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Spectral modeling of an oscillating surge wave energy converter with control surfaces

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ABSTRACT

The aim of this research is to use spectral techniques in evaluating the irregular wave performance of a novel wave energy converter concept that combines an oscillating surge wave energy converter with control surfaces. The control surfaces allow the wave energy converter to have a time-varying geometry that enables the hydrodynamic exciting and radiation coefficients to be altered. In the current state of development the device geometry is controlled on a sea state-to-sea state time scale and combined with control of the power take-off (PTO) on a wave-to-wave time scale to maximize power capture, increase capacity factor, and reduce design loads. Analysis begins with the application of linear hydrodynamic theory to evaluate the device performance in terms of absorbed power, foundation loads, and accumulation of fatigue damage on the PTO. To determine the linear PTO damping coefficient that maximizes the time-averaged absorbed power for a given sea state, an optimization problem was constructed while incorporating a motion constraint on the maximum pitch amplitude of motion. The inclusion of the motion constraint prevents linear scaling of the performance results with the significant wave height. Previous studies on the modeling of oscillating surge wave energy converter designs have included nonlinear hydrodynamics. Therefore, a quadratic viscous drag moment was added to the system dynamics through use of a quasi-linear viscous damping coefficient. The same performance quantities were calculated for both the linear and nonlinear models while assuming an irregular wave surface elevation described by a Bretscheider spectrum. One major effect of including the viscous drag moment was flattening of the capture width and structural load curves with respect to the wave spectrum peak frequency while reducing the sensitivity with respect to the significant wave height compared to the linear analysis.

1. Introduction

The worldwide marine renewable energy resource has the potential to significantly reduce the world's consumption of fossil fuels. The still nascent wave energy industry hosts a wide diversity of technologies, yet no convergence toward an optimal design and operation has emerged [1]. The current generation of wave energy converters (WECs) is facing several challenges: (1) the energy capture efficiency is lower than the theoretical maximum, (2) large structures are needed to withstand the hydrodynamic loads, and (3) the price of energy is too high and costs must be driven down before WECs can become commercially viable [2]. Therefore, the success of future WEC technologies will require the development of advanced control methods and structures that actively tune device performance to maximize energy generation under operational conditions and shed hydrodynamic loads in extreme sea states to reduce the structural mass and overall cost [3].

To address these issues the National Renewable Energy Laboratory has been developing a novel WEC concept that combines an oscillating surge wave energy converter (OSWEC) with active control surfaces [4]. The concept of controllable airfoils applied to wave energy conversion was pioneered by Atargis Energy Corporation with its cycloidal device [5]. The concept of large-scale geometric changes has been considered in the design of Weptos [6], though the focus has been on its survival mode. The concept developed in this article is more similar to a pitching device with a rotatable flap [7]; however, this work increases the number of rotatable surfaces for greater refinement of the hydrodynamic properties. The proposed design is expected to assist in tuning the hydrodynamic properties to match those of the incident wave climate while shedding loads in larger seas to increase its operational range.

The development of nearshore oscillating surge wave energy devices in recent years has been led by Aquamarine Power's Oyster

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[8], AW-Energy Oy's Waveroller [9], and Resolute Marine Energy's Surge WEC [10]. In addition, Langlee Wave Power [11] is currently developing a floating dual-flap OSWEC for deepwater deployment; however, these designs consist of a fixed geometrical body that generally does not operate as a resonant device [12] but relies on control of the power-take-off (PTO) system to optimize power capture. Point absorbers are generally designed to be resonant devices, though their motion is generally narrow-banded with high extraction efficiencies around a small frequency range near the natural period of the device. References [7,13] investigated the ability to tune the natural period of a pitching WEC by altering the mass moment of inertia by shifting the internal mass distribution. A device with a controllable geometry would not only be able to shed loads, but also tune the hydrodynamic coefficients to match the natural period of the device with the peak excitation period of the sea spectrum to broaden its effective operating range. Increasing the number of control surfaces will allow for greater tuning of the hydrodynamic excitation and radiation coefficients and will reduce the complexity that comes with pumping ballast water [7].

This article begins with an introduction to the device concept and discussion of the sensitivity in hydrodynamic properties with respect to various device geometries chosen for analysis. Next, modeling of the OSWEC in regular waves is reviewed to provide the preliminaries for extension into spectral models [14,15]. The performance quantities of interest include the rotational amplitude of motion, the time-averaged absorbed power from the PTO system, and the foundation loads required to keep the device fixed to the sea floor. The theory behind the spectral modeling of irregular waves is then introduced to obtain short-term performance statistics. OSWEC designs require considerations for modeling nonlinear hydrodynamics [12,16]; thus, a nonlinear quadratic viscous drag moment will be added to the system dynamics. To maximize the absorbed power for a given sea state, a nonlinear optimization problem was constructed to solve for the optimal linear PTO damping coefficient while satisfying a given motion constraint. Because the optimization focused solely on power generation, the corresponding foundation loads and fatigue damage accumulation to the PTO were calculated to highlight the benefit of controlled surfaces to shed loads in greater sea states to increase the lifetime of the device.

2. Device description and hydrodynamic modeling

A preliminary analysis of the device concept's feasibility was performed in [17], which showed that an actuated geometry could increase the capacity factor while maintaining a baseline power performance level. The concept was further developed in [4], which studied how the absorbed power and hydrodynamic loads varied with the device width and thickness. As described in the previous studies, the main body of the OSWEC has been replaced with a set of identical flaps that may be rotated, see Fig. 1. The flaps will be allowed to pitch about their center of rotation with the flap pitch angle, φ, measured positive clockwise from the radial axis of the body, see Fig. 2. The flaps were modeled as ellipses to provide a streamlined shape when the flaps are rotated parallel to the direction of wave propagation, $\varphi = \pi/2$, in an attempt to minimize viscous loses. The geometric dimensions used in this study can be found in Table 1. The structural mass will be evenly distributed; as such, the pitch mass moment of inertia, I_{55} and the linear hydrostatic pitch restoring coefficient, C_{55}, will remain constant. For this study the structural mass density, ρ_m, was set to half the fluid density, ρ.

For this study hydrodynamic coefficients were obtained from WAMIT version 7.0 [18] at a spacing of 0.01 rad/s for wave frequencies between 0–3.5 rad/s. The flaps were placed in either the fully open or closed configuration corresponding to $\varphi = \pi/2$ and $\varphi = 0$, respectively. This work considers four separate geometric configurations that consist of starting with the top flap open, one flap, and opening the next three flaps one at a time in sequential order. Results for the geometric configuration with zero open flaps is not discussed, because it has been previously researched and is not required to demonstrate the benefit of actuated control surfaces. The hydrodynamic coefficients for each geometric configuration considered can be found in Fig. 3. It is evident from Fig. 3 that the hydrodynamic coefficients do not scale linearly, when each additional flap is closed, with the largest increase corresponding to the closure of the second flap from the top of the device. As each flap is closed, the added moment of inertia increases up to 35 times the mass moment of inertia. Because the pitch mass moment of inertia and pitch hydrostatic restoring coefficient remain constant, for each geometric configuration, it is evident that the natural period will increase as the number of closed flaps increases.

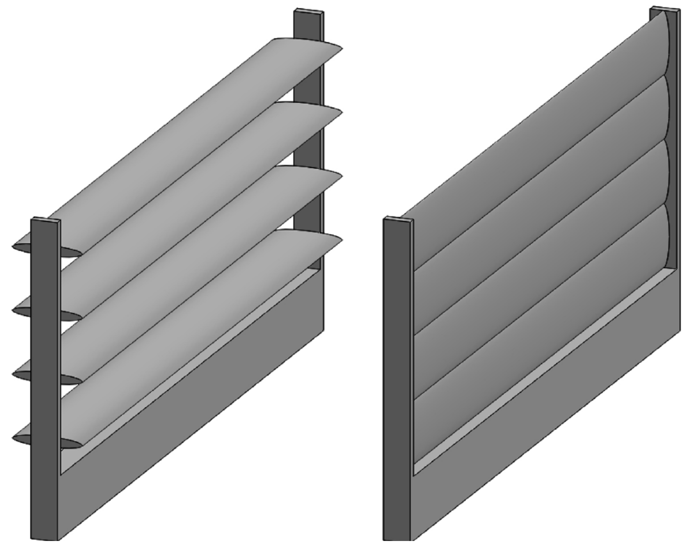

Fig. 1. Solidworks rendering of the OSWEC. Left: Perspective view of fully open configuration (4 flaps open) and right: perspective view of fully closed configuration (0 flaps open).

Table 1
Geometric parameters for hydrodynamic modeling.

Water Depth	h	10 m	Flap Minor Axis	t_f	1/3 m
OSWEC Height	H	10 m	Flap Major Axis	H_f	2 m
OSWEC Thickness	t	3/4 m	Side Support Height	H_s	10 m
OSWEC Width	w	20 m	Side Support Thickness	t_s	3/4 m
Flap Width	w_f	19.5 m	Side Support Width	w_s	1/4 m
Moment of Inertia	I_{55}	923.4 t.m^2	Center of Gravity	r_g	3.97 m
Volume	$\forall$	72 m^3	Mass	m	36 t

3. Regular wave analysis

3.1. Frequency domain equation of motion

It is common practice to calculate the response amplitude operator to access the performance of a WEC. For an incident wave described by:

$$\eta(x,t) = \Re\left\{-\frac{1}{g}\frac{\partial \phi_I}{\partial t}|_{z=h}\right\} = \Re\left\{Ae^{i(\sigma t - kx)}\right\} = A\cos(\sigma t - kx), \quad (1)$$

where η is the wave elevation, g is gravitational acceleration, ϕ_I is the incident wave potential, A is the wave amplitude, σ is the wave angular frequency, and k is the wave number, $i = \sqrt{-1}$ is the imaginary unit, and $\Re$ signifies the real component. The OSWEC