Effects of the location of horizontal baffle on liquid sloshing by MPS method

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ABSTRACT

In this paper, the effects of the location of one horizontal baffle on liquid sloshing under angular excitation are investigated. An in-house solver MLParticle-SJTU developed based on improved moving particle semi-implicit (MPS) method is used for numerical simulation. Firstly, a rectangular tank without baffles is modeled to show the validity of solver. Then, one horizontal baffle is installed in the tank and the location of it is changed. The results show that the arrangement of horizontal baffle makes significant effects on the impact pressure on the tank walls and the deformation of free surface.

KEY WORDS: Liquid sloshing; MPS; horizontal baffle; MLParticle-SJTU solver.

INTRODUCTION

In recent year, many countries focus on the exploitation and transportation of oil and natural gas with the rapid development of economy and the increasing demand of energy. LNGs, LPGs and VLCCs which can transport oil and liquefied gas have been built by large scale. For these liquid cargo vessels, the liquid sloshing is a common phenomenon in a partially filled container under external excitations, which will affect the structure of tank walls and the ship stability. The violent fluid induced by external excitations produces so high impact pressure acting on the tank walls that the structure may be destroyed. And the sloshing moment may disturb the ship stability and cause shipwreck. In order to reduce the damage of liquid sloshing, the filling level between 10% and 95% should be forbidden. But with the wide use of liquefied cargo vessels, the containers partially filled are inevitable. Many researchers have devoted themselves to studying the characters of liquid sloshing.

The investigations on the liquid sloshing can be classified as three main types: theoretical analysis, experimental study and numerical simulation. In past years, many analytical models were developed by some researchers. Faltisnen (1974) developed the boundary element method (BEM) to study the sloshing in a two-dimensional (2-D) rectangular tank under translational excitation[1]. Chen and Chiang (2000) used finite difference method (FDM) to analyze the effect of sloshing on the floating body in waves[2]. Faltinsen et al. (2000) derived the multidimensional modal system to describe nonlinear sloshing based on the Bateman−Luke variational principle and verified the validness of this theory by experiments[3]. Faltinsen and Timokha (2001) applied this theory to the analysis of 2-D nonlinear sloshing in a rectangular tank[4]. Frandsen et al. (2003, 2004) made a series of numerical analysis of 2-D liquid sloshing under horizontal and vertical excitations by σ-transformed finite difference method[5,6]. Maleki and Ziyaeifar (2008) developed a theoretical damping model based on Laplace’s differential equation to investigate the effect of ring baffle and vertical baffle on reducing sloshing amplitude[7].

The experiment is a common method to investigate the characters of liquid sloshing, which can provide the reliable data to numerical simulation and the design of liquid tank. Panigrahy and Saha (2009) investigated the effects of multi baffles and ring baffles on reducing the sloshing in 3-D tank under translational excitation[8]. Delorme et al. (2009) carried out a series of experiments to research the impact pressure of sloshing in 2-D shallow filled tank under roll excitation[9]. Kim et al. (2009) studied the sloshing in 1/25 scale longitudinal and transverse models 138K LNGC tank with two different filling levels and two different excitation amplitudes[10]. Kimmoun et al. (2010) compared the impact pressures in two scale tanks and achieved the Froude similarity of the global flows when correcting the transfer function of the flap wave maker in the low frequency region[11]. Marsh et al. (2010) studied the effectiveness of employing liquid sloshing as a structural control mechanism by many experiments[12]. Xue and Lin (2013) conducted a series of experiments to study liquid sloshing problems in a rectangular liquid tank with perforated baffle[13].

With the development of computer, Computational Fluid Dynamics (CFD) has been a significant method to study the complex sloshing problems which are limited by experimental conditions. Kim (2001) used SOLA scheme to solve the N-S equation with free boundary and simulated the sloshing flow in 2-D and 3-D tanks based on a finite difference method[14]. Kim et al. (2004) studied numerically slosh-induced impact pressures in 3-D and 2-D prismatic tanks by using VOF method[15]. Price and Chen (2006) applied modified Level-set method to the sloshing problems[16]. The results showed that the modified method can numerically simulate the nonlinear fragmentation of free surface. Xue and Lin (2011) also used VOF method to model a 3-D numerical tank with ring baffle and investigated the effect of different ring baffle arrangements on sloshing[17]. Shao et al. (2012) applied smoothed particle hydrodynamics method (SPH) to model 2-D liquid sloshing[18]. Koh et al. (2013) simulated liquid sloshing with constrained floating baffle in 3-D prismatic tanks by the improved consistent particle method (CPM)[19]. Yang et al. (2014, 2015) used another mesh-free method, moving particle semi-implicit method (MPS), to simulate liquid sloshing in 3-D tank under translational and angular excitations[20,21]. Zhang et al. (2014) used a parallel MPS method which adopts a domain decomposition strategy based on a background grid strategy and combines a dynamic load balance method to simulate 3-D liquid sloshing problem[22]. Tang et al. (2015) adopted the MPS method to research the effect of baffle height on sloshing in 2-D rectangular tank under angular excitation[23].

The objective of this paper is to study the effect of the location of horizontal baffle on liquid sloshing. For this purpose, a series of numerical simulations are carried out. At the beginning, sloshing in a partially filled rectangular tank without baffles under angular excitation is modeled to prove the effectiveness of our in-house solver. Then, the rolling frequency of the tank is increased to investigate the effect of horizontal baffle in suppressing the liquid sloshing. One horizontal baffle is installed in the tank. And the location of this baffle is changed to investigate its effects on impact pressure on walls and the deformation of free surface.

METHOD

The moving particle semi-implicit method (MPS) is a mesh-free method which is developed for incompressible flow with free surface. The mass, velocity and other information of fluid are included in particles. Because of this character, MPS method can simulate the complex deformation of free surface effectively. Koshizuka and Oka (1996) have introduced the MPS method[24]. In the following study, MPS method has been modified by many other researchers (Tanaka and Masunaga (2010)[25], Lee et al. (2011)[26], Zhang and Wan (2014)[27]). In this section, a brief introduction of numerical models is provided for MPS method.

Governing Equations

Governing equations are described as conservation laws of mass and momentum. For incompressible and viscous fluid, they can be presented as:

$$\frac{1}{\rho}\frac{D\rho}{Dt} = \nabla \cdot \vec{V} = 0 \tag{1}$$

$$\frac{D\vec{V}}{Dt} = -\frac{1}{\rho}\nabla P + \nu\nabla^2\vec{V} + \vec{g} \tag{2}$$

where ρ is the fluid density, t is the time, $\vec{V}$ is the velocity vector, P is the pressure, ν is the kinematic viscosity and $\vec{g}$ is the gravitational acceleration vector.

Particle Interaction Models

Kernel Function

In MPS method, governing equations are transformed to particle interaction equations. A kernel function is used to describe the interaction between two particles. In this paper, kernel function is as follows:

$$W(r)=\begin{cases}\dfrac{r_e}{0.85r+0.15r_e}-1 & 0\le r<r_e\\ 0 & r_e\le r\end{cases} \tag{3}$$

where r is the distance between two particles and r_e is the radius of the particle interaction. $r_e = 2.1l_0$ is applied for the particle number density and gradient model and $r_e = 4.0l_0$ is used for the Laplacian model, where l_0 is the initial distance between two adjacent particles.

Gradient Model

The gradient operator is modeled by using a local weighted average of the gradient vectors between particle *i* and its neighboring particle *j*.

$$<\nabla P>_i=\frac{D}{n^0}\sum_{j\neq i}\frac{P_j+P_i}{|\vec{r}_j-\vec{r}_i|^2}(\vec{r}_j-\vec{r}_i)\cdot W(|\vec{r}_j-\vec{r}_i|) \tag{4}$$

where D is the number of space dimension, n^0 is the initial particle number density and $\vec{r}$ is coordinate vector of fluid particle.

Laplacian Model

The Laplacian operator is modeled by weighted average of the distribution of a quantity ϕ from particle *i* to its neighboring particle *j*.

$$<\nabla^2\phi>_i=\frac{2D}{n^0\lambda}\sum_{j\neq i}(\phi_j-\phi_i)\cdot W(|\vec{r}_j-\vec{r}_i|) \tag{5}$$

$$\lambda=\frac{\sum_{j\neq i}W(|\vec{r}_j-\vec{r}_i|)\cdot|\vec{r}_j-\vec{r}_i|^2}{\sum_{j\neq i}W(|\vec{r}_j-\vec{r}_i|)} \tag{6}$$

where λ is used to guarantee that the increase of variance is equal to the analytical solution.

Model of Incompressibility

Tanaka et al. (2010) proposed a mixed source term method, which combines velocity divergence and particle number density[25]. Lee et al. (2011) rewrote the Poisson equation of pressure (PPE) as[26]:

$$<\nabla^2P^{k+1}>_i=(1-\gamma)\frac{\rho}{\Delta t}\nabla\cdot\vec{V}_i^*-\gamma\frac{\rho}{\Delta t^2}\frac{<n^*>_i-n^0}{n^0} \tag{7}$$

where γ is a blending parameter which varies from 0 to 1, n^* is the temporal particle number density and Δt is the time step. In this paper, $\gamma = 0.01$ is employed for all numerical simulations.

Free Surface Detection

Zhang (2012a) developed a modified surface particle detection method, which is based on the asymmetry arrangement of neighboring particles, is employed in this paper[27].

$$<\vec{F}>_i=\frac{D}{n^0}\sum_{j\neq i}\frac{1}{|\vec{r}_i-\vec{r}_j|}(\vec{r}_i-\vec{r}_j)W(r_{ij}) \tag{8}$$

$$<|\vec{F}|>_i\ >\ \alpha \tag{9}$$

$$\alpha=0.9\left|\vec{F}\right|^0 \tag{10}$$

where $\vec{F}$ is a vector which represents the asymmetry of arrangements of neighbor particles, $\left|\vec{F}\right|^0$ is the initial value of $\left|\vec{F}\right|$.

RESULTS AND DISCUSSIONS

Numerical Validation

In this case, 3-D liquid sloshing in a rectangular tank under angular excitation is simulated to validate MLParticle-SJTU solver. The tank model is the same as Akyildiz's experimental model[28]. The parameters of tank are shown in Fig. 1: the length (*L*) is 0.92 m, the width (*B*) is 0.46 m and the height (*H*) is 0.62 m. The filling ratio is 50%, corresponding liquid depth (*D*) is 0.31 m. According to linear potential theory, the lowest natural frequency is $\omega_1 = 5.128$ rad/s. The tank is subject to the rolling motion:

$$\theta = \theta_0 \cdot \sin(\omega \cdot t) \tag{11}$$

where θ is the angular amplitude of excitation which is set to 8 °and ω is the excitation frequency with the value of 2.0 rad/s. The center of rotation is the geometric center of tank. Two pressure probes are located at the wall, 0.06 m and 0.25 m away from the bottom. In following cases, the initial particle space is 0.007 m and 548161 particles are used. The time step is $\Delta t = 5 \times 10^{-4}$ s.

Fig. 2 compares the pressure on P1 between experiment and MPS. The overall changing tendency of experiment and MPS with time shows a favorable agreement. The variation of the pressure is periodic with the forced rolling motion of the tank under external sinusoidal excitation. Only a pair of minimum and maximum pressures can be observed in each period. The agreement between experiment and MPS proves that MLParticle-SJTU solver is valid for the simulation of liquid sloshing.

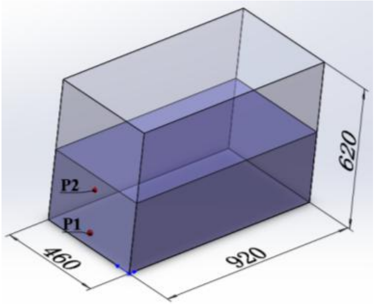


Fig. 1 3-D model of tank

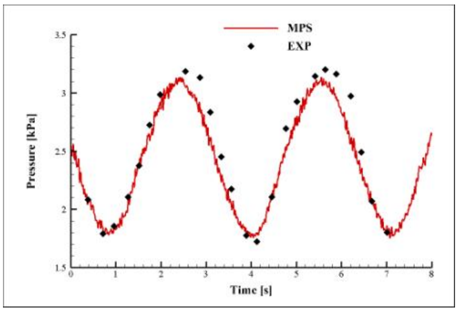
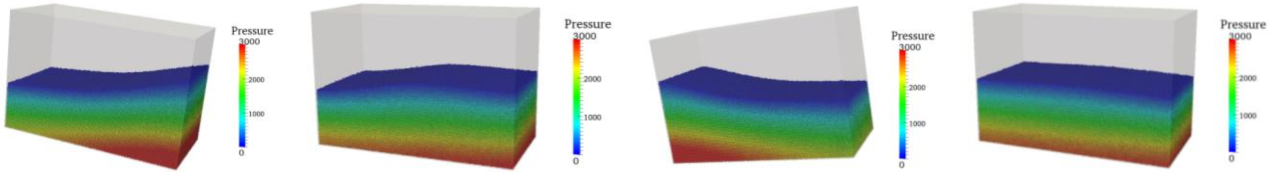


Fig. 2 Comparison of pressures on P1

Effects of horizontal baffle

In this section, the excited frequency is changed to $\omega = 4.0$ rad/s. One horizontal baffle is installed in the tank. And the location of baffle is changed to investigate its effect on impact pressure on side wall and the deformation of free surface. The baffle is 0.3 m long with the thickness is 0.014 m. And the distance between baffle and the bottom of tank is 0.1 m (Case 2), 0.2 m (Case 3) and 0.31 m (Case 4), respectively. Fig. 3~6 show many snapshots of numerical simulation. Fig. 7 gives the variation of impact pressure on P1 and P2.

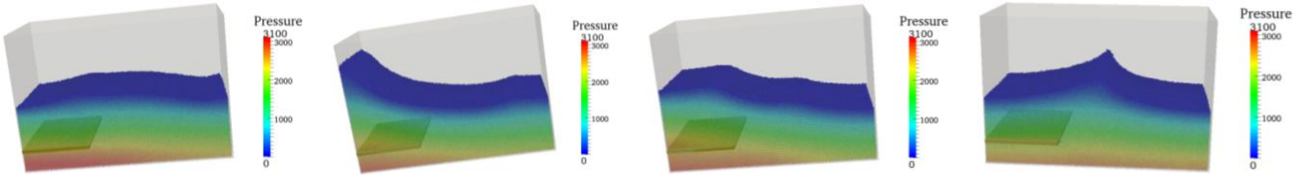
From Figs. 3(a)~(d) and Fig. 7(a), the deformation of free surface and variation of impact pressure in no baffled tank (Case 1) are periodic and sinusoidal. The fluid flow follows the movement of tank. There is no obvious nonlinear fragmentation of free surface in wave propagation. The max pressure of P1 and P2 is about 3249 Pa and 1459 Pa, respectively.



(a) t = 10.6 s (b) t = 11.0 s (c) t = 11.4 s (d) t = 11.8 s

Fig. 3 The snapshots of Case 1

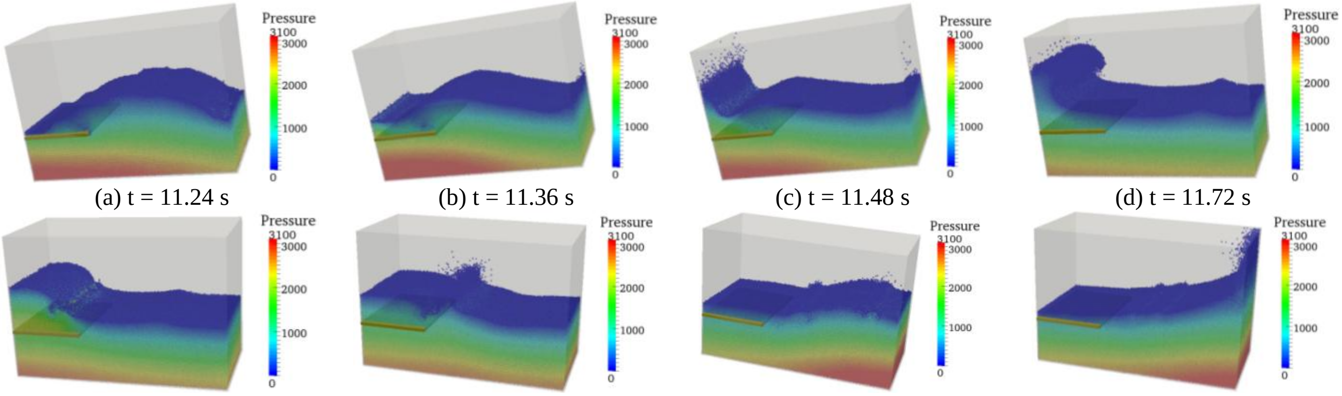
Figs. 4(a)~(d) present some instants of fluid field when the horizontal baffle is placed at 0.1 m height. From Fig. 7(b), the first pressure peaks of P1 and P2 are synchronous and earlier than that of no baffled tank. Two successive pressure peaks can be observed in the figure. When the fluid moves to the left side and runs along the wall, the horizontal baffle prevents the movement of bottom water. The bottom water impacts the baffle which produces the first pressure peak. Though the bottom water is blocked, the upper water still runs along the wall. When it arrives the highest point, the second pressure peak occurs. The max impact pressure of P1 in this case is 2945 Pa, 9.36 % smaller than that of no baffled tank. Comparing Fig. 3(c) and Fig. 4(b), water arrives higher point in baffled tank. The pressure peak of P2 is 1669 Pa and little larger than no baffled case. Two opposite wave propagations can be observed in Fig. 4(c). From Fig. 4(d), these two waves encounter with each other in the middle of tank and transmit to the right side wall.



(a) t = 11.2 s (b) t = 11.48 s (c) t = 11.68 s (d) t = 11.88 s

Fig. 4 The snapshots of Case 2

In order to explain the complicated variation of impact pressure, Figs. 5(a)~(h) give more instantaneous pictures of fluid field for 0.2 m high horizontal baffle. From Fig. 7(c), there are many fluctuations of the impact pressure, especially for P1. The variation of impact pressure in one period is selected to explain in details. The wave transmits at the horizontal baffle and impacts the left side wall, corresponding the first pressure peaks of P1 and P2. Then the upper fluid runs up along the wall and some water splashes. Therefore, the impact pressure of P2 increases gradually. When the tank moves in the opposite direction, the overturn of free surface happens. Accordingly, the impact pressure of P2 decreases. The falling water breaks on the free surface which induces the second impact pressure of P1 and P2. The subsequent deformations of free surface cause the fluctuation of impact pressure for P1. Then the fluid transmits to the right wall and hits the ceiling. Comparing the impact pressures, the horizontal baffle do not reduce the sloshing pressure, but makes a significant contribution to the high instantaneous impact pressure and complex variation. The function of horizontal baffle is to divide whole fluid field into two subfields. And the fluid flow in the upper field is similar to the partially filled tank.

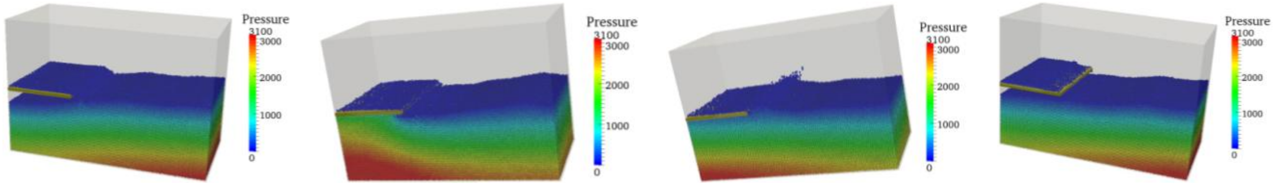


(a) t = 11.24 s (b) t = 11.36 s (c) t = 11.48 s (d) t = 11.72 s

(e) t = 11.84 s (f) t = 11.96 s (g) t = 12.2 s (h) t = 12.48 s

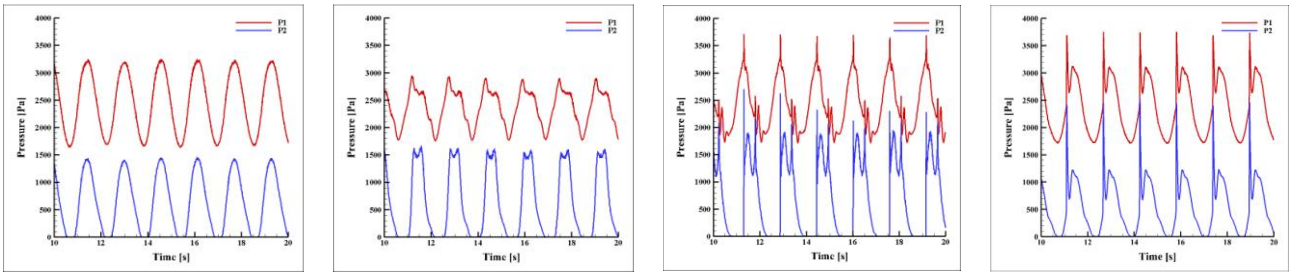
Fig. 5 The snapshots of Case 3

From Figs. 6(a)~(d), some fluid can be seen on the horizontal baffle. When whole fluid flows to the left side wall, the water on the baffle moves in the reverse direction and falls into whole fluid field. In this case, the blocking effect of horizontal baffle on sloshing water is the strongest. Because of the movements of tank and fluid in the opposite direction, the water impacts the baffle fiercely. Owing to this reason, the first pressure peak of P1 and P2 occurs in Fig. 7(d) and is larger than other cases. Then a small part of free surface turns over and moves on the horizontal baffle. When whole fluid field moves to the right side, the free surface is smooth which is similar to no baffled case.



(a) t = 10.8 s (b) t = 11.16 s (c) t = 11.32 s (d) t = 12.32 s

Fig. 6 The snapshots of Case 4



(a) Case 1 (b) Case 2 (c) Case 3 (d) Case 4

Fig. 7 The time history of pressure on P1 and P2

CONCLUSIONS

In this paper, the effects of one horizontal baffle on liquid sloshing are investigated numerically in 3-D tank by MLParticle-SJTU solver based on modified MPS method. The impact pressures of two pressure probes are measured and the deformation of free surface is observed. From the results, not all arrangements of baffle can reduce the sloshing amplitude. Incorrect location of baffle may increase the impact pressure. The function of horizontal baffle is to divide the fluid field. If the baffle is close to free surface, the sloshing liquid above the baffle will produce high impact pressure which is same to the tank with low filling level. And the horizontal baffle can block the bottom water flow in the process of sloshing, which generates instantaneous high pressure on baffle because of the slamming of liquid.

ACKNOWLEDGEMENTS

This work is supported by the National Natural Science Foundation of China (51379125, 51490675, 11432009, 51579145, 11272120), Chang Jiang Scholars Program (T2014099), Program for Professor of Special Appointment (Eastern Scholar) at Shanghai Institutions of Higher Learning (2013022), Innovative Special Project of Numerical Tank of Ministry of Industry and Information Technology of China (2016-23/09), to which the authors are most grateful.

REFERENCES

[1] FALTINSEN O M. A Numerical Nonlinear Method of Sloshing in Tanks with Two Dimensional Flow [J], Journal of Ship Research, 1978, 22(3), 193-202.

[2] CHEN B F, CHIANG H W. Complete two-dimensional analysis of sea-wave-induced fully non-linear sloshing fluid in a rigid floating tank [J], Ocean Engineering, 2000, 27(9), 953-977.

[3] FALTINSEN O M, ROGNEBAKKE O F, LUKOVSKY J A, TIMOKHA A M. Multidimensional modal analysis of non-linear sloshing in a rectangular tank with finite water depth [J], Journal of Fluid Mechanics, 2000, 407, 201-234.

[4] FALTINSEN O M, TIMOKHA A N. An adaptive multimodal approach to nonlinear sloshing in a rectangular tank [J], Journal of Fluid Mechanics, 2001, 432, 167-200.

[5] FRANDSEN J B, BORTHWICK A G L. Simulation of sloshing motions in fixed and vertically excited containers using a 2-D inviscid σ-transformed finite difference solver [J], Journal of Fluids and Structures, 2003, 18(2), 197-214.

[6] FRANDSEN J B. Sloshing motions in excited tanks [J]. Journal of Computational Physics, 2004, 196, 1, 53-87.

[7] MALEKI A, ZIYAEIFAR M. Sloshing damping in cylindrical liquid storage tanks with baffles [J], Journal of Sound and Vibration, 2008, 311(1), 372-385.

[8] PANIGRAHY P K, SAHA U K, MAITY D. Experimental studies on sloshing behavior due to horizontal movement of liquids in baffled tanks [J], Ocean Engineering, 2009, 36(3), 213-222.

[9] DELORME L, COLAGROSSI A, IGLESIAS A S, RODRIGUEZ R Z, VERA E B. A set of canonical problems in sloshing, Part I: Pressure field in forced roll-comparison between experimental results and SPH [J], Ocean Engineering, 2009, 36(2), 168-178.

[10] KIM H I, KWON S H, PARK J S, LEE K H, JEON S S, JUNG J H, RYU M C, HWANG Y S. An experimental investigation of hydrodynamic impact on 2-D LNGC models [C], Proceedings of the 19th International Offshore and Polar Engineering Conference, Osaka, Japan, 2009, 30-37.

[11] KIMMOUN O, RATOUIS A, BROSSET L. Sloshing and scaling: Experimental study in a wave canal at two different scales [C], Proceedings of the 20th International Offshore and Polar Engineering Conference, Beijing, China, 2010, 34-43.

[12] MARSH A P, PRAKASH M, SEMERCIGIL S E, TURAN Ö F. A shallow-depth sloshing absorber for structural control [J], Journal of Fluids and Structures, 2010, 26(5), 780-792.

[13] XUE M A, LIN P Z, ZHENG J H, MA Y X, YUAN X L, NGUYEN V T. Effects of Perforated Baffle on Reducing Sloshing in Rectangular Tank: Experimental and Numerical Study [J], China Ocean Engineering, 2013, 27(5), 615- 628.

[14] KIM Y. Numerical simulation of sloshing flow with impact load [J], Applied Ocean Research, 2001, 23, 53-62.

[15] KIM Y, SHIN Y S, LEE K H. Numerical study on slosh-induced impact pressures [J], Applied Ocean Research, 2004, 26, 213-226.

[16] PRICE W G, CHEN Y G. A simulation of free surface waves for incompressible two-phase flows using a curvilinear level set formulation [J]. International Journal for Numerical Methods in Fluids, 2006, 51(3), 305-330.

[17] XUE M A, LIN P Z. Numerical study of ring baffle effects on reducing violent liquid sloshing [J], Computers & Fluids, 2011, 52, 116-129.

[18] SHAO J R, LI H Q, LIU G R, LIU M B. An improved SPH method for modeling liquid sloshing dynamics [J], Computers and Structures, 2012, 100-101, 18-26.

[19] KOH C G, LUO M, GAO M, BAI W. Modeling of liquid sloshing with constrained floating baffle [J], Computers and Structures, 2013, 122, 270-279.

[20] YANG Y Q, TANG Z Y, WAN D C. Numerical Simulations of 3D Liquid Sloshing Flows by MPS Method [C], Proceedings of the Eleventh (2014) Pacific/Asia Offshore Mechanics Symposium, Shanghai, China, 2014.

[21] YANY Y Q, TANG Z Y, WAN D C. Numerical Simulation of 3D Sloshing Flows in a Rectangular Tank by MPS Method [C], Proceedings of the 9th International Workshop on Ship and Marine Hydrodynamics, Glasgow, UK, 2015.

[22] ZHANG Y X, YANG Y Q, TANG Z Y, WAN D C. Parallel MPS Method for Three-Dimensional Liquid Sloshing [C], Proceedings of the Twenty-fourth (2014) International Ocean and Polar Engineering Conference, Busan, Korea, 2014, 257-264.

[23] TANG Z Y, YANG Y Q, ZHANG Y L, WAN D C. Numerical Study of Sloshing in Baffled Tanks by MPS [C], Proceedings of the Twenty-fifth (2015) International Ocean and Polar Engineering Conference, Hawaii, USA, 2015, 937-944.

[24] KOSHIZUKA S, OKA Y. Moving-particle semi-implicit method for fragmentation of incompressible fluid [J], Nuclear Science and Engineering, 1996, 123(3), 421-434.

[25] TANAKA M, MASUNAGA T. Stabilization and smoothing of pressure in MPS method by Quasi-Compressibility [J], Journal of Computational Physics, 2010, 229(11), 4279-4290.

[26] LEE B H, PARK J C, KIM M H, HWANG S C. Step-by-step improvement of MPS method in simulating violent free-surface motions and impact-loads [J], Computer Methods in Applied Mechanics and Engineering, 2011, 200(9-12), 1113-1125.

[27] ZHANG Y X, WAN D C. Comparative study of MPS method and level-set method for sloshing flows [J], Journal of Hydrodynamics, 2014, 26(4), 577-585.

[28] AKYILDIZ H. A numerical study of the effects of the vertical baffle on liquid sloshing in two-dimensional rectangular tank [J], Journal of Sound and Vibration, 2012, 331, 41-52.