PS-9　境界条件を改良した粒子法による球形 LNG タンクのスロッシング計算

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1. Introduction

In the previous research[1], a series of numerical simulation based on Smoothed Particle Hydrodynamic (SPH) theory were performed which shows a good correlation with the model tests results. However, the accuracy of numerical prediction highly depended on the particle dimension utilized in the SPH model which involved with a computation-time-consuming problem for 3D simulation. In this research, the SPH model is improved to obtain the similar prediction accuracy based on the relatively larger particles. Smoothed boundary model (SBM) is proposed in the research to better describe the boundary with complex geometric. Unphysical gap is clearly observed based on the SBM. By eliminating the influence of this unphysical gap, the prediction accuracy for the sloshing load is improved a lot and similar prediction accuracy can be obtained by SPH model with two times larger particle dimension compared with the original SPH model.

2. SPH Model

In this research, the open-source code DualSPHysics is used to simulate the SPH flow. DualSPHysics[2] is developed for large-scale SPH calculation by utilizing the parallel computation ability of both CPU and GPU.

The basic governing equation in SPH can be written as:

$$\frac{d\boldsymbol{v}}{dt} = -\frac{1}{\rho}\nabla P + \boldsymbol{g} \qquad \text{momentum equation} \qquad (1)$$

$$\frac{d\rho}{dt} = -\rho\nabla\cdot\boldsymbol{v} \qquad \text{continuity equation} \qquad (2)$$

$$\frac{d\boldsymbol{r}}{dt} = \boldsymbol{v} \qquad \text{trajectory equation} \qquad (3)$$

$$P = B[\left(\frac{\rho}{\rho_0}\right)^{\gamma} - 1] \qquad \text{Tait's equation} \qquad (4)$$

3. Smoothed Boundary Model

In original DualSPHysics, the boundary with non-planar shape is approximately represented by the polygon boundary. As shown in Fig. 1, the blue curve represents the desired boundary and the black points represents the approximate polygon boundary utilized in SPH model. Even though the polygon boundary consists of the particles which are closest to the desired boundary, it is still not smooth enough when the particle dimension is relatively large and the distribution of the fluid particles near the boundary become irregular.

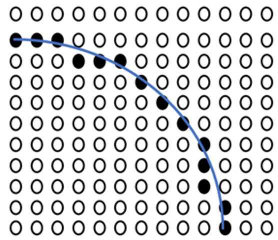

Fig. 1 Polygon boundary.

To solve the above problem, before SPH calculation, a smoothed boundary is generated which consists of evenly distributed particles with same boundary particle number utilized in the original SPH model. According to Vogel's method (1979), the golden angle spiral trick is used to distribute the particles with certain number evenly on the spherical surface as shown in Eq. 5-8.

$$x_i = R_i\cos((i-1)\theta) \qquad (5)$$

$$y_i = R_i\sin((i-1)\theta) \qquad (6)$$

$$R_i = \sqrt{R^2 - z_i^2} \qquad (7)$$

$$z_i = R(1 + \frac{1-2i}{N}) \qquad (8)$$

where, R is the radius of the sphere. i is the boundary particle id which is from 1 to N. N is the boundary particle number. θ is the golden angle which is defined as $\pi(3-\sqrt{5})$.

After the generation of the evenly distributed particles, the projection index between original boundary particles and new boundary particles is created based on the shortest distance criterion. According to the projection index, the original boundary particles are manually moved to the corresponding SBM particles in the initial phase of SPH simulation. During the initial phase, the fluid particles can be automatically relocated and get balance due to the gravity acceleration.

4. Results and Discussions

To check the influence of boundary models, two numerical models with polygon boundary and smoothed boundary are established with particle dimension 2cm. Besides, the simulation results with polygon boundary but smaller particle and higher prediction accuracy[1] are utilized to validate the performance of SPH models with larger particles. Table 1 shows the basic parameters for the SPH models with 1cm and 2cm particles.

Table 1. Parameter of SPH model

	SPH-1cm	SPH-2cm
Particle Number	569232	86756
Consumed Time /sec	1108 sec	91 sec

Fig. 2-3 present the comparisons of sloshing force in sway direction with different motion amplitude. The numerical sloshing force is obtained by integrating the fluid pressure around the tank surface. The x axis represents the regular motion period and the y axis corresponds the ratio between the sloshing force and motion amplitude. Four series data are shown in Fig. 2-3 which include the experiment results (Exp), the SPH-1cm results with original polygon boundary (SPH-1cm-Original), the SPH-2cm results with original polygon boundary (SPH-2cm-Original) and the SPH-2cm results with smoothed boundary (SPH-2cm-SBM). By comparing the results of SPH-2cm-Original and SPH-2cm-SBM, it can be found that, even though the boundary is smoothed by SBM, the integrated sloshing force does not change a lot. The discrepancy of prediction accuracy between SPH-2cm-SBM and SPH-1cm-Origianl is still significant. The sloshing natural period is underestimated which can be interpreted by the dynamic boundary condition (DBC) utilized in the SPH model. It is noticed that, due to DBC, unphysical gap occurs between the boundary and fluid particles[1] which decreases the fluid domain and then, the natural period becomes shorter than the real value. Generally, larger particle dimension (like SPH-2cm model) involves larger unphysical gap. The influence of unphysical gap can be easily eliminated by slightly increasing the tank radius based on the dimension of unphysical gap.

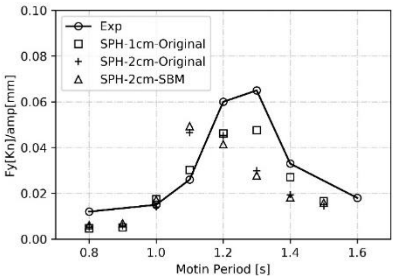

Fig. 2 Comparison of sloshing force in sway direction for motion amplitude 20mm

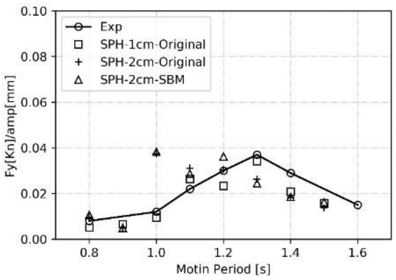

Fig. 3 Comparison of sloshing force in sway direction for motion amplitude 40mm

Fig. 4-5 show the similar comparison with Fig. 2-3. The results with smoothed boundary and enlarged tank radius are presented by SPH-2cm-SBM_LargeR. It is proved that, after utilizing the SBM with considering the influence of unphysical gap, the prediction accuracy of SPH model with 2cm particle increases a lot which is almost similar as that of the SPH model with 1cm particle. The natural period obtained by the SPH-2cm-SBM_LargeR becomes more reasonable as well.

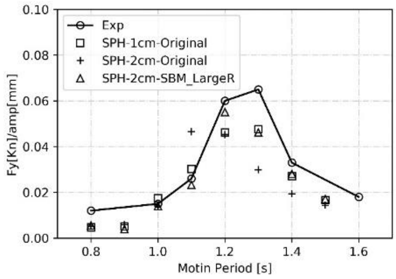

Fig. 4 Comparison of sloshing force in sway direction for motion amplitude 20mm with enlarged tank radius

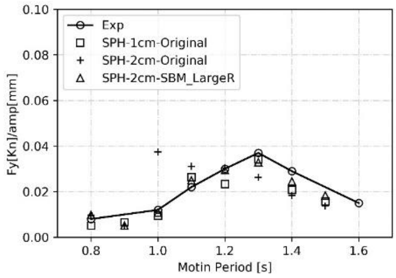

Fig. 5 Comparison of sloshing force in sway direction for motion amplitude 40mm with enlarged tank radius

5. Conclusions

In this research, it is proved that, even though the smoothness of the boundary has little direct influence on the prediction of the integrated sloshing force, by increasing the radius of tank to eliminate the influence of unphysical gap in smoothed boundary model, the prediction accuracy improved a lot. As the initial rearrangement of the boundary particles can be finished in few minutes, the consumed time based on proposed model with 2cm particle can be less than 10% of the original SPH model with 1cm particle while the similar prediction accuracy can be obtained.

Reference

1) Ma, C., Oka, M., Ando, T., Matsubara, N. (2017). "A Study on Sloshing Behavior for Moss Type LNG Tank based on SPH Numerical Simulation and Large-Scale Model Experiment," *Proceedings of ISOPE2017*.
2) Crespo, AJC et al. (2015). "DualSPHysics: Open-source parallel CFD solver based on Smoothed Particle Hydrodynamics (SPH)," *Computer Physics Communication*, 187, 204-216.