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Numerical Simulation for Sloshing Behavior of Moss-type LNG Tank Based on an Improved SPH Model

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In our previous research, a series of numerical simulations based on smoothed particle hydrodynamic (SPH) theory was performed, and these showed a good correlation with the model test results. However, the accuracy of the numerical prediction was highly dependent on the particle size used in the SPH model, which usually results in a computation-time-consuming problem for three-dimensional simulations. In this research, the SPH model was improved to obtain similar prediction accuracy with larger particles. A smoothed-boundary model (SBM) was proposed to better describe a boundary with complex geometry. An unphysical gap was clearly observed. Quantitative discussion of the relationship between the size of this unphysical gap and the particle size was presented based on a two-dimensional benchmark test. Dummy boundary conditions were applied to solve the unphysical gap problem caused by the original dynamic boundary conditions. The accuracy for prediction of the sloshing load was significantly enhanced by using dummy boundary conditions. Finally, the influence of the SBM on the local pressure and local particle distribution near the solid boundary was addressed.

INTRODUCTION

In the last century, when large-scale numerical simulation was unavailable, sloshing was mainly investigated experimentally. NASA (Sumner and Stofan, 1963) conducted an important experimental study that demonstrated an antisymmetric mode of liquid oscillation in a spherical tank. As a result of potential theory, theoretical analysis of sloshing, with the assumption that the fluid is inviscid, irrotational, and incompressible, became possible. Faltinsen and colleagues conducted much research on the steady-state solutions for sloshing with different tank shapes (Faltinsen et al., 2000; Faltinsen and Timokha, 2009, 2013). In their studies, the multimodal method and the Moisseev–Narimanov asymptotic model were used, and the occurrence frequencies of stable planar sloshing, stable swirling, and unstable sloshing could be theoretically predicted without considering the high-order natural sloshing frequency. However, they pointed out that the availability of this theoretical model is highly limited by secondary sloshing resonance, which may be located close to the first-order resonance. Splashing/overturning behavior also has a significant effect on the accuracy of the theoretical model.

To overcome these limitations in the theoretical model, in recent decades, computational fluid dynamics has been used in sloshing research. Many studies have demonstrated the accuracy of the Eulerian grid-based fluid model for sloshing simulations. Kishev et al. (2006) successfully used the constraint interpolation profile method to tackle the two-dimensional (2D) violent sloshing problem. The popular finite volume method (FVM) solver OpenFOAM has been widely used to investigate sloshing behavior (Moirod et al., 2010; Li et al., 2011; Jiang et al., 2015). Lee et al. (2007) used the commercial FVM solver FLOW-3D to examine the parametric sensitivity of the sloshing force in liquefied natural gas (LNG). In the above FVM models, establishing how to obtain the free surface is usually the crucial problem. Although this problem can be solved by volume-of-fluid (VOF) theory or level-set (LS) theory, new problems may be introduced, as VOF is essentially a step function, and the law of mass conservation is usually violated in LS models. Furthermore, numerically capturing the fluid surface and updating the fluid mesh make the numerical model more complex and more time consuming.

Smoothed particle hydrodynamics (SPH) has developed very quickly in recent years. As a Lagrangian meshless method, the fluid's free surface is obtained by solving the equation of motion for the fluid particles. This means that the surface-capture process is not necessary, and the numerical model can be significantly simplified.

Much research has been conducted into SPH to enhance the prediction accuracy, stability, and mass/energy conservation by using methods such as particle shift (Vacondio et al., 2013) and the diffusive scheme named delta-SPH (Molteni and Colagrossi, 2009). Khayyer et al. (2017) demonstrated enhancement of the stability and accuracy of particle methods using a particle regularization scheme and presented a comparative study on dynamic stabilization and particle shifting schemes in incompressible SPH (ISPH). Another technique for the enhancement of pressure calculations was used by Wang et al. (2019), who proposed a background mesh scheme. To achieve high calculation efficiency, which is usually a significant problem for the use of particle methods in engineering, variable particle resolution (Vacondio et al., 2013; Khayyer et al., 2019) and GPU/multi-GPU implementations (Dominguez et al., 2013) have been proposed. Recently, Gotoh and Khayyer (2018) published a paper reviewing the state-of-the-art of particle methods for engineering problems, which detailed the latest developments in simulation stability, consistency and conservation, multiphase models, multiphysics and multiscale systems, and the recent methodology of fluid–structure interactions. They addressed the accurate implementation of boundary conditions, particularly for the fluid–structure interaction problem. An ISPH–SPH coupled method was developed by Khayyer et al. (2018) for the fluid–structure interaction problem.

As a result of the above improvements, the robustness of SPH has been demonstrated, and it can be an efficient method for the simulation of sloshing. Even though the use of SPH for sloshing simulations has been demonstrated in many works (such as Gotoh

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KEY WORDS: Sloshing, SPH, SBM, unphysical gap, dynamic boundary conditions, dummy particle conditions.