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A 3D Hybrid Model Coupling SPH and QALE-FEM for Simulating Nonlinear Wave-structure Interaction

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This paper presents a three-dimensional hybrid model that couples the weakly compressible smoothed particle hydrodynamics (SPH) and the quasi-arbitrary Lagrangian-Eulerian finite element method (QALE-FEM) for modelling the wave-structure interaction (WSI) in extreme sea states. The former is a fully Lagrangian mesh-free approach that solves the one-phase incompressible Navier–Stokes model and has shown satisfactory performance in simulating the WSI. The latter is an arbitrary Lagrangian-Eulerian approach based on the fully nonlinear potential theory and can accurately simulate highly nonlinear nonbreaking water waves in a large scale with high computational efficiency. These two models are coupled using a one-way zonal approach, in which the SPH uses a small computational domain near the structure, whereas the QALE-FEM covers the rest of the computational domain and provides wave conditions at the inlet of the SPH domain. The present hybrid model is validated against the experimental results and applied to the CCP-WSI blind test on modelling wave energy converters subjected to extreme focusing waves. The accuracy and convergence of the presented model are discussed.

INTRODUCTION

The wave-structure interaction (WSI) in extreme sea status has been receiving extensive attention in the design and operation of the offshore and marine structures for their safety and survivability. The wave in such a condition is typically highly nonlinear and may exhibit local wave breaking, typically exceeding the range of applications of the linear, second-order, or Stokes wave theories. For a full development/formation of the extreme wave, the associated wave fetch length or propagation distance must be sufficiently large (Wang, Ma, and Yan, 2017, 2018). On the other hand, the structures subjected to such waves normally undergo significant motions and/or deformations. Consequently, small-scale physics, such as the viscous/turbulent effects, breaking wave impact, and aeration, may be important. This calls for numerical models with a capacity of dealing with both the large-scale wave propagation and the small-scale near-field physics simultaneously to deliver a reliable prediction on WSI in extreme sea conditions. Conventionally, two types of numerical models have been developed and applied in the engineering practices.

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The first one is the fully nonlinear potential theory (FNPT), which assumes that the fluid is inviscid, incompressible, and irrotational. The FNPT can be solved by the boundary element method (e.g., Grilli et al., 2001), the finite element method (FEM)—for example, the quasi-arbitrary Lagrangian-Eulerian finite element method (QALE-FEM) (Ma and Yan, 2006; Yan and Ma, 2007; Yan et al., 2015)—the spectral element method (Engsig-Karup et al., 2016), the high-order spectral method (Ducrozet et al., 2016), and the spectral boundary integral method (Wang et al., 2015). The applications of the FNPT on models have demonstrated its satisfactory accuracy on modelling highly nonlinear waves up to wave overturning (e.g., Ma and Yan, 2006; Yan and Ma, 2010a), extreme waves under the action of wind (Yan and Ma, 2010b) and current (Wang, Ma, and Yan, 2018), and nonlinear wave interactions with fixed structures (e.g., Yan, Xie, et al., 2019) or floating structures (e.g., Yan and Ma, 2007; Ma and Yan, 2009; Ransley et al., 2020). However, its theoretical assumptions invalidate its applications to the problems with significant viscous/turbulent effects, such as in cases with small-sized structures (typically < 0.2 in wavelength), gap resonances between two floating bodies in close proximity (Lu and Chen, 2012), and floating structures undergoing large rotational motion (e.g., Yan and Ma, 2007). It is also difficult to model breaking wave impacts on structures (Stansby, 2013).

The second one is the viscous flow theory (NS model), which solves the Navier–Stokes equation and the continuity equation with appropriate boundary conditions. The NS models can resolve the viscous/turbulence effects and deal with the violent wave