



Time domain prediction of power absorption from ocean waves with wave energy converter arrays



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ABSTRACT

A three-dimensional transient numerical code ITU-WAVE based on potential theory and Neumann-Kelvin approximation is extended to take into account wave interaction in an array system using two and four truncated vertical cylinder arrays. ITU-WAVE panel code is validated against analytical array results before applied to power absorption from ocean waves for different array configurations. The effects of the separation distances between array system and heading angles on energy absorption in both sway and heave modes are studied by the support of numerical simulations which show sway mode has wider bandwidth than heave mode for energy absorption. It is also shown that wave interactions are stronger when the array systems are close and these wave interactions are reduced significantly and shifted to larger times when the separation distance is increased. The wave interaction is much stronger at the same separation distance and heading angle in heave mode than in sway mode. Numerical experience also shows that more power is absorbed in sway mode than in heave mode in both two and four array systems at any separation distances and heading angles when the bodies in array system have the same displacement in both sway and heave modes.

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1. Introduction

The current development pace of wave energy converters indicates the possibility of the deployment of these converters as arrays at commercial scale. The accurate predictions of wave loads, motion characteristics, and power requirements are of critically important for the design of these devices which are in sufficiently close proximity to experience significant hydrodynamic interactions. The oscillation of each body radiates waves assuming that other bodies are not present. Some of these radiated waves that can be considered as incident waves interact with the bodies of the array causing diffraction phenomena while others radiate to infinity. The fluid response between arrays can affect overall power generation and could increase or decrease power generation compared to an isolated device. The power generation due to hydrodynamic interaction depends on separation distance, geometrical layout, direction of the incident wave, geometry in the array, incident wave length, mooring configurations, control strategies etc.

The pioneer work of [1] on wave energy converter arrays

introduced the point absorber approximation in which the response amplitude are considered as equal for all devices and optimal power absorption are independent from device geometry. Moreover, the characteristic dimensions (e.g. diameter) of the devices are considered small in terms of incident wave length. This approximation implicitly means that wave diffraction is not significant and can be ignored [2]. In these studies, the overall absorbed power value which increases and decreases with the wave impact is measured by interaction factor q -factor ($q > 1$ is for power increase and $q < 1$ is for power decrease). The interaction factor q -factor is measured as the ratio of power from an array to N times power from an isolated device. This q -factor is used to optimize the array layout in order to get maximum power [3]. One of the important finding from this work [3] was that the average value of q -factor is unity when overall heading is taken into account. This implicitly means the power absorption is constructive in some headings while it is destructive in other headings [4].

The restriction of point absorber approximation related to diffraction waves was removed by the use of plane wave analysis in which interactions of diverging waves considered as plane waves between devices are taken into account while the near-field waves (or evanescent waves) effects are ignored implying separation distance between devices is large relative to wavelength [5–8]. The

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restriction on separation distance between devices or exclusion of near-field waves was overcome by the use of multiple scattering methods in which the superposition of incident wave potential, diverging and near-field waves, and radiated waves by the oscillation of devices are taken into account. In this way, the wave field around devices can be represented accurately [9–13]. As the accurate solution requires high number of diffracted and radiated wave superposition with iteration, this process increases the computational time significantly [14].

The restriction on the computational time was avoided by the use of the direct matrix method in which the multiple scattering prediction are combined with a direct approximation [15] and unknown wave amplitudes are predicted simultaneously rather than iteratively. As the numerical results of this approach, which is exact depending on infinite summation truncation, were very accurate compared to other numerical approximations, this method was applied to many different engineering problems including near trapping problem in large arrays [16], very large floating structures [17,18], tension-leg-platforms [19], wave energy converters [20,21].

In addition to above exact formulations, the numerical tools to predict hydrodynamic interactions for multi-bodies are studied extensively by many researchers including [22] who used the strip theory in which the hydrodynamic interactions are considered as two-dimensional flow. The unified theory was used to overcome the low frequency limitations of strip theory [23–25]. These two-dimensional approaches give poor predictions as the hydrodynamic interactions including separation distances between the bodies are neglected in the calculations.

As the hydrodynamic interactions are inherently three-dimensional, three-dimensional numerical approximations need to be used for accurate prediction of the wave loads and motions over array systems as three-dimensional effects play a significant role in the dissipation of wave energy between bodies in arrays. The hydrodynamic interaction effects are automatically taken into account as each discretized panel would have its influence on all other panels in three-dimensional numerical models. The viscous Computational Fluid Dynamics (CFD) methods for full fluid domain or viscous CFD in the near field and inviscid CFD in the far field can be used for the prediction of three-dimensional non-linear flow field due to incident waves. However, the required computational time to solve these kinds of problems is not suited for practical purposes yet [26–28]. In these works, single wave energy converter is used with the order of 10^6 cells and the solution for single WEC requires 24–72 h to compute approximately 10 s.

An alternative approach to a viscous solution is the three-dimensional potential flow approximation to solve the hydrodynamic interactions. The computational time of potential (or inviscid CFD) which neglect the viscous effect is much less than viscous CFD and are used to predict the hydrodynamic loads over floating single bodies and arrays. The prediction of three-dimensional hydrodynamic interaction effects on arrays can be obtained using three-dimensional frequency and time domain approaches and two kinds of formulations were used for this purpose. These are Green's function formulation [29–31] and Rankine type source distribution [32–36].

The Green function's approach satisfies the free surface boundary condition and condition at infinity automatically, and only the body surface needs to be discretized with panels, while the source and dipole singularities are distributed discretizing both the body surface and a portion of the free surface in Rankine type formulation. The main disadvantage of Rankine type source distribution is the stability problem for the numerical implementation, since the radiation condition or condition at infinity is not satisfied exactly. The requirement of the discretization of some portion of the free surface using quadrilateral or triangular

elements increases the computational time substantially. The time domain and frequency domain results are related by the Fourier Transform in the context of the linear theory.

There are many different radiation/diffraction numerical codes that are used for the prediction of wave energy converter variables, such as, WAMIT [37], Aquaplan [38], AQWA [39]. WAMIT [37] is the most widely used commercial programme and uses frequency domain Green function to predict hydrodynamics loads over single bodies and arrays and used by many researchers for many different purposes including optimizing the damping characteristics of wave energy converters in the arrays, increasing the capture width of a line absorber with cylindrical floats, analysing the motions of a floating platform with several absorber attached [40–44]. Other non-commercial numerical approaches are used by many other researchers to predict the effects of hydrodynamic interactions on absorbed power, captured width, separation distances, directionality, interaction factors, efficiency of the numerical methods in the case of large number of wave energy converters in the array, optimum control [45–55].

In the present paper, two and four truncated vertical cylinders in both sway and heave modes as a wave energy converter arrays will be used to predict the absorbed energy from ocean waves. The time dependent hydrodynamic radiation and exciting forces impulse response functions (which are used for the time marching of the equation of motion in order to find displacement, velocity, and acceleration of the wave energy converters) are predicted by the use of the transient free-surface wave Green function [29,48,56–62]. The present ITU-WAVE numerical results for two and four truncated vertical cylinder array systems will be validated with analytical results [15]. The effects of the separation distances and heading angles on relative capture width and interaction factor are then studied in order to determine the maximum absorbed power from ocean waves and the constructive and destructive effects.

2. Equation of motion of array systems

A right-handed coordinate system is used to define the fluid action and a Cartesian coordinate system $\vec{x} = (x, y, z)$ is fixed to the body which is used for the solution of the linearized problem in the time domain Fig. 1. Positive x-direction is towards the forward, positive z-direction points upwards, and the $z = 0$ plane (or xy-plane) is coincident with calm water. The bodies undergo oscillatory motion about their mean positions due to incident wave field. The origin of the body-fixed coordinate system $\vec{x} = (x, y, z)$ is located at the centre of the xy plane. The solution domain consists of the fluid bounded by the free surface $S_f(t)$, the body surface $S_b(t)$, and the boundary surface at infinity S_∞ Fig. 1 [29].

The following assumptions are taken into account in order to solve the physical problem. If the fluid is unbounded (except for the submerged portion of the body on the free surface), ideal (inviscid and incompressible), and its flow is irrotational (no fluid separation and lifting effect), the principle of mass conservation dictates the total disturbance velocity potential $\Phi(\vec{x}, t)$. This velocity potential is harmonic in the fluid domain and is governed by Laplace equation everywhere in the fluid domain as $\nabla^2 \Phi(\vec{x}, t) = 0$ and the disturbance flow velocity field $\vec{V}(\vec{x}, t)$ may then be described as the gradient of the potential $\Phi(\vec{x}, t)$ (e.g. $\vec{V}(\vec{x}, t) = \nabla \Phi(\vec{x}, t)$).

The dynamics of a floating body's unsteady oscillations are governed by a balance between the inertia of the floating body and the external forces acting upon it. This balance is complicated by the existence of radiated waves which results from the oscillations of the bodies and the scattering of the incident waves. This means that waves generated by the floating bodies at any given time will persist indefinitely and the waves of all frequencies will be generated on the free surface. These generated waves, in principle, affect

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