SUPPRESSION OF SLOSHING IN LIQUEFIED NATURAL GAS DURING OCEAN-GOING TRANSPORTATION BY USING SPHERICAL FLOATERS AND BLANKET

Article history
Received
1 December 2017
Received in revised form
20 December 2017
Accepted
22 December 2017

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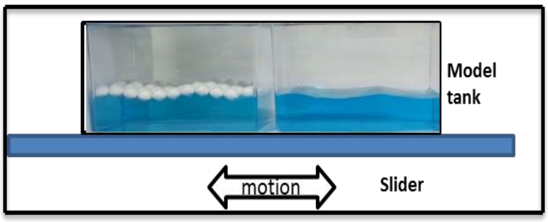
GRAPHICAL ABSTRACT



ABSTRACT

Malaysia National Key Economic Area (NKEA) is endeavouring to promote the liquefied natural gas (LNG) as one of the dominant greener energy resources which significantly benefits Malaysia as the world's third-largest exporter of LNG. However, safer sea transportation of LNG is in high demands because sloshing of liquid bulks can cause structural damage and disastrous safety issue towards the LNG carrier. Conventional methods, such as baffle inside the liquid tank still has major problems as it could be damaged by very violent liquid sloshing and require regular inspection. On the other hand, floaters and blanket have been proven as a more effective solution. However, a better understanding of the behaviours of floaters and blanket is needed to design more effective anti-sloshing devices, which have huge potential benefits to Malaysian LNG transporters. In this paper, sloshing experiment under random unidirectional excitations was conducted to investigate the effectiveness of liquid surface suppression by using floaters and blanket. The results of the liquid free surface without suppressors, liquid surface covered by scattered floaters and liquid surface covered by blanket were analysed and discussed. The findings are expected to contribute to the design of anti-sloshing devices towards safer sea transportation of LNG which could largely benefit our nation.

KEYWORDS

LNG carrier;floating LNG; anti-sloshing; liquid surface elevation

INTRODUCTION

As a contribution to improving oil, gas and energy challenges in the National Key Economic Area (NKEA) [1], liquefied natural gas (LNG) has huge potential to grow as one of the dominant greener energy resource supplies, rather than conventional fossil hydrocarbon, in the development of national energy industry. However, one of the most important issues to cost-effectively commercialize LNG is the safety in sea-route transportation of this highly flammable liquid due to sloshing effect. As Malaysia is the world's third-largest exporter of LNG and holds 10.2% of global market share [2], if safer sea-route transportation method of LNG is technologically unlocked, it is expected to bring significant business benefits to the nation.

Sloshing is a phenomenon where liquid in a partially filled container moves in back and forth motions inconsistently in the form of a splashing surface wave under periodic excitations in rotational and translational directions [3]. In the LNG industry, ships carrying LNG via sea-route transportation experience wave-induced motions which can trigger severe sloshing effects inside its liquid storage tanks. This phenomenon will be exaggerated when the frequency of the tank motion is close to the natural frequency of the interaction between sloshing fluid and structure [4]. Severe sloshing creates localized high impact loads on the tank walls and ceiling, which can eventually cause structural damage [4] and potential disastrous safety issue to the LNG carrier.

Several ship structural problems had been reported relevant to the sloshing loads in LNG tanks [3]. Recent years, with the active developments of LNG carriers and FPSO in the oil and energy industry, the sloshing effects in ship tanks have been gaining many research interests. Liquid sloshing can cause various significant engineering problems, such as dynamic instability and structural failure in the ships [5]. The fundamental issues of liquid sloshing are the accurate estimation of hydrodynamic pressure distribution, forces, moments and natural frequencies of the free-liquid surface [6]. These parameters can cause dynamic instability [6], lower performance of moving containers [7], and structural failures of the liquid containers [5]. In a large LNG carrier, the slamming forces caused by liquid sloshing could be higher [8]. On the other hand, the wave’s excitation can influence sloshing in tanks and further affect the ship's motion. In addition, the coupling effects between external waves and tank filling conditions may cause the tank sloshing flows to influence each other [9] and create large impulsive pressure which could damage the tank's structure [10]. Sloshing in partially filled LNG tanks can be more critical under certain wave conditions due to the resonances of structural frequencies and wave-induced ship motions [11]. This can subsequently affect ship stability in producing large loads on the internal tank membranes which can lead to structural damage to tank membranes and insulation, leakage and potentially to tank rupture [11] due to very large impact on the tank walls [5, 12].

In order to mitigate the sloshing issue for safer sea-route transportation of hazardous liquid bulks, the development of reliable and effective anti-sloshing system has been gaining interests from the shipbuilding industry. Anti-sloshing devices are in high demand for an LNG facility especially under the conditions of intermediate liquid levels. In real-world cases, resonance sloshing becomes unavoidable in LNG carrier where the liquid level changes constantly as a result of LNG production and offloading [13]. A popular device to reduce liquid sloshing is baffle [14-17] and it was found that LNG sloshing in partially filled membrane tank with vertical baffle at the middle of the tank bottom can significantly reduce the liquid sloshing motion and sloshing impact pressure [17]. Conventionally, a method of adding baffle [16, 17] inside the liquid tank has been reported useful to reduce the sloshing in LNG tanks. However, a major disadvantage of this anti-sloshing device is that it could be damaged by very violent liquid sloshing, deteriorate the insulation performance [18] and require regular inspection under the long term fatigue issue in cryogenic condition [19].

These challenges of sea-route transport infrastructure of LNG requirean innovative solution for assuring safer LNG transportation by reducing violent sloshing effects. Anti-sloshing floater was proposed by previous researchers [20, 21] to suppress the liquid surface elevation to reduce the impact pressure along the longitudinal bulkhead. The researchers used both experimental and numerical methods to investigate the floater and claimed that it is effective in reducing the liquid peaks. Moreover, floater-type blanket anti-sloshing device was proposed [22] and a series of the model tank test had been carried out to investigate the effects of the blanket on sloshing flow. Floaters [20, 21] and foam blanket [22] fabricated from synthetic foam have been reported to be able to suppress the sloshing effectively. The results showed that overall reduction of sloshing pressure is particularly more significant in low filling condition.

In this study, the effectiveness of spherical shape floater and blanket system in reducing the liquid sloshing is investigated. Experimental analysis has been conducted to compare both methods in reducing the liquid sloshing inside the model tank under random excited unidirectional motion. Sloshing effect is measured through the liquid elevation at the wall of the tank model.

METHODOLOGY

The effectiveness of spherical floaters and blankets in suppressing liquid sloshing by mitigating the surface elevation of internal liquid domain inside the tank were examined through experiment. The experiment was conducted in Marine Technology Centre (MTC) at UniversitiTeknologi Malaysia (UTM), Johor Bahru, Malaysia. The set-up of the experiment is shown in Figure 1 where a model tank was partially filled with liquid (water in this case study) and positioned on a roller cart.

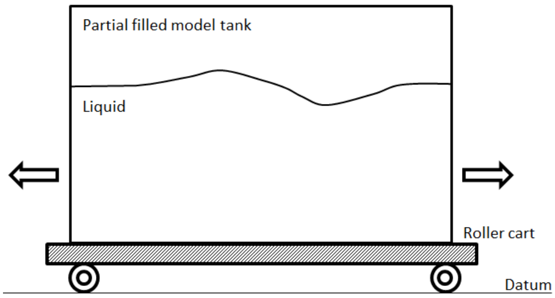


Figure 1: Experimental set-up of free-surface liquid sloshing

The size of the model tank is 320 mm in length, 220 mm in height, and 140 mm in breadth. The model tank together with the internal liquid was manually translated back-and-forth manually in a unidirectional motion, which simulates the surge excitation under random conditions. In order to simulate the damping effects attributed by external suppressors, a total of55 spherical floaters, made using polystyrene balls with diameter 29 ±1 mm were located dispersedly to cover all the surface area of the liquid, as shown in Figure 2.

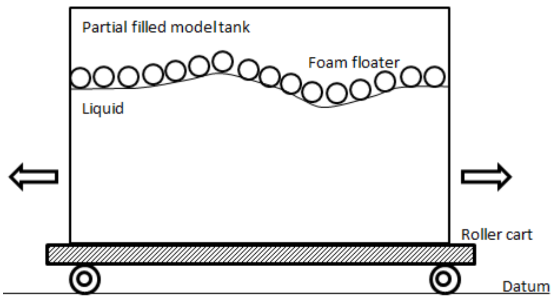


Figure 2: Experimental set-up of liquid sloshing suppressed with floaters

Furthermore, an anti-sloshing blanket is modified from the scattered spherical floaters by tying up the floaters together in an 11×5 formation by nylon strings, as shown in Figure 3. Since the motion of individual floater inside a blanket is coupled with, and restrained by, its neighbours, the group effects in anti-sloshing can be added by the blanket.

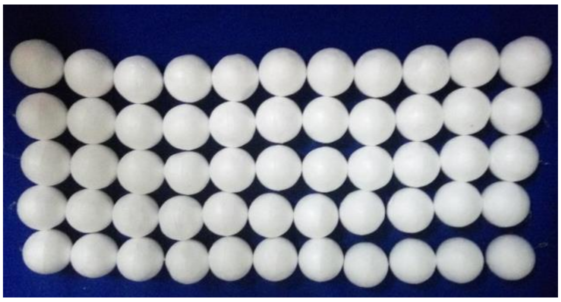


Figure 3: Anti-sloshing blanket

The experimental set-up of the model tank equipped blanket isillustrated in Figure 4. In this case study, the liquid surface was fully covered by a single layer of blanket.

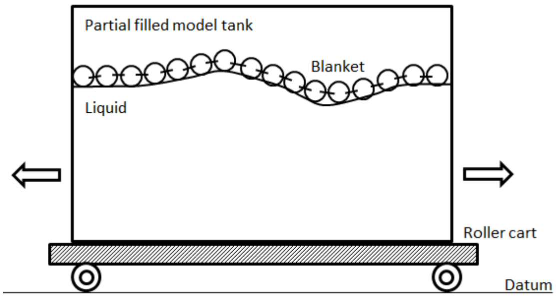


Figure 4: Experimental set-up of liquid sloshingsuppressed with blanket

Since the external translational motion in these experiments was exerted by manually pulling and pushing the roller cart in a back-and-forth direction, the excitation motion was random and not repeatable. Hence, the experiments were conducted in a pair of two cases as listed in Table 1.

Table 1: Case matrix of experiment

Case	Free-surface	Floater	Blanket
1	X	X	
2	X		X
3		X	X

The two identical model tanks with different configurations among (i) free-surface only, (ii) with the floaters, and (iii) with the blanket, were excited under a translational motion for ten times with which has 10 seconds for each time. The experiments were conducted under a total water volume of 30% of the volume of the model tank, which is considered as low-filled and can cause severe sloshing effects. In order to produce a better image for post-processing, the water inside the model tanks was dyed in light blue. The surface elevations of every case in the experiment were recorded using the camera for data processing.

Results and Discussion

The magnitudes of free surface liquid elevation for ten random excitations in Case 1 is shown in Figure 5.

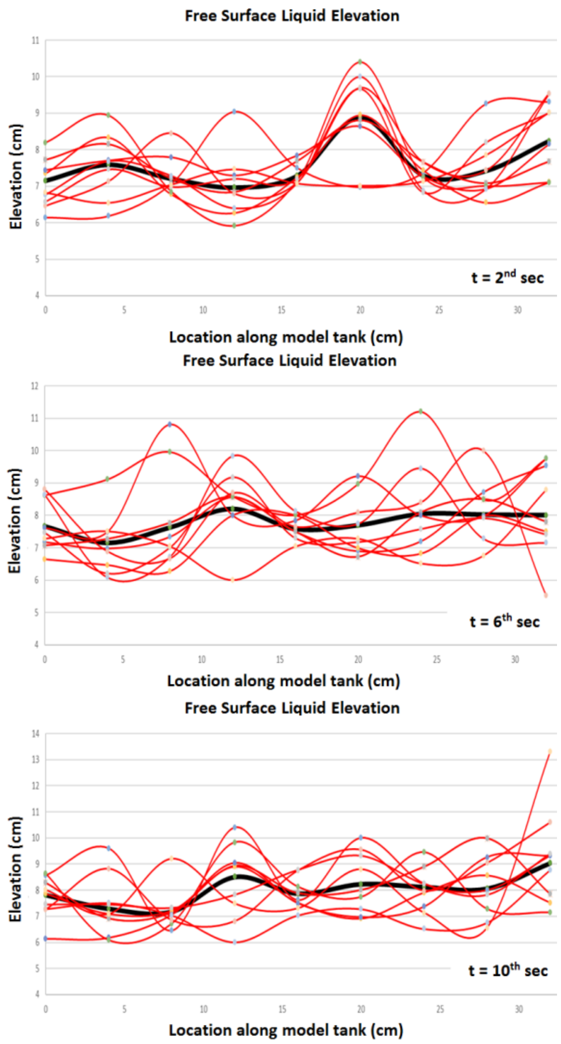


Figure 5: Magnitudes of free surface liquid elevation for ten random excitations in Case 1 and the average, for 2nd, 6th, and 10th second of the experiment

The instantaneous liquid free surface levels for the 2nd, 6th, and 10th second of the experiment for each random excitation have been shown. An average value of the liquid surface level, as indicated in bold solid line, for each point of interest along the length of the model tank was calculated basedon the 10 readings from random excitations. The data was obtained using the post-processed positioning method on the instantaneous images recorded during the experiment.Under the same ten random excitations in Case 1, the results for liquid surface covered by floaters are shown in Figure 6.

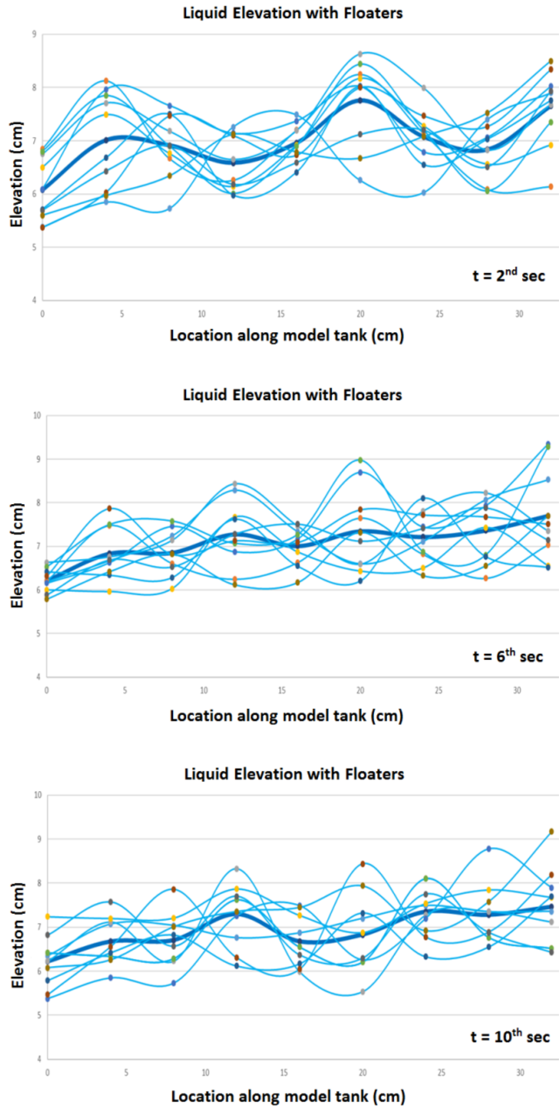


Figure 6: Magnitudes of liquid elevation with floaters for ten random excitations in Case 1 and the average, for 2nd, 6th, and 10th second of the experiment

From the liquid surface elevation in the time-progressive series, it can be found that the surface profiles are highly irregular. Due to the length of the model tank is 320 mm, the internal liquid was observed to be excited in 2 – 3 complete cycles in these cases. The surface elevation profiles are similar for both model tanks in the observation under the same random excitations. However, it can be found that the one covered with floaters is always lower, on average than the one without any suppression device

On the other hand, under another ten random excitations in Case 3, the results for liquid surface covered by floaters are shown in Figure 7.

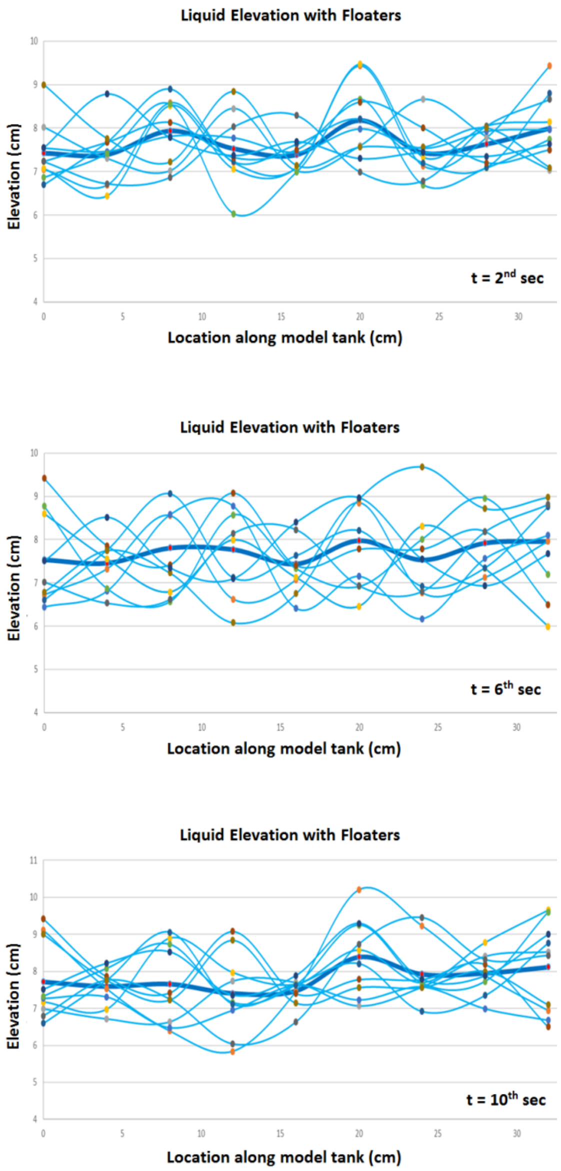
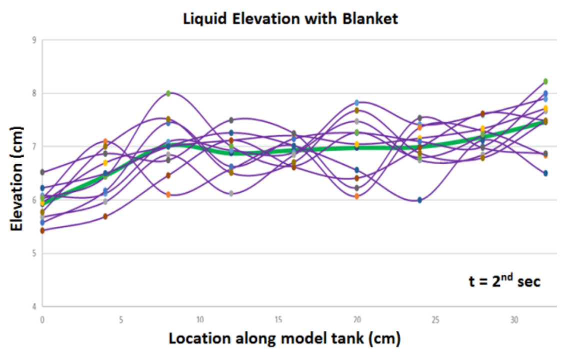


Figure 7: Magnitudes of liquid elevation with floaters for ten random excitations in Case 3 and the average, for 2nd, 6th, and 10th second of the experiment

Similarly, under another ten random excitations in Case 3, the results for liquid surface covered by blanket are shown in Figure 8.



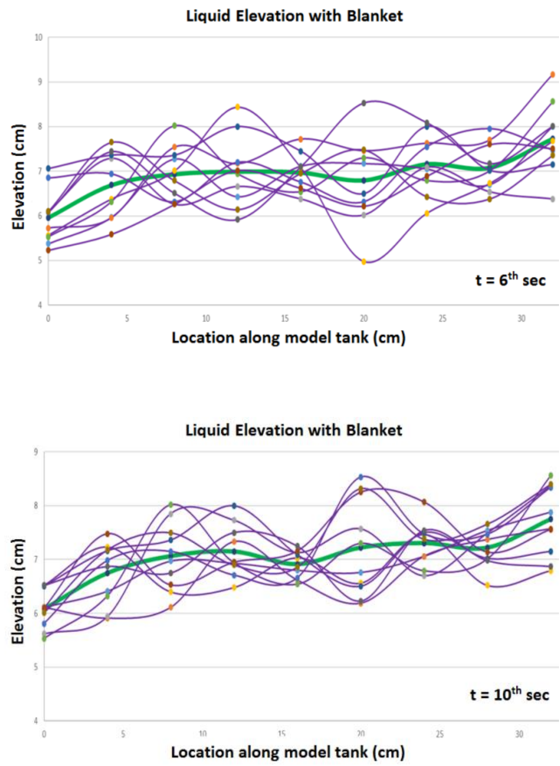
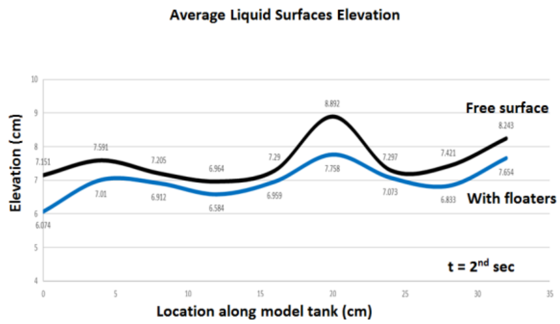


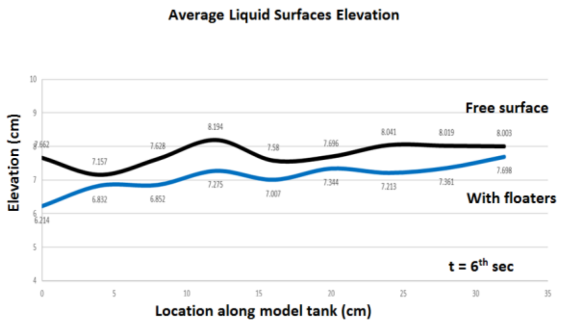
Figure 8: Magnitudes of liquid elevation with a blanket for ten random excitations in Case 3 and the average, for 2nd, 6th, and 10th second of the experiment

It is noteworthy that only results from Case 1 and Case 3 are presented here because Case 2 is just a reference to the authors to verify the consistency of the blanket, whereas the effectiveness of blanket can be clearly displayed in Case 3.

The surface elevation profiles, in Case 3, are similar for both model tanks in the observation under the same random excitations and it can be found that the one covered with blanket is always lower, on average than the one with floaters.

The average of liquid elevation for free surface and with floaters for ten random excitations in Case 1 is shown in Figure 9.





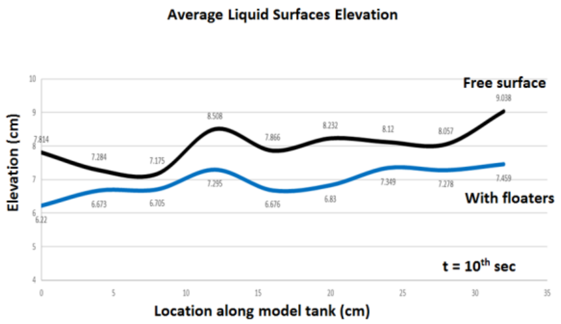
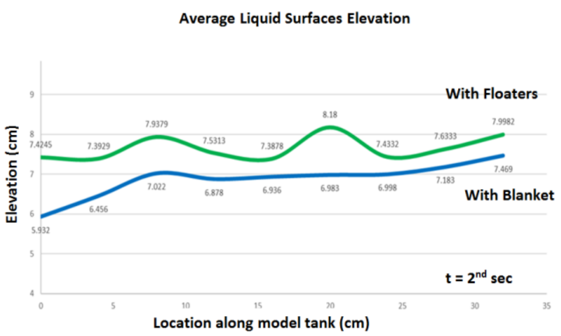
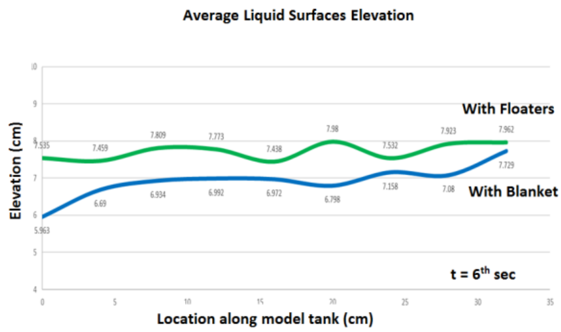


Figure 9: Average of liquid elevation for *free surface* and *with floaters* for ten random excitations in Case 1, for 2nd, 6th, and 10th second of the experiment

By averaging all the average values in Figure 9, the liquid elevation of the free surface is 7.9 cm while the liquid elevation with floaters is 7.0 cm. Hence, it can be found that the spherical floaters can reduce 11% of the sloshing induced by tank motion in this case study.The mitigation of liquid sloshing is due to part of the kinetic energy in the liquid is being transferred to the floaters. Hence, the floaters act as a damper to partially absorbthe sloshing energy.

The performance of sloshing suppression can be further improved using a blanket. As shown in Figure 10, the liquid elevation covered by a blanket, under random excitations in Case 3, can be reduced further by 10% (average of averages) from the one covered by floaters.





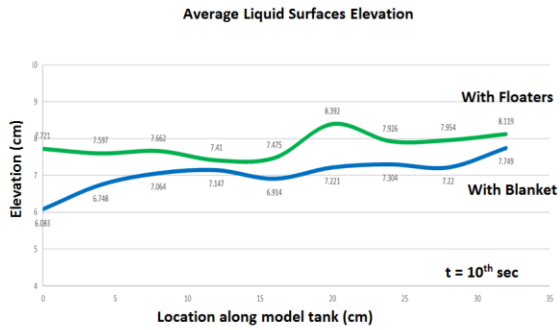


Figure 10: Average of liquid elevation *with floaters* and *with a blanket* for ten random excitations in Case 3, for 2nd, 6th, and 10th second of the experiment

The nylon strings tied up the polystyrene balls in a formation, created coupled dynamics of the floaters, hence, the motion of individual floater can now be restrained by its neighbours. Additional energy from the sloshed liquid is needed to overcome such coupled effects.

From the experiment, it can be found that,

(i) the additional afloat devices on the internal liquid inside a tank can act as damper to absorb partial kinetic energy from the sloshed liquid;
(ii) a tied up formation of scattered floaters can further create coupled effects to increase the rate of energy absorption.

These findings lead to a direction for the future investigation to further reduce the sloshing effects, such as performing a parametric study on the floaters and studying formation arrangement of the blanket.

CONCLUSION

A series of the experiment aimed to investigate the effects of anti-sloshing floaters and blankets have been reported in this paper. The model test was carried out through three cases which are (1) free surface only and with spherical floaters; (2) free surface only and with the blanket, and (3) with spherical floaters and with the blanket. The results indicated that a reduction of sloshed liquid elevation of 11% can be achieved by using spherical floaters in this case study and further reduction of 10% can be achieved by adding formation to these scattered floaters to form a floating blanket. The additional afloat devices on the internal liquid inside a tank can act as a damper to absorb partial kinetic energy from the sloshed liquid and a tied up formation of scattered floaters can further create coupled effects to increase the rate of energy absorption. The future works of this research can focus ona further parametric investigation of the floater and formation pattern of the blanket.

Acknowledgements

The authors would like to appreciate UniversitiTeknologi Malaysia (UTM) for the full support. Also, the corresponding author expresses gratitude to Dr. Kyung-Sung Kim from Tongmyong University, Busan, South Korea on his valuable discussion on this topic.

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