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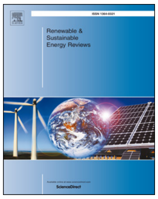

High-fidelity numerical modelling of ocean wave energy systems: A review of computational fluid dynamics-based numerical wave tanks

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ABSTRACT

For the research and development (R&D) of wave energy converters (WECs), numerical wave tanks (NWTs) provide an excellent numerical tool, enabling a cost-effective testbed for WEC experimentation, analysis and optimisation. Different methods for simulating the fluid dynamics and fluid structure interaction (FSI) within the NWT have been developed over the years, with increasing levels of fidelity, and associated computational expense. In the past, the high computational requirements largely precluded Computational Fluid Dynamics (CFD) from being applied to WEC analysis. However, the continual improvement and availability of high performance computing has led to the steady increase of CFD-based NWTs (CNWT) for WEC experiments. No attempt has yet been undertaken to comprehensively review CNWT approaches for WECs. This paper fills this gap and presents a thorough review of high-fidelity numerical modelling of WECs using CNWTs. In addition to collating the published literature, this review tries to make a step towards a best practice guideline for the applications of CFD in the field of wave energy.

1. Introduction

WECs have a strong potential to contribute to satisfying the increasing global energy demand [1]. Developing efficient, cost-competitive and survivable WECs is the focus of R&D efforts from both industry and academia in recent decades, and has proven to be a challenging task. An essential development trajectory to an economically competitive WEC, requires early stage optimisation and refinement of the device design and operation using numerical tools, before considering expensive physical prototype construction, deployment and experimentation [2].

1.1. Numerical wave tanks

A NWT is the generic name of numerical simulators for modelling nonlinear free surface waves, hydrodynamic forces and floating body motions, and have been used for many decades in ocean engineering to analyse FSI [3]. NWTs provide an excellent numerical tool for WEC R&D, enabling a cost-effective testbed for WEC experimentation, analysis and optimisation. The fluid dynamics within the NWT are governed by the transfer of mass and momentum, described by a set of nonlinear partial differential equations, known as the Navier-Stokes equations (NSE).

Following the continual increase in available computational power, different methods for simulating the fluid dynamics within the NWT have been developed over the years, with increasing levels of fidelity, and associated computational expense. The relative accuracy and computational cost of these methods is depicted in Fig. 1.

1.1.1. Potential flow

Historically, solving the NSE for offshore engineering applications was computationally infeasible. Therefore, the NSE were simplified to obtain a linear potential flow (PF) equivalent, whereby solutions are generated by linearising the problem through assumptions of small amplitude oscillations, inviscid fluid and irrotational, incompresisble flow. Although PF methods have been used successfully in many offshore engineering applications [5], the linearising assumptions are challenged by realistic WEC operation, where large amplitude motions will result from energetic waves or sustained wave/WEC resonance, resulting in viscous drag, flow separation, vortex shedding and other nonlinear hydrodynamic effects.

1.1.2. Computational fluid dynamics

At great computational expense, CFD provides a more rigorous nonlinear treatment of the NSE [6,7]. CFD solves the NSE numerically by discretising the domains in space and time to form a system of linear algebraic equations. The spatial discretisation is implemented via a mesh, with different methods used to interpolate between mesh cells:

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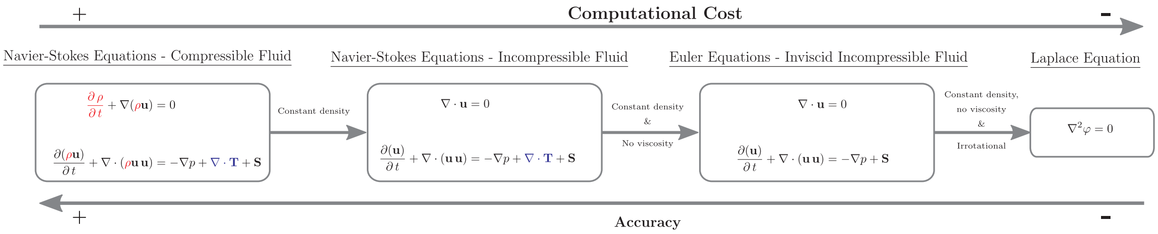

Fig. 1. Relative accuracy and computation cost of different methods for simulating the fluid dynamics within the NWT. **u** describes the fluid velocity field, p the pressure. is the viscous stress tensor and the source term (adapted from [4]).

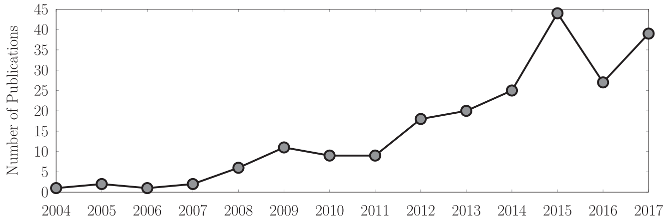

Fig. 2. Number of publications using CNWT analysis of WECs.

finite volume, finite difference and finite element. The temporal discretisation is achieved using timesteps. Compared to lower fidelity numerical tools, CNWTs have the advantage of capturing all relevant hydrodynamic non-linearities, such as large surface deformation, viscous drag or turbulent effects. Although CNWTs are more computationally costly, CNWT experiments deliver high resolution results, which are particularly useful for the investigation of specific flow phenomena around offshore structures.

1.2. NWTs for WEC experiments

Several reviews of numerical modelling approaches for WECs have been performed, in the pursuit of identifying the highest fidelity NWT experiments available for WECs:

- Li and Yu [8] specifically focus on the modelling methods of point absorbers (PAs), reviewing analytical and boundary integral equation methods, viscous drag calculation for PF solution and finally NSE methods.
- Folley et al. [9] focus on the understanding of the hydrodynamic interactions of WECs in arrays, presenting the underlying principles, strengths and weaknesses for a range of different models, covering PF, Boussinesq and mild-slope, spectral wave and CFD models.
- Coe and Neary [10] review modelling methods for WECs in extreme seas, highlighting the unique challenges of modelling survivability, covering semi-empirical, PF, CFD and physical modelling.
- Focusing on oscillating water column (OWC) devices, Bouhrim and El Marjani [11] present modelling approaches for the flow behaviour inside the OWC chamber. The study ranges from 1D to fully 3D viscous unsteady NSE solvers.
- Day et al. [12] present a state-of-the-art review of hydrodynamic modelling approaches of Marine Renewable Energy (MRE) devices. This study covers wave energy, tidal current and offshore wind energy systems and discusses physical modelling of Power Take-Off (PTO) systems, numerical modelling of MRE devices and wind load modelling for wind turbines.
- Wolgamot and Fitzgerald [13] review the use of nonlinear hydrodynamics to analyse WEC behaviour and performance, covering partially and fully nonlinear PF, CFD and Smoothed Particle Hydrodynamics (SPH) models.
- Most recently, Penalba et al. [14] review the influence of non-linear dynamics of the entire chain of a WEC (incoming wave trains, wave-structure interaction (WSI), power take-off systems or mooring lines) and furthermore presents different approaches to model nonlinear WSI.

However, no attempt has yet been undertaken to comprehensively review CNWT approaches for WECs. To fill this gap, this paper presents a thorough review of high-fidelity numerical modelling of WECs using CNWTs.

1.2.1. Objective of review

There are two main objectives of the present review paper: (i) Collating the publications relating to WEC analysis performed using CNWTs, and (ii) Offering guidelines for the application of CFD for WEC experiments.

The continual improvement and availability of high performance computing, has led to the steady increase of CNWTs for WEC experiments in recent years, as shown in Fig. 2 and Table 1. The data in Fig. 2 is based on the literature collated within the present review. Table 1 acts to chronologically order the reference numbers, so that the larger the reference number in this review, the more recent the study.

1.2.2. Framework and outline of review

The review begins by collating the published literature pertaining to the use of CFD for WEC analysis, categorised by the different WEC device types. The various WEC operating principles and subsystems are discussed to highlight the wide variety of systems included in the CNWT simulations. The types of analysis applications the CNWTs are employed towards are also explored:

- Section 2 presents the different device types and discusses the operating principles
- Section 3 discuses the different analysis applications and WEC subsystems included in the CNWT

The technical CFD aspects of the literature are then reviewed, delving into the general requirements of a CNWT for WECs:

- Section 4 outlines the problem discretisation for the numerical solution process
- Section 5 discusses modelling different flow regimes, such as inviscid, laminar and turbulent flows
- Section 6 details wave generation and absorption
- Section 7 investigates the FSI problem

Table 1
Publications using CNWT analysis of WECs.

Year	Publications	Year	Publications
2004	[15]	2011	[47–55]
2005	[16,17]	2012	[56–73]
2006	[18]	2013	[74–93]
2007	[19,20]	2014	[94–118]
2008	[21–26]	2015	[119–158]
2009	[27–37]	2016	[159–184]
2010	[38–46]	2017	[185–223]