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Journal of Computational Physics 205 (2005) 686–705

JOURNAL OF COMPUTATIONAL PHYSICS

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An efficient model for three-dimensional surface wave simulations. Part II: Generation and absorption

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Received 1 July 2004; received in revised form 25 November 2004; accepted 25 November 2004
Available online 25 February 2005

Abstract

Water wave generation procedures and efficient numerical beaches are crucial components of a fully non-linear numerical tank for water wave simulations. Linear formulae for pneumatic wave makers are optimized for efficient fully non-linear wave generation in three dimensions. Analytical integration of the (linear) applied free surface pressure provides formulae valid for all times of the simulation. The purely non-linear part of the wave making procedure becomes integrated in the fully non-linear formulation. Novel numerical beaches are introduced, damping the (scaled) tangential velocity at the free surface. More specifically, an additional term is introduced in the Bernoulli equation at the free surface, namely $\nabla^{-1} \cdot (\gamma \nabla \tilde{\phi})$, where γ is a non-zero (smooth) function in regions where damping is required and zero in the wave propagation domain, $\nabla \tilde{\phi}$ is the scaled tangential velocity at the free surface, and ∇^{-1} the inverse horizontal gradient operator. The new term results in a modified dynamic free surface condition which is integrated in time in the fully non-linear formulation. Extensive numerical tests show that the energy of the outgoing waves is completely absorbed by the new damper. Neither wave reflection nor emission are observed. A steep solitary wave is completely absorbed at the numerical beach. Damping of waves due to advancing pressure distributions are efficient as well. The implementation of the absorber in any existing numerical tank is rather trivial.

Keywords: Surface waves; Non-linear wave generation; Pneumatic wave makers; Absorbing boundary conditions; Integral equations, Laplace equation

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doi:10.1016/j.jcp.2004.11.038

1. Introduction

Despite intensive investigations by the scientific and engineering communities for about two centuries, many aspects of surface wave dynamics are far from understood. Experimental campaigns play a crucial role in the discovery and understanding of the phenomenae. Indeed, experiments are used to validate theories, test the design of offshore structures at laboratory scale, and to discover new features of the waves. Many of the experiments require quite large facilities which are expensive to build and maintain, however. A cheaper possibility consists in using numerical modelling. The numerical resolution of the equations governing surface waves is a non-trivial task. This is due to their non-linearity and the fact that the computational domain is unknown since the free surface evolves in time. In a companion paper, Fructus et al. [7] a fast and accurate numerical method for direct simulations of fully non-linear surface waves in three-dimensions was presented. The method was outlined for periodic free space problems, meaning that the evolution of the total (periodic) wave field is studied, given the wave field at an initial time. Realistic simulations of experiments require generation of wave fields from rest, however. Further, the problems are not always spacially periodic.

In this paper, novel procedures are derived for wave generation and wave absorption, including also a complete description of their numerical implementation and use in practice, extending the periodic wave tank explained in [7] (Part I of the paper). The hypotheses and notations used here are identical to those used in Part I. For an easy reference, they are briefly given in Section 2 of this paper. An accurate wave generation procedure involves all the steps from a rigorous linear wave analysis to an integrated, fully non-linear procedure. These are steps that require a thorough analysis and is the motivation for the derivations that are made here. Equally important is to communicate the mathematical and physical justifications of a novel fully non-linear wave damping procedure. While the theoretical deductions and considerations are of value in itself, their ultimate performance is illustrated in real simulations of steep water waves. The relevant method for such tests is the complementary rapid, fully non-linear wave simulator in 3D, derived in the accompanying paper, Part I. We shall see with the tests that the highly non-linear wave generation procedure is easily controlled. With regards to wave damping, the accurate three-dimensional simulations show that there is practically speaking a perfect absorption of the out-going non-linear waves and the associated energy at an arbitrary boundary of the computational domain. The generation and absorption procedures are the novel contributions in this paper.

To generate waves from rest we use pneumatic wave makers. We prescribe a pressure distribution at the surface that is localized in space and evolves in time. The method is easy to adapt and implement with an Eulerian description of the motion. This is the case for the present model. To be efficient, a wave maker must transmit as much energy as possible to the far field, meaning that the pneumatic wave maker cannot be chosen completely arbitrarily. The exact theory of wave generation is untractable, but the linear theory of pneumatic wave making is well established (see, Wehausen and Laitone [13, Section 21]). The linear theory allows us to optimize the wave makers. To our knowledge, the validity of this optimization is less tested in fully non-linear simulations. Formulae for three types of pneumatic generators are described in detail and implemented numerically: (i) a purely oscillating long-crested (two-dimensional) wave generator; (ii) a purely oscillating axisymmetric wave generator; (iii) a moving at constant speed non-oscillating pressure distribution, see Section 3. Many other pneumatic wave makers may as well be defined and optimized along the same lines. The examples given in this paper are general and sufficiently successful, making us believe that other pneumatic wave makers will be efficient as well.

Other methods for generating waves may also be considered. Piston wave makers and plunger wave makers are widely used in experimental facilities, for example. Their linear theory is well established [6]. These methods are less well suited than a pneumatic generation in fully non-linear simulations, however. Indeed, to model paddle wave makers one has to treat carefully the singularity at the intersection between the free surface and the paddle. That is a non-trivial task. Moreover, paddle wave makers impose condi-