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A Multiphase Compressible–Incompressible Particle Method for Water Slamming

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This paper presents a novel compressible–incompressible multiphase projection-based particle method for the prediction of water slamming pressures. The particle method considered is an extended version of an enhanced multiphase moving particle semi-implicit (MPS) method. The proposed method solves an integrated form of Poisson pressure equations (PPEs) for the liquid and gas phases. To further enhance accuracy, a modified version of the previously developed ECS scheme is devised for the gas phase through calculations of minimum and maximum theoretical base values for activation of the ECS scheme, thus imposing an allowable range of density variations for the compressible phase. Verifications are conducted by means of 2D liquid impact and impacts of rigid plates on flat water surfaces.

INTRODUCTION

The high-speed impacts between water and structures, often referred to as "slamming," are of crucial importance in the design of coastal/offshore structures. Several theoretical studies have been devoted to the prediction of slam loads (e.g., von Kármán, 1929; Wagner, 1932). However, in most classical theoretical studies, the air phase and its cushioning effect have been ignored. Several experimental works, on the other hand, highlighted the importance of the air phase during the impact. In particular, a pioneering experimental study by Chuang (1966) demonstrated considerably reduced impact pressures compared with the Wagner theoretical solution. Hence, numerical predictions of slam loads should be conducted by robust multiphase numerical methods that can appropriately model the dynamics of air and its cushioning (compressibility) effect.

A number of interesting numerical works have been devoted to the simulation of wave slamming with consideration of air entrapment and its cushioning effect. In particular, Ma et al. (2014) developed an advanced finite volume method (FVM)-based compressible multiphase method for violent aerated wave impact problems. Lind et al. (2015) proposed a compressible–incompressible smoothed particle hydrodynamics (SPH)-based method for wave slamming by solving the air phase via an explicit weakly compressible SPH (WCSPH) method and calculating the fluid phase via a semi-implicit incompressible SPH (ISPH).

This paper presents a novel compressible–incompressible multiphase projection-based particle method for the prediction of wave slamming loads. The considered particle method is an extended version of an enhanced multiphase moving particle semi-implicit (MPS) method (Khayyer and Gotoh, 2013). The proposed method solves an integrated form of Poisson pressure equations (PPEs) for the liquid phase and the gas phase. To further enhance accuracy, a modified version of the previously developed ECS scheme (Khayyer and Gotoh, 2013) is devised through calculations of minimum and maximum theoretical base values for activation of the ECS scheme, thus imposing allowable ranges of density variations for the phases.

Verifications are conducted by considering a set of liquid impact and slamming problems, including a 2D liquid impact (Braeunig et al., 2009) and impacts of rigid plates on flat water surfaces corresponding to the experiments by Lin and Shieh (1997) and Verhagen (1967).

NUMERICAL METHOD

Enhanced Multiphase MPS Method

The basic numerical method corresponds to an enhanced multiphase MPS method (Khayyer and Gotoh, 2013) benefitting from a higher-order source term of PPE (HS); a higher-order Laplacian model (HL); an error-compensating source term of PPE (ECS); a gradient correction (GC); and a density smoothing scheme, first-order-accurate density smoothing (FDS).

For a compressible–(nearly) incompressible gas–liquid multiphase system, the governing equations considered are the continuity and Navier–Stokes equations expressed as follows:

$$\frac{1}{\rho C_s^2}\frac{Dp}{Dt} + \nabla\cdot\boldsymbol{u} = 0 \tag{1}$$

$$\frac{D\boldsymbol{u}}{Dt} = -\frac{1}{\rho}\nabla p + \boldsymbol{g} + \nu\nabla^2\boldsymbol{u} \tag{2}$$

In Eqs. 1 and 2, $\boldsymbol{u}$ = particle velocity vector, t = time, ρ = fluid density, p = particle pressure, $\boldsymbol{g}$ = gravitational acceleration vector, ν = laminar kinematic viscosity, and C_s = speed of sound.

Because of the presence of numerical errors corresponding to incomplete/imprecise differential operator models and a first-order-accurate projection scheme, numerical solutions to Eqs. 1 and 2 will not result in accurate physical volume conservations. For this reason, in calculations by Khayyer and Gotoh (2009), an "artificial speed of sound" was devised rather than a physical one. To minimize the numerical errors, Khayyer and Gotoh (2011) proposed a so-called ECS scheme in the source term of PPE. For an assumed perfectly incompressible fluid phase, the PPE with the ECS scheme is formulated as follows:

$$\left(\frac{\Delta t}{\rho}\nabla^2 p^{k+1}\right)_i = \frac{1}{n_0}\left(\frac{Dn}{Dt}\right)_i^* + ECS$$
$$ECS = \left|\frac{n^k - n_0}{n_0}\right|\left[\frac{1}{n_0}\left(\frac{Dn}{Dt}\right)_i^k\right] + \left|\frac{\Delta t}{n_0}\left(\frac{Dn}{Dt}\right)_i^k\right|\left(\frac{1}{\Delta t}\frac{n^k - n_0}{n_0}\right) \tag{3}$$

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KEY WORDS: Slamming, multiphase flow, particle method, MPS method, compressibility effect.