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Numerical Simulation of Sloshing in Different Tank shape with Vertical and Horizontal Baffle Using Smoothed Particle Hydrodynamics

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Abstract

Computational Fluid Dynamics (CFD) is a numerical analysis used to solve problems related to free surface flows. Two major methods have been developed in the CFD, mesh-based and meshless CFD, in this paper. The meshless CFD approach, Smoothed Particle Hydrodynamics (SPH), is employed. SPH is a meshless method where each fluid is represented by a point or particle. In this study, a 3D simulation was carried out for the phenomenon of sloshing with roll motion in prismatic, square, cylindrical and spherical tanks with a duration of sloshing of 28 seconds. The filling ratio was 25% for all tanks used in this study. Vertical and horizontal baffles were also used to suppress the sloshing. The ratio height of the vertical baffle is 0.9, and the horizontal baffle is 0.2. The results of this study show a successful comparison of dynamic pressure, free surface heights, forces, and moments in various tank variations. The installation of baffles in the tank influences the sloshing phenomenon, especially in the use of vertical baffles, where the vertical baffle is the most effective baffle used in all tanks.

1. Introduction

One phenomenon that often occurs in liquid carrier is sloshing, i.e., a phenomenon in which a fluid moves due to an oscillatory motion caused by external excitation. The liquid carrier for instances LNG carrier in membrane tanks has prismatic tank that the shape has advantage similar to ship hull. The study of sloshing in membrane tank have been carried out both experimental and numerical approach. Energetic sloshing can made a damage to the tank structure, it can cause an explosion if the liquid in the tank is explosive [1]. In addition, sloshing can influence of the hydrodynamic forces and moments that arise due to the changing center of mass cause the stability of the vehicle to decrease [2]. Sloshing is affected by tank size, tank shape, tank type, liquid level, excitation frequency and anti-sloshing. The impact of sloshing can be prevented by minimizing fluid motion by using anti-sloshing or baffles [3]. Baffles serve as a mechanism to dissipate kinetic energy by creating vortices in the liquid. The efficiency of reducing sloshing by baffles is affected by the height and thickness of the baffles [4].

The sloshing phenomenon is related to free surface motion, The CFD method is one of the solutions for analyzing sloshing phenomenon. There is two major CFD method, mesh based and meshfree CFD that in this paper meshfree CFD so-called smoothed particle hydrodynamics (SPH) is used to tackle of sloshing in prismatic tank. This method has the advantage of being used in cases of sloshing because it does not need to carry out the meshing process as result the large deformations of free surface flows is well capture. SPH a system will be represented by a set of points or particles, which have their own material properties during computation [5]. SPH is a computational method developed by Monaghan for free surface flows, by applying SPH for dam break and water wave propagation simulations [6]. The SPH method has applied to square tanks by Cao et al [7], then the use of SPH for prismatic tanks with 2 phase flows has been validated with experimental data [1]. The use of baffles to reduce sloshing in sway motion for prismatic tanks [8]. Numerical research has been carried out on square tanks using baffles using the BEM method where the use of baffles can reduce the increase in free surface [9]. The use of complex baffle variations in square tanks using SPH has also been studied [10]. It indicates the SPH method has been applied for sloshing in different cases both with and without baffles. The results showed SPH has promising to applied in the nonlinier phenomenon.

This paper will carry out the study of sloshing in prismatic, rectangular, cylindrical, and spherical tank with 25% filling ratio. In addition, vertical and horizontal baffles were used to supress sloshing that external oscillation based on previous works [11]. The Open-source SPH solver DualSPHysics [12]was used to simulate the sloshing in 3D domain, in addition the advance post processing using VisualSPHysic was performed to get realistic simulation [13]. It indicates that dynamic pressure, hydrodynamic force and moment are effected by the tank shape although in some results is not significant.

2. Methods

2.1. Experimental Setup

Referring to previous studies, researchers wanted to compare the results of sloshing analysis in cylindrical tanks, square tanks, and prismatic tanks by adding vertical baffles and horizontal baffles to each tank using Smoothed Particle Hydrodynamics (SPH). The experimental itself was conducted in three filling ratios, in this paper only filling ratio of 25 % was used to reproduce sloshing in the low filling ratio. In the low filling ratio sloshing, it became more dangerous compare other filling ratio situation caused the movement of fluid more violent, in addition fluid has characteristic to move with the tank movement that can endanger ship. An excessive motion could be existed due to of sloshing in ship compartment. This is the reason the mitigation of sloshing in the low filling ratio is essentials for liquid carrier for instance LNG carrier. Figure 1 depicts the sketch of prismatic tank for SPH computation. In this paper, only sway motion was used to reproduce sloshing in the low filling ratio. The pressure sensor was fixed during sloshing in the experiment, the similar condition was used in the SPH simulation. Figure 2 shows the tank movement of roll sloshing in the experiment, the same movement was used in the SPH computation. The external frequency excitation is 1.04 Hz, with an amplitude of motion is 6.52 mm. This frequency is close to the natural frequency of a prismatic tank, 1.11 Hz for a filling ratio of 25%. Eq. (1) and Eq. (2) were used to calculate the natural frequency of the prismatic tank [14]. Where ω is the natural frequency of the i-mode for a rectangular tank, d represents the water height, and l represents the length of the free surface in the direction of tank movement. For a prismatic tank with a chamfered bottom, δ_1 and δ_2 are the horizontal and vertical dimensions of the chamfer, respectively. for the detailed information regarding sloshing experiment please see the ref. [1]:

$$\omega_n = \sqrt{\frac{i.\pi.g.\tan h.\left(\frac{i.\pi.d}{l}\right)}{l}} \tag{1}$$

$$\frac{{\omega'_n}^2}{{\omega_n}^2} = 1 - \frac{\delta_1.\delta_2^{-1}.\sin h\left(\frac{\pi.i.\delta_2}{l}\right) - \delta_1.\delta_2^{-1}\left(\sin\left(\frac{\pi.i.\delta_1}{l}\right)\right)^2}{\pi.\sin h\left(\frac{2.\pi.i.d}{l}\right)} \tag{2}$$

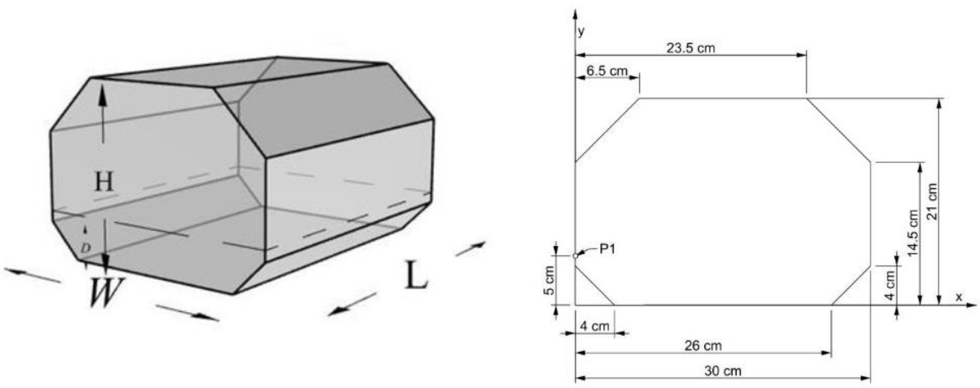

Figure. 1. Sketch of numerical domain and position of pressure sensor

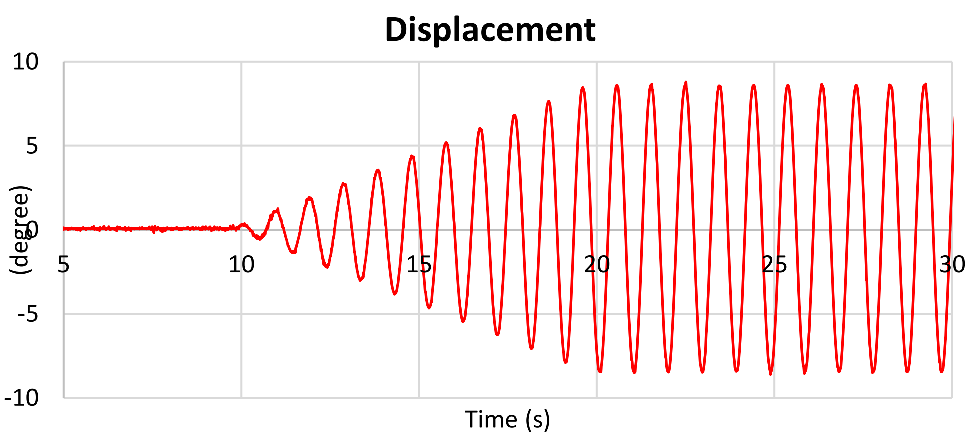

Figure. 2. The time history of tank displacement in rolling motion.

2.2. Smoothed Particle Hydrodynamics (SPH)

Gingold [15] and Lucy [16] pioneered the application of smoothed particle hydrodynamics (SPH) in the astrophysical field. It was later on developed by Monaghan [6] for free surface flow. SPH is a meshless and Lagrangian method that uses discrete evaluation points to approximate the physical values and derivatives of a continuous field. Smoothed particles are identifiable by their mass, velocity, and position. The quantities are computed as a weighted sum from nearby particles within the smoothing length to decrease the range of contribution from neighboring particles (h). The smoothing length is used to weigh the contribution of particle in the kernel function, where $\boldsymbol{r}_{ab}$ is the distance between particles a and b and W_{ab} is the kernel function which can be seen in Figure 3.

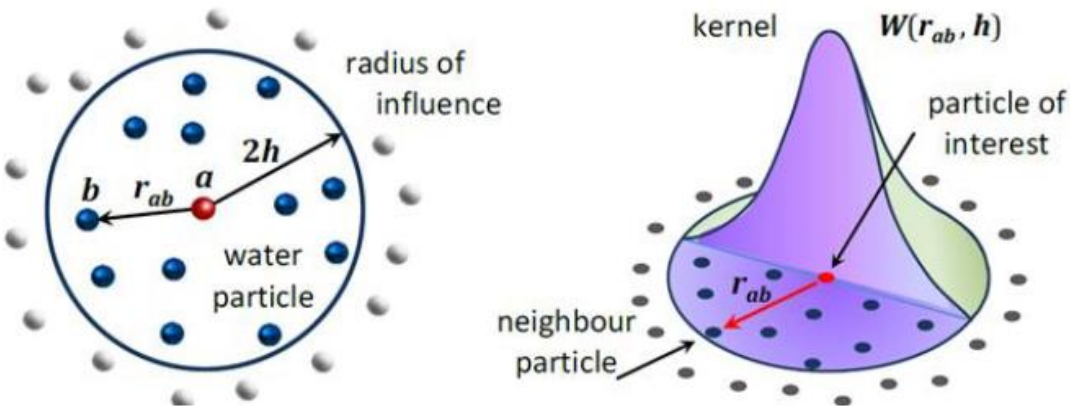

Figure. 3. Radius of the smoothing length and kernel function in SPH

The integral approximated field function $A(r)$ in domain shows in Eq. (3), where W and r are the kernel function and vector position, respectively.

$$A(\boldsymbol{r}) = \int_{\Omega} A(\boldsymbol{r})W(\boldsymbol{r} - \boldsymbol{r}', h)\, d\boldsymbol{r} \tag{3}$$

The particle approximation shows in Eq. (4), with a summation of the neighboring particles regarding the compact support of particle a at spatial position$r$.

$$A(\boldsymbol{r}_a) \approx \sum_b A(\boldsymbol{r}_b)W(\boldsymbol{r}_a - \boldsymbol{r}_b, h)\frac{m_b}{\rho_b} \tag{4}$$

The Wendland kernel function was used in all simulations, where α_D is equal to $21/164\pi h^3$ in 3D, q is the nondimensional distance between particles a and b represented as r/h in Eq. (5). Eq. (6) is the continuity equation with the delta-SPH term to reduce spurious pressure in SPH.

$$W(q) = \alpha_D\left(1 - \frac{q}{2}\right)^4 (2q + 1) \;\; 0 \leq q \leq 2 \tag{5}$$

$$\frac{d\rho_a}{dt} = \sum_b m_b \boldsymbol{v}_{ab} \cdot \nabla_a W_{ab} + 2\delta_{\Phi} h c_0 \sum_b (\rho_b - \rho_a)\frac{\boldsymbol{r}_{ab} \cdot \nabla_a W_{ab}}{\boldsymbol{r}_{ab}^2}\frac{m_b}{\rho_b} \tag{6}$$

Eq. (7) is the momentum equation in the SPH framework, where g is gravity due to acceleration, $P_a$and P_b are pressures in particles a and b, with the approach used included in Eq. (8). Π_{ab} is the artificial viscosity term, where $\mu_{ab} = hv_{ab} \cdot \frac{r_{ab}}{({r^2}_{ab}+\eta^2)}, \eta^2 = -0.01h^2 \bar{c}_{ab} = 0.5(c_a + c_b)$ is the mean speed of sound, and α is a coefficient that needs to be tuned to acquire proper dissipation.

$$\frac{d\boldsymbol{v}_a}{dt} = -\sum_b m_b\left(\frac{P_{a+P_b}}{\rho_a \cdot \rho_b} + \Pi_{ab}\right)\nabla_a W_{ab} + \mathbf{g}$$

$$where\ \Pi_{ab} = \begin{cases} \dfrac{-\alpha\overline{c_{ab}}\mu_{ab}}{\overline{\rho_{ab}}} & \boldsymbol{v}_{ab} \cdot \boldsymbol{r}_{ab} < 0 \\ 0 & \boldsymbol{v}_{ab} \cdot \boldsymbol{r}_{ab} > 0 \end{cases} \tag{7}$$

$$P = \frac{c_0^2\rho_0}{\gamma}\left[\left(\frac{\rho}{\rho_0}\right)^{\gamma} - 1\right] \tag{8}$$

The tank being modeled is a membrane-type prismatic tank, which is the experimental model of Trimulyono, et al. [1]. Cylindrical tanks and square tanks will be modeled the same or close to prismatic tanks, which illustrated in Figure 4.

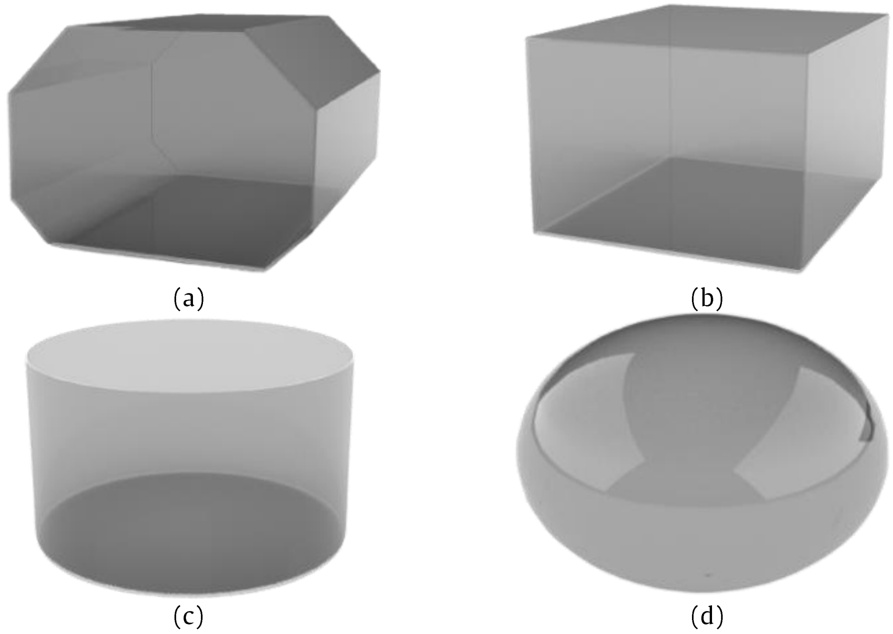

Figure 4. Tank shape: (a) prismatic, (b) rectangular, (c) cylindrical, and (d) spherical

This study will simulate the first is the variation of the shape of the tank model without using baffles, the second is the variation of the shape of the tank model using variations of horizontal and vertical baffles. The baffle thickness in this study is 0.006 meters. Models can be seen in Figure 5 and the height of the vertical and horizontal baffles can be found using the Eq. (9).

$$\frac{h_b}{h} = 0.9 \tag{9}$$

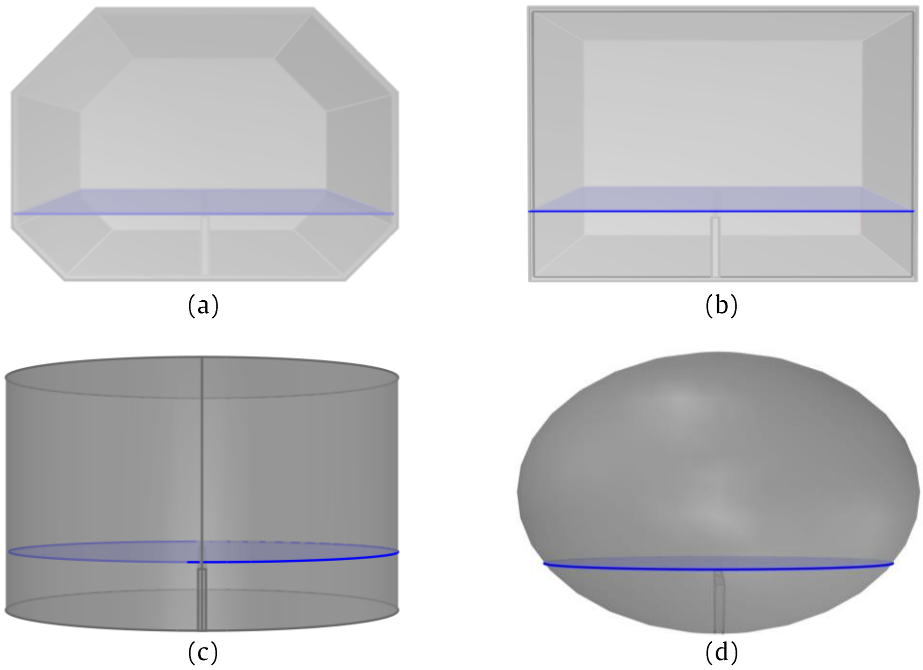

Figure 5. Use of vertical baffle in (a) prismatic tank, (b) rectangular tank, (c) cylindrical tank, and (d) spherical tank

In the use of horizontal baffles, baffles will be placed beside the tank which can be found using the Eq. (10) and the models can be seen in Figure 6.

$$\frac{D_b}{h} = 0.2 \tag{10}$$

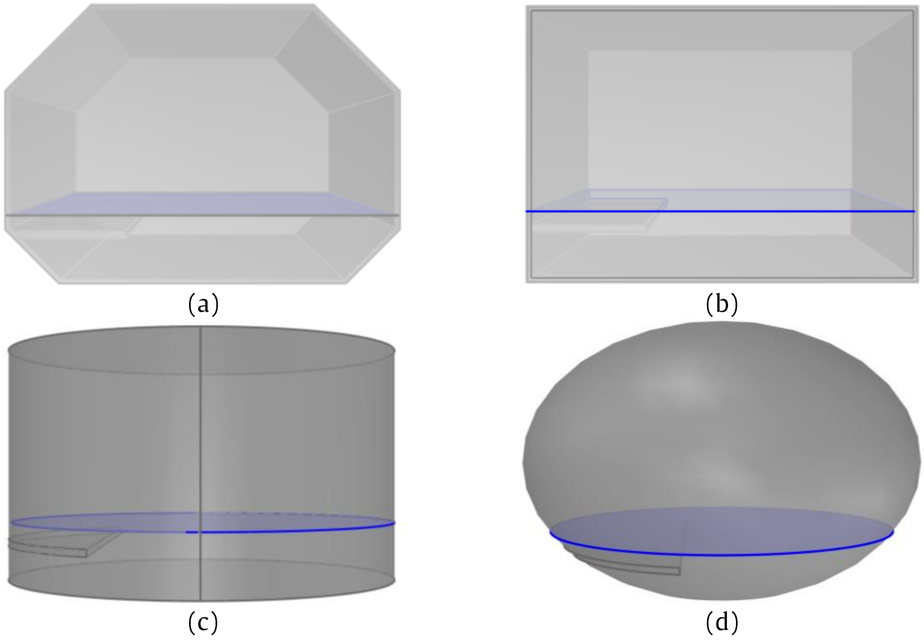

Figure 6. Use of horizontal baffle in (a) prismatic tank, (b) rectangular tank, (c) cylindrical tank, and (d) spherical tank

3. Results and Discussion

3.1. Dynamic Pressure

The results of SPH simulation in prismatic tanks with experiments in accordance with the average peak difference of 2%. The results of the SPH simulation with experiments can be seen in Figure 7.

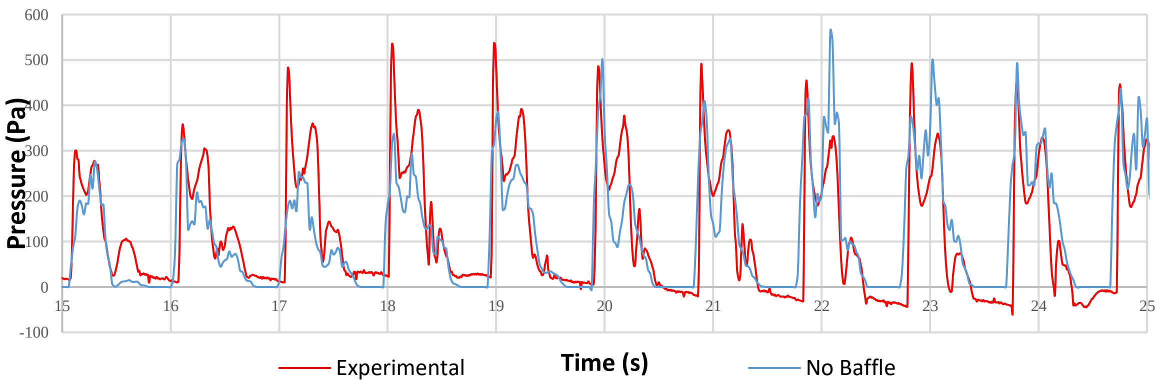

Figure 7. Comparison of dynamic pressure for SPH and experiment without baffle

The most effective use of vertical baffles can be seen in the use of baffles in a square tank which can be seen in the picture. The addition of vertical baffles can reduce dynamic pressure, the ability of these baffles is also almost the same as prismatic tanks due to the similar shape of the tanks. The use of baffles in spherical and cylindrical tanks is not as effective as in prismatic and square tanks where it only reduces small dynamic pressure as can be seen in Figure 8.

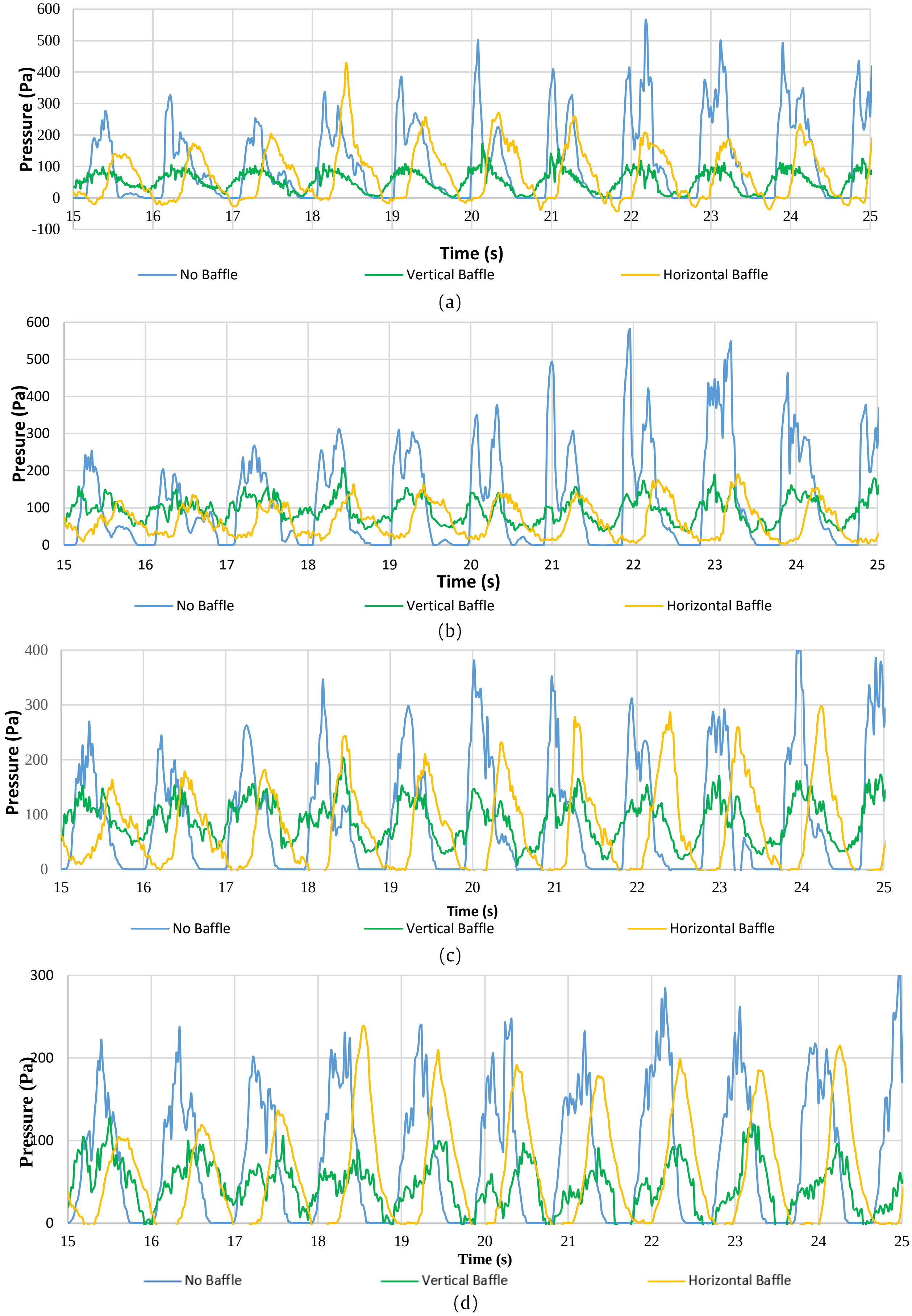

Figure 8. Comparison of dynamic pressure with SPH without baffle, using vertical baffle and horizontal baffle in (a) prismatic tank, (b) rectangular tank, (c) cylindrical tank, and (d) spherical tank

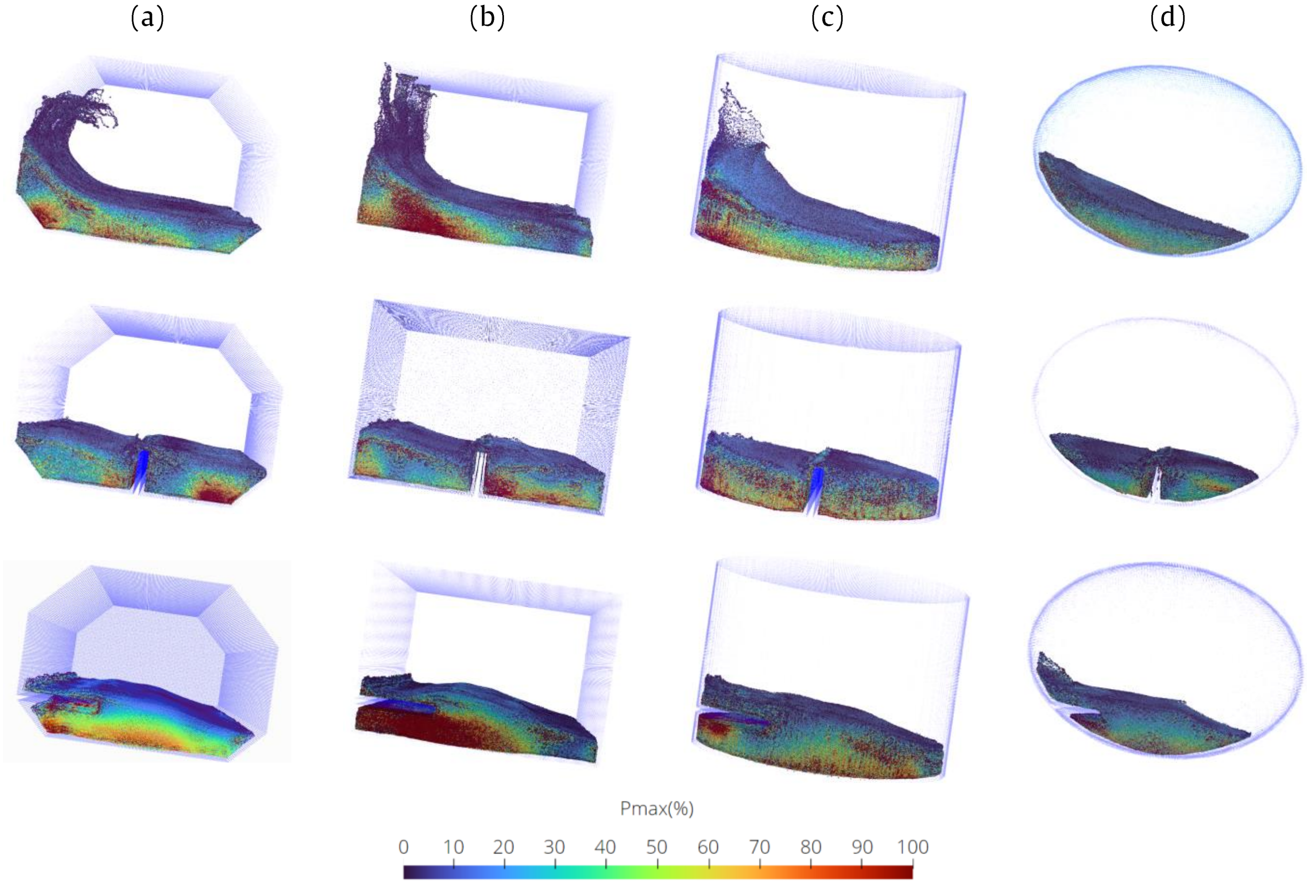

Figure 9. Pressure distribution without baffle, using vertical baffle and horizontal baffle in (a) prismatic tank, (b) rectangular tank, (c) cylindrical tank, and (d) spherical tank

3.2. Free Surface Deformation

The simulation results obtained, in tanks with vertical baffles can reduce 52% in prismatic tank, 56% in square tank, 47% for cylindrical tank, and 17% in spherical tank. Horizontal baffles can reduce 56% in prismatic tank, 62% in square tank, 57% in cylindrical tank, and 26% in spherical tank, as can be seen Figure 10.

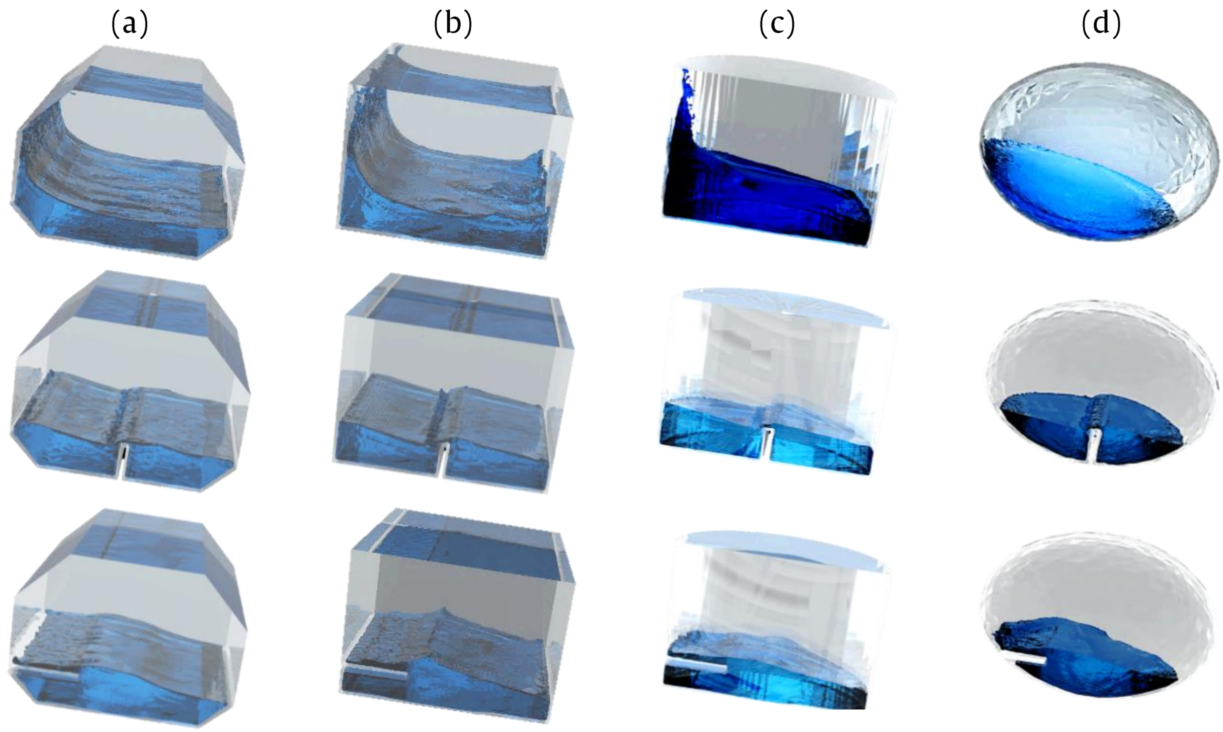

Figure 10. Blender visualization of tank without baffle, using vertical baffle and horizontal baffle: (a) prismatic tank, (b) rectangular tank, (c) cylindrical tank, and (d) spherical tank

3.3. Hydrodynamic Force

The hydrodynamic force is the result pressure force due to fluid inside of tank, in this cases the fluid moves caused by force oscillation motion. Because the motion is simple harmonic motion the difference results from is less compared than hydrostatic pressure which illustrated in Figure 11.

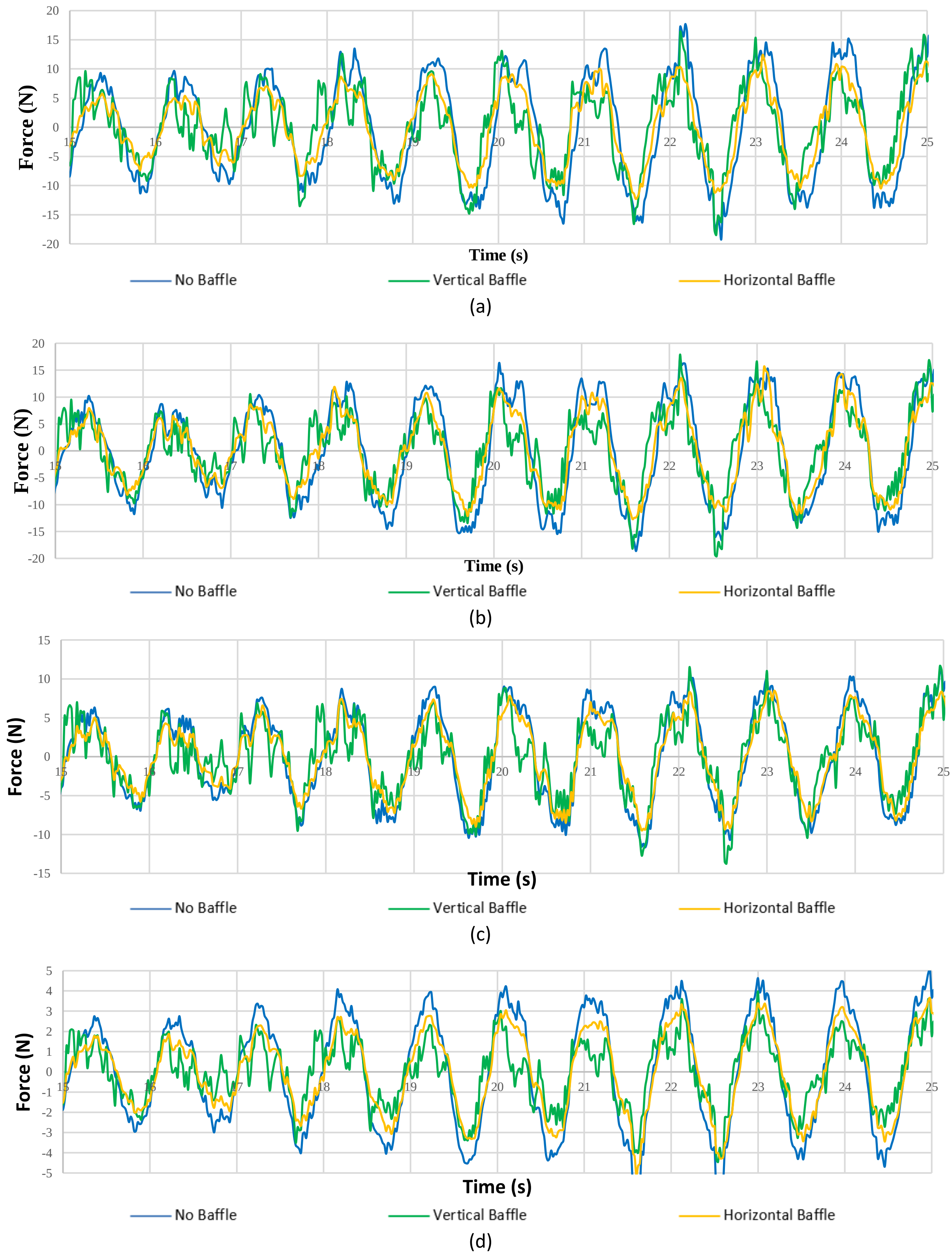

Figure 11. Comparison of hydrodynamic force with SPH without baffle, using vertical baffle and horizontal baffle in (a) prismatic tank, (b) rectangular tank, (c) cylindrical tank, and (d) spherical tank

The hydrodynamic forces in the tank are caused by oscillatory forces which are constant during the sloshing period. The tank is given a roll motion as a constant external oscillating force resulting in a hydrodynamic force on the tank, it caused that the hydrodynamic still exsit and there is small difference before and after baffles installed.

4. Conclusion

Smoothed Particle Hydrodynamics (SPH) was chosen in this study to analyze sloshing in prismatic tanks. The tank configuration and also the external oscillation force used in this study are in accordance with previous studies. The previous experiments obtained the desired pressure, height, force, and moment results. From this study the hydrodynamic pressure results have fairly good accuracy,

The addition of baffles to the tank in this study has an influence on the sloshing phenomenon, especially in the use of vertical baffles. The addition of vertical baffles can be seen its effectiveness in reducing dynamic pressure and free surface height. The use of horizontal baffles seems to be the most significant in reducing kinetic energy.

References

[1] A. Trimulyono, H. Hashimoto and A. Matsuda, "Experimental Validation of Single- and Two-Phase Smoothed Particle Hydrodynamics on Sloshing in a Prismatic Tank," *Journal of Marine Science and Engineering*, vol 17, no. 7, 2019.

[2] A. Hanafi, "Analisa Pengaruh Sloshing Terhadap Getaran Mobil Tangki Dengan Model Full Car," Undergraduate Theses, Sepuluh Nopember Institute of Technology, Department of Engineering Physics, 2011.

[3] M.-A. Xue, J. Zheng, P. Lin and X. Yuan, "Experimental study on vertical baffles of different configurations in suppressing sloshing pressure," *Ocean Engineering*, vol. 136, pp. 178-189, 2017.

[4] J. J. H., S. H. Yoon, C. Y. Lee and S. C. Shin, "A numerical study of the effects of the vertical baffle on liquid sloshing in two-dimensional rectangular tank," *Ocean Engineering*, vol. 44, pp. 79-89, 2012.

[5] J. R. Shao, H. Q. Li, G. R. Liu and M. B. Liu, "An improved SPH method for modeling liquid sloshing dynamics," *Computers and Structures*, Vols. 100-101, pp. 18-26, 2012.

[6] J. J. Monaghan, "Simulating Free Surface Flows with SPH," *Journal of Computational Physics*, vol. 110, no. 2, pp. 399-406, 1994.

[7] X. Y. Cao, F. R. Ming and A. M. Zhang, "Sloshing in a rectangular tank based on SPH simulation," *Applied Ocean Research*, vol. 47, pp. 241-254, 2014.

[8] A. Trimulyono, D. Chrismianto, H. Atthariq and Samuel. "Numerical Simulation Low Filling Ratio of Sway Sloshing in the Prismatic Tank Using Smoothed Particle Hydrodynamics," *CFD Letters*, vol. 14, no.7, 2022.

[9] Y. Guan, C. Yang, P. Chen and L. Zhou, "Numerical Investigation on the Effect of Baffles on Liquid Sloshing in 3d Rectangular Tanks Based on Nonlinear Boundary Element Method," *International Journal of Naval Architecture and Ocean Engineering*, vol. 12, pp. 399-413, 2020.

[10] X. Zheng, Y. You, Q. Ma, A. Khayyer and S. Shao, "A Comparative Study on Violent Sloshing with Complex Baffles Using the ISPH Method," *Applied Sciences*, vol. 8, no. 6, 2018.

[11] A. Trimulyono, A. Haikal, D. Chrismianto, S. Samuel, "Investigation of Sloshing in The Prismatic Tank With Vertical And T-Shape Baffles, " *Brodogradnja* , vol. 73, pp. 43–58, 2022.

[12] J.M. Domínguez, G. Fourtakas, C. Altomare, R.B. Canelas, A. Tafuni, O. García-Feal, I. Martínez-Estévez, A. Mokos, R. Vacondio, A.J.C. Crespo. "DualSPHysics: From Fluid Dynamics to Multiphysics Problems," *Computational Particle Mechanics,* vol. 9, pp. 867-895, 2021.

[13] O. García-Feal, A.J.C. Crespo, M. Gómez-Gesteira. "VisualSPHysics: Advanced Fluid Visualization for SPH Models, " *Computational Particle Mechanics,* vol. 9, pp. 897-910, 2021.

[14] O. M. Faltinsen and A. N. Timokha, Sloshing, vol. 577, New York: Cambridge University Press, 2009.

[15] L. B. Lucy, "A Numerical Approach to the Testing of the Fission Hypothesis," *The Astronomical Journal,* vol. 18, no. 12, 1977.

[16] R. A. Gingold and J. J. Monaghan, "Smoothed Particle Hydrodynamics: theory and application to non-spherical stars," *Monthly Notices of The Royal Astronomical Society*, vol. 181, pp. 375-389, 1997.