initiative was ground breaking, the outcomes have been limited, since as presented, the phenomena are yet too complex to be modeled with state of the art CFD technologies. Compared to that, the present test case aims at simplifying the setup significantly seeking the highest feasible repeatability. Repeatability in sloshing tests has not received, to our knowledge, much attention in the literature. Bogaert et al. (2010) pay attention to wave heights and Kimmoun et al. (2010) to pressure records, with a limited repetitions number. An analysis of this issue, focusing on the first 4 impacts is provided in the paper. In addition, an exact description of the tank motion, data for a larger fluid viscosity and a study of the two-dimensionality of the problem using a tank configuration that can be adjusted to 4 different thicknesses are documented. As a significant drawback, the ullage pressure has not been controlled, it is therefore the atmospheric, and the pressure values shown correspond to relative pressures. Previous experimental campaigns using the same rig and similar geometrical configurations have been described in reference (Botia-Vera et al., 2010); they have been used for CFD validation in references (Delorme et al., 2009; Khayyer and Gotoh, 2009; Brizzolara et al., xxxx; Cheng et al., 2009).

In the literature in general, a significant contribution is due to Lugni et al. (2006, 2010), who have described the extraordinary accelerations during wave impact events, though their work is not specifically arranged so as to be useful as reference for CFD validation attempts. Major contributions are due to Graczyk and Moan (2008); Graczyk et al. (2007) who provided statistical fitting for long series of sloshing impact pressure recordings. During ISOPE 2009 and 2010 relevant works have been presented covering aspects as crucial for industry as the scaling of impact pressures from models to prototypes. A significant contribution in these regards has been published as a journal paper(Yung et al., 2010).

The present paper is organized as follows: First the experimental setup is described, later lateral impacts for all conditions are discussed. Pressure peak values will be the monitored variables, leaving the analysis or rising times as in (Graczyk and Moan, 2008) for future studies. Subsequently, roof impacts are discussed. Some conclusions and future work threads are presented to close the paper.

EXPERIMENTAL SETUP

The used tank is rectangular, built with plexiglass. Its dimensions [mm] as well as the pressure sensor positions can be seen in figure 1. It is a 50 times scaled down longitudinal section of

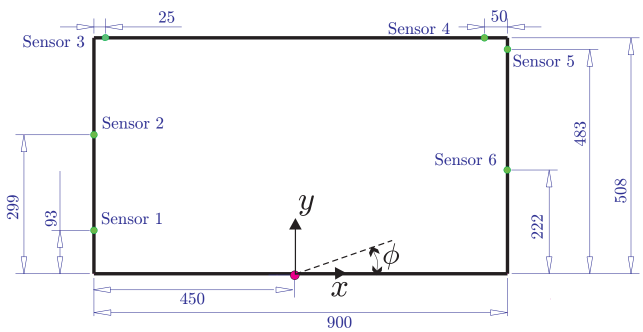

Figure 1: Tank dimensions and sensor positions

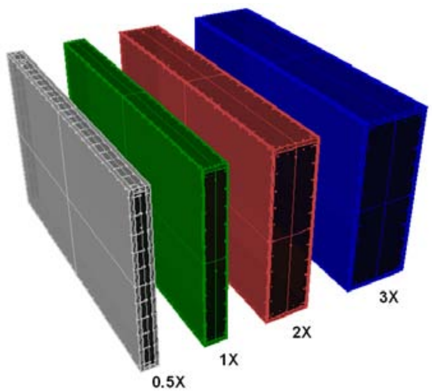

Figure 2: Tank thickness configurations

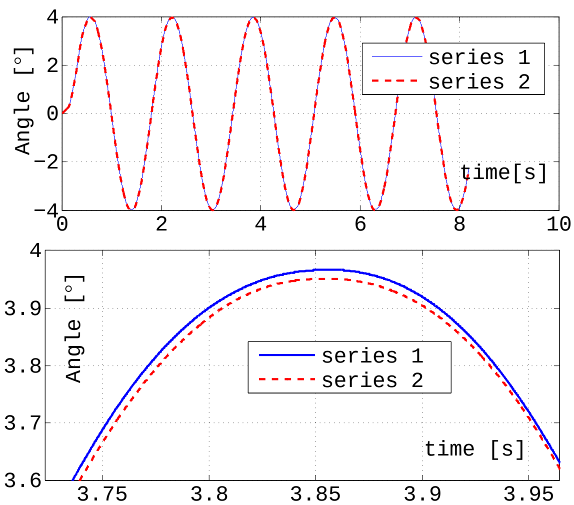

Figure 3: Roll angle samples series (top), zoom (bottom)

Table 1: Physical properties of the liquids: ρ for density, μ for the dynamic viscosity, ν for the kinematic viscosity, σ for surface tension

	ρ [kg/m^3]	μ [kg/m/s]	ν [m^2/s]	σ [kg/s^2]
Water	998	8.94e-4	8.96e-7	0.0728
Oil	900	0.045	5e-5	0.033

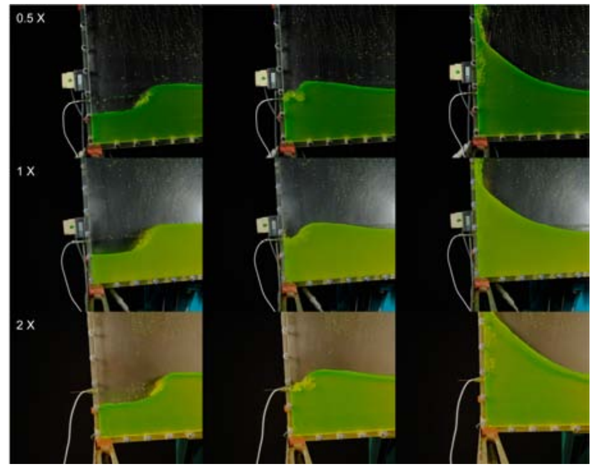

Figure 4: Lateral impact with water: evolution of free surface during first peak event

a LNG vessel tank. The dimension perpendicular to the paper (thickness hereinafter) can be changed by halving (0.5x cases), doubling (2x) and tripling (3x) the dimension (1x=62mm) of the original tank (figure 2). The sensors are placed exactly in the center plane of the tank in the thickness direction. The aim of these multiple configurations is to assess whether the data obtained from the experiments can be considered $2D$. The rotation center is at the center of the bottom side. The motion is harmonic, produced by a rod-crank mechanism, and its amplitude is 4 degrees. It is recorded with a precision of 0.0012 degrees and the repeatability threshold from one test to another is bounded by 0.0358 degrees (figure 3). All tests start from the same fixed position, with zero initial velocity. The liquids used in the experiments can be considered Newtonian at standard testing conditions and their physical properties are presented in table 1. If we define the Reynolds number from the liquid filling depth and the propagation velocity of an equivalent dam-break, Re of approximately 2000 and 100000 are considered, with a similar Webber number (of the order of 1000). Though some authors recommend sampling rates for the pressure of 40Khz and even higher(Repalle et al., 2010), we have used 20Khz, as in (Lugni et al., 2006; Graczyk and Moan, 2008). With our experimental capabilities, the underlaying electronic noise introduces a reference noise level of ±0.4 mb, therefore this will be an upper limit to our precision. For further details on the experimental setup, we forward the reader to references (Delorme et al., 2009; Souto-Iglesias et al., xxxx).

LATERAL IMPACTS

Lateral impact with water

The liquid level H for the lateral impact tests is $H = 93$ mm, corresponding to sensor 1 in figure 1. The first sloshing period for this depth is calculated using shallow water dispersion relation with $L = 900$ mm, to have $T_1 = 1.9171$ s. The period of oscillation for the water tests has been $0.85T_1 = 1.6295s$, which was found to be the period with the highest first pressure peak. For this filling ratio and period, overturning waves are generated that impact, as plunging breakers, on the lateral wall of the tank, close to the still water level surface (figure 4).

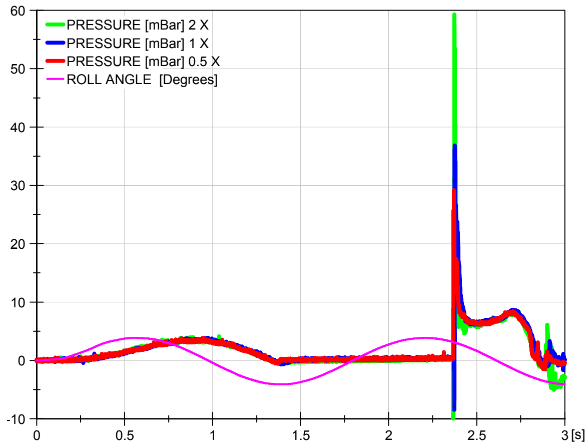

Figure 5: Lateral impact with water: First peak pressure register representative sample

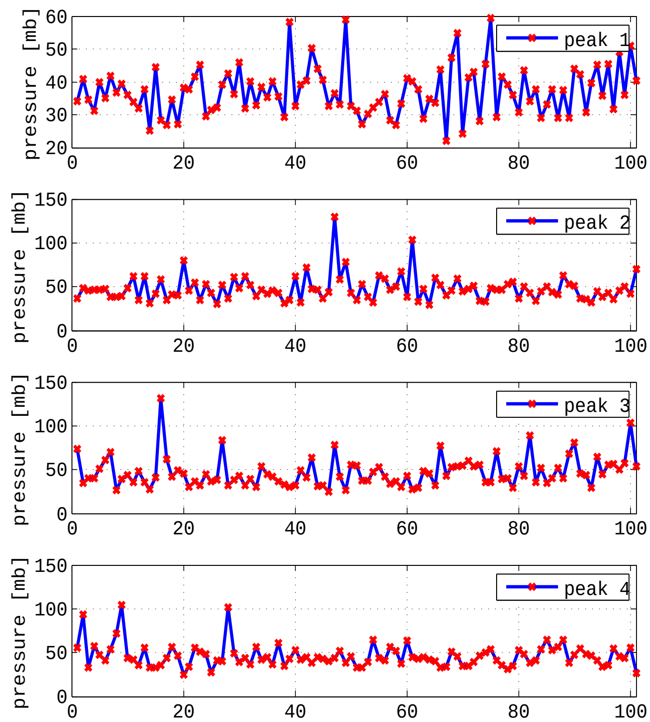

Figure 6: Lateral impact with water: Peaks 1-4, tank 1x

The impact pressure events are characterized by the church shape (figure 5). The impact pressure peak values show random behavior. To characterize it, for each of the cases considered in this paper, 100 experiments were run, leaving 3 minutes to allow the liquid come to rest between each run. Independence of the series of experiments has been checked using reverse arrangement tests(Bendat and Piersol, 2000). Representations of the first, second, third and fourth impact events pressure peak values for these 100 runs are presented in figure 6.

It is relevant to assess which kind of relationship there is between the statistical measures of the first 4 peaks and the peaks obtained in a long series of impacts (3 hours duration tests have been performed, that correspond to 20 hours full scale regular roll motion). In principle, having an statistical description of the pressure peak in each individual impact (either first, X_1, second, X_2, third, X_3, ...) is relevant for elaborating a statistical model of the maximum M_n of a number n of impacts (see Coles (2001), chapter 3).

$$M_n = \max\{X_1, X_2, X_3, X_4, \ldots, X_n\} \tag{1}$$

Using harmonic motion allows to have an impact in every cycle, which facilitates this type of analysis and prevents the need for using the POT (peak over threshold) approach. Harmonic motions were also used by Kim et al. (2010), who performed both 2D regular motion and 3D irregular motion experiments, but did not provide insight into the similarities or particularities of those regimes. A comparison of the pressure values in every cycle for the first four impacts is presented in figure 18. As in reference (Kim et al., 2009), the chosen measures are the maximum peak pressure, the average of one tenth highest pressures, the average of one third highest pressures and the average pressure. Apart from the first impact, the 2nd, 3rd and 4th behave similarly to the long run taking into account the average measures. The maximum changes dramatically. The 3 hours sample comprises around 7000 data whilst the first impact records include 100 data.

For CFD validation we aim at having a deterministic approach at least to the first impacts, for which the cumulative numerical error is not that large. In each individual experiment, the realization of each peak (1,2,3,4th) can be described as:

$$X_i = \text{true}(X_i) + \text{measurement error}, i = 1, 2, 3, 4$$

The measurement error comprises the one due to technical limitations and also the one that is due to the randomness of all physical phenomena. In the case of impact pressure, small variations in the initial conditions induce significant variation in the measurement X_i. The true value, true(X_i), will be estimated as the mean, $\overline{X}_i$, of the sample.

If the measurements organize around the mean following a normal distribution, we could then treat the phenomena using the standard uncertainty analysis techniques for quality assessment of experimental data(AIAA, 1995; Souto-Iglesias et al., xxxx). The distribution and the Gaussian fit for the first impact can be seen for the three thicknesses in the lateral case in figure 19. It can be appreciated that the distribution is not symmetric around the mean, and therefore the hypothesis of normality is difficult to sustain. Other distributions, like the generalized extreme value (GEV) (see Coles (2001)), provide better fit for the first impact in some of the cases. It is possible to resort to the analysis of the individual time histories during impact events to understand why the normal fit is not the most adequate in this case; this is nonetheless left out of this paper due to lack of space.

In regards to the two-dimensionality, in figure 4, a sequence of images with regards to the first impact event for the range of different thickness (0.5x, 1x, 2x) tanks is presented. The dynamics observed in the three cases sequence is similar. The pressure register presented in figure 5 are the ones closest to the mean peak of all 100 experiments for each thickness. Regardless of the similar dynamics of the impact for the 4 tanks (0.5x, 1x, 2x, 3x), as shown in figure 4, the impact pressure mean value increases substantially with the tank thickness until stabilizes from 2x to 3x. This is most noticeable looking at figure 5 and table 2, where the mean and standard deviation of the 100 tests is shown for each case. The conclusion from this is that some assessment of this kind is necessary previous to using experimental data for validation of 2D simulations.

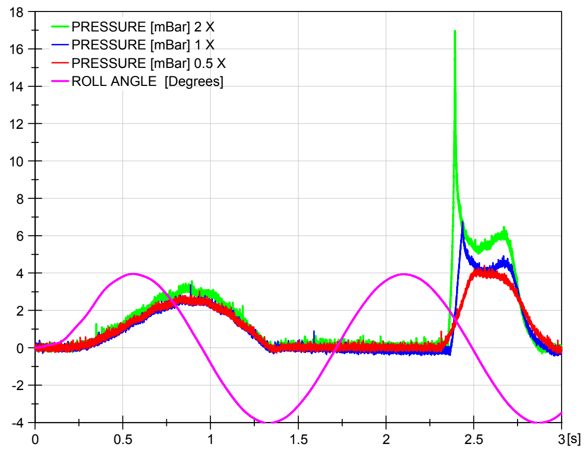

Figure 7: Lateral impact with oil: First peak pressure register

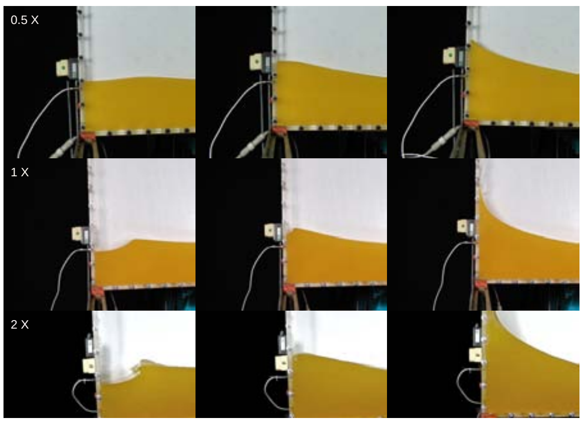

Figure 8: Lateral impact with oil: Free surface shape during first peak event

Lateral impact with oil

The mechanical properties of the oil used in the experiments are shown in table 1. The dynamics differs from water substantially, consistently with the drop in Reynolds number due to the increased kinematic viscosity, and the corresponding thickening of the boundary layer. If we take a look at the selected pressure registers of figure 7 for the first impact event, it is noticeable that no impact actually takes place for 0.5x tank. In figure 8, a sequence of images corresponding to events during the impact is shown. A breaking event, though mild, occurs only for 2x case. Case 1x is particularly relevant because no 3D structures seem to onset which makes it a good candidate for a laminar 3D simulation. It is noticeable as well that the repeatability of the impact pressure values increases dramatically compared to the water case, as can be observed from the statistics in table 2 (0.5x is missing since no impact takes place) and figure 13.

ROOF IMPACTS

Roof impact with water

The roof impacts are quite relevant in the industry due to the tank roof being often less reinforced than the bottom part and

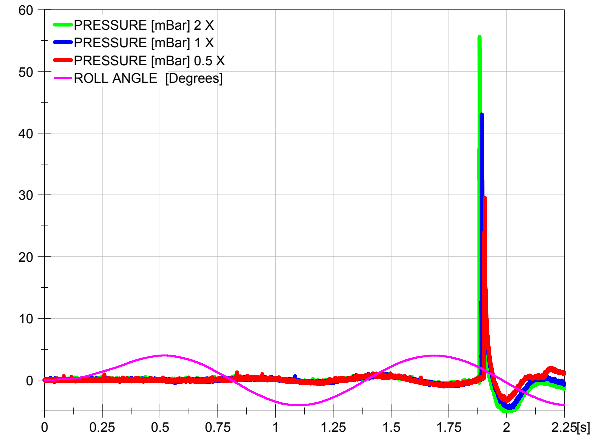

Figure 9: Roof impact with water: First peak pressure register

hence subject of higher risks for same order impact pressure values. The liquid level for this set of experiments corresponds to a 70% fill ratio. The period of oscillation is the first sloshing period for this depth, $T_1 = 1.1676s$ and roof impacts are generated in each cycle. In this configuration neither overturning nor breaking waves are generated. It seems that air is not entrapped during the impact event and this could have a substantial influence on the pressure field(Lugni et al., 2006). This difference makes this case a distinct challenge compared to the lateral sloshing one, maybe more appropriate for monophasic computational models. A sequence of images during the first impact event for the range of different thickness (0.5x, 1x, 2x) tanks is shown in figure 10. The general dynamics seems similar for the three thicknesses. Likewise the lateral impacts, 100 experiments were run, leaving a 3 minutes gap between each run. The registers presented in figure 9, corresponding to sensor 3 in figure 1, are those whose pressure peak is closest to the mean peak of the 100 experiments. As for the lateral case, the mean of the pressure peak increases with the tank thickness, thus meaning the case cannot be considered in principle two-dimensional. The repeatability of the case is similar to the water lateral case of previous section, as can be observed from the statistics in table 2, but it is noticeable that the ratio between the standard deviation and the mean is smaller and skewness to the right is less patent. Actually, the normal fitting for the first impact could be reasonable (see figure 16). It is relevant to mention that there are significant differences between the first 4 impacts as can be appreciated through the statistical measures shown in figure 14.

Roof impact with oil

The dynamics is similar to the water roof impact case because air is not entrapped during the impact. This was not the case in lateral impact in which air was entrapped in the water case but not in the oil case. A sequence of images for each thickness is shown in figure 12. As can be seen, in the 0.5x case impact does not occur. For 1x case the the impact takes place after the second oscillation cycle, and for the 2x case the impact takes place after the first cycle. This in itself provides enough grounds to state that the case is not two-dimensional, which is confirmed by observing the pressure registers, shown in figure 11. Notwithstanding this, the stats of the first impact for both cases are pretty similar (see table 2). The repeatability of the first pressure peak is significant

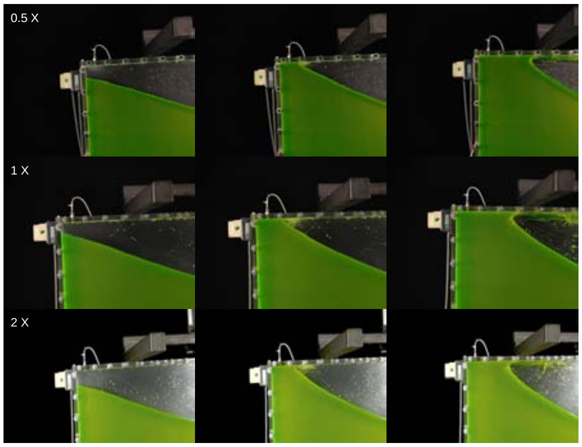

Figure 10: Roof impact with water: Free surface shape during first peak event

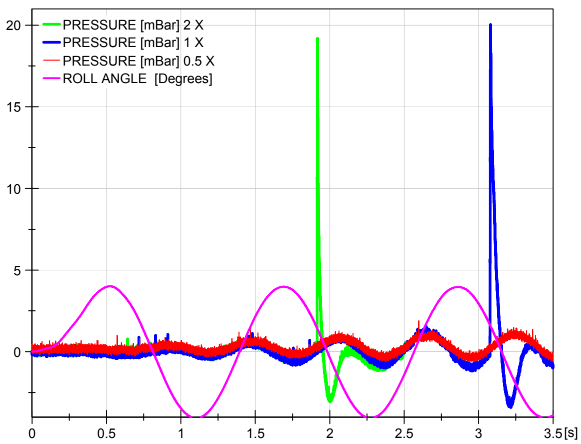

Figure 11: Roof impact with oil: First peak pressure register

though less evident than for the oil lateral impact, as can be noticed comparing the stats in table 2 and in figure 15. The normal fitting for the first impact could be reasonable (see figure 17) but further investigation is necessary since the density histograms for the first impact present substantial tendency changes, mainly for the 2X case (figure 17(b)), suggesting in this case even a puzzling bimodal nature of the distribution.

CONCLUSIONS

Canonical test cases for sloshing wave impact problems have been presented and discussed. Both lateral and roof impact have been studied. A statistical analysis of the impact pressure of the first impact events has been provided in all cases. A Gaussian fitting is not feasible for all cases. The tests have been conducted with both water and oil in order to obtain high and moderate Reynolds number data. The repeatability of impact pressure values increases dramatically when using oil. A study of the two-dimensionality of the problem using a tank configuration that can be adjusted to 4 different thicknesses has been carried out. It has been shown that the impact pressure values of the first impact events change substantially from the small to the large aspect ratios thus meaning that attention has to be paid to this

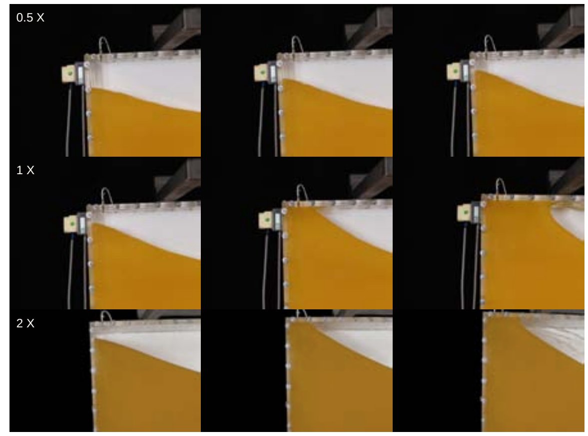

Figure 12: Roof impact with oil: Free surface shape during first peak event

issue when reference data is used for validation of 2D and 3D CFD codes. All the necessary information to implement them in CFD simulation codes has been made available through the web link http://canal.etsin.upm.es/ftp/SPHERIC_BENCHMARKS/. Main future work thread are listed below:

1. Depressurize the tank in order to perform experiments with reduced ullage pressure.
2. The statistical model that fits the individual impacts is far from being clear at this stage. 100 samples have not been enough to characterize this phenomenon from the statistical point of view and indicators are needed in order to assess which is the best fitting.
3. Incorporate the model to an uncertainty analysis in order to provide, with error bounds, data useful for CFD validation.
4. Modify cases configuration (period, amplitude, distance to the rotation center, etc...) to look for those with highest pressure peak values and repeatability.
5. Perform long measurements in order to provide statistical information about the peaks distribution, considering irregular motion of the tank.

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Table 2: Peak 1 stats (mean, standard deviation, skewness). (L) for lateral, (R) for roof, (W) for water, (O) for oil

Test	$\overline{X}_1$[mb]	σ [mb]	$\sigma/\overline{X}_1$	s
LW-0.5x	28.91	5.52	0.19	0.79
LW-1x	37.10	7.32	0.20	0.76
LW-2x	58.53	11.28	0.19	1.16
LW-3x	59.49	8.07	0.14	0.02
LO-1x	6.86	0.16	0.02	0.07
LO-2x	16.94	0.25	0.01	3.26
RW-0.5x	29.90	3.25	0.11	0.25
RW-1x	43.00	7.99	0.19	0.60
RW-2x	55.75	6.98	0.13	-0.32
RO-1x	20.18	2.34	0.12	0.02
RO-2x	19.17	2.50	0.13	-0.11

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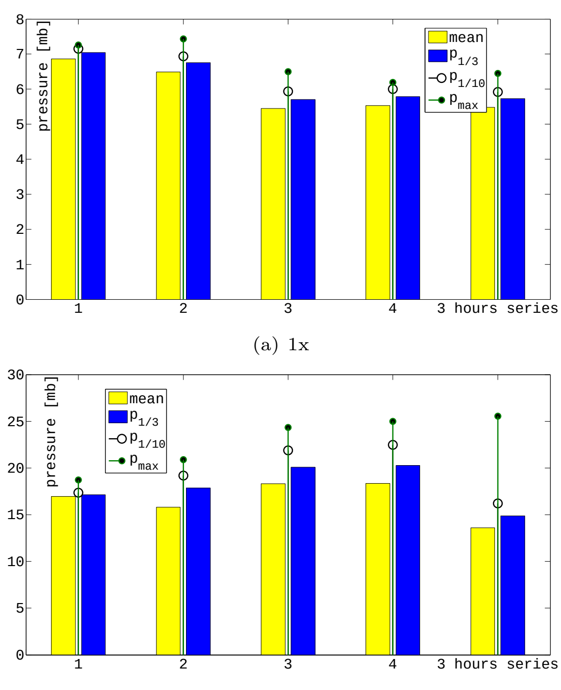
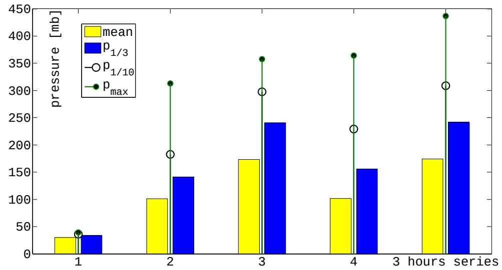


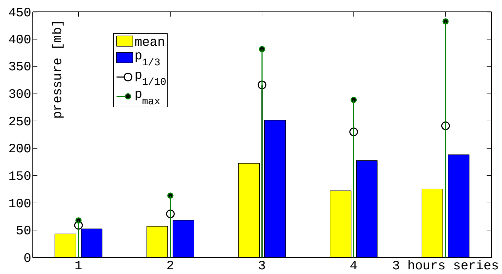
(a) 1x

(b) 2x

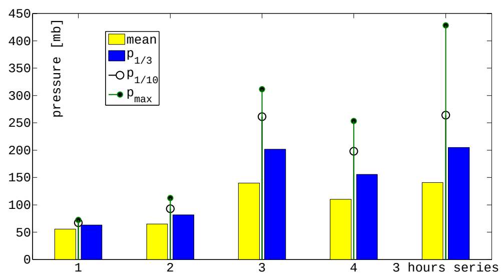
Figure 13: Lateral impact with oil: peaks 1-4 (100 samples) + 3 hours continuous sample



(a) 0.5x

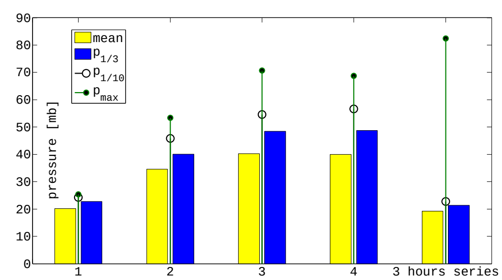


(b) 1x

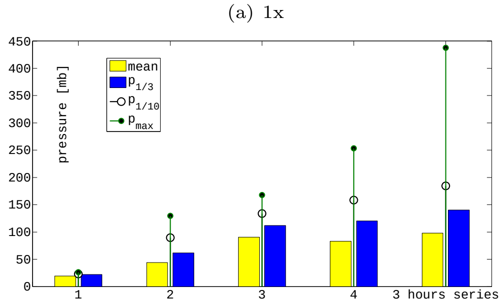


(c) 2x

Figure 14: Roof impact with water: peaks 1-4 (100 samples) + 3 hours continuous sample

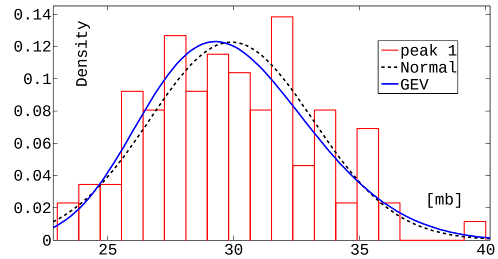


(a) 1x

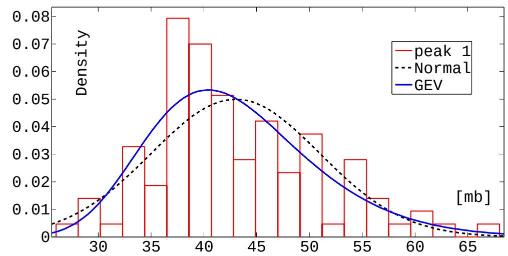


(b) 2x

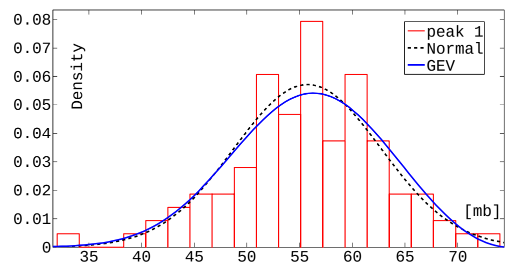
Figure 15: Roof impact with oil: peaks 1-4 (100 samples) + 3 hours continuous sample



(a) 0.5x

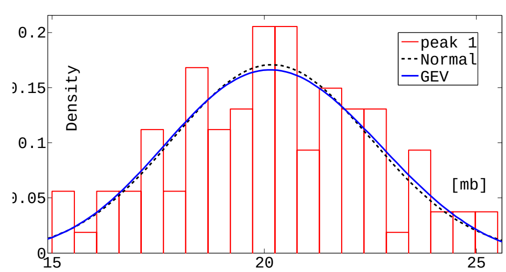


(b) 1x

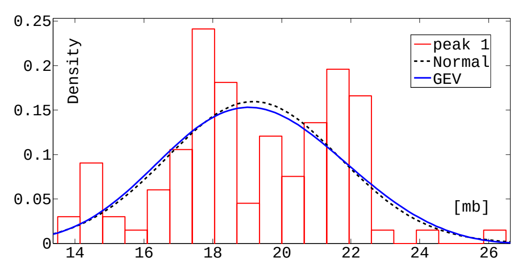


(c) 2x

Figure 16: Roof impact with water: First peak distribution fitting (100 samples)

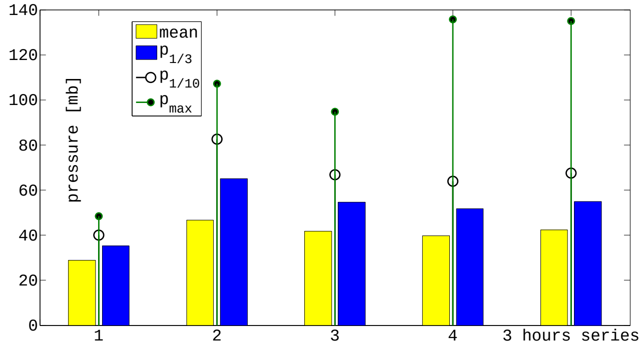


(a) 1x

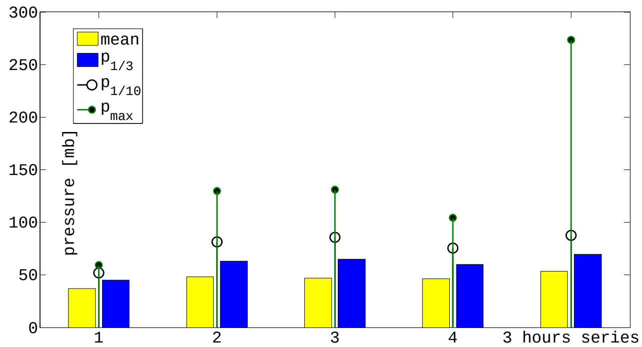


(b) 2x

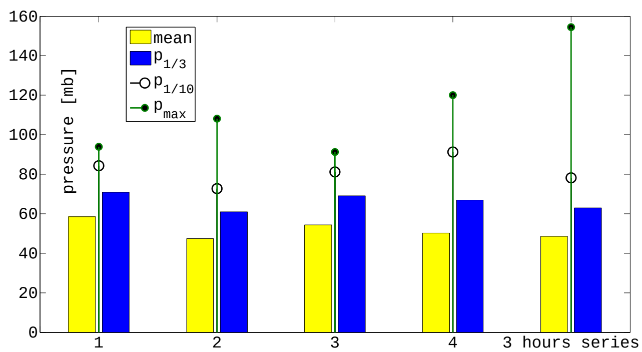
Figure 17: Roof impact with oil: First peak distribution fitting (100 samples)



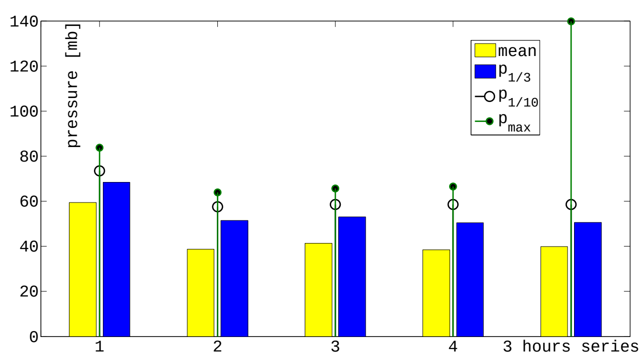
(a) 0.5x



(b) 1x

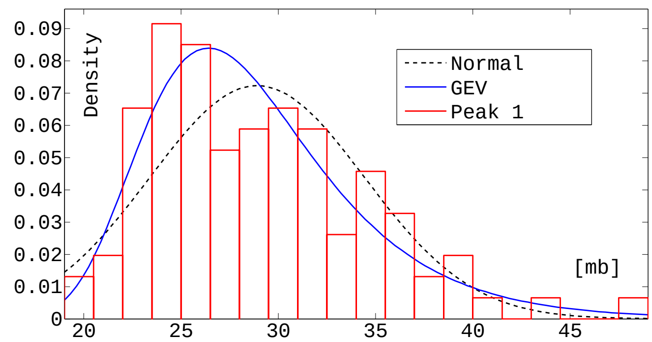


(c) 2x

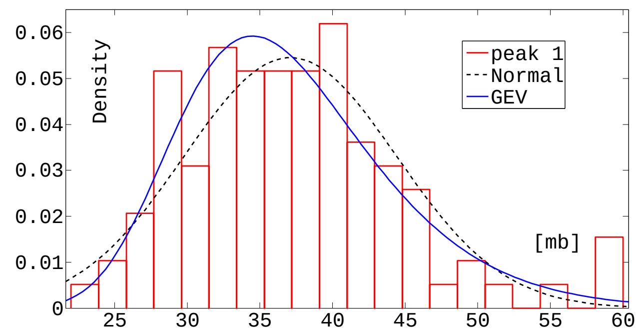


(d) 3x

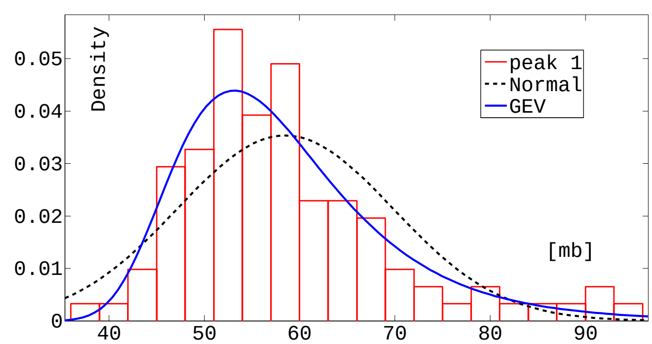
Figure 18: Lateral impact with water: peaks 1-4 (100 samples) + 3 hours continuous sample



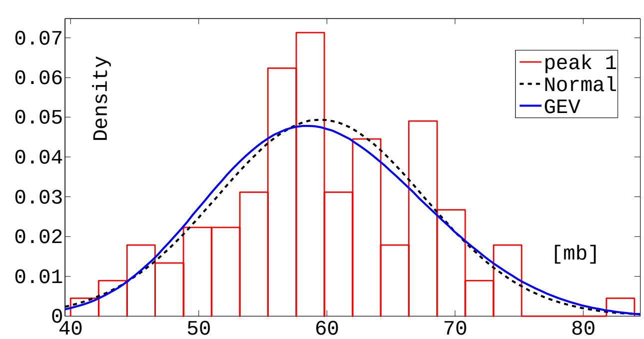
(a) 0.5x



(b) 1x



(c) 2x



(d) 3x

Figure 19: Lateral impact with water: First peak distribution fitting (100 samples)