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On the Coupling of Incompressible SPH with a Finite Element Potential Flow Solver for Nonlinear Free-Surface Flows

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This paper presents a two-dimensional, one-way coupling methodology between the quasi-arbitrary Lagrange–Euler finite element method (QALE-FEM) nonlinear potential flow solver and the incompressible smoothed particle hydrodynamics (ISPH) Navier-Stokes equations solver. Nonlinear potential flow solvers such as the QALE-FEM are highly efficient solvers for propagating waves in large domains; however, when extreme nonlinearity takes place, such as fragmentation, breaking waves, and violent interaction with marine structures, the methodology becomes incapable of dealing with these flow features. The particle method ISPH is known to be accurate for such highly nonlinear fragmentized flows and provides near-noise-free pressures. ISPH is thus ideal for near-field flows involving overturning, splashing, and slamming. Herein, we propose a one-way coupling methodology between QALE-FEM and ISPH where the methods are used for the far-field and inner/local regimes, respectively. To validate the one-way coupling algorithm, two sinusoidal waves have been used with satisfactory results. The intention is to extend this approach to the strong coupling of the potential flow solver with ISPH using a two-phase (air–water) solver. The aim is to reliably predict extreme wave forces and slamming on offshore structures such as decks and platforms for marine renewable energy and the oil and gas industry.

INTRODUCTION

Structures for offshore oil and gas and, more recently, for supporting wind turbines and machines for marine renewable energy conversion have been the subject of sustained research and development for a number of years. These offshore structures are often located in depths where waves may be classed as intermediate, with breaking, bore-like waves that can result in extreme loads. However, impulsive loading and slamming due to extreme waves is not well defined, particularly when structural response occurs. The problem is complex: important characteristics such as slamming pressures and loads as a result of breaking wave impact forces involve two or more phases such as air–water and/or fluid–structure interaction (Lind et al., 2015; Khayyer and Gotoh, 2016). Just as important, different scales ranging from the far-field propagation to near-field slamming are significant as highly nonlinear incident waves from the far-field directly determine near-field, possibly breaking wave dynamics (Skillen et al., 2013).

Nonlinear potential flow solvers such as the quasi-arbitrary Lagrange–Euler finite element method (QALE-FEM) (Ma and Yan, 2006; Yan and Ma, 2007) have been proven to be robust and highly efficient for large domains when breaking does not occur. However, potential flow solvers have limitations, making them inappropriate for a near-field flow since they are constrained by a mesh that may be suitable for the initial stages of wave overturning but not for reconnecting with the water surface following breaking or for solid surface interaction with high deformations characteristic of impact. The incompressible smoothed particle hydrodynamics (ISPH) scheme (Xu et al., 2009; Lind et al., 2012), based on a divergence-free velocity field using a projection method, is known to be accurate for such flows with noise-free pressures and kinematics for internal and free-surface flows, following recent developments of the diffusion-based particle shifting. ISPH is thus ideal for the near-field and slamming because of its ability to treat highly nonlinear flows and free-surface flows with overturning and splashing while providing accurate pressure predictions (Lind et al., 2016). The ISPH method is, however, computationally demanding and is thus suited to small domains. For a review of recent developments in smoothed particle hydrodynamics (SPH), the reader is directed to Violeau and Rogers (2016) and Gotoh and Khayyer (2016).

The idea of hybrid models is well documented in the literature for weak or strong coupling. Examples of weak coupling models include boundary element (BEM) and volume of fluid (VOF) models (Lachaume et al., 2003; Biausser et al., 2004), fully nonlinear potential flow theory (FNPT) solvers with VOF (Hildebrandt et al., 2013), and FNPT and Lattice–Boltzmann models (Janssen et al., 2010). Strong coupling is also evident in the literature, in models such as BEM-level set methods (Colicchio et al., 2006) and BEM and VOF models (Kim et al., 2010; Guo et al., 2012). Fully nonlinear potential flow theory solvers such as QALE-FEM and particle method hybrid algorithms have also been tested with success, such as in the work by Sriram et al. (2014).

Recently, the creation of hybrid models with SPH has also become popular with the adoption of finite volumes (FVs). In Marrone et al. (2016), a weakly compressible SPH formalism was used, while a previous study by Napoli et al. (2016) coupled ISPH

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KEY WORDS: Coupling, weak coupling, ISPH, particle method, QALE-FEM, potential flow, free-surface flows, regular wave.