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Generation of free-surface waves by localized source terms in the continuity equation

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ABSTRACT

Wave reflections at the wave-maker are a common problem in experiments and simulations of free-surface flow around bodies in waves. To overcome this problem in numerical investigations, a new method for deep water wave generation is presented. The waves are created by introducing mass source terms in the governing equations for a small part of the solution domain. By positioning the wave-maker inside the solution domain, wave damping can be applied to all domain boundaries. Wave reflections from the solution domain boundaries can thus be eliminated in simulations. The formulation of the mass source terms and the influence of the shape and location of the source region, where the mass source terms are introduced, are investigated in two-dimensional (2D) flow simulations based on the Navier–Stokes equations. It is demonstrated that the wave-maker can produce regular and irregular waves scale-independently for wave height to length ratios of $H/\lambda \leq 0.056$. A simulation of constructive and destructive water wave interference illustrates that incident waves can pass through the wave-maker without significant reflection. The wave-maker can be easily implemented in most computational fluid dynamics codes based on the Navier–Stokes equations (such as Reynolds-averaged Navier–Stokes (RANS) or Euler equation solvers).

1. Introduction

The standard procedure for simulating free-surface waves using the Navier–Stokes equations is to prescribe the corresponding values for the velocities and volume fraction at the inlet boundary, see e.g. Schellin et al. (2011). Alternatively, waves can be generated in the same fashion as in experiments, e.g. by imposing a flap-like movement of one or more boundaries of the solution domain as in Perić et al. (2015). However, when the wave-generating boundary is hit by waves reflected at structures within the flow domain or other boundaries, it produces undesired wave reflections traveling back into the solution domain, which are often a problem in simulations as well as in experiments. This is especially relevant when studying the flow around bodies, which do not move or move with a velocity u lower than the phase velocity c of the liquid phase ($u/c \leq 1$), in combination with waves.

It is often the case in simulations of free surface flows that very large or infinite domains are to be modeled although only the solution in a small part of the domain is of interest. In order to decrease the computational effort, it is necessary to keep the solution domain as small as possible. Therefore, increasing the domain size to delay the arrival of reflections from the wave-maker in the domain parts of interest is not an option. For most applications, modeling an infinite domain means that waves traveling out of the solution domain must not be reflected from its boundaries.

In flow simulations based on the Navier–Stokes equations, wave reflections from domain boundaries can be minimized by coarsening the computational grid towards the corresponding boundary, or by applying a numerical damping zone (also called sponge layer, porous media zone, etc.) in the vicinity of the boundary, where the waves are damped via source terms in the governing equations. Several approaches have been presented for this (e.g. Cao et al., 1993; Choi and Yoon, 2009; Ha et al., 2011; Israeli and Orszag, 1981; Park et al., 1999). The latter family of methods is widely used in commercial and research CFD solvers. In this paper, the wave damping approach by Choi and Yoon (2009) is used. However, these approaches cannot be applied to wave-generating boundaries since the created waves would experience damping as well. Another option, which is not further considered in this work, is to combine boundary-based wave generation with wave destruction, by using active wave absorption techniques (e.g. Cruz, 2008; Higuera et al., 2013; Schäffer and Klopman, 2000) or by either forcing the flow to a known solution in the vicinity of the boundary or coupling the Navier–Stokes-based flow solver to another (e.g. potential flow based) solver (e.g. Ferrant et al., 2008;

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Nomenclature

All indices used (i, j, k,…) run from 1 to 3 and the Einstein summation convention applies. Index$_0$ denotes wave parameters from deep water linear wave theory.

A	source region cross-section area: $A = r_w \cdot r_h$
2D	two-dimensional
3D	three-dimensional
a	wave amplitude
c	phase speed
C	Courant number
CFD	computational fluid dynamics
CV	control volume
d	water depth
Fr	Froude number
FVM	finite volume method
g	gravitational acceleration
H	wave height
h_a	distance of the source region top to the undisturbed free surface
$\mathbf{i}_j$	unit vector in the x_j-direction
K	dimensionless coefficient for scaling the mass source term
k	wave number or turbulent kinetic energy
L_x, L_z	dimensions of the simulation domain
$\mathbf{n}$	unit vector normal to S or normal to the source region in horizontal plane
p	pressure
q_c	sum of all mass source terms
q_i	sum of all volumetric momentum source terms in the x_i-direction
q_z^d	momentum source term for damping of the w-velocity component
q_{α_i}	volumetric source term of α_i
r_w	source region width in the x-direction
r_h	source region height in the z-direction
$\Delta x, \Delta z$	cell size in the x- and z-direction
x, y, z	Cartesian coordinates, also denoted as x_1, x_2, x_3
x_d	extent of the damping zone from the corresponding boundary
x_r	distance of the source region center to the nearest domain boundary
RANS	Reynolds-averaged Navier–Stokes
S	closed surface of CV
t	time
Δt	time step
T	wave period
u_i	Cartesian velocity component in the x_i-direction
$\mathbf{v}$	velocity vector of the fluid
V	volume of a CV
VOF	volume of fluid
α_i	volume fraction of phase i, here either *air* or *water*
ε	turbulent dissipation
η	free-surface elevation
λ	wavelength
μ	dynamic viscosity
ρ	density
τ_{ij}	component of the viscous stress tensor
φ	phase shift
ω	wave frequency or specific dissipation

Guignard et al., 1999; Kim et al., 2012, 2013; Wöckner-Kluwe, 2013).

An alternative to wave generation at the domain boundaries is to place the wave-maker inside the solution domain. In this case, wave damping can be applied to all domain boundaries, which requires that waves can pass through the wave-maker undisturbed, i.e. without reflections. This can be achieved by introducing localized source terms in the continuity and/or the momentum conservation equations. In this work, only wave generation based on mass sources will be discussed. Several such wave-makers have been proposed so far. In Boussinesq-type equations, a line source wave-maker was presented by Larsen and Dancy (1983) and source function methods have been proposed by Wei et al. (1999). A generalization of these and other source wave-makers for Boussinesq-type equations can be found in Liam et al. (2014). Liam et al. (2014) also discuss domain-internal wave-makers for other governing equations. Some of these are also valid in deep water, such as Groesen et al. (2010) for the AB-equations. Furthermore, domain-internal wave-makers have been proposed for potential flow solvers based on the boundary element method (e.g. Brorsen and Larsen, 1987; Chatry et al., 1999). For flow simulations based on the Navier–Stokes equations, Lin and Liu (1999) presented a 2D shallow-water wave-maker, which is based on injecting and extracting mass in a rectangular source region below the free surface. The method was extended to 3D by Ha et al. (2011). However, all these wave-makers are either restricted to shallow water conditions (depth $d \leq 0.05\lambda$) or have not yet been shown to be applicable to viscous flow simulations in Navier–Stokes-type equations.

Therefore, in this work, the method by Lin and Liu (1999) is taken as a starting point to develop a deep water ($d \geq 0.5\lambda$) wave-maker for Navier–Stokes-type equations based on localized source terms in the continuity equation. In Section 3, the approach by Lin and Liu (1999) and the necessary modifications for the application to deep water are discussed. Furthermore, the main characteristics of the presented deep water wave-maker are briefly described. The subsequent sections illustrate the capacities and peculiarities of the wave-maker via the results from 2D flow simulations. A grid study is performed in Section 4. The influence of the source term as well as the source region shape and location are investigated in Sections 5–7. Section 8 discusses the influence of turbulence modeling and viscosity on the wave-maker performance. The capability to simulate irregular waves and to allow waves to pass through the wave-maker without significant reflection is discussed in Sections 9 and 10. Appendix A gives an overview of the linear wave theory formulas employed in this work. Although all simulations are performed in 2D, the wave-maker can be applied to 3D without modification (Perić, 2013; Perić and Abdel-Maksoud, 2015).

2. Governing equations and solution method

The governing equations for the simulations are the Navier–Stokes equations, which consist of the equation for mass conservation and the three equations for momentum conservation:

$$\frac{\mathrm{d}}{\mathrm{d}t}\int_V \rho \, \mathrm{d}V + \int_S \rho \mathbf{v} \cdot \mathbf{n} \, \mathrm{d}S = \int_V \rho q_c \, \mathrm{d}V, \tag{1}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\int_V \rho u_i \, \mathrm{d}V + \int_S \rho u_i \mathbf{v} \cdot \mathbf{n} \, \mathrm{d}S \quad = \int_S (\tau_{ij}\mathbf{i}_j - p\mathbf{i}_i) \cdot \mathbf{n} \, \mathrm{d}S + \int_V \rho g \mathbf{i}_i \, \mathrm{d}V + \int_V q_i \, \mathrm{d}V. \tag{2}$$