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Sloshing suppression by floating baffle

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Abstract. Sloshing is a phenomenon which may lead to dynamic stability and damages on the local structure of the tank. Hence, several anti-sloshing devices are introduced in order to reduce the impact pressure and free surface elevation of liquid. A fixed baffle is the most prevailing anti-sloshing mechanism compared to the other methods. However, the additional of the baffle as the internal structure of the LNG tank can lead to frequent damages in long-term usage as this structure absorbs the sloshing loads and thus increases the maintenance cost and downtime. In this paper, a novel type of floating baffle is proposed to suppress the sloshing effect in LNG tank without the need for reconstructing the tank. The sloshing phenomenon in a membrane type LNG tank model was excited under sway motion with 30% and 50% filling condition in the model test. A regular motion by a linear actuator was applied to the tank model at different amplitudes and constant period at 1.1 seconds. Three pressure sensors were installed on the tank wall to measure the impact pressure, and a high-speed camera was utilized to record the sloshing motion. The floater baffle was modeled on the basis of uniform-discretization of domain and tested based on parametric variations. Data of pressure sensors were collected for cases without- and with-floating baffle. The results indicated successful reduction of surface run-up and impulsive pressure by using a floating baffle. The findings are expected to bring significant impacts towards safer sea transportation of LNG.

Keywords: sloshing; floating baffle; membrane tank; LNG

1. Introduction

Sloshing is a crucial fluid-structure interaction issue associated with the structural integrity of partially filled tank. In the LNG industry, ships carrying LNG via sea-route transportation experience wave-induced motions which can trigger severe sloshing effects inside their liquid storage tanks. Several ship structural damages had been related to the sloshing loads (Hamlin 1990, Paik and Shin 2006, Zhu *et al.* 2015). In recent years, with active developments of LNG carriers and floating production storage and offloading (FPSO) unit in the oil and gas industry, the sloshing

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effects in ship tanks have gained many research interests. Liquid sloshing can cause various significant engineering problems, such as dynamic instability (Kumar 2013), structural failure in ships (Kang *et al.* 2002), and declining performance of moving vessels (Vakilaadsarabi *et al*. 2012). In a large LNG carrier, the sloshing forces could be higher (Graczyk 2008), and the analysis will be more complicated due to the coupling interactions with the ship's motion (Faltinsen and Rognebakke 2000). The coupling effects between sea waves and tank filling conditions may also cause the flows inside the tank to create large impulsive pressure, which could damage the tank's structure (Zhuang *et al.* 2016) and engender safety issue during LNG transportation.

Various methods have been used to study sloshing from various perspectives. Early pioneers such as Abramson (1966) proposed a systematic review on the sloshing phenomena. Later, Faltinsen (1974) developed a nonlinear analytic method using a perturbation theory for potential flow to predict sloshing. The limitation of the theoretical method is that it only considers liquid sloshing in highly nonlinear motions. Therefore, in line with the development of computational power, various numerical methods have been introduced to study liquid sloshing, such as numerical methods including boundary element integral methods, finite element methods for potential flow, finite volume method (Sanapala *et al*. 2018), smoothed particle hydrodynamics method (SPH) (Bakti *et al*. 2016), moving particle simulation (MPS) (Kim *et al*. 2014), and fluid surface interaction (FSI) (Yamauchi *et al.* 2019). Recently, a combination of several numerical methods was introduced to obtain more accurate prediction (Xu *et al*. 2011, Zhao *et al*. 2015).

The highly nonlinear behaviours of sloshing have always been the greatest challenge in solving this problem analytically and computationally. Model test is considered to be the most reliable method in predicting the maximum impact pressure especially for violent sloshing (Chen 2011, Arif *et al.* 2019). Akyildiz and Ünal (2005) studied liquid sloshing in a rectangular tank subjected under pitch oscillation. The result showed that the maximum pressure was greater, as the water in the tank was deeper and pitch amplitude was higher. The liquid depth and frequency of oscillations affected the sloshing waves. Rognebakke *et al.* (2005) conducted a similar experiment to predict sloshing load with various combination of tank filling, ship heading, and sea-state parameters. They found that the impact pressure peak often covered a much larger area in a low filling ratio condition. This finding was further supported by the works of Graczyk (2008). Younes and Younes (2015) studied sloshing phenomenon by measuring impact pressure in a partially filled rectangular tank under sway excitation. Higher amplitude oscillation was selected to provide large slosh forces, which could be accurately measured in lower filling condition. Filling ratio is another main concern in sloshing model tests. Pastoor *et al.* (2004) investigated the effects of partially filling, sea state severity, and other aspects of liquid sloshing to assess the structural strength of various cargo containment systems, as well as the supporting hull structure. Panigrahy *et al*. (2006) found that sloshing was more prominent in the top free surface, and revealed a huge slope of pressure near the shallow region. Kim *et al*. (2016) suggested that the most critical condition for sloshing occurred when the water depth was around 30% of the tank height. Filling ratio is one of the contributors of resonance of sloshing in LNG carrier, where the liquid level changes constantly as a result of LNG production and offloading (Kobayakawa *et al.* 2015).

Anti-sloshing devices are in high demand for LNG facilities especially under the conditions of intermediate liquid levels. The anti-sloshing device is mainly divided into the fixed type and the floating type. A baffle is a fixed anti-sloshing device with several thin plates mounted as protruding structures on the surface of the tank to redirect the flow in a fluid domain. This means modification on the wall structure inside the tank. A baffle in vertical arrangement has been found able to reduce sloshing impact pressure (Wang and Xiong 2014) and alter the first-mode natural frequency of liquid-tank (Xue *et al*. 2017). For a bottom-mounted vertical baffle, the first-mode natural frequency of the tank will be lower if the baffle is flushing with a liquid free surface, and it will be higher if the baffle is surface-piercing (Xue *et al*. 2017), which can be further explored for resonance avoidance. On the other hand, a baffle in horizontal arrangement was reported able to significantly suppress violent resonant sloshing responses after being integrated with a porous plate design to dissipate the sloshing energy (Cho *et al*. 2017, Gnitko *et al.* 2017, Kolaei *et al.* 2017, Demirel and Aral 2018). However, a major disadvantage of fixed type baffle is that the plates need to be welded inside the liquid tank of LNG carrier, and it must be restrained from the impact load of sloshing flow. Besides, fixed baffles could be damaged by violent liquid sloshing. The structural facture will further deteriorate the insulation performance (Lee *et al.* 2014) and cause LNG leakage. Therefore, fixed baffle requires regular inspection to prevent damage and excessive fatigue (Lee *et al.* 2013).

Floating type anti-sloshing devices have also been proposed in previous researches (Arai *et al.* 2013, Yu *et al*. 2017) to suppress liquid surface elevation and reduce impact pressure. The researchers used both experimental and numerical methods to investigate the floater, and claimed that it was effective in reducing the liquid peaks. Floating type blanket anti-sloshing device has proposed as well (Kim *et al.* 2013), in which a series of model tank test had been carried out to investigate the effects of the blanket on sloshing flow. The results showed that the overall reduction of sloshing pressure by floating blanket was significant, particularly more in low filling condition. Zhang *et al*. (2019) introduced a floater in solid foam, which can also be considered as fragments of floater-type blanket (Kim *et al.* 2013).

In this paper, a floating baffle which combines the advantages of both baffle and floating blanket is presented. The novelty of this paper has two-folds; firstly, the design inherits the advantages of the vertical- and horizontal baffles in a grid form, and secondly, it further reduces the usage of volume inside the LNG tank as compared to floating blanket. The floating baffle floats in the vicinity of the liquid surface. The original free surface is divided into sub-surfaces. Floating baffle could be a more economical choice as the floating baffle occupies lesser space inside the tank as compared to floating blanket. Besides, the floating anti-sloshing system seems to be more convenient to install compared to fixed baffle. The objectives of this paper are (i) to investigate the performance of a floating baffle based on uniform-discretization of free-surface domain in sloshing suppression, and (ii) to identify the sloshing profile with- and without using a floating baffle.

2. Experimental setup

The experimental setup for the sloshing test consisted of three main parts, which were a closed prismatic membrane model tank installed with three pressure sensors, data acquisition system (DAQ), and a direct-current (DC) linear actuator, as shown in Fig. 1. The membrane model tank was made from transparent acrylic plate with scale of 1:100 and thickness of 5 mm. Fig. 2 shows the principal dimension of the model tank and the locations of pressure sensors (from S1 to S3, respectively). In the experiment, the filling ratio of water inside the model tank was set to 30% and 50%, respectively, of the total tank volume.

The fluid domain in the membrane model tank was excited in regular unidirectional sway motion $y(t) = A \sin(2\pi t/T_p)$ with amplitudes, A = 3.0 cm, and period, T_p = 1.1 sec. When the frequency of the tank motion is close to one of the natural frequencies of the fluid, large sloshing responses will be stimulated; this phenomenon is known as resonance (Akyildiz and Ünal 2005). Hence, the excitation frequency in this experiment was calculated based on the dimension of the tank according to the following equation

$$\omega_n^2 = g\frac{n\pi}{L}\tanh\left(\frac{n\pi}{L}d\right) \tag{1}$$

where ω_n is natural frequency of the tank associated with the fluid, g is gravitational acceleration, n is number of modes which is defined as n = 1 in the experiment, L is tank width, and d is depth of liquid inside the tank. Based on Eq. (1), the natural period for filling ratio 30% and 50% is listed in Table 1.

The linear actuator, with a direct-current (DC) motor, functioned to induce a unidirectional excitation. The regular excitation followed the predefined sloshing motions under the swaying amplitude, A = 3.0 cm and period, T = 1.1 sec. Due to the nonlinearity of the sloshing problem, resonance might not have been induced ideally according to the natural frequency of the fluid domain. Nonetheless, it could happen at a frequency very close to the theoretical value (Akyildiz and Ünal 2005). Hence, the period of 1.1 sec was chosen for both filling conditions for the reason of limiting the linear motion actuator. An Arduino UNO board was operated to apply a proportional and integral (PI) controller with controller gains of K_p and K_i to heuristically fine-tune the excitation. As shown in Fig. 2, the maximum deviation of linear excitation was found at filling ratio = 50%, where the linear actuator drove large inertia (water mass) and changing direction at high frequency. The maximum deviation was maintained below 11.3% of swaying amplitude, A.

Table 1 Natural period of each filling condition

Filling ratio, f (%)	30	50
Natural period, T_p(s)	1.1	0.9

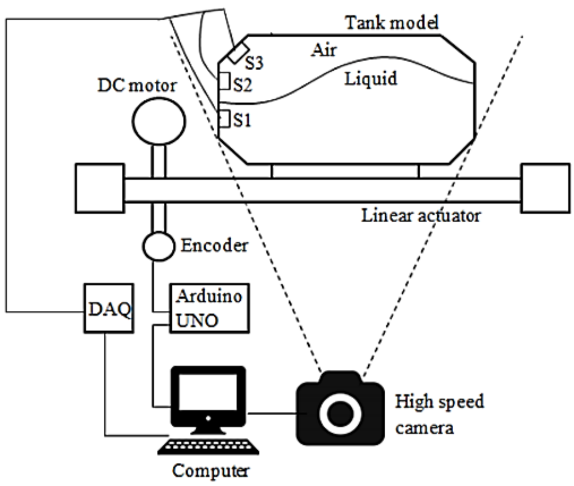

Fig. 1 Schematic drawing of sloshing experiment setup

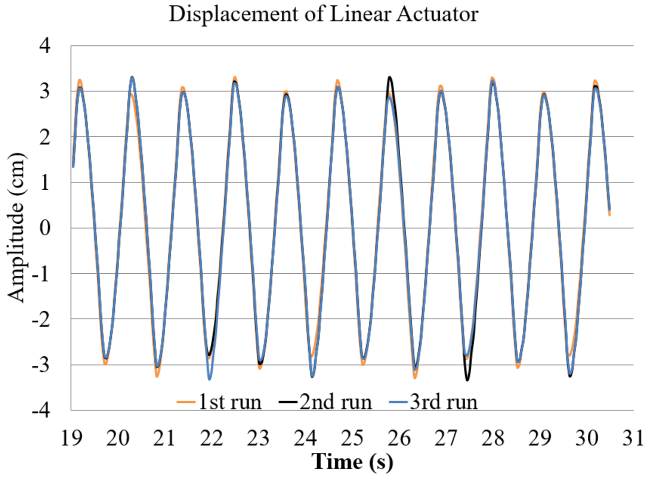

Fig. 2 Time series of linear actuator's displacement for three test runs (desired amplitude = 3 cm, filling ratio = 50%). Time range was recorded from 19 s to 31 s, which is coincident with T_i = 0 s – 12 s, after fully ramping up

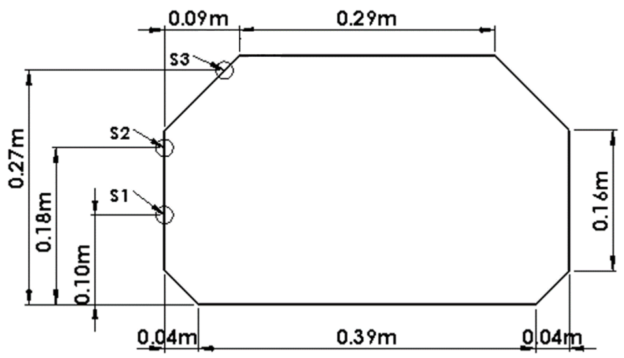

Fig. 3 Principal dimensions of model tank and location of sensors (S1-S3) from front view

A camera was set up to capture the sloshing motion inside the model tank at a frame rate of 25 frames per second (fps) and pixel resolution of 1280×720. For the recording, the camera was placed at distance of 1 m in front of the mid-position of the linear actuator. Three pressure sensors were installed on the side wall of the model tank, as shown in Fig. 3. The model of the pressure sensor is NXP MPX5010. It has a maximum capacity to measure pressure up to 10 kPa with 5% maximum error. It is noteworthy that the pressure sensors were originally incorporated to measure the air pressure. Therefore, robust modification and calibration were significantly needed to transform them into a low-cost pressure sensor which is appropriate in service in the water domain. A National Instrument USB-6001 DAQ board was used to record the voltage reading from the sensors. The sample rate was 100 kHz. Each reading in the experiment was repeated for three times.

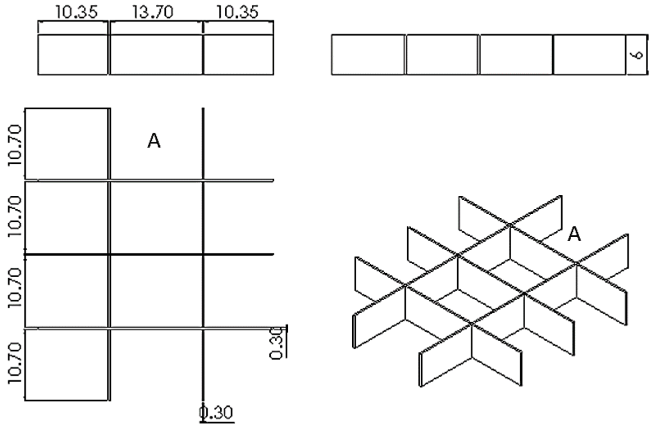

Fig. 4 Principal dimensions of model of floating baffle (unit in centimeter)

The model of floating baffle was illustrated in Fig. 4. The model in the experiment was fabricated from polypropylene cardboard. However, in actual application under a cryogenic condition, the floating baffle can be built by using a flexible material such as melamine foam, as it is able to withstand a cryogenic condition and safe to be used with LNG (Kim *et al.* 2013). However, further study needs to be done to attempt implementing the material into a baffle structure since melamine is very soft. In this model, the floating baffle divided the upper section of the fluid domain into 12 smaller subsections. The pressure sensors were in the immediate vicinity of subsection A. The width of the floating baffles was 0.91 L, where L is the width of the tank. Hence, it should be able to float freely along the vertical tank wall. The area of primary concern in this experiment was the filling ratios, which were 30% and 50% of the total tank volume, which was situated below the sensor S2. A condition of filling ratio of 70% will be investigated in future works with modified shape and stiffness of floating baffle. The baffle size was chosen based on the total volume of floating baffles was less than 1% of the total volume of membrane tank, where the ratio for the actual model in the experiment was 0.7%. On the other hand, the area of each region after the uniform-discretization will be controlled below 10% of the total liquid surface area A_w inside the membrane tank, where the area for region A is 8.2% of A_w.

3. Performance of sloshing suppression

The sloshing motion of a half-cycle in the membrane tank under filling ratio, F_v = 30% and 50%, excitation amplitude, A = 3 cm, period T = 1.1 sec is shown in Figs. 5 and 6. Cases with- and without floating baffle were intended for comparison. The sloshing profiles were captured at five instantaneous moments with time interval of two consecutive snapshots in between 0.13-0.14 sec. The snapshots showed that the water run-up decreased from climax at one side and reached the maximum position at the wall of the other side of the tank. This indicates that the variation of the maximum run-up on the tank wall was larger at a lower filling ratio. As shown in Figs. 5 and 6, the floating baffle could effectively reduce the water run-up and hydraulic jumps on the side wall. The floating baffle had also significantly attenuated the splashing to the top plate of the tank in the case of 30% filling ratio.

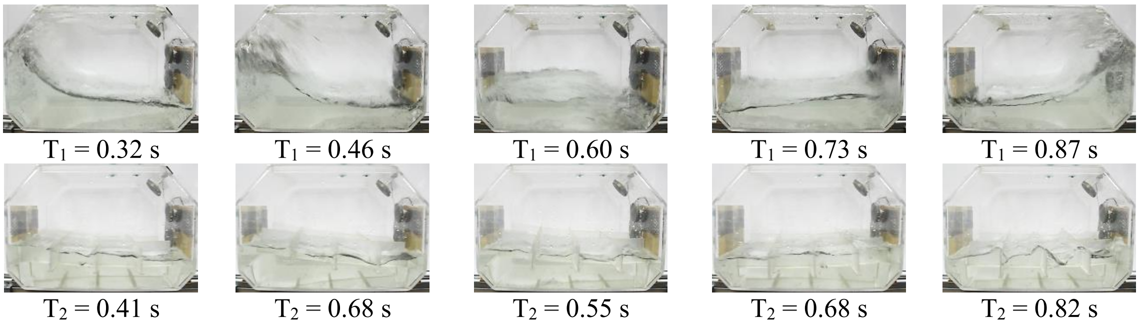

Fig. 5 First half-cycle of sloshing under excitation with amplitude = 3.0 cm, period = 1.1 sec, and filling ratio 30%, (upper) without floating baffle, and (bottom) with floating baffle

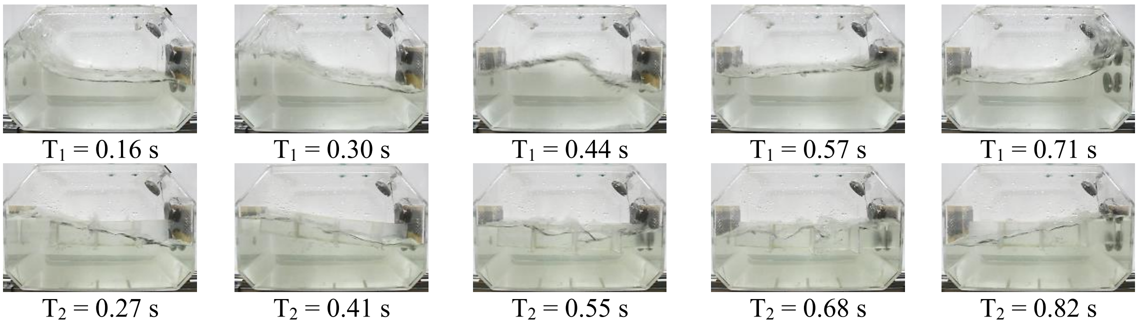

Fig. 6 First half-cycle of sloshing under excitation with amplitude = 3.0 cm, period = 1.1 sec, and filling ratio 50%, (upper) without floating baffle, and (bottom) with floating baffle

The repeatability of the sloshing profiles was verified by comparing the first nine peaks of sloshing under a consecutive excitation, as shown in Figs. 7 and 8. These sloshing profiles were post-processed from the experimental images to determine the surface elevation. These figures illustrate the sloshing profiles at instantaneous moment when the run-up reached maximum position at the tank wall. The time interval for two consecutive snapshots was approximately 1.1 sec, which was the period of unidirectional excitation. After plotting the sloshing profile in Fig. 9 according to the surface elevations, the repeatability of the liquid surface had been shown very consistent. For the case of filling ratio of 30%, the maxima of run-up on the tank wall had been reduced to 51.7% of original run-up after adding the floating baffles, while the filling ratio of 50% had been reduced 77.0% of the original run-up. However, it should be noted that the actual sloshing profile for the filling ratio of 30% was more complex after considering the splashing effect, as truncated in Fig. 9.

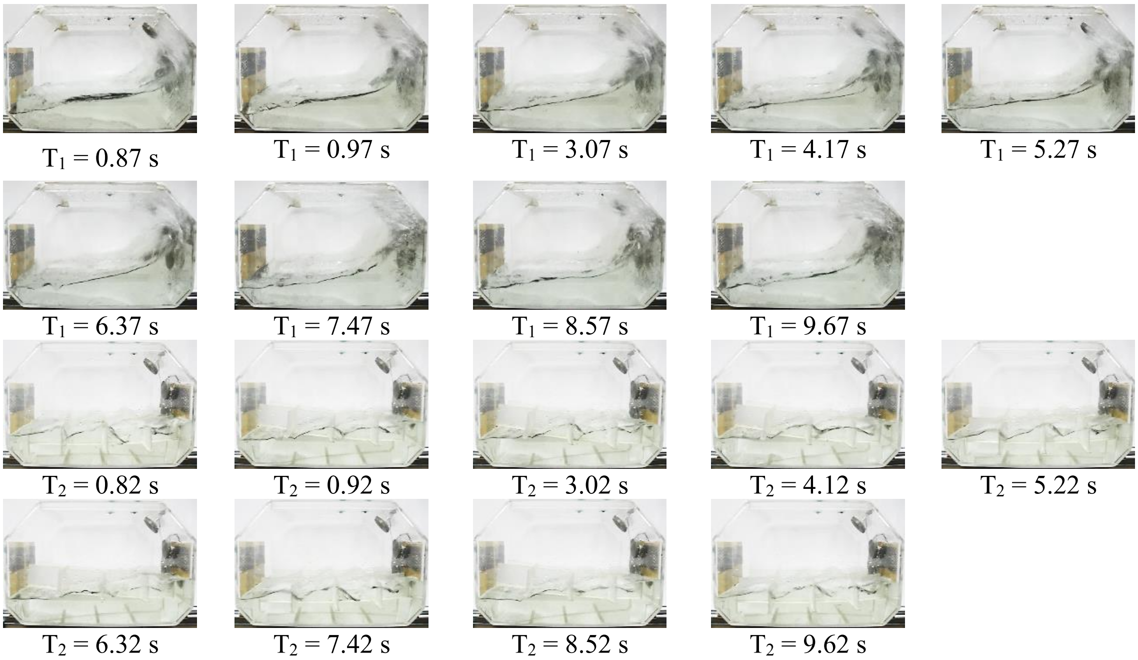

Fig. 7 First nine peaks of sloshing under excitation with amplitude = 3.0 cm, period = 1.1 sec, and filling ratio 30%, (upper) without floating baffle, and (bottom) with floating baffle

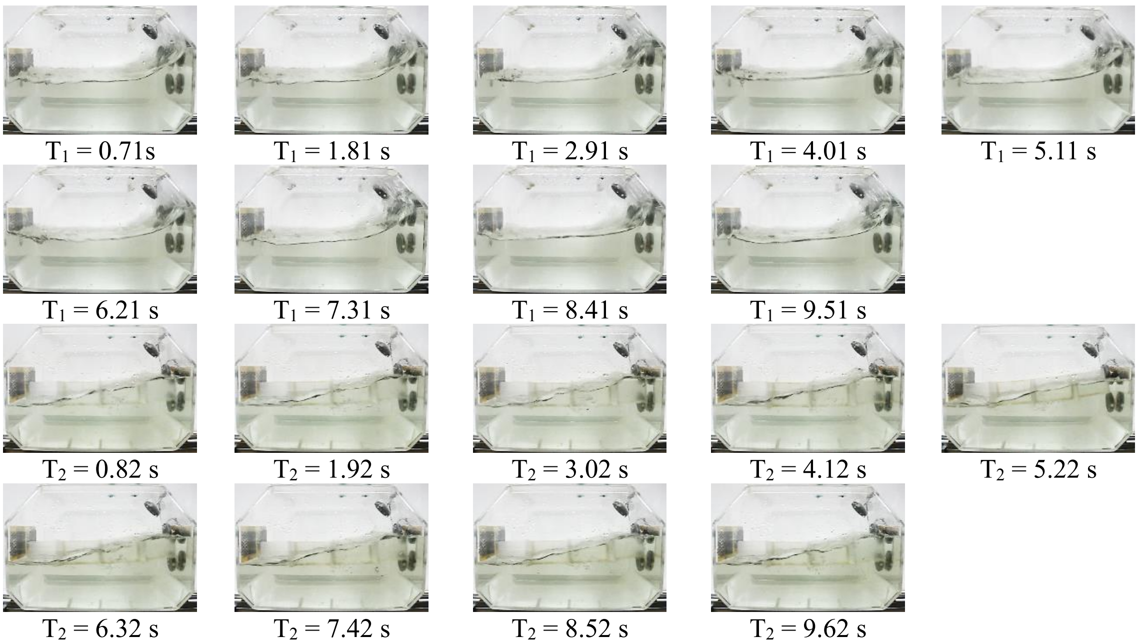

Fig. 8 First nine peaks of sloshing under excitation with amplitude = 3.0 cm, period = 1.1 sec, and filling ratio 50%, (upper) without floating baffle, and (bottom) with floating baffle

The voltage recorded by the low-cost NXP MPX5010 pressure sensor was then used to identify the pattern of sloshing effects to the tank wall. However, the pressure sensors were originally built to measure the air pressure. Therefore, robust modification and calibration were significantly needed to transform them into low-cost pressure sensors which should be appropriate in service in the water domain. In this experiment, the pressure sensors had been modified to connect to a stainless-steel funnel, which had a latex diaphragm cover at the other end. The water particles inside the tank hit the latex diaphragm, causing deflection of the diaphragm. The deflection compressed the air inside the funnel, causing the air volume change; consequently triggering a voltage change on the sensor. It should be noted that in this study, instead of using pressure, the authors used the voltage signal of the low-cost pressure sensors to identify the sloshing effect in the tank wall. The voltage recorded by the sensor at S1 for both cases with- and without a floating baffle, with filling ratio of 30%, is shown in Fig. 10. The larger impact loads from the liquid sloshing induced higher voltage. The pattern of the voltage reading for all the three test runs displayed a highly consistent time series in the sloshing dynamics. The sloshing liquid created two types of dynamic pressure, which were impulsive- and non-impulsive pressures (Rebouillat and Liksonov 2010). Impulsive pressure is a rapid pressure pulse due to the impact between the liquid and the solid surface, where pressure fluctuation in spike-form can be observed. Impulsive pressure is much localized and has extremely high magnitude, which is usually associated with hydraulic jumps (Akyildiz and Ünal 2005). On the other hand, a non-impulsive pressure is referred to slowly varying pressure in an oscillating fluid domain. The impact loads due to water run-up and splash caused impulsive pressure reading in the time series, in the form of spikes. The floating baffle was able to effectively eliminate the impulsive pressure at the location of S1 and significantly attenuate the slowly varying pressure.

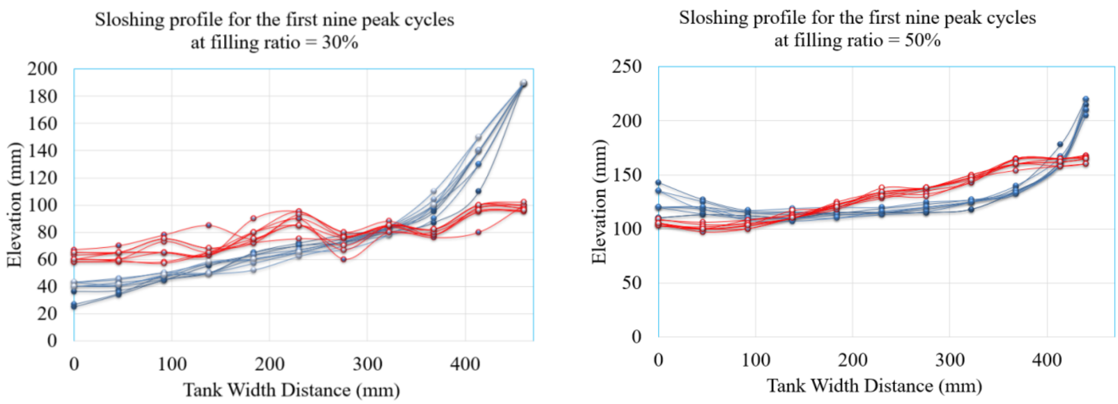

Fig. 9 Sloshing profile for first nine peaks of liquid under excitation with amplitude = 3.0 cm, period = 1.1 sec, (left) filling ratio = 30%, and (right) filling ratio = 50% (blue lines: without floating baffle, red lines: with floating baffle)

The trajectory of voltage changes in pressure sensor S1 is shown in Fig. 11, with regard to identification of the stability and variation of the sloshing system. It clearly indicates that the voltage reading of the sloshing was stable in both the cases with- and without baffles. However, the impulsive pressure acting on the tank wall induced many outliners as shown in Fig. 10, where abrupt changes of voltage could be identified. Moreover, on the horizontal axis, the range of trajectory for the case without floating baffle was more than three times larger than the one after incorporated with floating baffle.

The voltage recorded by the sensor at location S2 for both cases with- and without a floating baffle, with filling ratio of 50%, is shown in Fig. 12, while Fig. 13 shows the trajectory of voltage changes in pressure sensor S2 under the same filling ratio. The characteristics of this 50% filling ratio case were generally similar to the case of 30% filling ratio.

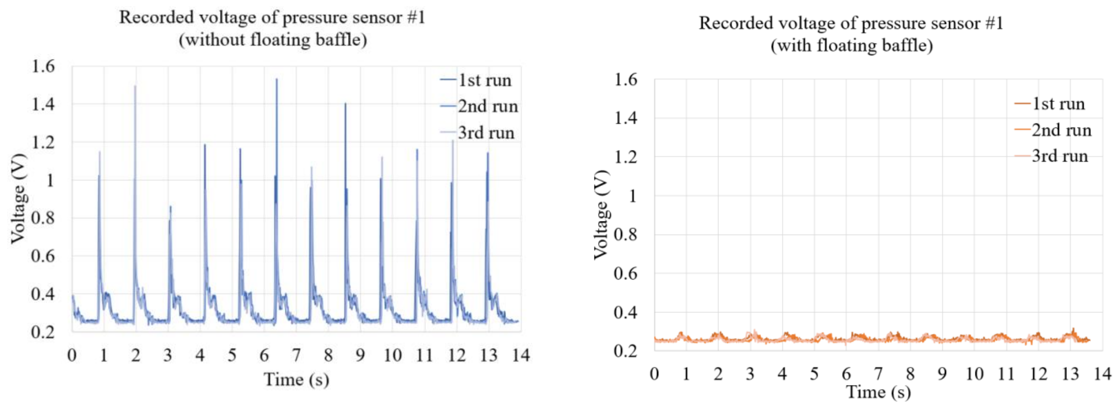

Fig. 10 Voltage recorded by pressure sensor at location s1 under sloshing by excitation with amplitude = 3.0 cm, period = 1.1 sec and filling ratio 30%, (left) without floating baffle, and (right) with floating baffle

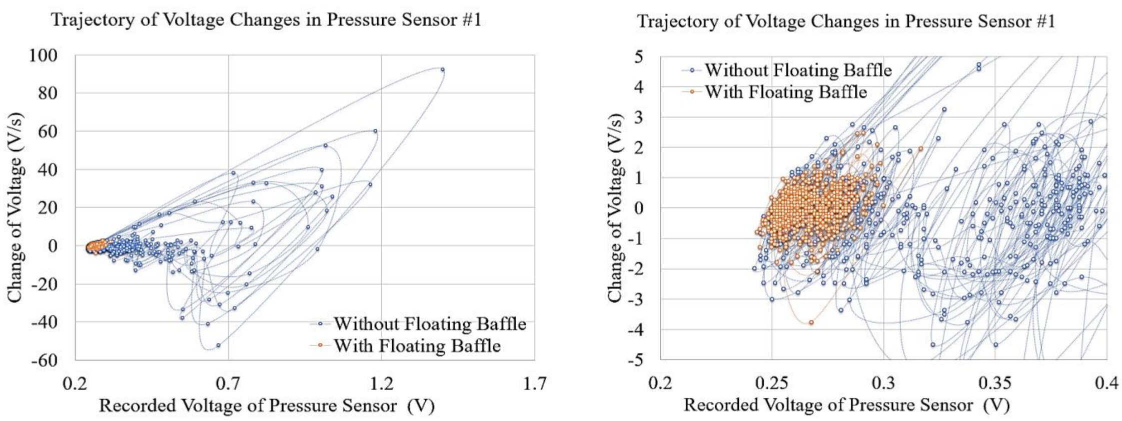

Fig. 11 Trajectory of voltage changes by pressure sensor at location S1 under sloshing by excitation with amplitude = 3.0 cm, period = 1.1 sec, and filling ratio 30%, (left) full view, and (right) zoom in view

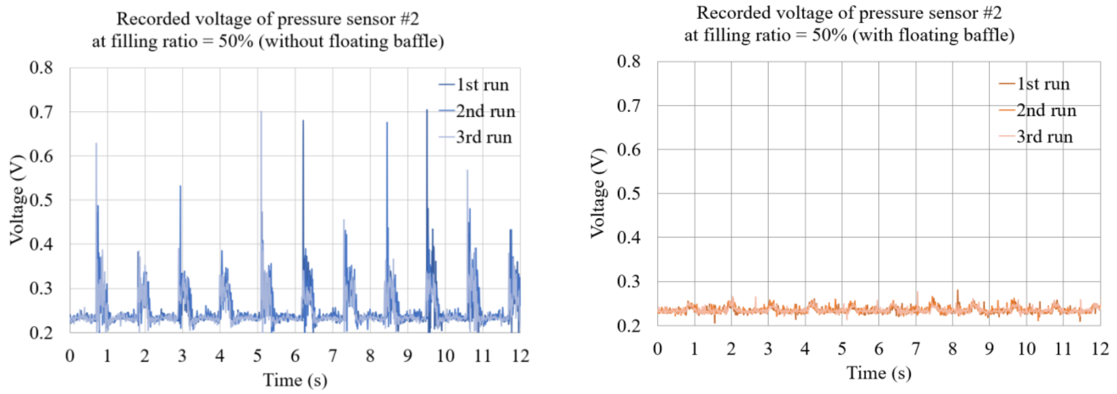

Fig. 12 Voltage recorded by pressure sensor at location S2 under sloshing by excitation with amplitude = 3.0 cm, period = 1.1 sec, and filling ratio 50%, (left) without floating baffle, and (right) with floating baffle

The sloshing impact pressure was apparently detectable at the locations S1 and S2 under the conditions of low filling ratio. On the other hand, the voltage reading at S3 was relatively negligible due to minimal water jet hitting the top plate of the tank in the experiment. Thus, the result of S3 is not presented here. The impulsive pressure was caused by higher impact run-up at this low filling ratio when the excitation frequency was close to its natural period. In contrast to the results of S1, the filling ratio, F_v = 50% showed more significant impact pressure reading at location S2. In this experiment, the impulsive pressure during F_v = 30% could not be recorded clearly at S2 because wave breaking occurred in this region (refer to Fig. 7). Therefore, the magnitude of voltage reading became lower. The severity of sloshing motion and its accompanying dynamic impact pressure depended on the filling ratio, F_v, amplitude, A of the tank motions, and excitation frequency, f (Akyildiz and Ünal 2005). The nonlinearity of sloshing flow

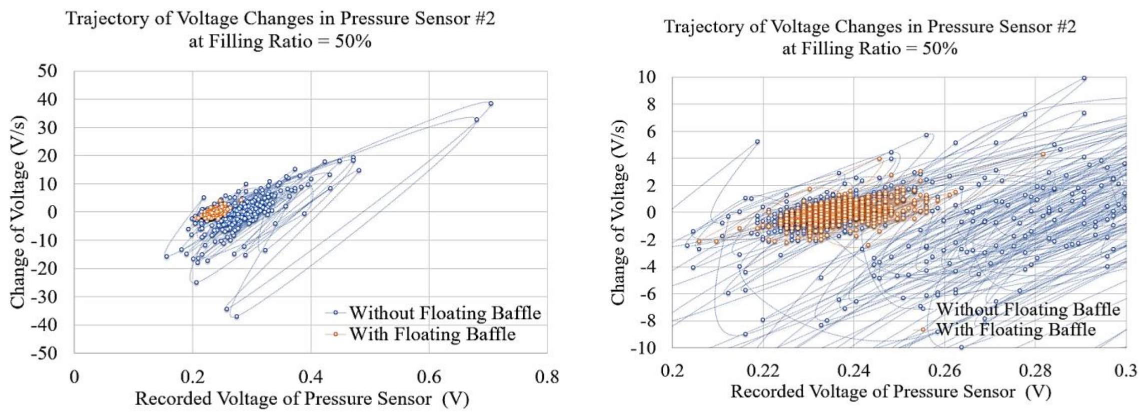

Fig. 13 Trajectory of voltage changes by pressure sensor at location S2 under sloshing by excitation with amplitude = 3.0 cm, period = 1.1 sec, and filling ratio 50%, (right) full view, and (right) zoom in view

was dominant at the lower filling ratio, where the sloshing was characterized by a hydraulic jump and water spray formation. As a result, sloshing impacts in tanks with a low filling ratio generally had larger impact pressure to the tank wall. It is noteworthy that the experiment was restrained in unidirectional excitation and regular motion. In real-life application, the excitation could be in multi-dimensional. Nevertheless, the current study can provide an insightful understanding on sloshing impact pressure.

5. Conclusions

The suppression of liquid sloshing by using a floating baffle in a membrane tank model with a scale of 1:100 had been investigated. Tank model with water filling ratio of 30%, and 50%, respectively, were excited under regular sway motion with amplitude, A = 3 cm, and period, T = 1.1 sec. The main findings are summarized as follows:

- The variation of surface elevation due to side-wall run-up was larger with lower filling ratio. The phenomenon of splashing to the top plate of the tank in the case of 30% filling ratio without floating baffle had been fully attenuated by using the floating baffle;
- For the case of filling ratio of 30%, the maxima of run-up on the tank wall had been reduced to 51.7% of original run-up after adding the floating baffles, while for filling ratio of 50% the reduction was 77.0% of the original run-up;
- By using a floating baffle, the impulsive pressure at the location of S1 had been eliminated, along with the attenuation of the slowly varying pressure.

The experiment was conducted as a pilot comparative study for conditions with- and without the floating baffle. In future works, more accurate pressure sensors must be used for sloshing impact measurement. Further investigation should also consider wider range of wave conditions and filling ratio. Other than that, the contact pressure in between the floating baffle and the inner tank wall must be studied, before further upscaling this concept for potential industrial applications.

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