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Suppression of hydrodynamic sloshing in liquefied natural gas tank with floating baffle: Experimental and numerical studies

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Abstract. A fixed anti-sloshing mechanism such as baffles which modifies the tank structure may lead to increment of the maintenance cost. This paper proposes a floating baffle, and reviews its investigation on the sloshing behaviour in a membrane-type tank model under unidirectional excitation with 30% and 50% of filling ratio. An LNG tank was numerically simulated in OpenFOAM under regular sinusoidal motion with an amplitude of 3 cm and excitation frequency set to the natural frequency at 1.1 seconds. Impulsive pressure on the tank wall was obtained, and then benchmarked with the experimental results from the pressure sensors. The simulation and experiment results showed an acceptable agreement with a root mean squared error of less than 10%. The findings are expected to become a significant reference for safer sea transportations such as conventional LNG vessels.

1. Introduction

Several ship structural defects had been associated with sloshing loads [1]. Sloshing may lead to dynamic instability [2], failure of ship's tank structural system [3] and declining performance of global motion of LNG carriers [4].

Various methods have been used to study sloshing, such as analytical, numerical and simulation. Grotle *et al.* [5] investigated sloshing at shallow-liquid depths in a rectangular container by using experimental and open-source finite difference CFD. The results proved that the open-source CFD tool was able to predict the sloshing waves with good accuracy. Colagrossi et al. [6] used both single- and two-phase flow (gas and liquid) SPH models to track the whole flow evolution of sloshing profile. Similar sloshing predication had been conducted [7-8], in which the numerical solution showed good behaviour in describing sloshing phenomenon.

Anti-sloshing devices are in high demand from LNG facilities especially for intermediate fluid level conditions. A baffle an example of fixed anti-sloshing device is developed to direct the liquid sloshing flow [9-10]. A major disadvantage of this baffle is that it will further impair insulation performance [11] and cause LNG leakage. Therefore, fixed baffle requires regular inspection [12]. Kim *et al.* [13] proposed using floating blankets, in which a series of model tank tests had been conducted to investigate the effects of blankets on the sloshing phenomenon. The results showed that the overall reduction in sloshing pressure with floating blanket was significant, particularly during low filling ratio. Zhang *et al.* [14] introduced a floater in solid foam, which can also be considered as a form of floater-type blanket. The disadvantage of float-type is the requirement of large volume of storage space inside the LNG tank. The complexity of design and fabrication process of these floaters are also some reasons why there are only a few research studies on float-type compared to fixed baffle.

This paper also proposes a novel type floating baffle (FB), which combines both the advantages of fixed- and float-type anti-sloshing mechanism. The prototype had been tested, and the efficiency of floating baffle had been investigated by using both experiments in a controlled unidirectional excitation, and numerical simulations in OpenFOAM. The liquid free-surface elevation and impact pressure had been evaluated as well.

2. Methodology for testing hydrodynamics behaviours of floating baffle

2.1 Experimental setup

The experimental setup of prototype testing is illustrated in Figure 1. Detailed explanation of this setup can be referred to the previous work of the authors [15].

The excitation frequency, ω selected was close to the natural frequency ω_n for filling ratio, γ=30% in order to simulate the most violent case of sloshing phenomenon. The equation to calculate the natural frequency of the tank is given as:

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

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. The dimensions of the tank were 46.6 cm in length (L), 28.6cm in height (H), and 38.1cm in breadth (B). The LNG tank model, as illustrated in Figure 1, was simulated with a regular sinusoidal motion with amplitude A=3cm, and excitation frequency set as the natural period, T=1.1 seconds for filling ratio γ=30%. The input data of frequency and amplitude were scaled down based on a 10-year return period condition of the South China Sea with a scale ratio of λ=100 [16].

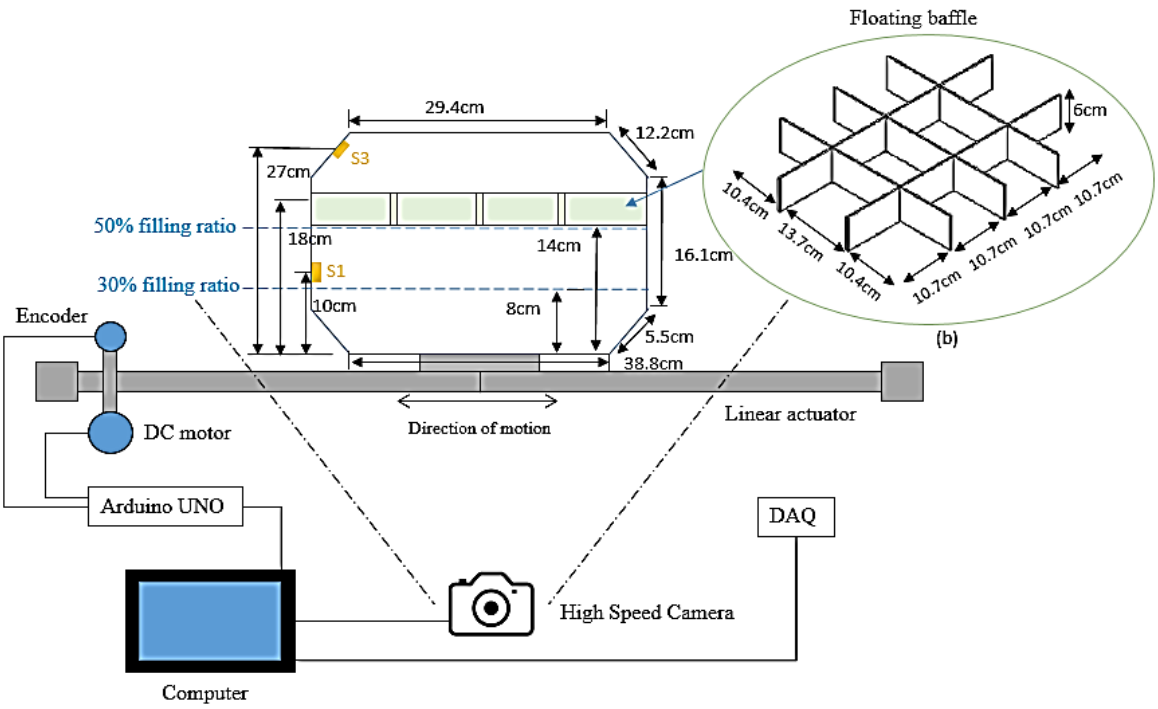

Figure 1. Experimental setup

2.2 Prototype of floating baffle

The model in the experiment was fabricated from polypropylene cardboard is illustrated in Figure 1. However, in actual application under cryogenic conditions, the floating baffle can be built by using a flexible material which is safe to be used with LNG [27]. However, further studies need to be done for the implementation of the material. In this model, the floating baffle had its upper section of the fluid domain divided into 12 smaller subsections. The pressure sensors were in the immediate vicinity of subsection A.

2.3 Calibration of pressure sensors

The pressure sensor model used in the experiment was MPX5010 (air pressure sensor) with maximum pressure of 10 kPa. Modification and calibration had been made to use this sensor to measure sloshing pressure. As shown in Figure 2, a stainless-steel funnel was covered with latex diaphragm on the surface to receive liquid sloshing impact. The other end of the funnel was connected to the sensor. The surface fluctuation of latex diaphragm would compress the air inside the funnel and give signal variation to the MPX5010 sensor. The calibration of this converted device was conducted using various loads, *m* (5g, 10g, 20g, 50g, and 100g) loaded at the centre of the latex diaphragm, and the variations of voltage readings were recorded. A graph of the voltage reading with respect to the variations of loads was then plotted as shown in Figure 3. The plot indicated a linearly proportional relationship between the pressure/loads and the voltage readings in this experiment.

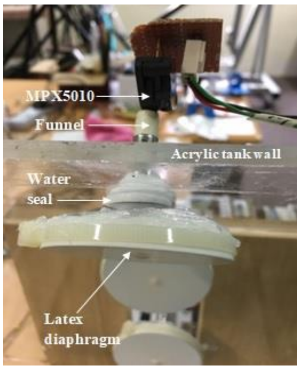

Figure 2. Modification of pressure sensor

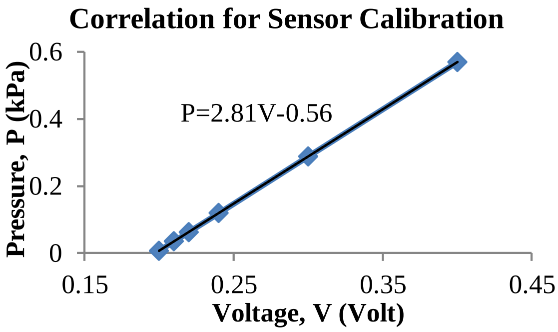

Figure 3 Correlation between voltage reading and pressure on latex diaphragm

2.4 Numerical simulation setup

The simulation for liquid free surface of sloshing was conducted by using OpenFOAM, an open source CFD package. The solver *interDyMFOAM* was utilized to solve the case study. The geometry modelling represents the boundary of the water in the simulation. In the research case, the geometry setup values was scaled down to 100:1. Grid size of 60×30×34 units was used for the simulation. The results was generated based on experimental time setting which was 30 second. The floating baffle (FB) model was drawn in FreeCAD according to the floating baffle model. In the simulation, the pressure values at the sensor location (S1 to S3) were determined by using the probes function in OpenFOAM.

3. Hydrodynamics behaviours of floating baffle

3.1 Sloshing profiles without floating baffle

The sloshing profiles of liquid (water) in the tank model under sloshing test are shown in Figures 4 and 5, for filling ratios γ=30% and γ=50%, respectively. The time interval for a complete sloshing cycle was 1.1 seconds. The results of the experiment and simulation matched well from the sloshing profile, time-step, and maximum run-up on tank wall. Hydraulic jump was found in both filling ratios, where the liquid run-up caused by the sloshing on the tank wall could generate large impact force to the structural integrity. For the case of γ=30%, resonance was observed, and more violent sloshing profiles occurred.

3.2 Sloshing profiles with floating baffle

Sloshing profiles after incorporation of floating baffle (FB) are shown in Figures 6 and 7. The results of the simulation and experiment matched well. Thereafter, the sloshing profiles were no longer in a smooth continuous form due to the flow intervention of the floating baffle. Flow vortices were observed in the simulation at the vicinity of the surface flow and the floating baffle. Due to the existence of floating baffles, the fluid domain in the tank had been divided into smaller subdomains, with more scatter flow pattern. Hydraulic jumps and water run-up on the side wall had been significantly reduced, especially in the case of filling ratio γ=30%.

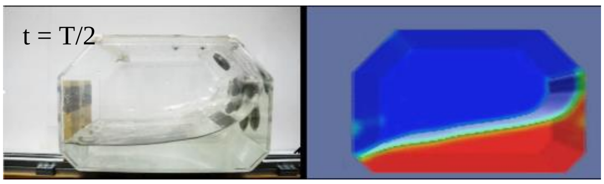

Figure 4. Sloshing profile of 30% filling condition at half cycle (without floating baffle)

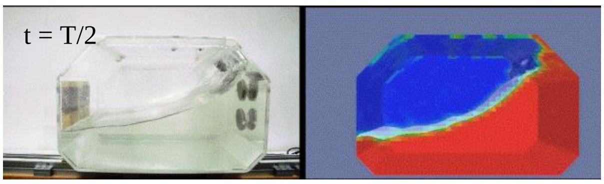

Figure 5. Sloshing profile of 50% filling condition at half cycle (without floating baffle)

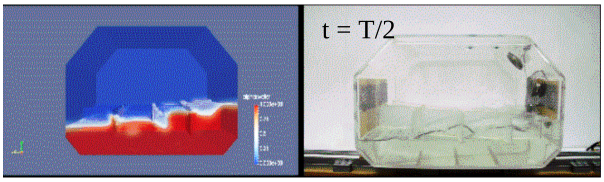

Figure 6. Sloshing profile of 30% filling condition at half cycle (with floating baffle)

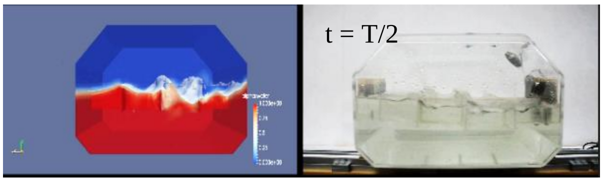

Figure 7. Sloshing profile of 50% filling condition at half cycle (with floating baffle)

3.3 Free surface elevation

The average free surface elevation along the length of the tank model is shown in Figure 8 for γ=30%, and Figure 9 for γ=50%). The average free surface elevation was calculated by averaging the free surface profile when the maximum run-up on the sensor-sized wall had been reached. A total of nine run-up surface profiles under a consecutive excitation were taken for calculation. The free surface elevation as shown in Figures 8 and 9 indicates that the repeatability of the free surface suppression after incorporation with floating baffle is very significant, in both experiment and simulation results. For filling ratio γ=30%, the maxima of run-up on the tank wall was reduced to 51.7% of the original run-up after adding the floating baffle, while the filling ratio γ=50% had been reduced to 77.0% of the original run-up. The free surface after adding floating baffle was less smooth with more fluctuation near the locations at the vicinity of boundary of floating baffle subdomain. This phenomenon was displayed clearly in the simulation results for both cases of γ=30% and γ=50%.

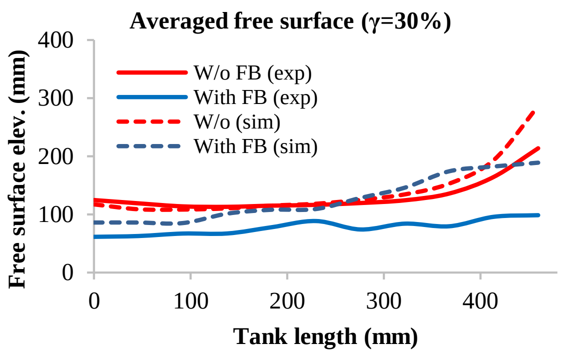

Figure 8. Average wave elevation for 30% filling condition

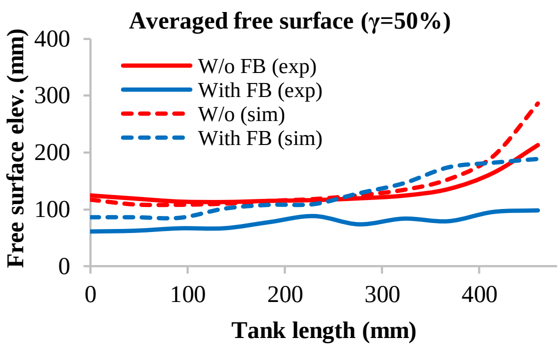

Figure 9. Average wave elevation for 50% filling condition

3.4 Normalized pressure

The impact pressure exerted on the tank wall is shown in Figure 10 for γ=30%, and Figure 11 for γ=50%. The dynamic pressure was obtained from the conversion of voltage reading, as explained in Section 2.2. The sloshing impact pressure was well detected at locations S1 and S2. The impulsive pressure for the eleven consecutive excitation cycles had been recorded in a time series. In order to present meaningful pressure reading where the sensor would receive most impact according to different filling ratio, the S1 was used for γ=30% and S2 was used for γ=50%. For filling ratio γ=30%, the maximum pressure was 3.60kPa when there was no floating baffle. However, the maximum pressure was reduced to only 0.14kPa when the floating baffle was incorporated. On the other hand, for γ=50%, the maximum pressure was reduced from 0.96kPa to 0.05kPa after adding the floating baffle. The results showed that the pressure from the experimental work was lower than that of the simulation. This discrepancy could be caused by high nonlinearity of sloshing experiment in real life, including the interaction effects of the floating baffle and hydrodynamics damping.

3.5 Stability analysis of floating baffle

The dynamical system stability before and after the tank was being incorporated with floating baffle are shown in Figure 12 (γ=30%) and Figure 13 (γ=50%). These figures clearly indicate that 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 Figure 12 and Figure 13, where abrupt changes of pressure had been identified. Moreover, on the horizontal axis, the range of stability diagram for the case without floating baffle was more than three times larger than the one with the incorporation of the floating baffle.

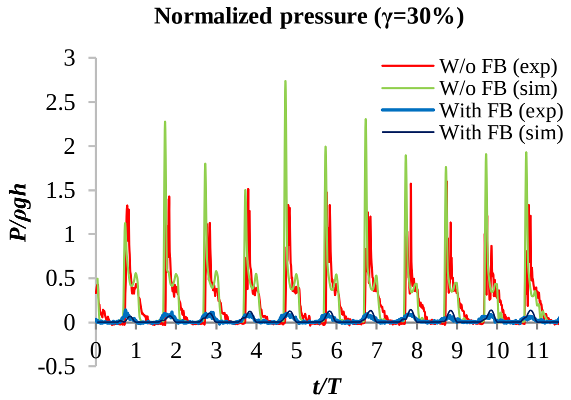

Figure 10. Normalized pressure on sensor S1 for 30% filling condition

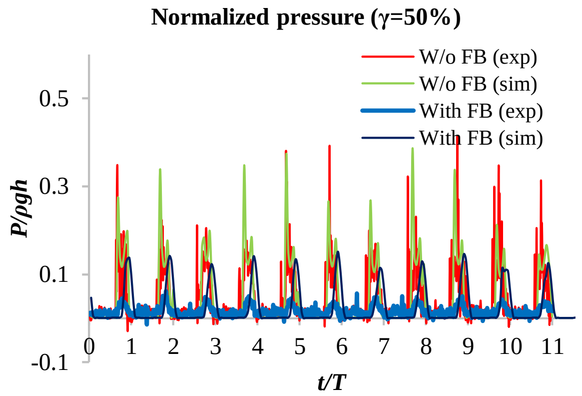

Figure 11. Normalized pressure on sensor S2 for 50% filling condition

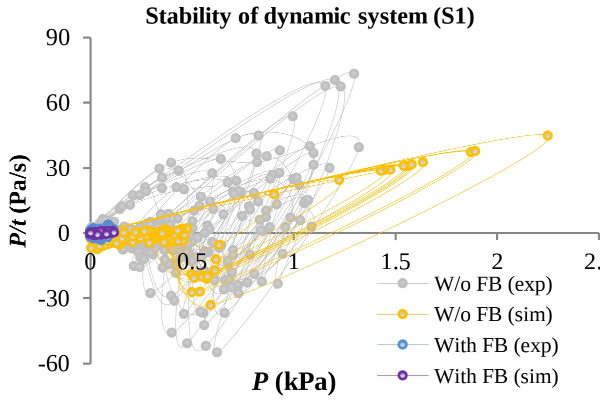

Figure 12. Stability of dynamic system for γ=30% (results from S1)

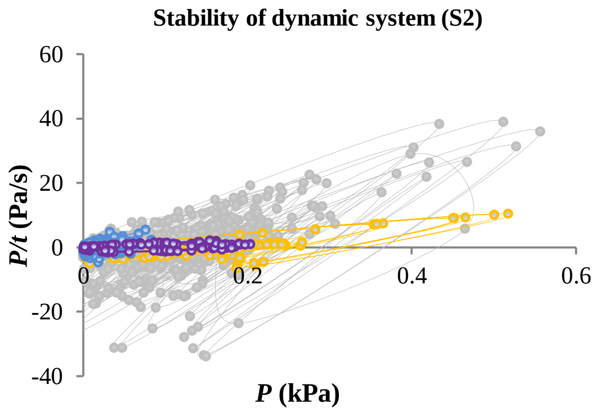

Figure 13. Stability of dynamic system for γ=50% (results from S2)

From the sloshing tests for the floating baffle in both experiment and simulation, it is noteworthy that the nonlinearity of sloshing flow was dominant under lower filling ratio, where the sloshing was characterized by hydraulic jump and water spray formation. As a result, sloshing impact in tanks with low filling ratio was generally high on the tank wall. In real life application, the excitation could be multi-dimensional. Nonetheless, the current study can provide an insightful understanding on the efficiency of floating baffle, as a novel anti-sloshing device.

4. Conclusion

The efficiency of floating baffle by liquid sloshing in a unidirectional exciting tank had been investigated. A tank with filling ratios of γ =30% and γ =50% with the installation of floating baffle had been tested through experimental and numerical methods. A good agreement between the sloshing profile, free surface elevation and sloshing pressure results was concluded from both methods. Liquid sloshing becomes violent and highly nonlinear under lower filling conditions. However, the liquid phenomenon such as water jet and spray formation were captured well in experiment compared to simulation test. Hence, experimentation is important to better understand the hydrodynamics of sloshing. Findings in this study proves that floating baffle can effectively reduce the peak pressure of liquid sloshing, particularly under lower filling condition. Floating baffles can be regarded as a potential innovation to suppress violent sloshing inside LNG tanks. Nonetheless, more future works are needed to increase the technology readiness level (TRL) of floating baffles before real life feasibility can be determined.

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