An Efficient Three-Dimensional FNPF Numerical Wave Tank for Large-Scale Wave Basin Experiment Simulation

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This paper presents a parallel implementation and validation of an accurate and efficient three-dimensional computational model (3D numerical wave tank), based on fully nonlinear potential flow (FNPF) theory, and its extension to incorporate the motion of a laboratory snake piston wavemaker, as well as an absorbing beach, to simulate experiments in a large-scale 3D wave basin. This work is part of a long-term effort to develop a "virtual" computational wave basin to facilitate and complement large-scale physical wave-basin experiments. The code is based on a higher-order boundary-element method combined with a fast multipole algorithm (FMA). Particular efforts were devoted to making the code efficient for large-scale simulations using high-performance computing platforms. The numerical simulation capability can be tailored to serve as an optimization tool at the planning and detailed design stages of large-scale experiments at a specific basin by duplicating its exact physical and algorithmic features. To date, waves that can be generated in the numerical wave tank (NWT) include solitary, cnoidal, and airy waves. In this paper we detail the wave-basin model, mathematical formulation, wave generation, and analyze the performance of the parallelized FNPF-BEM-FMA code as a function of numerical parameters. Experimental or analytical comparisons with NWT results are provided for several cases to assess the accuracy and applicability of the numerical model to practical engineering problems. [DOI: 10.1115/1.4007597]

Keywords: numerical wave tank, three dimensional, wave-basin experiment, fully nonlinear waves, potential flow, piston wavemaker, high-performance computing, boundary element method, fast multipole algorithm

1 Introduction

Over the past decade, as modern computing platforms gradually increased in power, accurate and efficient three-dimensional (3D) computational wave basins (called numerical wave tanks or simply NWTs in this paper) have been under development. These NWTs are intended to simulate complex processes of ocean wave generation; propagation over arbitrary bottom topography; interaction with ocean structures; and dissipation over sloping beaches. The NWTs will be useful in the development, design, and analysis of many ocean engineering systems including offshore platforms, vessels and crafts, wave-energy conversion devices, and coastal infrastructure (breakwaters, piers, and docks). Until recently, the analysis and design of the complex ocean processes and engineering systems had been mostly investigated by performing laboratory experiments in large-scale 3D (or directional) wave basins, which are both expensive and time consuming to operate. To complement such facilities, NWTs can be used to accurately duplicate the exact physical operation of large-scale wave basins, including wave-generation algorithms, to simulate and optimize planned physical experiments ahead of time, and thus allow the users to more efficiently devote time and efforts to targeted laboratory experiments. As an added advantage, once validated, the NWTs can simulate time series of detailed flow parameters (e.g., velocity, pressure) everywhere in the numerical model, while these are usually available only at a limited number of experimental probes (and at the sacrifice of flow-field intrusion) at physically accessible locations in laboratory experiments.

It is beyond the scope of this paper to provide an exhaustive literature review of the many methods that have been used to develop NWTs. We will only present and discuss a limited number of references, targeted to the type of models used in our work, i.e., models simulating nonlinear waves based on inviscid fully nonlinear potential flow (FNPF) theory, and implemented based on a higher-order boundary integral equation (BIE) method, in a finite-element (FEM) formalism, which is referred to as the boundary-element method (BEM). Besides its numerical efficiency and accuracy, the main advantage of the BEM in engineering applications is that the dimensionality of the discretized problem is reduced by one. Thus, 3D problems can be discretized using a surface-only (i.e., two-dimensional) mesh, which reduces the effort devoted to developing relevant numerical grids. Additionally, while the governing equation (here Laplace's equation) is satisfied only approximately over the 3D-BEM domain boundary, it is satisfied exactly within the domain. Due to the reduced dimensionality, the numerical solution can be computed efficiently even for higher-order schemes and highly resolved BEM surface grids. Hence, problems such as free-surface waves can be solved very accurately. Finally, if required, it is easier to regrid the (2D) boundary mesh, unlike (3D) domain-discretization based methods (e.g., FEM). This is particularly useful for moving-boundary problems (e.g., free-surface waves), wherein regridding will be redistributing nodes evenly during wave propagation. The main drawback of the standard BEM, however, is that it yields nonsymmetric and fully populated linear system matrices, which for large problems becomes prohibitive to solve, and thus require fast solution methods or a more advanced implementation that

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