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Nonlinear hydrodynamic effects on a generic spherical wave energy converter

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ABSTRACT

Analytical and numerical modelling techniques have been used extensively to predict the performance and power output of these devices using linear, inviscid and irrotational theory with the knowledge that nonlinear effects become relevant in extreme cases. This study applies Reynolds averaged Navier-Stokes (RANS) computational fluid dynamics (CFD) model to simulate the diffraction and radiation problems for a single submerged spherical WEC operating in both heave and surge. Wave and device oscillation amplitudes from 30 mm to 60 mm and frequencies from 0.8 Hz to 1.2 Hz are employed to examine the fluid dynamics near the spherical WEC as the hydrodynamics deviate away from the linear regime. Results of the hydrodynamic coefficients from wave basin experiments are used to validate linear finite element and CFD models for small wave amplitudes. The nonlinear CFD model is then extended to model larger amplitudes. The hydrodynamic coefficients are here found to be amplitude dependent with free surface interactions being a key component of the deviation from linear theory. The rate of these deviations from low wave height, linear values via increasing wave heights is also found to vary with frequency. The outcomes highlight limitations in the linear approach and address the factors most important to WEC performance.

1. Introduction

A wave energy converter (WEC) has the potential to become a viable technology for clean, renewable energy production. This technology may prove invaluable to meet the growing demands for electrical power and the apparent changing climate conditions. WEC designs and potential power output rely heavily on the sea conditions and bathymetry surrounding their potential sites and require extensive testing prior to the deployment of a commercially operating device. With the challenges and high costs of prototype testing in open ocean conditions, numerical studies have been employed extensively to study the performance and estimate potential power-take-off (PTO) capabilities of WECs. Most numerical studies of WECs are based on linear water wave theory. The excitation force coefficient, added mass and radiation damping parameters for a floating device must be derived from the theory in order to estimate the performance of a WEC design. Several analytical and numerical methods with various capabilities have been developed in order to derive these quantities.

Budar and Falnes [1] used an analytical method to approximate the power output of floating bodies in waves by applying the point absorber approximation which considers the horizontal extent of a WEC to be much smaller than the incident wave wavelength. The optimal power output for a WEC system can then be determined in Ref. [1], given that the device operates at resonance with an optimised damping mechanism via PTO. Applying this approach, a set of theoretical added mass and damping coefficients for a floating cylinder was first presented by Yeung [2] where eigen-functions were used to calculate the added mass and damping coefficients for heave, sway and rolling motions.

The point absorber approximation was then extensively used to calculate the PTO of single devices as in Eriksson et al. [3] who modelled a linear generator as a viscous damper exposed to harmonic and real ocean waves. PTO estimates for the device were presented with particular focus on the near resonance characteristics. A two-body WEC system was also studied following the point absorber approach in Berggren and Johansson [4] where the relative motion between a floating buoy and submerged plate are used to extract energy. The relative influence of the changing hydrodynamic coefficients from each body onto the other were calculated.

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WEC array interaction have also been studied by combining the single-body dynamics and the multiple scattering method to account for interference effects between devices in Mavrakos and Kalofonos [5]. Analytical techniques thus provide efficient and quick performance estimates of WECs but require simplified geometries in order to be applicable as suggested by Li and Yu [6]. When considering more complicated geometries, alternative numerical approaches must be employed to calculate the hydrodynamic coefficients for a given WEC.

With increasing complexity in WEC designs and the need for more accurate estimates of the hydrodynamic coefficients, numerical techniques such as the boundary element method (BEM) and finite element method (FEM) have been applied in WEC studies. Payne et al. [7] apply the BEM to a sloped heaving buoy WEC design and analyze the response under various damping conditions. This study maintains linearised boundary conditions throughout the model. Other devices such as the oscillating water column (OWC) type WEC has been studied using BEM to determine long term PTO efficiency [8] in offshore sea conditions. More complex models including shore-based WECs can also be modelled with BEM. Brito et al. [9] investigated a shore-based WEC including bathymetric and topological aspects of the surroundings in the model. Extending to WEC arrays, investigations analysing the total PTO for various WEC spacings and incident wave angles have been studied as in Balitsky [10]. The outcomes provide recommendations for an array configuration based on a WEC geometry.

FEM studies have also been utilised for WEC development. Nader et al. [11], applied a 3D FEM model to a floating, moored OWC type WEC showing that a proper choice of the mooring restoring forces and PTO damping can increase the overall device efficiency. These FEM studies have also investigated the interaction of multiple OWCs. Nader et al. [12,13] showed that device spacing has a significant influence on the power capture efficiency of a WEC array and must be considered during the array development phase.

These BEM and FEM studies all employ linearised boundary conditions, in particular on the free surface. The assumptions can become largely inaccurate for large WEC motions near resonance frequencies [6]. Nonlinear free surface boundary conditions can be applied to BEM and FEM models allowing for higher order waves. Second-order wave theory was applied by Nader [14] showed an important decrease in mean power output due to nonlinear interactions near resonance. Fully nonlinear free surface boundary conditions can be solved in the time domain. Bai and Taylor [15] studied the interaction between an impulse wave and an oscillating cylinder and Ferrant et al. [16] investigated the nonlinear diffraction fields around a surface piercing structure over a wide range of incident wave frequencies. Following the FEM approach Ma et al. [17] studied the interaction between fully nonlinear waves and vertical, surface piercing cylinders. Although these models can implement nonlinear, steep waves, the potential flow limitations remain. While limited in their capabilities they continue to have the advantage of speed over more complex and computationally expensive CFD approaches.

Few studies have applied fully nonlinear CFD codes to the study of WECs. Agamloh et al. [18] applied the volume of fluid (VOF) technique to simulate one and two inline heaving buoy WECs in a wave flume. This study successfully captured the interaction between multiple devices but was restricted in scope due to the computational time requirements for simulations. The VOF method was again utilised by Yu and Li [19] in a two-body heaving buoy system showing significant nonlinear interactions between both components of the WEC. These CFD studies show the importance of nonlinear effects on WEC performance but due to the computational requirements and the relative complexity of CFD modelling, this approach is not commonly used. With the steadily increasing availability of the computational resources needed for CFD and steadily improving solver algorithms, CFD studies of single and multiple WECs are becoming possible.

The novel CFD WEC investigation applied here assumes the diffraction and radiation problems are separable and treatable independently, as is the case for linear models. With this method it is possible to analyze the wave height and oscillation amplitude effect on the excitation force and radiation damping coefficients which are essential to predict WEC performance. This work serves as a direct extension of the experiments on submerged spherical WECs performed in the wave basin at the Australian Maritime College. Preliminary results from which are presented in Penesis et al. [20] and Nader et al. [21]. The experimental conditions remain within linear theory applicability allowing the results to be scaled in the absence of significant nonlinear behaviour. The current study aims to investigate the onset of nonlinear dynamics on a submerged heaving and surging spherical WEC in open water. Experimental results from the presented in Refs. [20,21] are used to validate and quantify the error in linear and nonlinear modelling. Firstly, a study of the diffraction problem is presented followed by the radiation problems for both heaving and surging WECs. The hydrodynamic coefficients are investigated in all three cases along with an analysis of the flow profiles surrounding the WEC. The final results suggest that the impact of the WEC design on the surrounding wave field has a non-negligible impact on the forcing dynamics which is ultimately used to generate energy.

2. Modelling a wave energy converter

2.1. The problem description

A heaving or surging point absorber type WEC is excited via the incoming waves from the environment. The motions of a WEC of this type are described following the equations of motion given a displacement X_i with $i = h, s$ for heave and surge motions respectively,

$$M\frac{d^2X_i}{dt^2} + \lambda_{pto}\frac{dX_i}{dt} + K_{pto}X_i = F_i, \tag{1}$$

where M is the WEC mass, λ_{pto} is the damping induced by the PTO system, K_{pto} is the restoring force coefficient including PTO and mooring effects and F_i is the hydrodynamic force which can include nonlinearities such as viscous, turbulent or free surface interactions. The equation of motion Eqn. (1) can be readily solved using analytical or linear numerical methods.

2.2. Linear theory

2.2.1. Water waves

Linear wave-body interaction modelling is based on the irrotational, incompressible and inviscid flow giving a velocity potential, $\Phi(x, y, z, t)$, such that,

$$\nabla^2\Phi = 0, \tag{2}$$

which describes the flow field valid everywhere in the computational domain. By considering infinitesimal wave amplitudes the linearised mean surface boundary condition can be written as,

$$\frac{\partial\Phi}{\partial z} + \frac{1}{g}\frac{\partial^2\Phi}{\partial t^2} = 0. \tag{3}$$

Eqn. (3) can be solved for a given incident wave frequency making a solution for more complicated sea states obtainable via