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A free surface interpolation approach for rapid simulation of short waves in meshless numerical wave tank based on the radial basis function

Longfei Xiao [a], Jianmin Yang [a], Tao Peng [a], Longbin Tao [b],*

[a] State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
[b] School of Marine Science and Technology, Newcastle University, NE1 7RU England, United Kingdom

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ABSTRACT

The meshless Numerical Wave Tank (NWT) has been developed based on the collocation method and the radial basis function. For simulating short waves, a free surface interpolation approach is proposed in this study in order to mitigate numerical dissipation and accelerate the simulation. A number of fundamental free surface nodes are employed in the procedure of solving algebraic equations with a full coefficient matrix, while many more free surface nodes are utilized in the time-stepping and smoothing procedure by applying the interpolation technique between each adjacent fundamental nodes. The NWT with the free surface interpolation approach is applied to simulate regular waves and irregular waves, and is then validated by both analytical solutions and experimental results. The numerical results are significantly improved by using the approach to increase the number of free surface boundary nodes, whilst the time consumption increases proportionally. For shorter waves, more interpolation nodes need be used. The good agreement between the present numerical results and the analytical and experimental results indicates that the free surface interpolation approach succeeds in rapidly and accurately simulating the propagation of short waves and irregular waves, covering a wide range of wave frequencies.

1. Introduction

Rapid development in offshore activities, along with increasingly extreme environments, demands more accurate prediction of the hydrodynamic performance of offshore structures. Among the various numerical tools used for such prediction, the time-domain simulation method has been commonly accepted as the most effective tool, owing to the fact that the coupling effects of wave–structure and hull–mooring–riser interactions can be calculated in real-time [1]. As an essential input for the calculation, the time series of random waves is usually obtained by using a linear summation model with random seeds or experimentally calibrated waves. However, the linear summation model is too simple to consider the wave nonlinearities, wave–wave interactions, and water depth effects, whereas the experimental data are limited and unavailable at the early design stage. Therefore, the Numerical Wave Tank (NWT) tends to be an effective tool for obtaining the time series of random waves by using nonlinear free surface boundary conditions and considering water depth effects.

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* Corresponding author. Tel.: +44 (0) 191 208 6670; fax: +44 (0) 191 208 5491.
E-mail address: longbin.tao@newcastle.ac.uk (L. Tao).

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The NWT for simulating surface gravity water waves is an important topic in the field of coastal and offshore engineering. Along with the increasingly improved computer techniques and power, a great deal of success in the computational study of nonlinear NWTs has been continuously achieved on the basis of various numerical schemes, including the Finite Difference Method (FDM) [2], the Finite Element Method (FEM) [3], the Boundary Element Method (BEM) [4], the Boundary Integral Equation Method (BIEM) [5], the Boussinesq-Type (BT) model [6], the Computational Fluid Dynamics (CFD) method [7], as well as Meshless Methods (MMs) [8]. A detailed review of the available NWT for simulating nonlinear water waves with and without overturning can be seen in Refs. [9,10] containing a large number of references therein. In the potential NWT on condition that the viscosity is not important, BEM has been very popularly employed to solve boundary value problem at each time step because of its efficiency and accuracy. Continuous improvements have been achieved in recent years. The High-Order BEM (HOBEM) attracted more and more attention for the numerical simulation of nonlinear wave–wave and wave–body interactions [4,11–13]. A parallel implementation of NWT was developed by using HOBEM combined with a Fast Multipole Algorithm (FMA) [14]. A force-feed back absorption controller was implemented in a BEM-type NWT [15]. In comparison with BEM, the MMs require neither domain nor surface meshing; they construct the numerical approximation from nodes for the purpose of partly eliminating the difficulties associated with mesh-based methods, such as mesh-based interpolation, distorted or low-quality meshes that lead to considerable errors, and moving discontinuities [16].

One of the MMs is the Smooth Particle Hydrodynamics (SPH) method, which was proposed to solve problems in fluid dynamics such as free surface flows [17,18]. By handling turbulence, fluid viscosity, and density, the SPH model is able to model breaking waves on beaches, the green water overtopping of decks, and wave–structure interactions [19]. A strictly Incompressible SPH (ISPH) model was further developed to simulate free surface flows, in which the pressure was obtained by solving a pressure Poisson equation from a hydrodynamic formulation [20]. An improved ISPH model with redefined mirror particle treatment for solid boundaries was recently applied to simulate free surface wave interactions with coastal structures of various shapes [21]. In addition, a δ-SPH model with numerical diffusive terms was proposed to simulate different free surface flows, including 2D gravity waves generated by a wave maker [22].

Another MM, known as the Meshless Local Petrov–Galerkin (MLPG) method, which is based on local weak forms in overlapping subdomains [23], was proposed by Ma [24] to deal with nonlinear water wave problems. Satisfactory agreement was achieved in comparison to the analytical solutions and finite element results. This formulation is based on general fluid-governing equations, and the boundary value problem is solved by using the MLPG method at each time step. The improved MLPG method based on the Rankine source solution, which boasts a larger computational efficiency, was further developed to simulate freak waves and breaking waves [25,26].

Amongst the existing MMs, the one using Radial Basis Function (RBF) networks offers a continuously differentiable and integrable grid-free scheme for representing surfaces and partial derivative estimations. A set of RBFs is employed, and the derivatives can be calculated directly. In the applications to solve boundary problems, the fundamental solution of the linear operator is usually chosen as the RBF [27], which will automatically satisfy the governing equation, except at the center of the RBF – i.e., the source point. Furthermore, if all the source points are set outside the computational domain, there will be no singularity in the domain at all, and the governing equation will be satisfied automatically. Consequently, the only task that remains as this stage is to satisfy the boundary conditions. By collocating points on the boundary, the boundary conditions can be solved directly without singular numerical integration; in this way, it becomes easier to implement the solution procedure.

An RBF method that uses the fundamental solution of Laplace's equation has been proposed for simulating nonlinear free surface water waves and wave–structure interactions [8]. The method is further employed by Xiao et al. [28] to simulate nonlinear irregular waves in shallow water by introducing a new form of the NWT with improvements on the incident boundary conditions; this model has been validated by corresponding experimental measurements. However, the RBF method produced dense coefficient matrices for the linear system of algebraic equations, the solution of which tends to be time-consuming. Therefore, relevant numerical techniques warrant further research to accelerate the computation. Similar to the multi-subdomain approach with BEM [29], Senturk [30] proposed the localized meshless RBF method in the simulation of free surface waves by breaking down the computational domain into a number of subdomains, leading to a sparse global system matrix. This approach is particularly advantageous in mitigating the time-consuming nature of the simulation process.

The random wave usually consists of many wave components with a wide range of periods; this leads to more difficulties in the simulation than would arise from a simulation consisting solely of monochromatic waves. Thus for simulating random waves, many more collocation nodes tend to be required because of the existence of short-period waves. However, a larger number of nodes lead to a more time-consuming computation. As one of the highlights specifically addresses this issue in the present study, a free surface interpolation approach is proposed to accelerate the simulation using the MM based on the RBF, whilst increasing the number of free surface nodes. Through the application of the meshless NWT in simulating regular waves with different periods, the dissipation is clearly seen for short-period waves. The free surface interpolation approach is then introduced to improve the numerical results without significantly increasing the time consumption. Detailed effects of the approach are presented on both the numerical results and the overall time consumption. A number of regular waves within a wide range of periods are then simulated and validated by using analytical solutions. On this basis, the meshless NWT with the free surface interpolation approach is extended to simulate random shallow-water waves; furthermore, the results of wave spectra with varying interpolation node numbers are compared to evaluate the efficiency of the improved model. Corresponding experimental measurements are finally utilized to verify the numerical results.