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A hybrid method for modelling two dimensional non-breaking and breaking waves

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ABSTRACT

This is the first paper to present a hybrid method coupling an Improved Meshless Local Petrov Galerkin method with Rankine source solution (IMLPG_R) based on the Navier–Stokes (NS) equations, with a finite element method (FEM) based on the fully nonlinear potential flow theory (FNPT) in order to efficiently simulate the violent waves and their interaction with marine structures. The two models are strongly coupled in space and time domains using a moving overlapping zone, wherein the information from both the solvers is exchanged. In the time domain, the Runge–Kutta 2nd order method is nested with a predictor–corrector scheme. In the space domain, numerical techniques including 'Feeding Particles' and two-layer particle interpolation with relaxation coefficients are introduced to achieve the robust coupling of the two models. The properties and behaviours of the new hybrid model are tested by modelling a regular wave, solitary wave and Cnoidal wave including breaking and overtopping. It is validated by comparing the results of the method with analytical solutions, results from other methods and experimental data. The paper demonstrates that the method can produce satisfactory results but uses much less computational time compared with a method based on the full NS model.

1. Introduction

The available numerical models for strongly nonlinear interactions between water waves and marine structures are mainly based on solving either the fully nonlinear potential flow theory (FNPT) or the Navier–Stokes (NS) equations. The problems formulated by the FNPT model are usually solved by a time marching procedure, originally proposed by Longuet-Higgins and Cokelet [1]. In this procedure, the key task is to solve the boundary value problem (BVP) for the velocity potential at each time step by using a numerical method, such as the boundary element method (BEM) and the finite element method (FEM). The BEM including higher order BEM and those based on domain decomposition technique has been attempted by many researchers, as reviewed by Kim et al. [2]. The FEM was used by Wu and Eatock Taylor [3] for the 2D cases and by Ma et al. [4] for 3D cases, and it was further extended to handle complex objects and floating bodies simulations forming the QALE-FEM (Quasi-Arbitrary Lagrangian and Eulerian finite element method) by Ma et al. [5,6], Yan et al. [7–9] and SALE-FEM (Semi-Arbitrary Lagrangian and Eulerian finite element method) by Sriram [10], respectively. It has been shown that the FEM is more efficient for modelling strongly nonlinear waves while the BEM is more efficient for modelling linear or weak nonlinear problems [9]. The problems formulated by using the NS model are usually solved by employing a mesh-based method or a meshfree method. There are a large number of publications for both approaches.

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Table 1
Classifications of the literature based on coupling method adopted.

	Solvers	Weak coupling	Strong coupling		
			Explicit	Implicit	Intrinsic
Mesh based methods	FNPT/NS	Lachaume et al. [33]; Biausser et al. [37]; Hildebrandt et al. [54]; Yan and Ma [55]		Colicchio et al. [38]; Kim et al. [35]; Grilli [34]; Guo et al. [36]	
	Others	Janssen et al. [39]	Fujima et al. [32]; Sitanggang [40];		
Particle methods	FNPT/NS		Sueyoshi et al. [41]	Present paper	
	Boussinesq/NS	Narayanaswamy et al. [42]; Kassiotis et al. [43]			

Extensive review on them would diverse the focus of this paper but a brief review will be given here for completeness. In the mesh based methods, finite volume methods [11–14] and finite difference methods [18,19] have been extensively used. In order to handle large domains, a multi-resolution capability and far-field boundary conditions to the regular fixed-grid NS solver have also been proposed using chimera and moving grid methods [15–17]. The advantage of such a strategy is the use of regular grids that could avoid the numerical stability issues; however, if viscous effects are introduced then there will be a restriction on the length time step. On the other hand, the meshfree (or particle) methods have been recognised as promising approaches in recent years, particularly for modelling violent waves and their interaction with structures owing to their advantages that meshes are not required and numerical diffusion associated with convection terms is eliminated compared to traditional mesh based methods. The notable papers based on particle methods for the topics related to wave–structure interactions include but are not limited to Refs. [22–24] for using smoothed particle hydrodynamics (SPH), [25] for using moving particle semi-implicit method (MPS), [26,27] for using Meshless Local Petrov Galerkin with Rankine Source (MLPG_R). Some simplified test cases reported in the literature using these models showed a good agreement with the experimental measurements, see for example, [1–10,20,28] for the FNPT models and [21–25,29–31] for the NS models.

These two types of models have their own advantages and disadvantages. When using the FNPT models, one cannot model breaking waves or consider viscous effects, but can conserve the energy for long time and long distance simulations with higher computational efficiency. Whereas, when employing the NS models, one could handle violent waves and consider viscous effects but normally see loss of energy for long time and long distance simulation and use prohibited computational time. Due to their disadvantages, neither of the two types of models is suitable for modelling large scale wave propagation incorporating both non-breaking and breaking processes, such as the wave scenarios in a large area from offshore to coastal zone. The ideal model should meet the following criteria:

i) To properly resolve the physical scales of interest in wave–structure interactions and
ii) The simulations must be sufficiently accurate and efficient for practical applications.

Hybrid models seem to be a promising one that can meet the criteria. In such a model, one may use the fully nonlinear potential flow theory (FNPT) and full NS equations in sub-domains wherever appropriate, thus not compromising on the physics.

The idea of the hybrid model has been reported in recent literature. The classification of the literature as per type of coupling techniques employed is summarized in Table 1. The literature is broadly classified into weak and strong couplings of two models. In the weak coupling, initially only one solver will be run completely without the need for other, the result is then feed into other solver to complete the simulation. Whereas, in the strong coupling the information from both the models are exchanged, and their solutions are mutually dependent. Notable works on weak coupling were presented by Lachaume et al. [33] and Biausser et al. [37]. In the references, the FNPT model based on the BEM was combined with the NS model based on a finite volume method (FVM) for the simulation of solitary wave breaking over the sloped terrain. Yan and Ma [55] and Hildebrandt et al. [54] used the weak coupling between the FNPT model based on finite element method and commercial software STAR-CCM and ANSYS, respectively. Janssen et al. [39] coupled the BEM based on the FNPT with the discrete Boltzmann equation using Lattice Boltzmann method to study the solitary wave breaking. The strong coupling can be further classified into explicit, implicit and intrinsic technique. In explicit coupling, the FNPT solver results are obtained using the information from the previous time step and the results are then feed into the NS solver to complete the simulation at every time step. In implicit coupling, every time step is split into several sub-steps. In the sub-steps, the results from the FNPT solver are not only sent to the NS solver, the results from the NS solver are also feed back to the FNPT solver. Whereas, in the intrinsic technique both solvers are iterated till convergence is reached. So far no papers using the intrinsic technique have been found, perhaps because of its high computational cost. On the strong coupling approach, the notable works were carried out by Grilli [34], Kim et al. [35], Guo et al. [36] by combining the FNPT model based on the BEM with the NS model based on the FVM. Colicchio et al. [38] adopted a similar method to model a dam breaking problem and applied it to wave slamming on the deck. The two models are strongly coupled through a fixed overlapping