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A novel simulation method for predicting power outputs of wave energy converters

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ABSTRACT

In this paper a novel transformed linear simulation method is first proposed for predicting the power outputs of wave energy converters placed in shallow water nonlinear waves. The bottom effects on the power performances of wave energy converters have also been taken into account during the calculations. The novel simulation method is based on a Hermite transformation model in which the transformation is chosen to be a monotonic cubic polynomial, calibrated such that the first four moments of the transformed model match the moments of the true process. It is demonstrated in the calculation examples that the novel transformed linear simulation method is a faster method than the traditional second order nonlinear simulation method.

1. Introduction

Wave power is an abundant source of renewable energy that exists in many parts of the world oceans. In order to exploit this vast amount of energy, various concepts of wave energy converters (such as point absorber wave energy converter (WEC), surging WEC, oscillating water column, overtopping device, hinged multi-module WEC, etc.) have been developed by the engineers and scientists in different parts of the world. A point absorber wave energy converter is a floating structure which absorbs energy from all directions through its movements at/near the water surface. It converts the motion of the buoyant top relative to the base into electrical power (Sergiienko et al. [1], Zhang and Yang [2]). The vertical motion of the buoyant top is utilized to alternate the compression of a gas or liquid in some form of container, converted into rotational movement of the power generator, or converted in other similar ways. A surging WEC (considered in this paper) extracts energy from wave surges and the movement of water particles within them. The arm oscillates as a pendulum mounted on a pivoted joint in response to the movement of water in the waves. An oscillating water column is a partially submerged, hollow structure (Zhou et al. [3]). It is open to the sea below the water line, enclosing a column of air on top of a column of water. Waves cause the water column to rise and fall, which in turn compresses and decompresses the air column. This trapped air is allowed to flow to and from the atmosphere via a turbine, which usually has the ability to rotate regardless of the direction of the airflow. The rotation of the turbine is used to generate electricity. An overtopping device captures water as waves break into a storage reservoir. The water is then returned to the sea passing through a conventional low-head turbine which generates power (Martins et al. [4]). A hinged multi-module WEC consists of two identical floaters (including the fore raft in the upstream of incident waves and the aft raft in the downstream), which are hinged together by a joint. This device captures energy from the relative motion of the two floaters as the wave passes them (Zhang et al. [5], Zheng and Zhang [6]).

During the design analysis of a wave energy converter, the wave inputs to the dynamic filter must be as accurate as possible in order to obtain reliable simulation results. Unfortunately, until present a WEC's power outputs prediction is almost always performed by inputting unrealistic linear irregular waves to the dynamic filter in the simulation process. For example, Cargo et al. [7] used linear wave theory in their research work of optimisation and control of a hydraulic power take-off unit for a wave energy converter. In the hydrodynamic modelling of a direct drive wave energy converter, Eriksson et al. [8] also applied the linear wave theory. Fan et al. [9] applied the linearly simulated waves in their research study of the design and control of a point absorber wave energy converter with an open loop hydraulic transmission. Gomes et al. [10] obtained the irregular free surface elevation by using linear summation of all regular wave components in their study of the dynamics and power extraction of bottom-hinged plate wave energy converters in irregular waves. Herber and Allison [11] modeled an irregular incident wave field with a linear superposition of a finite number of linear Airy wave components in their research work on the

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wave energy extraction maximization in irregular ocean waves. In their control performance assessment and design of optimal control to harvest ocean energy, Sánchez et al. [12] approximated the surface elevation resulting from irregular ocean waves as a superposition of multiple harmonic waves under the assumption of linear theory. Stelzer and Joshi [13] applied linear theory to obtain the wave time series in their evaluation of wave energy generation from buoy heave response. Using linear wave theory, Wang and Isberg [14] created irregular wave elevation by summing regular wave components of small height in their study of the nonlinear passive control of a wave energy converter. Yu et al. [15] simulated irregular waves using linear wave theory in their design and analysis for a floating oscillating surge wave energy converter.

In the field of ocean engineering, it is the common knowledge that linear irregular waves only exist in very deep sea and from a very moderate sea state. For sea areas with shallow to intermediate water depths where most of today's WECs will be placed (Fernandes and Fonseca [16]), the nonlinear irregular wave theory should become more appropriate. However, to the best knowledge of the author of this article, in the current literature there is only one work (Wang and Wang [17]) in which the nonlinear irregular wave model has been utilized to generate shallow water waves as the inputs in the power outputs prediction of a wave energy converter. In Wang and Wang [17] the power outputs of an oscillating surge wave energy converter operating in shallow water nonlinear waves have been realistically predicted. The generated power of the oscillating surge wave energy converter has been predicted by using a nonlinear simulation method that incorporates a second order random wave model into a nonlinear dynamic filter. It is shown that the nonlinear random wave model in Wang and Wang [17] can be utilized to generate irregular waves with more realistic crest-trough asymmetries than a linear wave model can do, and when used in combination with the nonlinear dynamic filter will produce more accurate power output predictions. However, a major disadvantage of the nonlinear irregular wave simulation model in Wang and Wang [17] is that it is too time-consuming. Furthermore, the bottom effects on the power performances of the wave energy converter had not been considered in the study of Wang and Wang [17]. It is well-known that in a shallow sea area the wave energy will be dissipated due to the existence of a bottom boundary layer (see e.g. Fernandes and Fonseca [16], Kitaigorodskii et al. [18]). Therefore, extension of the research work in Wang and Wang [17] is very much needed in order to conduct faster simulations for predicting the power outputs of wave energy converters also considering the sea bottom effects.

Motivated by the aforementioned facts, in this article, the power outputs of an oscillating surge wave energy converter (OSWEC) operating in shallow water nonlinear irregular waves will be predicted by using a nonlinear simulation method. The bottom effects on the power performances of the OSWEC will simultaneously be considered during the simulation process. In order to further improve the irregular wave simulation efficiency, a novel transformed linear simulation method will be first proposed in this article for generating equivalent waves as those obtained from the nonlinear simulation method. The generated irregular waves will be utilized as the inputs in the subsequent time simulation of the oscillating surge wave energy converter. In the literature there exist some studies focused on the time simulation of wave energy converters. The book of Folley [19] offers a comprehensive review on the time domain modelling of wave energy converters based specifically on the Cummins equation. In the research work of Ricci et al. [20] a time-domain solution of a heaving single-body wave energy converter has been proposed and its accuracy has been checked with linear and non-linear PTO configurations. Bosma et al. [21] provides a design guide on wave energy converter modelling in the time domain. Saulnier et al. [22] conducted time simulation of a resonant wave energy converter in order to investigate the influences of different irregular wave simulation techniques on the mean power outputs of the wave energy converter. Pastor and Liu [23] presents, assesses, and optimizes a heaving point absorber wave energy converter through numerical modeling, simulation, and analysis in time domain. Yu et al. [24] performed design and analysis for a floating oscillating surge wave energy converter. The power generation performance of the design was modeled using a time-domain numerical simulation tool.

In this paper the accuracy and efficiency of the proposed novel transformed linear simulation method will be verified through some specific calculation examples.

This paper begins in Section 2 by elucidating the theories behind the proposed transformed linear simulation method. It continues in Section 3 by introducing the time domain equations of motion of the wave energy converter. In Section 4 the calculation examples, prediction results and discussions are presented, with concluding remarks provided in Section 5.

2. The theories behind the proposed transformed linear simulation method

The free surface elevation for an irregular two-dimensional sea state (with a constant water depth d) is denoted by $\eta(x, t)$, in which x is the longitudinal coordinate and t is time. Assuming this irregular sea state is characterized by a specific wave spectrum $S_\eta(\omega)$ in which ω denotes the angular frequency, it has been shown in Wang and Wang [17] that a first order linear solution for $\eta(x, t)$ can be expressed as follows:

$$\eta^{(1)}(x, t) = \mathrm{Re}\sum_{n=1}^{N} c_n \exp(\mathrm{i}(\omega_n t - k_n x + \varepsilon_n)) \tag{1}$$

as N tends to infinity. In the above equation, i stands for the imaginary unit, c_n denotes the random complex valued amplitude for each elementary sinusoidal wave, ω_n denotes the angular frequency, k_n denotes the wave number, and ε_n is the phase angle uniformly distributed in the interval [0, 2 π]. Furthermore, the individual frequencies ω_n and wave numbers k_n in Eq. (1) are functionally related through the following dispersion relation:

$$\omega_n^2 = gk_n \tanh(k_n d) \tag{2}$$

where g and d are the gravitational acceleration and water depth, respectively.

We rewrite Eq. (1) at a specific reference location (say$x = 0$) as follows:

$$\begin{aligned}\eta^{(1)}(x, t) &= \eta^{(1)}(0, t) = \eta^{(1)}(t)\\ &= \mathrm{Re}\textstyle\sum_{n=1}^{N} c_n \exp(\mathrm{i}(\omega_n t + \varepsilon_n)) = \sum_{n=1}^{N}(a_n\cos(\omega_n t) + b_n \sin(\omega_n t))\end{aligned} \tag{3}$$

In the above equation, $\omega_n = 2\pi n/T$, T is the time interval, c_n' s are mutually independent of one another, and a_n and b_n are Gaussian random variables. Meanwhile, the coefficients of the above formula have the following properties (see Langley [25]):

$$E[a_n^2] = E[b_n^2] = S_\eta(\omega)d\omega;\; E[a_n b_m] = 0; \tag{4}$$

$$E[a_m a_n] = E[b_m b_n] = 0 \qquad m \neq n \tag{5}$$

$$c_m^2 = a_m^2 + b_m^2 \tag{6}$$

$$\varepsilon_m = \tan^{-1}(-b_m/a_m) \tag{7}$$

In Eq. (4) $E[\bullet]$ denotes mathematical expectation, $S_\eta(\omega)$ is the wave spectrum and $d\omega = 2\pi/T$. In the following we re-express the complex term appearing in Eq. (3) in the form (see Langley [25]):

$$c_m \exp(\mathrm{i}(\omega_m t + \varepsilon_m)) = \sqrt{S_\eta(\omega_m)d\omega}\,(x_m + \mathrm{i}y_m) \tag{8}$$

With comparison with Eq. (3) shows that:

$$x_m\sqrt{S_\eta(\omega_m)d\omega} = a_m\cos(\omega_m t) + b_m\sin(\omega_m t) \tag{9}$$

$$y_m\sqrt{S_\eta(\omega_m)d\omega} = a_m\sin(\omega_m t) - b_m\cos(\omega_m t) \tag{10}$$