International Journal of Offshore and Polar Engineering (ISSN 1053-5381)

Vol. 26, No. 1, March 2016, pp. 26–32; http://dx.doi.org/10.17736/ijope.2016.ak09

http://www.isope.org/publications/publications.htm

2D Numerical ISPH Wave Tank for Complex Fluid–Structure Coupling Problems

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In this paper, we provide a hybrid incompressible smoothed particle hydrodynamics (ISPH) model for fluid–structure interactions. The numerical algorithms include the mirroring treatment of solid boundaries, free-surface tracking, wave damping using a sponge layer, and fluid–solid coupling model. The proposed ISPH wave tank is applied to a series of wave–structure coupling problems, including sloshing in a baffled tank, solitary wave impact on an underwater obstacle, water entry of a cylinder, and balance dynamics of a floating object. The simulation results demonstrate that the ISPH model provides an accurate simulation technique in various fluid–structure coupling studies.

INTRODUCTION

Fluid–structure interaction is a common issue in coastal and offshore hydrodynamics, and according to the nature of interaction between the fluid and solid structure, it can be classified into two types, i.e., kinematic and dynamic couplings. The former assumes that the solid structure is either fixed or follows a prescribed motion, while the latter is much more complicated because the motion of the solid also depends on the instantaneous response of the fluid. Smoothed particle hydrodynamics (SPH) modeling techniques have demonstrated great potential in dynamic coupling because there is no need to frequently generate or adjust the mesh system near the interface between the fluid and solid boundary, or to treat the information exchanges between them; thus, the solution algorithms can be simplified, which has considerable merits over many traditional Eulerian grid methods. A good understanding and efficient numerical simulation of the fluid–structure interactions are crucial in predicting fluid impact forces on the structure as well as the structural responses to the fluid in a wider engineering practice.

Since the pioneering work that introduced the concept of SPH to hydrodynamics (Monaghan, 1994), the method has been used in a large number of fluid–structure interaction applications. Because of its mesh-free feature, the SPH method is well suited to analyze many kinds of moving boundary and large surface deformation problems (Lind et al., 2012; Gotoh et al., 2014). Quite a few works have been carried out by using the standard weakly compressible SPH (WCSPH) approach, including that of Vandamme et al. (2011), who simulated the wedge and cylinder entries with fixed boundary particle treatment on the solid surface, and of Oger et al. (2006), who used a variable smoothing length to improve the local accuracy of the impact area for a wedge entry using mirror particle boundary. Also, Omidvar et al. (2012) have used a variable mass approach for the study of more practical wave–solid interactions, because computational efficiency was greatly improved as a result of the adoption of nonuniform particle configurations. The latest fluid–structure interaction work was reported by Liu, Shao, and Li (2014), in which more advanced kernel corrections and solid boundaries were used to improve numerical performance. In the field of incompressible SPH (ISPH) (e.g., Violeau and Leroy, 2015), Bøckmann et al. (2012) simulated a series of fluid–structure interaction problems by following the approach of Koshizuka et al. (1998), in which the solid object was temporarily treated as another fluid that is deformable during the computation, and then a correction algorithm was used to recover the deformed solid object to its original configuration. This practice is based on the conservation of momentum between the fluid and solid particles, and a good point is that pressure integrations over the fluid–solid interface are avoided. This would be more useful in situations when the pressure fluctuation is large and accurate prediction of the fluid forces is difficult. However, the fluid incompressibility near the structure boundary cannot be strictly satisfied because of the assumption used. During fluid–structure interactions, the solid boundary treatment is an important issue, and two kinds of boundaries have been commonly used in SPH approaches, i.e., fixed/dummy particles and mirroring particles. The fixed or dummy particle methods used by Monaghan (1994) and Shao and Lo (2003) are computationally efficient, but the computational errors arising from the divergence of velocity on the solid boundaries could lead to large pressure oscillations. The mirroring particle methods, as originally proposed by Cummins and Rudman (1999)

Received May 28, 2015; revised manuscript received by the editors November 23, 2015. The original version was submitted directly to the Journal.

KEY WORDS: ISPH, fluid-structure coupling, free surface, damping layer, force moment, structure rotation.