Experimental Study of Surface Tension Effects on Sloshing Impact loads

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1. INTRODUCTION

It is well known that liquid impacts lead to a large variability of local pressure measurements. This is experienced for instance during wave impact tests in flume tanks or during sloshing model tests even when, starting from rest, the tests succeed to repeat precisely the same global wave shape before a first impact. This variability of local loads is the malediction of liquid impact studies: It imposes to repeat many times the different long duration conditions studied during sloshing model tests to gather significant samples of pressure peaks for relevant statistics. It also makes the influence of any relevant parameter on impact loads more complex to discriminate experimentally. Furthermore, it prevents any serious experimental validation of numerical simulations as far as local pressures are concerned. Despite its crucial influence, the variability of local pressures has been considered as a fatality and their physical causes starts only to be studied.

As shown in Frihat et al. (2016), there are three main sources of variability: the development of free surface instabilities induced by a strong shearing gas flow at the interface just before any impact; the fall of liquid droplets onto the interface after splashing and the production/evolution of bubbles within the liquid. All these sources of variability are generated by gas-liquid interactions during wave breakings and liquid impacts. They are strongly related to the surface tension at the interface. They not only lead to a large variability of the local pressures but also, progressively, to variations of the global wave shapes even in between impacts. Fortunately the perturbations induced by these different phenomena dissipate thanks to viscous friction, increased by turbulence within the thick perturbed interface, but also to the regularization role of the forced motions and gravity. After a certain lapse of time a balance between variability production and dissipation/regularization is reached in such a way that when a sloshing test is repeated, even after a long test duration, the flow can always been considered as a perturbed flow with regard to an ideal global flow: the perturbations do not build up sufficiently impact after impact to lead to divergent flows. Indeed, Karimi et al. (2015) showed that if a small uncertainty window is introduced, impacts always happen at the same instants when the same condition is repeated. Such impacts are referred to as *coincident impacts*.

When considering any given coincident impact, it has been shown (Frihat et al., 2016) that only a short sequence of the irregular excitation motions, extracted from the signals of the full irregular motions just before the selected impact, is sufficient to generate a statistical distribution of measured pressure peaks by a relevant number of repetitions equivalent to the reference statistical distribution of pressure peaks for the coincident impact obtained by a relevant number of repetitions of the full irregular tests. The tests with a short sequence of motions are called *singularization tests*. Whatever the coincident impact selected, the statistical distribution obtained by repetitions of singularization tests is equivalent (within the meaning of Anderson-Darling test) to the reference one as soon as the duration of the test is larger than a threshold m_e of a few tens of seconds (typically 90 s at scale 1:20). Furthermore, changing the initial flow conditions for a singularization test does not affect the statistical distribution as soon as the test duration is larger than m_e. For a coincident impact occurring at a time t_x, what happened before t_x-m_e does not matter. Thus, m_e can be considered as a flow memory.

This abstract shows preliminary results from a more complete study on the influence of surface tension on sloshing impact loads through 2D sloshing tests with different aqueous solutions.

2. TEST SET-UP AND TEST CONDITIONS

The model tank is made of PMMA and represents, at scale 1:20, a transverse slice of tank#2 (out of 4) of a membrane LNG carrier with a total capacity of 152.000 m^3. The inner tank geometry at scale 1 is

38.970 m wide and 26.970 m high. The model tank was placed on the platform of a hexapod (Stewart platform), checking carefully its alignment with regard to the reference system of the platform and the positioning of the center of the tank bottom.

A rectangular sensor array of 27x6 PCB 112A21 piezo-electric pressure sensors was located on the portside vertical wall and covered the impact areas of interest. The sensors have a sensitive circular area of 5.5 mm diameter. They were arranged on horizontal and vertical lines with a 1 cm distance between two consecutive sensors. The data acquisition system sampled at 40 kHz. The data acquisition software recorded data continuously in a buffer but stored data only for short times around impact events when a threshold of 100 mbar was exceeded. A high speed camera (Phantom V7.2) was fixed to the platform of the hexapod looking at the impact area, also on the portside of the tank, through the transverse transparent wall. It acquired at 4000 fps and was synchronized with the pressure acquisition. Series of LEDs located in the background of the tank ensured an indirect lighting.

All results presented in this abstract were performed with different aqueous solutions, including pure water as a reference, with a filling ratio of 20% of the tank height and with air as ullage gas. The different aqueous solutions were obtained either with ethanol, with a surfactant or with Propanol-1. The surface tensions of the different solutions range from 0.030 to 0.072. These different mixtures and their main properties are summarized in Table 1.

Table 1 Different aqueous solutions tested and their properties at 25°C

Name	Composition	Density (kg/m^3)	Surface tension (N/m)
Mixture 1	Water	998	0.072
Mixture 2	Water + Ethanol	997	0.060
Mixture 3	Water + Surfactant	998	0.040
Mixture 4	Water + Surfactant	998	0.035
Mixture 5	Water + Propanol-1	985	0.035
Mixture 6	Water + Propanol-1	974	0.030

Two types of forced motions in the plane of the tank have been studied: short excitations (a few seconds) starting from rest and leading to a single impact, referred to as Single Impact Waves (SIW), and singularization tests (SING) with a duration of 90 s for different coincident impacts corresponding to irregular ship motions as calculated at scale 1 for a five-hour transverse sea-state of significant wave height H_s=6 m, after relevant down-scaling. Whatever the type of excitation, at least 100 repetitions of each condition are carried out to build the statistics of peaks over threshold. For each impact, only the maximum pressure among the 162 pressure signals (sensor of max.), is considered in the statistical samples shown in this abstract. As the densities of the different mixtures shown in Table 1 are slightly different, the pressures are scaled to the density of pure water (Mixture 1) before comparisons.

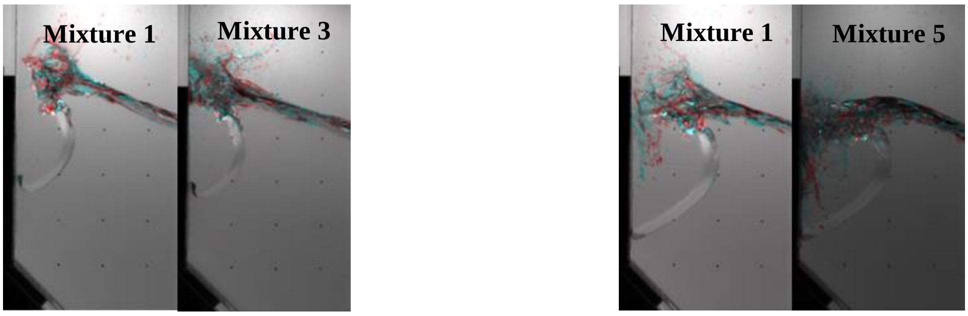
3. EFFECTS OF SURFACE TENSION ON SINGLE IMPACT WAVES

The results presented in this section correspond to two SIWs defined with pure sway motions. Nevertheless, they illustrate general trends for SIW-type of excitations. The sway motion signals *y(t)* are composed of half a period *T/2* of a cosine connected to fifth degree polynomial ramps at both ends. These ramps last also *T/2* and enable a smooth connection of position, first and second derivatives with the cosine part of the curve. The period has been fixed to the resonant period of the liquid: *T*=2.47 s. The amplitudes selected are *a*=236 mm for SIW_1 and *a*=244 mm for SIW_2.

Whatever the SIW studied, there is an excellent repeatability of the wave shape until free surface instabilities develop around the crest area when the wave starts to break. Even when these instabilities are fully developed the wave shape just before impact repeats very well from the trough to the base of the crest. Only the cap of the crest differs from one repetition to another although a characteristic pattern remains. For SIWs, as the free surface starts at rest, the development of free surface instabilities can thus be considered as the only source of variability of the flow.

Fig. 1 compares the wave shapes as captured by the high speed camera just before impact when using pure water or Mixture 3 for SIW_1 (left) and when using pure water or Mixture 5 for SIW_2 (right). Each picture actually corresponds to the superimposition of two pictures representing the same instant of a test condition repeated twice. When superimposed, both images are post-processed so that pixels that are with the same intensity on both pictures are represented in grey while for the others cyan and red colorations enable to discriminate the pictures.

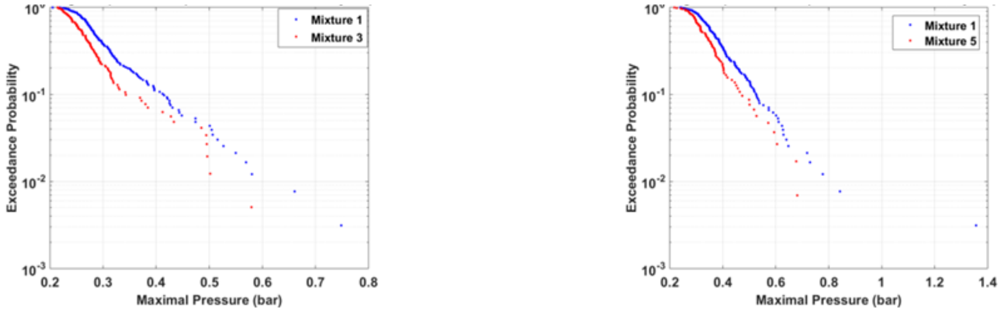
The wave shapes are precisely the same from the trough to the base of the crest whatever the surface tension in the studied range. On the other hand, the liquid filaments or films are more developed and the droplets smaller (more fragmentation) with a lower surface tension.



SIW_1 : a=236mm, T=2.47s *SIW_2 : a=244mm, T=2.47s*

Fig. 1 Comparison of the wave shapes before impact when using aqueous solutions with different surface tensions, for SIW_1 (left) and SIW_2 (right). Each picture is the superposition of two pictures: gray color indicates similarities, red and cyan colors indicate differences.

Fig. 2 shows the comparisons of the empirical probability of exceedance curves for the same cases as those shown in Fig. 1.



SIW_1 : a=236mm, T=2.47s *SIW_2 : a=244mm, T=2.47s*

Fig. 2 Comparison of empirical probability of exceedance distributions when using liquid solutions with different surface tensions, for SIW_1 (left) and SIW_2 (right).

Whatever the level of probability considered, the pressure is reduced when using a smaller surface tension.

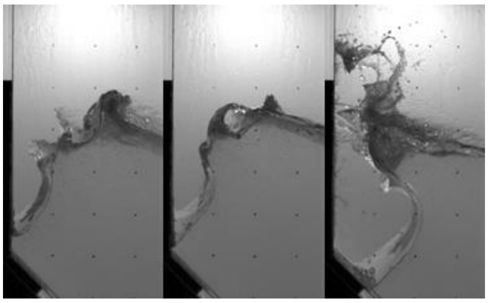
4. EFFECTS OF SURFACE TENSION ON COINCIDENT IMPACTS FROM IRREGULAR TESTS

The results presented in this section correspond to singularization tests with a duration of 90 s for two coincident impacts corresponding respectively to instants t_x=361.00 s for $SING_1$ and t_x=3283.64 s for $SING_2$. Nevertheless, they illustrate general trends for SING-type of excitations.

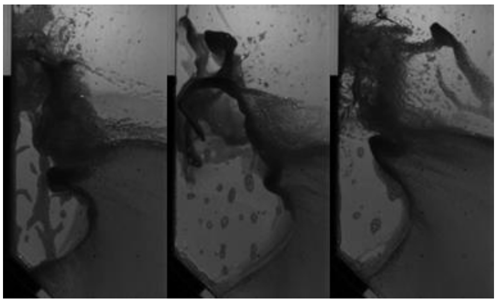
Fig. 3 compares the wave shapes as captured by the high speed camera just before impact when using pure water or Mixture 5, respectively for $SING_1$ (top) and for $SING_2$ (bottom). At each time three pictures are shown corresponding to three repetitions of the same condition.

Whatever the SING and the mixture studied, there are variations of the wave shape before impact not only at the crest level due to the development of free surface instabilities but also for the global wave shape. Here also, a low surface tension favors fragmentation into small droplets and the creation of a spray which looks like an aerated foam. Moreover, more and smaller air bubbles persist inside the liquid with lower surface tension, which makes the liquid darker.

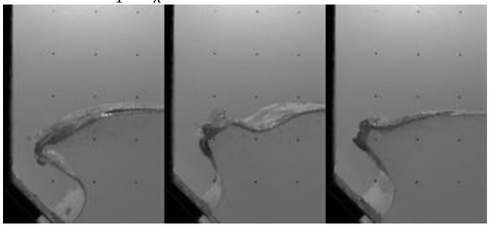
Fig. 4 shows the comparisons of the empirical probability of exceedance curves for $SING_1$ with five different aqueous solutions(left) and for $SING_2$ with four of them (right). Whatever the level of probability considered, the pressure is reduced when using a smaller surface tension. Moreover, for the same surface tension obtained with different aqueous solutions, which is the case for mixtures 4 and 5, the same empirical exceedance curves are obtained according to Anderson-Darling test. The rate of pressure reduction depends clearly on the wave impact considered.



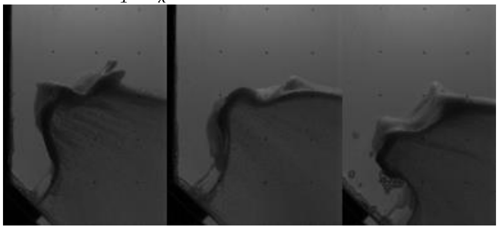
$SING_1$: t_x=361.00 s with Mixture 1



$SING_1$: t_x=361.00 s with Mixture 5

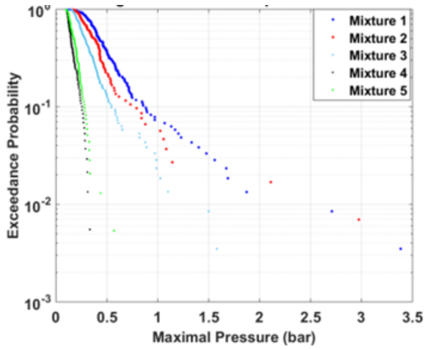


$SING_2$: t_x=3283.64 s with Mixture 1

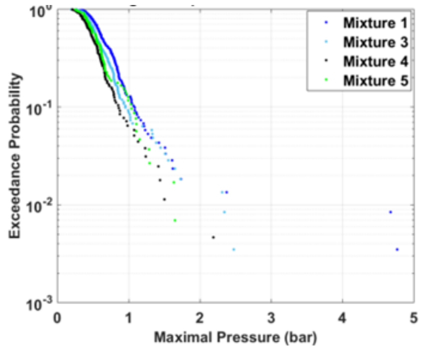


$SING_2$: t_x=3283.64 s with Mixture 5

Fig. 3 Comparison of the wave shapes before impact when using liquid solutions with different surface tensions, for $SING_1$ (top) and $SING_2$ (bottom).



$SING_1$: t_x=361.00 s with five different solutions



$SING_2$: t_x=3283.64 s with four different solutions

Fig. 4 Comparison of empirical probability of exceedance distributions when using liquid solutions with different surface tensions, for $SING_1$ (left) and $SING_2$ (right).

5. CONCLUSIONS

The phenomena responsible for the variability of the flow and therefore for the variability of the pressure measurements when precisely repeating a same forced excitation (SIW or SING) during sloshing model tests are all related to the surface tension at the interface. When the surface tension is reduced the statistical pressures are reduced whatever the level of probability or the return period considered. This also means that the probability to exceed a given pressure is reduced whatever this pressure. Performing sloshing model tests at scale 1:40 for the assessment of sloshing in floating LNG tanks should ideally be performed with a surface tension at the interface about 800 times smaller than that at scale 1 to comply with Weber similarity. Therefore, using water and a mixture of SF_6 and Nitrogen, as it is done in GTT to get the right gas-to-liquid density ratio, leads to a much too stiff surface tension with regard to the ideal target. This turns out to be a source of conservatism when this parameter is considered separately.

REFERENCES

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