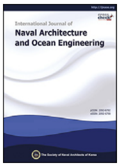
Available online at www.sciencedirect.com
ScienceDirect
Publishing Services by Elsevier
International Journal of Naval Architecture and Ocean Engineering xx (2017) 1−19
http://www.journals.elsevier.com/international-journal-of-naval-architecture-and-ocean-engineering/



An improved solid boundary treatment for wave−float interactions using ISPH method

Xing Zheng [a,*], Xipeng Lv [a], Qingwei Ma [b], Wenyang Duan [a], Abbas Khayyer [c], Songdong Shao [d,e]

[a] *College of Shipbuilding Engineering, Harbin Engineering University, Harbin 150001, China*
[b] *School of Mathematics, Computer Science and Engineering, City, University of London, London EC1V 0HB, UK*
[c] *Department of Civil and Earth Resources Engineering, Kyoto University, Kyoto 615-8540, Japan*
[d] *Department of Civil and Structural Engineering, University of Sheffield, Sheffield S1 3JD, UK*
[e] *State Key Laboratory of Hydro-Science and Engineering, Tsinghua University, Beijing 100084, China*

Received 17 March 2017; revised 1 July 2017; accepted 1 August 2017
Available online ■ ■ ■

Abstract

The Smoothed Particle Hydrodynamics (SPH) method has proved to have great potentials in dealing with the wave-structure interactions. Compared with the Weakly Compressible SPH (WCSPH) method, the ISPH approach solves the pressure by using the pressure Poisson equation rather than the equation of state. This could provide a more stable and accurate pressure field that is important in the study of wave-structure interactions. This paper improves the solid boundary treatment of ISPH by using a high accuracy Simplified Finite Difference Interpolation (SFDI) scheme for the 2D wave-structure coupling problems, especially for free-moving structure. The proposed method is referred as the ISPH_BS. The model improvement is demonstrated by the documented benchmark tests and laboratory experiment covering various wave-structure interaction applications.

Keywords: ISPH; Moving boundary; SFDI; Wave−float interactions; ISPH_BS

---

1. Introduction

The research of wave action on structure has drawn wide attentions, especially in the coastal and ocean engineering. People have made numerous efforts in the study of moving object in the waves, and proposed a variety of approaches to investigate the interaction between the wave and the object. From the simple Morrison formula to the advanced 3D Reynolds-Averaged Navier−Stokes equations (RANS) model (Lin and Liu, 1998), the researchers have developed different theoretical and numerical modelling approaches. The early Boundary Element Method (BEM) based on the frequency domain theorem could solve the motion of floating body in a linear wave with sufficient accuracy. However, they could not perform satisfactorily in the more complex and common nonlinear wave field. To partially solve the problem, Faltinsen (1977) proposed a mixed Eulerian−Lagrangian Boundary Element method to investigate the interaction between the wave and a rigid body, but could not capture the large deformation of free surface under the wave breaking. Afterwards the mesh-based Navier−Stokes (N−S) numerical models have been used to overcome the deficiency of previous approaches, but they need additional tracking algorithm to describe the free surface. Since these methods are based on a fixed Eulerian grid, the treatment of free surface is complex in the violent breaking waves and during the wave-structure interactions.

In the past two decades, the Smoothed Particle Hydrodynamics (SPH) method has emerged as a promising mesh-free Lagrangian modelling technique in many areas of solid and fluid dynamics. Monaghan et al. (2003) used the WCSPH to

---

[*] Corresponding author.
E-mail address: zhengxing@hrbeu.edu.cn (X. Zheng).
Peer review under responsibility of Society of Naval Architects of Korea.

http://dx.doi.org/10.1016/j.ijnaoe.2017.08.001
2092-6782/

Please cite this article in press as: Zheng, X., et al., An improved solid boundary treatment for wave−float interactions using ISPH method, International Journal of Naval Architecture and Ocean Engineering (2017), http://dx.doi.org/10.1016/j.ijnaoe.2017.08.001

investigate the water entry of a box travelling down the slope. Najafi-Jilani and Rezaie-Mazyak (2011) used the SPH to study the movement of a floating breakwater. Bouscasse et al. (2013) modelled the interactions between a 2D box and a wave packet by using the ghost-fluid technique on the solid surface. Canelas et al. (2015) used the noise-free δ-SPH on the unsteady motion of bodies through a free surface. Jun et al. (2015) carried out a comprehensive dynamic analysis of floating body in the fluids combining the SPH with physical experiment. Ren et al. (2015) used the WCSPH to analyse the wave-induced motion of a freely floating body. In the latest practical SPH applications, Rudman and Cleary (2016) studied the impact of a rogue wave on the moored floating offshore structure with a focus on the effect that different mooring systems have on the platform. Besides, Gomez-Gesteira et al. (2012) published the open source code SPHysics with case examples on the wave—float interaction. To improve the pressure prediction, the Incompressible SPH (ISPH) method has also been used in the wave-structure interactions with a promising performance in the computational accuracy and stability. For example, Asai et al. (2012) developed a stabilized ISPH pressure solution with the eddy viscosity and relaxation coefficient to calculate the free water entry of a falling object. Liu et al. (2014) used the ISPH to simulate the coupled structure interactions with a free surface flow based on an improved mirror particle boundary. Gotoh et al. (2014) developed an enhanced ISPH scheme to study the violent sloshing flow based on a higher-order Laplacian and error compensating source term. Aly et al. (2015) proposed a stabilized ISPH pressure solution method with a density-invariant relaxation condition to simulate the highly nonlinear liquid sloshings. In addition, Ikari et al. (2011) used a Moving Particle Semi-implicit (MPS) method to predict the mooring forces on a floating body. Further improvement on MPS has been done by Lee et al. (2013) for the simulation of nonlinear floating-body motions. The state-of-the-art review on the projection-based particle methods and wave-structure interactions has been provided by Gotoh and Khayyer (2016). It should be mentioned that the pioneering work on wave—float interaction using the mesh-free particle modelling approach should be attributed to Koshizuka et al. (1998).

Although the ISPH approach could predict better pressure field than the WCSPH does, the numerical accuracy and efficiency could be compromised when the solid boundary is complex for the wave-structure interaction especially with the moving boundary. This is due to that the accurate implementation of boundary condition for the pressure Poisson equation becomes more challenging. In order to improve the kernel approximation near the solid boundary, many researchers have made efforts. Liu et al. (1995) proposed the reproducing kernel particle method to improve the accuracy of particle approximations. Bonet and Lok (1999) introduced a renormalized kernel function approach by use of a variational framework. Dilts (1999) resorted to the moving-least-square particle hydrodynamics. Quinlan et al. (2006) investigated the effect of kernel functions and support domains with corrected kernel approximations. Liu and Liu (2006) introduced a consistent kernel approximation to improve the accuracy of first-order derivative calculation. Oger et al. (2007) introduced a Taylor SPH scheme towards higher-order convergence. Ma (2008) introduced a Simplified Finite Difference Interpolation (SFDI) scheme to improve the particle approximation accuracy. Macia et al. (2011) carried out quite a few benchmark studies on the truncation error near the solid boundary.

The present paper proposes an improved solid boundary treatment for the wave—float interactions in the ISPH framework. The numerical treatment is based on the SFDI scheme originally developed by Sriram and Ma (2012) to increase the stability of pressure gradient calculation in MLPG_R, which was coupled with the ISPH solver for wave impact simulations (Zheng et al., 2014, 2017). However, the potentials of SFDI scheme have not been fully demonstrated in the wave-structure and wave—float interactions with the solid boundary effect. In the present study, we will use both the benchmark tests and self-designed laboratory experiment to show the promising performance of this technique in the SPH application field.

2. Review of ISPH methodology

2.1. SPH equations and solution algorithms

The Navier—Stokes equations are used to describe the fluid motion. In the incompressible SPH method, the fluid density is considered as a constant, and the mass and momentum conservation equations are written in the Lagrangian form as

$$\nabla \cdot \mathbf{u} = 0 \tag{1}$$

$$\frac{D\mathbf{u}}{Dt} = -\frac{1}{\rho}\nabla P + \mathbf{g} + \nu_0 \nabla^2 \mathbf{u} \tag{2}$$

where ρ is the fluid density; $\mathbf{u}$ is the particle velocity; t is the time; P is the particle pressure; $\mathbf{g}$ is the gravitational acceleration; and ν_0 is the kinematic viscosity. A two-step projection method is used to solve the velocity and pressure field from Eqs. (1) and (2). The first step is the prediction of velocity in the time domain without considering the pressure term. The intermediate particle velocity $\mathbf{u}_*$ and position $\mathbf{r}_*$ are obtained as

$$\mathbf{u}_* = \mathbf{u}_t + \Delta\mathbf{u}_* \tag{3}$$

$$\Delta\mathbf{u}_* = \left(\mathbf{g} + \nu_0 \nabla^2 \mathbf{u}\right)\Delta t \tag{4}$$

$$\mathbf{r}_* = \mathbf{r}_t + \mathbf{u}_* \Delta t \tag{5}$$

where $\mathbf{u}_t$ and $\mathbf{r}_t$ are the velocity and position at time t; Δt is the time step; $\Delta\mathbf{u}_*$ is the velocity increment; and $\mathbf{u}_*$ and $\mathbf{r}_*$ are the intermediate velocity and position.

The second step is the correction step, in which the pressure term is added, and $\Delta\mathbf{u}_{**}$ is the correction of particle velocity as

$$\Delta\mathbf{u}_{**} = -\frac{1}{\rho}\nabla P_{t+\Delta t}\Delta t \tag{6}$$

Please cite this article in press as: Zheng, X., et al., An improved solid boundary treatment for wave—float interactions using ISPH method, International Journal of Naval Architecture and Ocean Engineering (2017), http://dx.doi.org/10.1016/j.ijnaoe.2017.08.001