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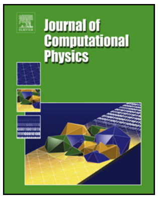

Force-controlled absorption in a fully-nonlinear numerical wave tank

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ABSTRACT

An active control methodology for the absorption of water waves in a numerical wave tank is introduced. This methodology is based upon a force-feedback technique which has previously been shown to be very effective in physical wave tanks. Unlike other methods, an *a-priori* knowledge of the wave conditions in the tank is not required; the absorption controller being designed to automatically respond to a wide range of wave conditions. In comparison to numerical sponge layers, effective wave absorption is achieved on the boundary, thereby minimising the spatial extent of the numerical wave tank. In contrast to the imposition of radiation conditions, the scheme is inherently capable of absorbing irregular waves. Most importantly, simultaneous generation and absorption can be achieved. This is an important advance when considering inclusion of reflective bodies within the numerical wave tank.

In designing the absorption controller, an infinite impulse response filter is adopted, thereby eliminating the problem of non-causality in the controller optimisation. Two alternative controllers are considered, both implemented in a fully-nonlinear wave tank based on a multiple-flux boundary element scheme. To simplify the problem under consideration, the present analysis is limited to water waves propagating in a two-dimensional domain.

The paper presents an extensive numerical validation which demonstrates the success of the method for a wide range of wave conditions including regular, focused and random waves. The numerical investigation also highlights some of the limitations of the method, particularly in simultaneously generating and absorbing large amplitude or highly-nonlinear waves. The findings of the present numerical study are directly applicable to related fields where optimum absorption is sought; these include physical wavemaking, wave power absorption and a wide range of numerical wave tank schemes.

1. Introduction

Numerical wave tanks (NWTs) have become important tools for simulating the interactions of water waves with both fixed and floating structures. The term NWT commonly refers to a computational domain that provides the numerical equivalent of a physical wave flume (two-dimensional) or wave basin (three-dimensional). Within such a domain, a set of

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governing equations and boundary conditions seeks to represent the relevant physical processes. Depending upon the exact nature of the governing equations and boundary conditions, a variety of NWT schemes may be implemented.

In the most general case, the Navier–Stokes equations are adopted as the governing field equations and implemented using CFD solvers [1,2]. If viscous effects are neglected, the Navier–Stokes equations reduce to the Euler equations. Making the additional assumption that the flow is irrotational, leads to potential flow schemes. Within this latter category an important distinction lies in the extent to which the nonlinearity of the boundary conditions is considered. A linearised form of the boundary conditions is often implemented in computationally efficient radiation–diffraction codes, most commonly operating in the frequency domain.

A number of fully-nonlinear potential flow NWTs have been proposed in the past, often based upon the Boundary Element Method (BEM). This has been shown to be particularly successful in modelling nonlinear water waves and their interactions with structures. The conformally-mapped approach for solving the Cauchy integral formula has been very successfully applied in two dimensions [3–6]. However, whilst this approach is accurate and efficient, it involves calculations in the complex plane, and cannot be extended to three dimensions. Therefore, more recent efforts have focused on using Green's second identity [7], which is located in physical space and can be applied to three-dimensional simulations [8]. Significant progress using this approach has been made by Graziani and Landrini [9], Xue et al. [10] and Fochesato et al. [11]. Most recently, Hague and Swan [12] have developed a physical-space BEM that utilises multiple fluxes to overcome problems associated with computations at the domain corners, thereby avoiding the need to perform explicit smoothing, filtering or re-griding.

All physical-space NWT schemes represent the fluid within a closed computational domain, in which unwanted reflections from the downstream boundary may quickly contaminate the testing area. In traditional NWTs this reflected wave energy is removed using either an absorbing (passive) sponge layer, a Sommerfeld [13] radiation condition, or a combination of the two [12]. The passive sponge layer is most effective for high frequency waves, requiring an absorption length of at least two times the incident wavelength. In contrast, the Sommerfeld [13] radiation condition performs best for long wave lengths, but relies on an *a-priori* knowledge of the wave phase velocity. Both methodologies are well established for regular waves; their absorption efficiency decreasing significantly in irregular waves. To resolve this problem, Clement [14] suggests a combined technique which seeks to obtain the best performance from both a passive sponge layer and a radiation condition; the former absorbing high frequency waves and the latter radiating long wavelengths.

Hague [15] performed numerical simulations with a multiple-flux BEM to examine the efficiency of three absorption techniques: (i) a numerical sponge layer, (ii) a Sommerfeld radiation condition and (iii) the combined technique following Clement [14]. For a small amplitude regular wave simulation, with a sponge layer twice as long as the incident wave, Hague [15] found amplitude reflection coefficients of 6.02%, 1.98% and 0.75% for (i)–(iii) respectively. Hague [15] also simulated a small amplitude irregular wave spectrum, where the phase velocity required for the Sommerfeld radiation condition was aligned with the phase velocity of the spectral peak. In this case, an average amplitude reflection coefficient of 7.41%, 5.81% and 2.97% was observed for (i)–(iii) respectively. For both regular and irregular waves the combined technique, (iii) above, provided the best absorption efficiency. Unfortunately, this methodology requires a sponge layer of considerable length, increasing the number of computational nodes and hence the computational effort.

If a structure is placed within a NWT, waves will inevitably be reflected back towards the wave generating boundary. Unfortunately, re-reflections from this boundary will quickly contaminate the model testing area. To overcome (or limit) this difficulty two approaches are possible. First, by increasing the size of the NWT, the arrival time of the unwanted reflections can be delayed. Although this may be relevant to the generation of wave groups, of relatively short duration, it does not enable the generation of long random wave records. Furthermore, it is also associated with a significant computational cost; particularly where calculations involve a high spatial resolution or are undertaken in a three-dimensional domain. Alternatively, the input boundary could be specified such that it is able to generate the required incident waves and, simultaneously, absorb any unwanted wave reflections. This second approach is commonly adopted in physical wave tanks, but has not thus far been implemented in a fully-nonlinear NWT.

The recent study by Newman [16] describes a scheme for the absorption of waves along the lateral boundaries of a circular NWT. However, this was implemented in the frequency domain and the absorption technique relies on an *a-priori* knowledge of the wave reflections from the test structure. If a nonlinear time–domain scheme is adopted, the absorption technique must also operate in the time domain. In this case, an *a-priori* computation of the wave reflections is not possible.

Active wave absorption in the time domain has long been established in physical wave flumes and wave basins; a number of techniques being reviewed by Schäffer and Klopman [17], Naito [18] and Spinneken and Swan [19]. In this context, active wave absorption based on force-feedback control has been shown to be both efficient and accurate [19–21]. The purpose of the present paper is to establish whether such a technique can be successfully applied in a NWT operating in the time domain.

To achieve this goal, a force-feedback absorption controller has been implemented in a NWT based on a BEM scheme; the latter retaining the full nonlinearity of the boundary conditions. To demonstrate the capabilities of the absorption scheme, a bottom-hinged flap-type wavemaker has been implemented in a two-dimensional NWT. The choice of this wave board geometry directly affects the nature of the absorption controller, a number of alternative geometries having been discussed in [22]. However, absorbing flap-type wavemakers are widely applied in physical wave tanks; experimental evidence of their performance having been provided in [19,21]. As a result, the findings of the present numerical work will also be directly applicable to a wide range of existing physical wavemaking facilities.