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Numerical Investigation of Water-Entry Problems Using IBM Method

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This paper presents a systematic numerical investigation of the water-entry problems associated with dropping triangular wedges or ship sections that uses an incompressible Immersed Boundary Method (IBM). In the IBM, the solid bodies are treated as an additional phase, and their motions are solved by a unified equation similar to those governing the air and water flows; a level-set technique is used to identify the air-water interface, and a projected Heaviside function is developed to identify the fluid-solid interface. For the purpose of comparison, a corresponding numerical simulation with or without consideration of the compressibility of the fluids is also carried out by using OpenFOAM. All results are compared with the experimental data provided by the comparative study of ISOPE 2016. The results suggest that the unified equation in the IBM can well predict the motion of the dropping bodies; the IBM can capture the entrapped air and produce an impact pressure and local and global forces that agree fairly well with the experimental data.

INTRODUCTION

The water entry is a complex and nonlinear fluid-structure interaction (FSI) problem involving many physical phenomena such as air trapping, spray, and extreme free-surface deformation. A large impulsive pressure and slamming forces possibly lead to the damage of the offshore structure and are of interest for engineering purposes. Both numerical modelling and experiments have been conducted for the prediction and validation of the water-entry problems, in particular the effect of the compressibility, aeration, and hydro-elasticity (Miyamoto and Tanizawa, 1985; Okada and Sumi, 2000; Huera-Huarte et al., 2011; Ma et al., 2014, 2015; Mai et al., 2015). Against such a background, the International Hydrodynamic Committee of the International Society of Offshore and Polar Engineers has proposed a comparative numerical study of such an issue, in which the experimental data from the third iteration of the Wave Induced Loads on Ships (WILS) Joint Industry Project (MOERI, 2013) are provided. This paper presents our numerical results for the comparative study, and therefore only relevant reviews of numerical approaches have been given herein.

Great effort has been devoted to deriving analytical solutions and empirical formulas to predict the slamming forces associated with the water-entry problems, e.g., Wagner (1932), Dobrovol'skaya (1969), Armand and Cointe (1986), and Cointe (1991), which benefit the design practices although such solutions may be suitable only for simple-geometry or wedge-type bodies. However, the body shapes and impact angles, in particular the structures with a small deadrise angle, are important for the impact pressure development and free surface formation near the impact surface, as observed by the experiment (Okada and Sumi, 2000; Huera-Huarte et al., 2011). Due to the limitation of the analytical and empirical methods, the numerical methods have been utilised to solve the engineering problems with more complex geometry. Both the potential theory, in which the flow is assumed to be incompressible, inviscid, and irrotational, and the general viscous flow theory, i.e., the solution of the Navier-Stokes modelling, have been attempted.

The application of the potential flow theory, e.g., Greenhow (1987), Zhao and Faltinsen (1993), and Zhao et al. (1996), may be justified by the fact that the water entry is mainly a procedure dominated by the Froude number, in which the viscous and turbulent effects may not play a significant role in terms of the maximum load and pressure on the body, which occur in a short duration following the entry of the body and often before the formation of the broken wave surface. However, the simplification of the fluid through the use of potential models limits the applications. First, the viscosity of the fluid is ignored in the potential models, but the viscous effect is important, particularly in the formation of the local breaking waves around the body surfaces. Second, the effect of the air is ignored in the potential theory or other single-phase numerical models (Gao et al., 2012; Oger et al., 2007; Skillen et al., 2013). However, the aeration (Ma et al., 2014) and the compressibility of the air (Ma et al., 2015) are important for the water-entry problem, in particular when the deadrise angle is smaller than 10°. A recent experimental and numerical work by Lind et al. (2015) focused on the horizontal plate impact on a wave crest or a flat water surface, where the air and water are treated as compressible and incompressible fluids solved by the multiphase Smooth Particle Hydrodynamics (SPH) model. The work has confirmed the important role of the air phase in modelling the slamming pressure and forces. A similar conclusion has been drawn from the earlier experimental studies, e.g., Miyamoto and Tanizawa (1985). They concluded that the impact pressure is reduced and the water surface is deformed before body contact with the water surface. In order to tackle these challenges, a multiphase flow model based on the general viscous flow theory is necessary.

The multiphase models are usually solved via two types of numerical methods, i.e., the meshless method and the mesh-based method. For the former, the fluids are represented by particles, and the compressibility of the fluids can be considered by the involvement of the equation of the state (Lind et al., 2015). For the latter, the computational domain is discretized into elements and cells, and the free surface is captured or tracked by specific techniques, e.g., the volume of fluid (VOF) (Kleefsman et al., 2005) and the level set (Sussman et al., 1994; Sanders et al., 2010). By means of these numerical methods, the necessity of considering the air phase (Kleefsman et al., 2005; Yang and Qiu,

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