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On wave damping occurring during source-based generation of steep waves in deep and near-shallow water

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ABSTRACT

Generation of steep waves ($H/\lambda > 0.03$) in a NSE-based NWT is a challenging task and is seldom attempted in near-shallow water ($kh < 1.0$). Failure towards attainment of the target steepness is characterized by an under-prediction of the wave height (H) along the length of the NWT. The issue of height damping has received limited attention in literature. In this context, a NSE based NWT has been developed using a PLIC-VOF formulation and a mass source-based wave generator. Wave damping at the NWT boundaries has been achieved using sponge layers. A total of nine wave designs have been simulated in three categories each of steepness (low, moderate and large) and relative depth (near-shallow, intermediate and deep). Criteria for selecting spatio-temporal resolution within the tank have been determined through parametric analysis. For $H/\lambda > 0.03$, it is seen that wave height reduction in excess of 5% occurs in near-shallow and deep water. It is found that height reduction in deep water is largely attributable to free-surface damping as predicted by Airy theory. However, numerical height damping in near-shallow water is observed to be much stronger, especially near the source. A deeper analysis reveals that mass source-based wave generation induces strong and persistent vortical activity in near-shallow water which in turn leads to dissipation of source-injected momentum. Appropriate modifications in source design, that are aimed at reducing wave-vorticity interactions in the near-field, are proposed for steep wave generation in $kh < 1$ and $kh > 2.5$. Substantial improvement in the prediction of far-field wave height is hence reported.

1. Introduction

Wave tanks belong to a specialized class of devices used for replicating ocean wave propagation in scaled and controlled conditions in a laboratory. Wave tanks can be broadly classified into two principal classes: experimental wave tanks (or flumes) and computational/numerical wave tanks (or NWTs). A flume is a physical enclosure having a wavemaker at one end which periodically agitates water to generate a progressive train of waves. The waves pass through a region of interest where scientific observations and measurements are carried out following which the wave packets get dissipated at an artificial beach to prevent energetic reflections. The numerical wave tank is the computational counterpart of wave flumes. Versatile NWT designs have recently emerged as a much needed secondary standard to wave flume experimentation. NWT configurations are increasingly being implemented to address a wide range of problems pertaining to ocean engineering. These include analysis of wave-structure interaction (Ahmad et al., 2015), vortex dynamics beneath breaking waves (Christensen and Deigaard, 2001; Watanabe et al., 2005; Lakehal and Liovic, 2011), performance evaluation of wave energy converters (Kamath et al., 2015) and modeling ship motion (Cha and Wan, 2015). Simulation of wave propagation in a NWT is achieved through numerical solution of a set of governing differential equations such as the Laplace (Brorsen and Larsen, 1987), Boussinesq (Larsen and Dancy, 1983) or the Navier-Stokes equations (Hafsia et al., 2009). The Navier-Stokes equations (NSE) allow for a fully viscous description of wave mechanics. In addition, the extension of NSE solvers to two-phase flows using the volume-of-fluid (VOF) method (Nichols and Hirt, 1981) has facilitated simultaneous simulation of wave-induced flow dynamics in both water and air. A two-phase Navier-Stokes representation of wave propagation in a NWT can hence be considered as the highest "fidelity" because of the closeness of the description to actual oceanographic conditions.

The wavemaker in a NWT is a mathematical formulation that generates waves by artificially forcing a pre-defined[1] surface elevation (η) and velocity potential (ϕ) into the framework of governing equations. Wave reflection from the boundaries of the NWT is prevented by gradual dissipation of packet energy in porous domains known as

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[1] known apriori either from measurements or an appropriate wave theory.

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sponge layers. The sponge layers work antagonistically to the wave generator by forcing the wave solution (ϕ, η), induced by the generator, to attenuate to still water conditions at the lateral boundaries of the NWT. It is noteworthy that whilst the variables ϕ and η have dedicated transport equations in the Laplace framework, they do not appear explicitly in the NSE (Choi and Yoon, 2009). Hence, the task of designing wave generators and sponge layers for Navier-Stokes based NWTs is complicated; the variables ϕ and η (that describe the target wave field) need to be implicitly linked to the Eulerian velocities (U,V) and pressure (p) using the equations of continuity and momentum. This implicit linking has been achieved through a number of approaches which can be broadly classified in terms of wavemaker design: (a) *inflow boundary*, (b) *mass source function*, (c) *volume flux*, (d) *momentum source function* and (e) *moving boundary* based techniques.

The earliest of the NSE-based wave generators include the inflow (Lin and Liu, 1998) and mass source function (Lin and Liu, 1999) techniques. In the inflow methodology, the variables U, V, p and η are directly specified at a vertical boundary of the computational domain. The inflow generator hence functions as a time-varying Dirichlet boundary condition (not equivalent to the "free-slip" boundary condition on a moving wavemaker) in the NSE framework. However, the inflow technique has a drawback that a finite amount of mass is added to the domain during one wave period (Horko, 2007). This happens because $\int_T \int_{\eta(t)} U(y,\, t)\mathrm{d}y\ \mathrm{d}t \neq 0$ even in case of Airy theory. The problem of mass addition becomes more severe as the steepness of the target waveform increases.[2] The inflow-based wavemaker was succeeded by the mass source generator in which the equation of continuity is modified within a small group of cells (termed as the "source region") through the addition of a time varying source term $s(t)$. During a wave period, the region acts as a source during crest generation and a sink during trough generation with $s(t)$ being directly proportional to the topology $\eta(t)$ of the target waveform. The source generator has a larger number of design variables associated with itself. To be specific; the size, shape, placement and order of wave theory used to define the source region play simultaneous role in deciding the quality of the generated waves (Lin and Liu, 1999; Perić and Abdel-Maksoud, 2015; Chen and Hsiao, 2016). Also, the periodic ingestion and ejection of mass by the source region leads to the formation of *two* wave trains moving away from the generator in opposite directions which necessitates modeling the computational domain on both sides of the wavemaker. It is worth mentioning that the original source function technique proposed by Lin and Liu (1999) was implemented in intermediate water ($kh \approx 1.0$) and has only been recently extended to deep water ($kh \approx 40$) by Perić and Abdel-Maksoud (2015) and Chen and Hsiao, (2016). The two-dimensional source region of Lin and Liu (1999) was subsequently reduced to a (one dimensional) horizontal line source by Hafsia et al. (2009) with a prescribed vertical velocity. The generator can be regarded as a volume flux technique rather than a mass-source based technique. The performance of their method was not demonstrated at large steepness by Hafsia et al.. However, an obvious advantage of the volume flux methodology is the simplification achieved in defining the geometry of the source region. The volume flux technique was succeeded by momentum source-based wave generators (Choi and Yoon, 2009; Ha et al., 2013). In this case, acceleration terms obtained from the Boussinesq equations are directly added as sources in the equations governing momentum transport. Hence, superiority of momentum source-based approaches is often claimed over mass source-based techniques (Choi and Yoon, 2009; Ha et al., 2013). However, the former has a limitation in that the Boussinesq equations are depth-averaged which precludes the application of the generator to deep water (Ha et al., 2013). The fifth category of NSE based wavemakers has only recently emerged in the form of moving boundary based techniques. In this case, the wavemaker is physically modeled within the NWT as a moving wall, either through regridding techniques (Finnegan and Goggins, 2012) or using an immersed boundary formulation (Anbarsooz et al., 2013). The moving wall method claims highest fidelity in terms of wave generation over all other techniques in the NSE framework since the mechanics of wave generation in an experimental flume is exactly replicated. The moving wall approach is advantageous in that it is applicable for wave generation in both shallow and deep water using the complete wavemaker theory for piston and flap type motion (Dean and Dalrymple, 1991). Further, the moving boundary method only requires the stroke (S) and frequency (ω) of the paddle as inputs. The sole drawback of the moving wall generator is the extensive implementation involved in modeling regridding or immersed boundary approaches in a two-phase Navier-Stokes framework.

It is apparent that the task of wave generation can be approached in multiple ways within the NSE framework with a variety of wavemaker designs being proposed (as a consequence) in the past one and a half decades. However, the task of generating steep waves in a numerical wave tank is found to be challenging. At large steepness ($H/\lambda \geq 0.03$), the numerically generated waves are susceptible to height damping as they propagate away from the wavemaker. In this context, a review of NWT simulations of regular waves carried out in the literature is reported in Table 1.

Of the 38 wave generation cases considered in Table 1, a total of 31 simulations pertain to NSE based NWTs. An appreciable reduction ($>5\%$) in the target wave height has been observed in 8($\approx 25\%$) of these 31 cases. This is exclusively observed for viscous (NSE-based) NWTs that too when the target steepness is 0.025 or larger. The review illustrates the fact that steep wave generation in Navier-Stokes based NWTs is challenging. To quantify the argument, the maximum steepness yet achieved in a NWT by a wavemaker is about ≈0.05 in near-shallow (Lin and Liu, 1999) and ≈0.06 in deep water (Perić and Abdel-Maksoud, 2015) while the maximum limiting steepness allowable by the Miche-Stokes limit (Cherneva et al., 2013) is ≈0.11 in near-shallow and ≈0.14 in deep water respectively. In both cases, the maximum numerical steepness successfully achieved is less than half the limiting steepness.

The above-mentioned problem of height reduction has received limited attention in the literature. The review presented in Table 1 indicates that almost every category of NSE based NWTs has faced the issue of height dampening during the simulation of steep waves. This would in turn indicate that either,

1. the phenomenon of height reduction is independent of the wavemaker design and rather depends on other factors external to the design of the wavemaker or,
2. the phenomenon of height reduction is largely dependent on the wavemaker design which in turn, is sensitive to the mechanics of wave generation itself changing character with steepness and relative depth.

Surprisingly, both arguments are equally befitting explanations to the phenomenon of height reduction observed during steep wave generation. For instance, waves generated in a NSE based wave tank would steadily lose some finite amount of energy towards (a) inducing vorticity in the air phase, (b) interfacial boundary layer formation, (c) viscous dampening induced by the water column in deep water and (d) bottom boundary layer formation in shallow water. The waves would also undergo numerical damping due to a finite resolution of the mesh and due to various numerical errors encountered while approximating the NSE in discrete form (Ferziger and Perić, 2002; Perić and Abdel-

[2] at large steepness, mass addition by an inflow boundary can be corrected through the inclusion of a returning current (U_r) that compensates for the Stokes drift. For regular waves, the value of U_r can be obtained from, $U_r = -\dfrac{H^2\omega}{8\,h\tanh(kh)}$ where, H is wave height, ω is the circular frequency, h is the still water depth and k is the circular wavenumber.