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A numerical study of violent sloshing problems with modified MPS method *

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Abstract: A numerical study on violent liquid sloshing phenomenon in a partially filled rectangular container is carried out by using moving particle semi-implicit (MPS) method. The present study deals with the implementation of five modifications all together over the original MPS method. The modifications include improved source terms for pressure Poisson equation, special approximation technique for the representation of gradient differential operator, collective action of mixed free surface particle identification boundary conditions, effecting Neumann boundary condition on solving the PPE and fixing judiciously the parting distance among particles to prevent collision. The suitability of the kernel function used in the original MPS method along with these five modifications is investigated for violent sloshing problems. The present model ensures a good agreement between numerical results with the existing experimental observations. The model is successfully applied to a partially filled tank undergoing horizontal sinusoidal excitation to compute the sloshing wave amplitudes and pressure on tank walls. The assessment of dynamic behaviour manifested in terms of base shear, overturning moment and impact pressure load exerted on tank ceiling induced by violent sloshing motion using MPS method is not reported in the open literature and has been efficiently carried out in the present study.

Key words: Sloshing, particle method, impact pressure, base shear, overturning moment

Introduction

The sloshing event refers to the movement of liquid with a free surface inside a partially filled container due to external excitations. It comprises a significant class of problems in many engineering fields such as aerospace, civil, marine and nuclear and so on. There is a considerable need for understanding of the sloshing behaviour with regard to safety of water retaining structures and several transportation means, such as surface haulage of oil tankers, ocean going ships with liquid cargo and liquid propellant tanks used in satellites and spacecraft vehicles. In this context, the principal concern is to predict the interesting effects arising from the motion of the liquid-free surface, due to sloshing, in a partially filled container.

The study of sloshing phenomenon has long since drawn the attention of researchers[1]. The analytical models have been used to evaluate the sloshing effects successfully where the motions of the liquid as well as container are assumed to be small. The performance of the analytical study is limited to waves of low height, simple tank geometry and uncomplicated boundary conditions[2]. The analytical solution is also observed to be unsound for studying sloshing in resonance frequency and in case of extensive fluid-structure interaction with complex geometry. A good number of experimental works have been carried out to understand the complex sloshing behaviour in tanks of different shapes under varieties of external excitations[3]. Generally the experimental studies furnish accurate results regardless of type of motion and boundary conditions. The constraint of the experimental works is a subject of huge expense with a prolonged effort. The numerical methods such as finite difference method (FDM)[4], boundary element method (BEM)[5], and finite element method (FEM)[6] are in prevalence for the study of sloshing motions. However, it is difficult to model the violent sloshing phenomenon with changing and breaking of free surface with these grid based methods.

To overcome these difficulties, a distinctive class

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of meshless method called particle method is adopted in recent time. The basic idea of the meshless method is to solve the flow field based on a set of Lagrangian particles. The particle methods are the Lagrangian messless methods where particles are free to move in a specified domain. So these methods have the ability to model highly deformed free surface flow, especially the problem involving complicated boundary and interface. The smoothed particle hydrodynamics (SPH) and moving particle semi-implicit (MPS) methods are two of the more powerful approaches. One of the earliest and most often used particle methods is the SPH method. It was primarily developed for astrophysical problems and later extended to model a wide range of hydrodynamics problems[7]. Shao et al.[8] presented an improved SPH method for modelling viscous incompressible liquid sloshing dynamics. They studied the effect of middle baffle with different heights on the wave elevation in a partially filled rectangular tank. Shao et al.[9] used SPH simulation to investigate the effect of different baffles such as I-shaped baffle, T-shaped baffle and porous baffle on liquid sloshing in a rectangular tank due to a horizontal excitation. They concluded that the I-shaped and T-shaped baffles can be good choices to mitigate sloshing effects. The MPS method is another class of particle methods. It was originally proposed for simulation of incompressible free-surface fluid flows.

In the MPS method, fluids are represented by particles. Each particle is followed in a Lagrangian manner. The Lagrangian approach in hydraulic flow simulation is advantageous as convection is directly calculated by the motion of particles without any numerical diffusion. The motion of each particle is calculated through the interaction of its neighbouring particles by means of a kernel (or weight) function and according to the governing equations of fluid motion. Deterministic particle interaction models are used to approximate the differentials like gradient, Laplacian and divergence. Constant particle number density criterion is followed to express the incompressibility of fluid. The Poisson equation of pressure is solved implicitly to calculate pressure while other terms are calculated explicitly.

Examples of implementation of MPS method for flow problems belonging to different classes of engineering and science have been reported in the literature. Dam break flow simulation is adopted as a test problem by a number of researchers to discuss the performance of the developed method. Kondo and Koshizuka[10] have employed a modified PPE containing three source terms to suppress the unphysical pressure oscillation which is a very common feature in the studies with original MPS method. Tanaka and Masunaga[11] have made some modifications to the original MPS method. However, their studies are limited to the simulation of dam breaking flow problems. Khayyer and Gotoh[12] used a modified MPS for the prediction of wave impact pressure and compared the numerical results with the experimental data. Zhang et al.[13] have simulated the heat transfer problem with the use of MPS method. Khayyer and Gotoh[14] have used a modified MPS method to simulate liquid sloshing in a 2-D container under harmonic excitation. The study contains only the time history of pressure at a specified location of the tank wall and a validation test. Lee et al.[15] have used MPS method with a kernel function of higher order than that of original one to simulate sloshing flow in a 2-D liquid tank.

The assessment of pressure, base shear, overturning moment and impact pressure on tank ceiling under violent sloshing motion is very important for the safe design of ground supported liquid retaining container. Again the liquid tanks are also employed in tall structures to act as dampers to attenuate the unwanted vibrations due to wind or earthquake. The computation of developed base shear in case of sloshing motion helps in assessing the effectiveness of these kinds of dampers. The local effects such as broken free surface and turbulence have importance in some cases, but the simulation of global flow plays a more critical role in many sloshing problems[16]. Lee et al.[17] stated in their study that the effect of liquid turbulence on the impact pressure appeared to be negligible.

In the present study, the suitability of the kernel function used in the original MPS method along with five modifications is investigated for violent sloshing problems. As the study focuses on global violent liquid motion, the local effect such as turbulence is not considered. However, the modified MPS method used in this study can competently capture the flow dynamics with distorted and broken free surface. The assessment of dynamic features such as hydrodynamic pressure, sloshing wave elevation, base shear, overturning moment and impact pressure load on tank ceiling evolved during a violent sloshing motion is carried out which is not reported by earlier studies available in the open literature.

1. Original MPS method

1.1 *Governing equations*

The governing equations for incompressible viscous flows are the continuity and Navier-Stokes equation as follows:

$$\frac{\mathrm{D}\rho}{\mathrm{D}t} = 0 \tag{1}$$

$$\frac{\mathrm{D}u}{\mathrm{D}t} = -\frac{1}{\rho}\nabla p + \nu \nabla^2 \boldsymbol{u} + \boldsymbol{F} \tag{2}$$