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Coupling methodology for smoothed particle hydrodynamics modelling of non-linear wave-structure interactions

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ABSTRACT

A two-way coupling methodology for wave propagation and wave-structure interaction with SPH is hereby presented. The methodology consists of combining a fast, fully non-linear wave propagation model, OceanWave3D, with an accurate Smoothed Particle Hydrodynamics (SPH) solver, DualSPHysics. At the coupling interface in the SPH zone, moving dynamic boundary particles are applied, which move according to the horizontal velocity calculated in the wave propagation model. The surface elevation is registered in the SPH zone and transferred back to the wave propagation model. Using this coupling methodology, a large domain can be simulated with the wave propagation model, with small, discrete SPH zones embedded to locally obtain higher accuracies. The communication between the solvers is implemented using OpenMPI. Three connected processes are run: OceanWave3D, DualSPHysics and Python. The latter is used to monitor the data transfer and manipulate the data in an efficient manner. The coupling methodology is validated by simulating wave propagation of linear and non-linear waves, and comparing the surface elevations and orbital velocities to a theoretical solution. Comparison with two experimental datasets is performed as well. The coupling methodology proofs that it is able to accurately propagate waves and shows a good agreement with theoretical and experimental results.

1. Introduction

During the past decades, construction of offshore and nearshore structures has known a steady increase. Next to traditional oil platforms, offshore and nearshore areas are suited for the installation of fixed and floating wind turbines, artificial islands, tidal turbines and wave energy converters. These structures, fixed or floating, have a significant influence on the local wave field. Within coastal engineering it is of great interest to be able to accurately identify the wave transformations influenced by these structures. The deployment of an offshore/nearshore structure affects the incident wave field by exhibiting wave reflection and diffraction, as well as wave radiation in the case of a floating structure (see Fig. 1). These wave interactions close to the structures are called ”near-field” effects, while the propagation of these waves further away from the structures are called ”far-field” effects. The superposition of these phenomena results in a complex perturbed wave field (Stratigaki et al., 2014a, 2014b; Troch and Stratigaki, 2016). Simulating the wave transformations within and around a WEC array is complex; it is difficult, or in some cases impossible, to simulate both near-field and far-field effects using a single numerical model, in a time and cost-efficient way in terms of computation time and effort. This can be achieved by coupling of a wave-structure interaction solver for the near-field effects and a wave propagation model for the far-field effects. This strategy is well documented in literature, for weak and strong coupling methods.

Weakly coupled models, where one model is run before the other (1-way information transfer), have been applied to connect a Boundary Element Method (BEM) solver with a Volume-Of-Fluid (VOF) solver in Lachaume et al. (2003) and Biausser et al. Similarly, a fully non-linear potential flow (FNPF) model has been used to initialize a VOF model in Hildebrandt et al. (2013). A similar coupling is realised in Janssen et al. (2010), where a particle-based Lattice-Boltzman model is nested within the FNPF model. For linear simulation over variable bathymetry, there have been studies coupling a wave propagation model (shallow water equations or potential flow theory) and a BEM wave-structure interaction solver (Verbrugghe et al., 2016, 2017a; Charrayre et al., 2014; Verao Fernandez et al., 2017; Troch and Stratigaki, 2016).

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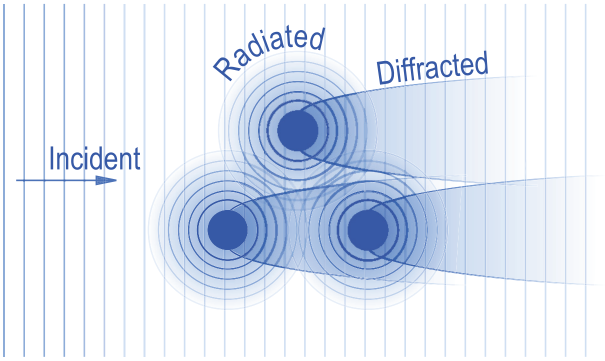

Fig. 1. Visual representation of incident, radiated and diffracted waves around an array of 3 floating structures. The combination of these wave fields results in the total wave field around the 3 floating structures.

Strong coupling is also evident in the literature, for example BEM-level set methods (Colicchio et al., 2006) and models where BEM is coupled to VOF (Kim et al., 2010; Guo et al., 2012). Fully non-linear potential flow theory solvers and particle methods hybrid algorithms have also been tested with success, demonstrated by Sriram et al. (2014).

In this research, focus is put on coupling of a fully non-linear 3D potential flow solver (OceanWave3D (Engsig-Karup et al., 2009)) with a weakly-compressible SPH (WCSPH) wave-structure interaction solver (DualSPHysics (Crespo et al., 2015)). The objective is to simulate wave impacts on floating and fixed structures in real sea and storm conditions, characterised by irregular, 3D waves with the occurrence of non-linear effects. The coupling is performed in a two-way manner, allowing the disturbed wave field around the structure to be propagated towards the far-field. The coupled model allows for simulation of offshore structures in higher order irregular waves and more extreme wave conditions. This coupling methodology has been developed to combine:

1. The advantages of the approach of wave-structure interaction solvers based on smoothed particle hydrodynamics, which accurately formulate and efficiently resolve the physical processes, specifically with a high accuracy for wave forces (Altomare et al., 2015).
2. And, the benefits of the approach of wave propagation models, which resolve the propagation and transformation of waves over large distances, with a fast computation time, including bathymetric variability over the domain and wave transformation processes when approaching the coastline.

Smoothed particle hydrodynamics are a flexible Lagrangian and mesh-less technique for Computational Fluid Dynamics (CFD). The Lagrangian reference frame of SPH makes it useful in solving problems with large deformations and distorted free surfaces. In comparison with other numerical methods, the SPH formulation is simple and robust (Monaghan, 2005). SPH has been successfully applied to a number of free-surface problems that involve wave breaking and splashing (Monaghan and Kos, 1999; Dalrymple and Rogers, 2006). The impact between a rigid body and water has been studied in Monaghan et al. (2003). A fixed cylinder in a wave train and forced motion of cylinders generating waves is mentioned in Omidvar et al. (2012), while floating bodies in waves have been successfully studied in 2D (Manenti et al. 2008). The feasibility of applying SPH for modelling of wave energy converters has been studied in Verbrugghe et al. (2017b). 3D problems of wave generation by a heaving cone and a floating body in waves undergoing predominantly heave motion are investigated in Omidvar et al. (2013). The latter has also indicated that there is a large benefit of calculating with a variable particle mass distribution. Coupling SPH solvers to other models is one of the SPHERIC Grand Challenges (Spheric - grand challenges). A general algorithm for one-way coupling of SPH with an external solution has been proposed in Bouscasse et al. (2013). The interaction between the SPH solver and the external solution is achieved through an interface region containing a ghost fluid, used to impose any external boundary condition. In Fourtakas et al. (2018), A hybrid Eulerian-Lagrangian incompressible SPH formulation is introduced, where two different SPH formulations are coupled rather than two completely different solvers. The SPH solver DualSPHyics has been coupled in Altomare et al. (2016), where a one-way coupling was realised with the wave propagation model SWASH. A numerical wave flume has been created to simulate wave impact and run-up on a breakwater. The first part of the numerical flume is simulated using the faster SWASH model, while the wave impact and run-up are calculated using DualSPHysics. Here, a one-way coupling is sufficient, since there is only interest in the impact of waves on the breakwater. In Kassiotis et al. (2011), a similar approach has been adopted, where a 1D Boussinesq-type wave model is applied for wave propagation in most of the spatial domain, and SPH computations focus on the shoreline or close to off-shore structures, where a complex description of the free-surface is required. Similarly, an incompressible SPH solver has been coupled to a non-linear potential flow solver QALE-FEM in Fourtakas et al. (2017). In Chicheportiche et al. (2016), a one-way coupling between an potential Eulerian model and an SPH solver is realised, applying a non-overlapping method using the unsteady Bernouilli equation at the interface. These studies applied coupling to speed up the simulation time by minimizing the computationally intensive SPH domain. Other studies apply coupling to combine both the benefits of mesh-based and mesh-free CFD methods. In Didier et al. (2013), the wave propagation model FLUINCO is coupled to an SPH code, and validated with experimental data of wave impact on a porous breakwater. A hybrid multiphase OpenFOAM-SPH model is presented in Kumar et al. (2015), where the SPH method is used on free surfaces or near deformable boundaries whereas OpenFOAM is used for the larger fluid domain. A similar coupling is used, where breaking waves are modelled with SPH and the deeper wave kinematics are modelled with a Finite volume method. This has been demonstrated in Marrone et al. (2016) for a weakly-compressible SPH (WCSPH) solver and in Napoli et al. (2016) for an incompressible SPH (ISPH) solver. In the present research, the main reasons for developing coupling is to save computation time and to achieve fully non-linear wave generation. Compared to all the coupling methodologies described above, the here presented coupling methodology differentiates itself based on the following novel features:

- The coupling methodology contains two coupling interfaces: one ’upwave’ of the SPH domain and one ’downwave’ of the SPH domain;
- The individual models are coupled at every time step using a Message Passing Interface (MPI) implementation;
- The coupling information is shared between the coupled models based on a two-way principle;

The SPH solver receives detailed information on the wave kinematics from the wave propagation model, while the transformed surface elevations (reflection, diffraction and radiation) resulting from the wave-structure interaction are transferred back to the wave propagation model. This is necessary for two reasons. Firstly, the interest is to study the motions of offshore and near-shore floating structures. Extending the SPH domain until the coastline, would lead to an unnecessarily large computational cost. For this, boundary conditions are needed upwave and in the lee of the floating structure. A two-way coupling ensures the most accurate implementation of these boundary conditions. Secondly, apart from the floater motions, the main interest is to study the effects of the floating structures on the wave field and the propagation of that disturbed wave field further away from the device. For this reason a two-way coupling where the surface elevation is coupled back to the wave propagation model, is mandatory.

In Section 2 of this paper, the principles of the coupling methodology are presented. A detailed description of the models, employed to demonstrate the proposed coupling, is provided, followed by an