SAND2013-0911C

Wave Energy Converter Design Tool for Point Absorbers with Arbitrary Device Geometry

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ABSTRACT

In order to promote and support the wave energy industry, a Wave Energy Converter (WEC) design tool has been developed for modeling point absorber WECs with arbitrary device geometry. The design tool provides a numerical modeling structure and methodology capable of modeling of heaving point absorber WEC response and performance to regular and irregular operational waves. Its time-domain formulation is based on frequency-domain hydrodynamic coefficients from Boundary Element Method (BEM) codes, and provides a framework for studying WEC design and innovative control strategies.

KEY WORDS: wave energy; point absorber; time-domain; design tool.

INTRODUCTION

Wave Energy Converters (WECs) are devices designed to convert the constant motion of ocean waves into usable power. Despite being conceptualized and patented for over a century, WECs still remain largely in the phase of research and development (McCormick 2007). The only developer that has achieved continued full-scale deployment and production of electricity to the national grid, is the Wavegen Limpet which has been deployed on the Scottish island of Islay since 2000.

In order to promote development of the wave energy industry, current wave energy research is largely influenced by developer needs and lessons learned from related industries. Because of its nascent state, wave energy research areas are broad, spanning topics from environmental concerns and resource assessments to WEC farm interactions (DON 2003, Child 2007, Lenee-Bluhm 2010). Ultimately for a wave energy project to be successful, in addition to public support, researchers, developers, investors and utilities need to estimate the device's performance before deployment. In the wind industry, generic turbine models were developed to estimate a turbine's performance for a particular wind resource. The goal of this research is to develop similar publicly available models for WECs that can be used to estimate a device's performance for a potential site's wave climate.

Unlike the wind industry where the three-bladed horizontal axis wind turbine has become the predominant design, there are many different WEC technologies being actively pursued. These WEC technologies include: Oscillating Water Columns (OWCs), overtopping devices, surge devices and oscillating bodies. OWCs, such as the shore-based Wavegen Limpet, are devices that utilize the cyclic compression and decompression of air above the wave surface to run a turbine. Overtopping devices, like the Wave Dragon, focus waves toward an elevated basin which is used to run water through a low head turbine. Surge devices, such as the Oyster, are typically submerged and operate by pitching with the circular motion of ocean waves, and converting this motion into usable power through a power take-off system. Oscillating bodies are devices that operate by floating on the water surface and converting the body's motion into usable power. They are typically split into two subcategories: attenuators and point absorbers. Attenuators, such as the Pelamis, are devices large in extension that consist of multiple bodies connected by hinges that articulate along the direction of wave propagation. Point absorbers, like the OPT Powerbuoy, are much smaller than the incident wavelength and operate by oscillating in heave with the wave. The work presented in this paper focuses on developing a methodology that can be used to model heaving point absorber WECs with arbitrary device geometry. This methodology and overall structure is the basis of a DOE EERE funded project which will extend this work to include application to other WEC archetypes, including multiple degrees of freedom, power take-off and mooring.

WAVE ENERGY CONVERTER MODELING

Point absorber WECs are oscillating bodies subject to stochastic ocean waves which are composed of many waves with different frequencies and directions. Because of this, a natural progression is to model point absorbers in the frequency-domain using the principle of linear superposition. However, while frequency-domain modeling is a valuable tool for linear system analysis, WECs are subject to many non-linearities such as those from power take-off systems, control strategies, end stops, and complex mooring systems. Time-domain models of heaving point absorber WECs with idealized geometries have been developed by wave energy researchers in order to accurately capture these non-linearities and evaluate device performance.

For example, A. F. Falcao (2007, 2008) modeled a point absorber as a heaving hemisphere with a hydraulic power take-off system and implemented different methods of control. Kara (2010) modeled a heaving hemisphere point absorber in order to compare a point absorber's power absorption with and without latching control. A heaving cylinder point absorber was modeling by Ricci (2008) in order to compare its performance with a hydraulic versus a direct drive power take-off system. Eidsmoen (1998) modeled a heaving cylinder point absorber with a hydraulic power take-off system and end stops to estimate yearly power output with and without phase control. These are all examples of point absorbers modeled in the time-domain as a single-body with a basic geometry; however point absorber designs currently pursued by developers are rarely single-body WECs with basic geometries.

The OPT PowerBuoy and Wavebob are both examples of two-body point absorbers WECs with complex geometries that convert the relative motion between two heaving bodies into usable power. In order to represent these more complicated WEC designs, Candido (2011) and Eidsmoen (1996) have independently extended time-domain modeling of single-body point absorbers to develop two-body point absorber models. More recently, Garrad Hassan released a WEC modeling tool, WaveDyn, capable of modeling point absorbers, attenuators and surge devices in the time-domain. The goal of the work presented in this paper is to develop an open source, publicly available time-domain WEC model and methodology that can be used to determine device performance, optimize WEC design and test innovative control strategies. This paper demonstrates preliminary results towards the development of the open source WEC design tool, by demonstrating its application to heaving point absorber WECs.

POINT ABSORBER MODELING METHODOLOGY

The point absorber WEC modeling methodology presented in this paper is intended for use as an initial design tool to estimate the performance of a point absorber WEC with arbitrary geometry for a specified wave climate. It is a time-domain model currently restricted to heave motion only since heave is the degree of freedom in which most point absorbers extract power. In reality, the point absorber will move in all six degrees of freedom (corresponding to heave, sway, surge, yaw, pitch and roll), but for the purpose of simplification the model solves for heave motion only.

A flowchart presenting the point absorber WEC modeling methodology is shown in Fig. 1. The first step is to define the 3D WEC geometry. Once the 3D geometry is created, it is then imported into a frequency-domain Boundary Element Method (BEM) code where the WEC's frequency-domain hydrodynamic response is determined. For the results presented in this paper, AQWA was used [21]. Next, the complex frequency-domain excitation force, $f_e(i\omega)$, is used to calculate the time-domain excitation Impulse Response Function (IRF), $f_e(t)$, the frequency-domain radiation, $f_r(\omega)$, is used to calculate the time-domain radiation IRF, $f_r(t)$, and the limit at infinity of the frequency-domain added mass is evaluated, $A(\infty)$. These hydrodynamic terms, $f_e(t)$, $f_r(t)$ and $A(\infty)$, are the building blocks of the time-domain WEC Equations of Motion (EOM) that will be defined in a later section. Once the hydrodynamic terms are determined, the user can define regular or irregular waves as input to the WEC Dynamics Model developed in MATLAB/Simulink. The WEC Dynamics Model solves the governing time-domain EOM for the WEC's displacement and velocity and calls on a Mooring System Model that uses that WEC's displacement and velocity to determine the mooring force imparted on the WEC. By using the WEC's frequency-domain hydrodynamic response to develop time-domain EOM, the WEC modeling methodology presented in Fig. 1 accounts for arbitrary device geometry, and can thus be used to compare different WEC designs.

In the following sections each step of the point absorber WEC modeling methodology will be described and applied to a specific point absorber design. In the next section, a single-body point absorber with complex geometry will be modeled using the WEC modeling methodology. Then, the WEC modeling methodology will be applied to model a two-body point absorber.

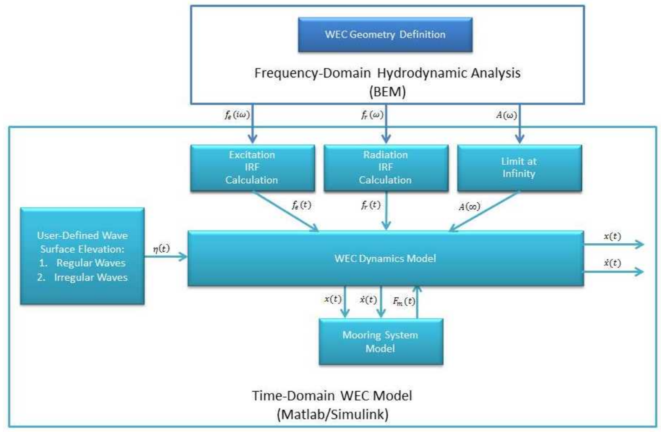

Fig. 1 - Flowchart of Point Absorber WEC Modeling Methodology

SINGLE-BODY POINT ABSORBER MODEL

The single-body point absorber is modeled as one rigid body consisting of a buoy, spar, and damping plate, as shown on the left side of Fig. 2. This geometry was chosen because it is representative of point absorbers designs currently being developed, with the simplification of being modeled as one rigid body. Additionally, this single-body WEC geometry has experimental data available from wave tank testing, and numerical results from a RANS simulation (Li 2011, Yu 2011). The experimental data for the single-body geometry was used to validate the WEC Dynamics model presented in this paper, results which will be presented in a later section. The right side of Fig. 2 demonstrates how a generic single-body point absorber model can be applied to a specific WEC design. The generic single-body model consists of a WEC of mass m, heaving in the x direction. The point absorber model is subject to an incident wave, $\eta(t)$, and is moored to the sea floor at water depth h.

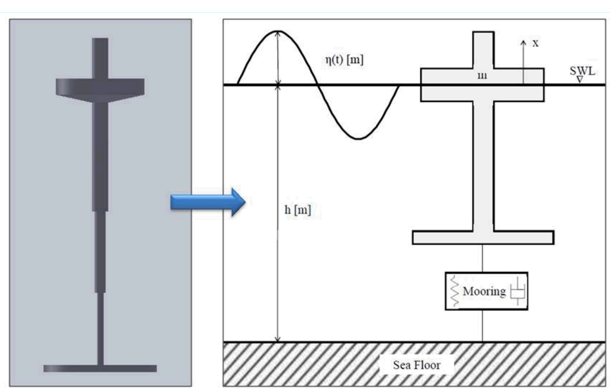

Fig. 2 - Single-Body Point Absorber: (left) Single-Body Point Absorber Geometry, (right) Generic Single-Body Point Absorber Model

Single-Body Equations of Motion

Before applying the point absorber modeling methodology, it is important to first understand the model's governing equations. The single-body point absorber time-domain EOM are formulated based on the integro-differential EOM for ship motions in six degrees of freedom. These time-domain EOM use the IRF formulation and were first introduced by Cummins (1962) for ship motions. This formulation uses the ship's IRFs to account for the fluid structure interaction of the ship with the wave. Due to similarities between ship motions and WEC dynamics, the Cummins formulation can be modified to represent a single-body heaving point absorber as shown in Eq. (1), where x represents the WEC's heave motion, as modified based on Falnes (2002).

$$F_e(t) - F_r(t) - F_m(x,\dot{x}) = (\rho_{SW} g A)x + b_v \dot{x} + \big(m + A(\infty)\big)\ddot{x} \qquad (1)$$

The left hand side of Eq. (1) consists of forcing functions that account for the WEC's interaction with incident waves and the mooring system. The first term is the excitation force, or the force the incoming wave imparts on the WEC. The excitation force, $F_e(t)$, is calculated via Eq. (2) by the convolution of the water surface elevation, h(t), with the non-causal excitation IRF, $f_e(t)$. The second term is the radiation force, which is the force the WEC creates by moving and thus radiating waves. The radiation force, $F_r(t)$, is determined by the convolution of the radiation IRF, $f_r(t)$, with the WEC's velocity, $\dot{x}$, as shown in Eq. (3). The last term, $F_m(x,\dot{x})$, accounts for the force imparted on the WEC by the mooring system. The mooring force is generally a function of the WEC's displacement and velocity and dependent on the mooring stiffness, km, and damping, bm, as defined by Eq. (4).

$$F_e(t) = \int_{-\infty}^{\infty} \eta(\tau) f_e(t-\tau) d\tau \qquad (2)$$

$$F_r(t) = \int_{-\infty}^{t} f_r(t-\tau)\dot{x}(\tau) d\tau \qquad (3)$$

$$F_m(x,\dot{x}) = k_m x, + b_m \dot{x} = 8k_m\left(1 - \frac{l_m}{\sqrt{{l_m}^2 + x^2}}\right)x \qquad (4)$$

Since the single-body point absorber geometry was chosen in order to be validated against experimental data, the mooring force was determined based on the experimental setup used by Li (2011). The experimental setup had eight mooring lines in total, each with stiffness km of 160 [kN/m] and initial length, l_m, equal to 1.7 [m]. The mooring configuration consisted of two layers of crosses that were fixed to the walls of the wave tank, initially in a horizontal position. The equivalent mooring force felt by the WEC in the heave direction, determined using trigonometric relationships, is a function of the WEC's displacement only as defined on the right hand side of Eq. (4). The terms on the right hand side of point absorber EOM defined in Eq. (1) are similar to a mass-spring-damper system with terms multiplied by the WEC's displacement, velocity and acceleration. These terms are the hydrostatic stiffness, viscous damping, b_v, and the added mass at infinite wave frequency, $A(\infty)$. The hydrostatic stiffness is equal to the product of the density of sea water, $\rho_{SW} =$ 1,025 [kg/m^3], acceleration due to gravity, $g =$ 9.81 [m/s^2], and the cross sectional area of the point absorber, A, at the still water level. This is multiplied by the WEC's displacement to determine the restoring force of the water on the body known as the hydrostatic force. In the single-body point absorber model the hydrostatic stiffness is assumed to be a constant. Viscous damping, b_v, is a correctional term used to account for viscous effects that are not otherwise accounted for in the time-domain formulation. The process used to determine the viscous damping constant will be described in a later section. The added mass, $A(\omega)$, is a frequency dependent term that represents the additional force required to move a mass in water compared to the force required to move the same mass in air. The single-body point absorber EOM calls for the limit of the added mass as the wave frequency approaches infinity, $A(\infty)$.

Single-Body Hydrodynamic Response

In order to implement the single-body point absorber EOM defined in the previous section, the WEC's hydrodynamics response must be determined. The frequency-domain hydrodynamic response is then used to determine the WEC's excitation IRF, radiation IRF, and added mass at infinity, the building blocks of the time-domain point absorber EOM. The 3D geometry of the single-body point absorber shown on the left of Fig. 2, with dimensions defined in Table 1, was imported into AQWA where the WEC's frequency-domain response was determined. AQWA is a BEM code based on the principles of linear wave theory, so the frequency-domain response has the assumptions of incompressible, irrotational, and inviscid flow. The single-body point absorber was modeled in AQWA with a mass of 250,000 [kg] at a water depth of 70 [m]. While AQWA was used to determine the frequency-domain response presented in this paper, any hydrodynamic code capable of determining frequency-domain excitation, radiation and added mass could be used for the modeling methodology.

Table 1. Single-Body Point Absorber Dimensions

Buoy	Diameter	11 [m]
	Height	2 [m]
Spar	Diameter	2 [m]
	Height	41.34 [m]
Plate	Diameter	14 [m]
	Height	0.84 [m]

The single-body point absorber's complex frequency-domain hydrodynamic excitation force, $f_e(i\omega)$, is shown in Fig. 3 and the WEC's radiation force, $f_r(\omega)$, and added mass, $A(\omega)$, are shown in Fig. 4. In order to properly calculate heave IRFs, the frequency-domain response should have a truncation frequency of 2 [rad/s] with a frequency spacing of 0.01 [rad/s] (Silver 2008). When the WEC geometry is imported into a frequency-domain hydrodynamic code, the mesh should be sized to meet these requirements because the mesh determines the frequency range response the code solves for. The results presented in Fig. 3 and Fig. 4 use linear interpolation and extrapolation to determine response with the appropriate spacing at low-frequencies. Based on the single-body point absorber's frequency-domain added mass, the infinite added mass, $A(\infty)$, was determined to be 1,225,100 [kg].

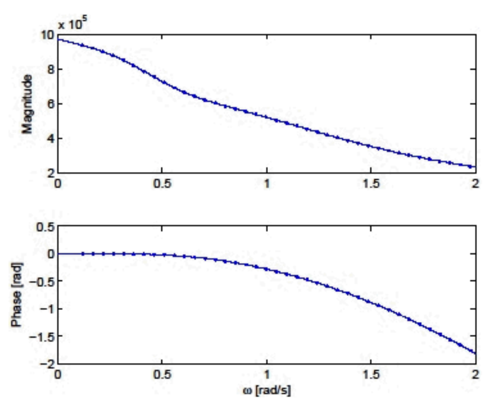

Fig. 3 - Single-Body Point Absorber Frequency-Domain Excitation

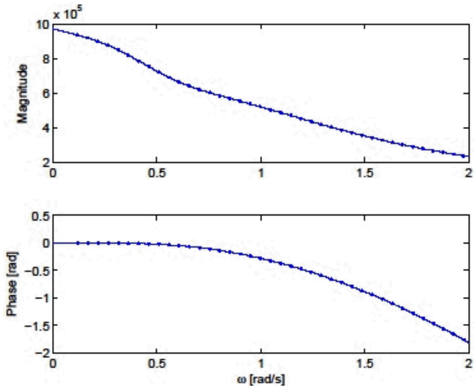

Fig. 4 - Single-Body Point Absorber Frequency-Domain Radiation: (top) Radiation Damping, (bottom) Added Mass

After the single-body point absorber's frequency-domain response is determined, the hydrodynamic terms are used to calculate the WEC's time-domain IRFs. For the single-body point absorber EOM, an excitation IRF and a radiation IRF must be calculated. The non-causal time-domain excitation IRF is calculated via Eq. (5) using the frequency-domain excitation magnitude and phase (Falnes 1995). The causal time-domain radiation IRF is calculated by Eq. (6) using the WEC's frequency-domain radiation. Both IRFs are calculated using trapezoidal integration in MATLAB according to the process shown in Fig. 1.

$$f_e(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} f_e(i\omega)e^{i\omega t}d\omega \quad (5)$$

$$F_r(t) = \int_{-\infty}^{t} f_r(t-\tau)\dot{x}(\tau)d\tau \quad (6)$$

Single-Body WEC Dynamics Model

Once the single-body point absorber's IRFs are calculated, time-series wave surface elevation must be defined, then the governing EOM can be solved for the WEC's displacement and velocity in the MATLAB/Simulink WEC Dynamics Model. Using the WEC modeling methodology presented in Fig. 1, regular and irregular wave time-series can be used to run the WEC Dynamics Model. For the results shown in this paper, the time-series wave surface elevation is imported directly from NDBC Umpqua Offshore buoy 46229 which is deployed off the coast of Oregon north of Reedsport (NDBC). The time-series is from June 2008, which represents a relatively low energy wave climate according to seasonal trends (Lenee-Bluhm 2010). In the following sections, first the MATLAB/Simulink WEC Dynamics Model will be introduced by describing the model's systems and subsystems, then output from the WEC Dynamics Model will be presented in addition to results from the single-body point absorber model validation.

WEC Dynamics Model Structure

The single-body point absorber WEC Dynamics model takes the wave surface elevation, $\eta(t)$, as its input and solves for the WEC's displacement and velocity. The top level of the WEC Dynamics Model implemented in Simulink, shown in Fig. 5, defines the model's input and its outputs as well as its subsystems: Excitation Force Determination, WEC Dynamics, and Mooring Force Determination. The Excitation Force Determination subsystem calculates the excitation force due to the incident wave on the WEC, $F_e(t)$, according to Eq. (2). The WEC Dynamics subsystem, shown in Fig. 6, implements Eq. (1) by taking the excitation and mooring forces as its inputs and solving for the WEC's displacement and velocity. In this subsystem, a Finite Impulse Response (FIR) filter is used to determine the radiation force, $F_r(t)$, by convolving the WEC's radiation IRF with the WEC's velocity according to Eq. (3). The last subsystem on the top level of the WEC Dynamics Model is the Mooring Force Determination. In this subsystem, the force the mooring system imparts on the single-body point absorber is calculated using the second line of Eq. (4).

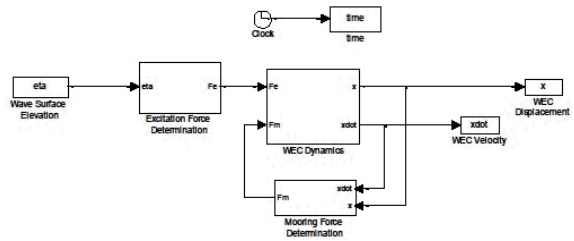

Fig. 5 - Simulink Single-Body Point Absorber Model: Top Level

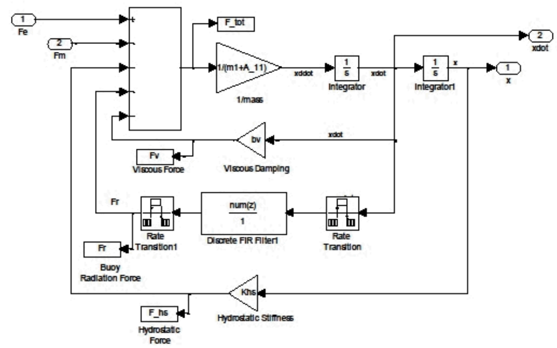

Fig. 6 - Simulink Single-Body Point Absorber Model: WEC Dynamics Subsystem

WEC Dynamics Model Output

The geometry for the single-body point absorber model was chosen because experimental data from wave tank testing is available to validate the WEC modeling methodology for this geometry. The experimental data was used to determine the viscous damping term defined in Eq. (1) for the single-body point absorber geometry through the following process. First, the single-body WEC Dynamics Model was run with regular wave input to determine the heave Response Amplitude Operators (RAOs) for a 3 [m] wave height. The RAO is defined as the magnitude of the heave response divided be the amplitude of the incoming wave. A tuned b_v value was determined for each wave period by matching the RAOs from the WEC Dynamics Model with the experimental heave RAOs, these tuned b_v values are shown in Fig. 7.

In order to determine the single-body point absorber's response to irregular waves, a constant viscous damping term, b_v= 507;692 [N/m/s], was chosen by averaging the tuned b_v values for 9 to 13 [s] wave periods which are representative of the Oregon wave climate. The RAO from the single-body point absorber WEC Dynamics Model using the averaged viscous damping term is compared with the experimental heave RAOs in Fig. 8. While the resultant RAOs do not match the experimental RAOs well for low periods, these results show that the WEC Dynamics Model provides an accurate estimate of the single-body point absorber's response for Oregon's dominant wave periods. Alternatively, the viscous damping term could be chosen to match lower wave periods to estimate response for a different wave climate.

For further comparison, Fig. 8 also includes RAOs from a RANS simulation for the same single-body point absorber geometry (Li 2011). The RANS simulation estimates experimental RAOs well for the wave periods tested, however this is a much more computationally demanding simulation. The RANS simulation took upwards of 8 hours to solve on 64 cores, whereas the WEC Dynamics Model solves in less than 30 seconds. These modeling approaches perform different types of analysis, and are intended for different stages in development. A RANS simulation is best suited for modeling a final WEC design in cases where there is highly nonlinear interaction between the wave and the WEC, such as a wave breaking on the WEC. Whereas the WEC modeling methodology presented in this paper is intended for use as an initial design tool to estimate a WEC's performance.

Once the viscous damping term for single-body point absorber model is determined, the WEC Dynamics Model can be used to estimate the WEC's response to irregular waves. The top of Fig. 9 shows the wave-surface elevation from NDBC buoy 46229 in June 2008 with the WEC's displacement response, and the bottom shows the WEC's corresponding velocity which is an important term because it drives the Power Take-Off (PTO) system. The response in Fig. 9 shows a phase shift between the incoming wave and the single-body point absorber's displacement response, with the WEC's velocity ranging within +/- 1 [m/s]. In the previous sections, the WEC modeling methodology has been used to model a single-body point absorber, and validated against experimental data. In the following sections, the WEC modeling methodology will be applied to a two-body point absorber geometry.

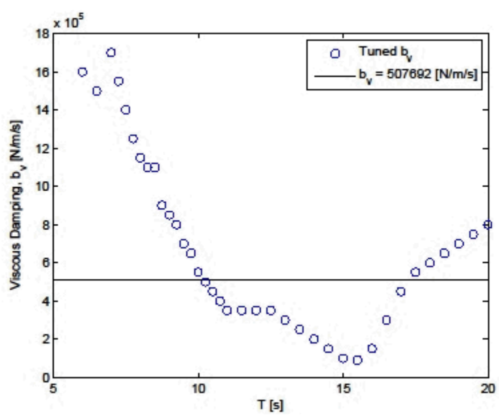

Fig. 7 - Viscous Damping Tuned to Match Experimental RAOs, and Average of 9-13 [s] Wave Periods

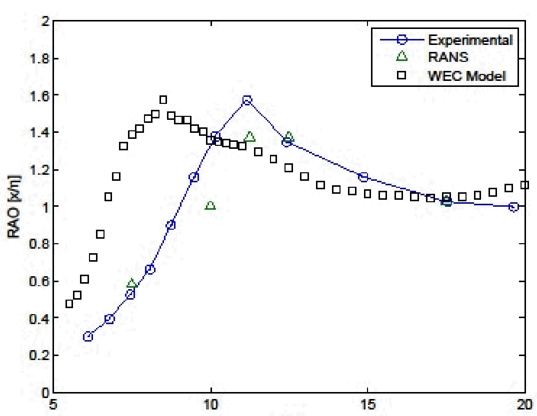

Fig. 8 - Single-Body Point Absorber Heave RAOs

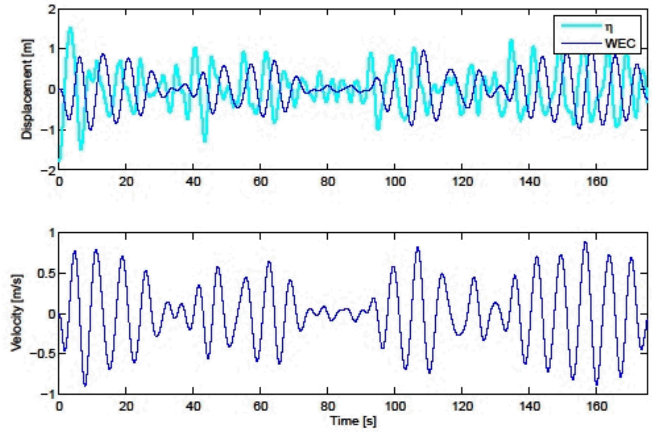

Fig. 9 - Single-Body Point Absorber Irregular Wave Response: (top) Wave and WEC Displacement, (bottom) WEC Velocity

TWO-BODY POINT ABSORBER MODEL

Previously, the point absorber modeling methodology was applied and validated for a single-body geometry. In the following sections the modeling methodology is used to model a two-body point absorber and the WEC Dynamics Model developed in MATLAB/Simulink is extended to account for the additional complexity of interacting bodies. To demonstrate how the modeling methodology can be applied to a two-body point absorber, Fig. 10 shows how the L10 point absorber on the left can be represented by a generic two-body point absorber model on the right. The L10 is a two-body point absorber designed by Oregon State University in collaboration with Columbia Power Technologies that was tested off the coast of Newport, Oregon in 2008 (Elwood 2009). The generic two-body point absorber model consists of a buoy of mass m_1, heaving in the x_1 direction, and a spar/plate of mass m_2, heaving in the x_2 direction. While the L10 is modeled without a drag plate, the second body is referred to as the spar/plate because many two-body designs incorporate a drag plate. Similar to the single-body point absorber, the two-body point absorber is subject to an incident wave $\eta(t)$, and the spar/plate is moored to the sea floor at water depth h.

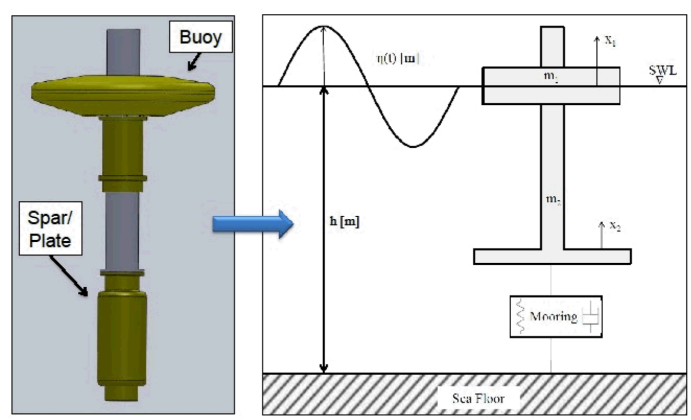

Fig. 10 - Two-Body Point Absorber: (left) L10 Point Absorber, (right) Generic Two-Body Point Absorber Model

Two-Body Equations of Motion

The two-body point absorber EOM are similar to the single-body point absorber EOM defined in Eq. (1). The buoy and spar/plate EOM each have a viscous damping term, and the excitation and radiation forces calculated in the same way. However the two-body point absorber EOM have additional forcing terms that were not accounted for in Eq. (1). The two-body point absorber has governing EOM defined by Eq. (7) for the buoy, and Eq. (8) for the spar/plate. These EOM are derived from the two-body point absorber EOM used by Eidsmoen (1995). With a two-body WEC design, there are a coupling radiation interaction forces due to each body's motion, $F_{r_{12}}(t)$ and $F_{r_{21}}(t)$. The buoy's motion radiates waves which influence the spar/plate's motion, defined by Eq. (9), and the spar/plate's motion also radiates waves that in turn influence the buoy's motion, defined by Eq. (10). In the two-body point absorber model the hydrostatic stiffness is assumed to be a constant. Since the mooring system is connected to the spar/plate, Eq. (8) has a mooring force term due to the force the mooring system imparts on it. The mooring force, $F_m(x_2, \dot{x}_2)$, is typically a function of the spar/plate's displacement and velocity. The same mooring system defined for the single-body model was used for the two-body model, and is defined in the second line of Eq. (4). Now that fundamental understanding of the WEC model's governing EOM has been established, the first step in the modeling methodology is to create a WEC geometry and determine its frequency domain response, this process will be described in the next section.

$$F_{e_1} - F_{r_{11}} - F_{r_{12}} = \rho_{SW} g A_1 x_1 + b_v \dot{x}_1 + (m_1 + A_{11}(\infty))\ddot{x}_1 \quad (7)$$

$$F_{e_2} - F_{r_{22}} - F_{r_{21}} - F_m(x_2, \dot{x}_2) = b_v \dot{x}_2 + (m_2 + A_{22}(\infty))\ddot{x}_2 \quad (8)$$

$$F_{r_{12}} = \int_{-\infty}^{t} f_{r_{12}}(t-\tau)\dot{x}_2(\tau)d\tau + A_{12}(\infty)\ddot{x}_2 \quad (9)$$

$$F_{r_{21}} = \int_{-\infty}^{t} f_{r_{21}}(t-\tau)\dot{x}_1(\tau)d\tau + A_{21}(\infty)\ddot{x}_1 \quad (10)$$

Two-Body Hydrodynamic Response

Once a WEC's 3D geometry is modeled, the next step is to determine the WEC's frequency-domain response using a hydrodynamic code. This step is necessary because the frequency-domain response is used to calculate time-domain IRFs, which are needed to define the two-body point absorber EOM, (8) and (9). The 3D geometry of L10 WEC was modeled using the dimensions defined in Table 2, then it was imported into AQWA and meshed, as shown in Fig. 11. The two-body point absorber was modeled with m_1 = 2,625.3 [kg] and m_2 = 2,650.4 [kg] at a water depth of 100 [m]. AQWA is then used to solve for the frequency-domain hydrodynamic complex excitation force, $f_e(i\omega)$. radiation force coefficient, $f_r(\omega)$, and added mass, $A(\omega)$, for both the buoy and spar/plate, all terms which are necessary to solve the two-body point absorber EOM. The two-body point absorber's frequency-domain added mass is used to determine the buoy's infinite added mass, $A_{11}(\infty) =$ 8866.7 [kg], the spar/plate's infinite added mass, $A_{22}(\infty) = 362$ [kg].

Table 2. Two-Body Point Absorber Dimensions

Buoy	Diameter	3.5 [m]
	Height	0.76 [m]
Spar/Plate	Diameter	1.1 [m]
	Height	7.03 [m]

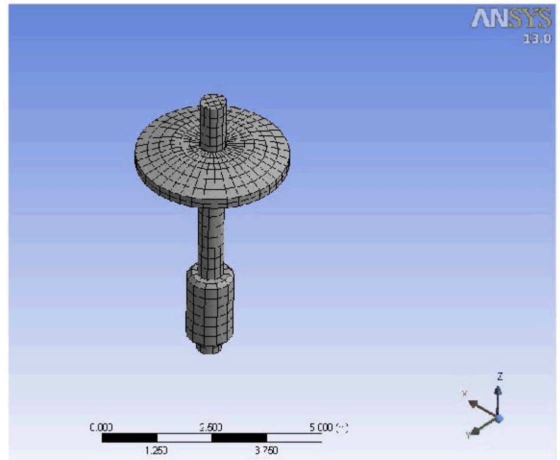

Fig. 11 - L10 Wave Energy Converter Meshed in AQWA

After the L10's frequency-domain response is determined using a hydrodynamic code, the complex excitation force, $f_e(i\omega)$, and radiation force coefficient, $f_r(\omega)$ are used to calculate the WEC's time-domain IRFs. For the two-body point absorber EOM, excitation IRFs must be calculated for the buoy, and spar/plate and radiation IRFs must be calculated for the buoy, spar/plate and coupled interaction. The non-causal time-domain excitation IRFs are calculated via Eq. (5) using the frequency-domain excitation magnitude and phase, and the causal time-domain radiation IRFs are calculated via Eq. (6) using the frequency-domain radiation coefficient.

Two-Body WEC Dynamics Model

Once the two-body point absorber's time-domain IRFs are calculated, the next step is to solve the governing EOM for the WEC's displacement and velocity. The two-body point absorber EOM defined in Eq. (7) and Eq. (8) are implemented and solved in MATLAB/Simulink. First, the MATLAB/Simulink two-body WEC Dynamics Model will be introduced by describing the function of the model's systems and subsystems. Then output from the two-body WEC Dynamics Model will be presented for the same irregular wave surface elevation used for the single-body point absorber. The time-series wave surface elevation used is from NDBC buoy 46229 data in June 2008.

WEC Dynamics Model Structure

Similar to the single-body WEC Dynamics Model, the two-body WEC Dynamics Model takes the wave surface elevation, $\eta(t)$, as its input and solves for the velocity and displacement of the buoy and spar/plate. The top level of the two-body WEC Dynamics Model as implemented in Simulink is shown in Fig. 12. The top level of the model defines the system's input and its outputs as well as its subsystems: Excitation Force Determination, WEC Dynamics, and Mooring Force Determination. The Excitation Force Determination subsystem calculates the excitation force due to the incident wave on the buoy, $F_{e_1}(t)$, and on the spar/plate, $F_{e_2}(t)$. The Mooring Force Determination subsystem calculates the force the mooring system imparts on the WEC as a function of the spar/plate's displacement and velocity, $F_m(x_2, \dot{x}_2)$, using the second line of Eq. (4). The WEC Dynamics subsystem, shown in Fig. 13, shows the modeling structure that solves for the two-body WEC dynamics consisting of the following subsystems: Buoy Dynamics, Coupling Radiation Damping Force, and Spar/Plate Dynamics. The Buoy Dynamics subsystem implements Eq. (7) and solves for the buoy's displacement and velocity, and the Spar/Plate Dynamics subsystem implements Eq. (8) and solves for the spar/plate's displacement and velocity. Both the Buoy Dynamics and the Spar/Plate Dynamics subsystems are very similar in structure to the single-body point absorber subsystem. The Coupling Radiation Damping Force subsystem uses Eq. (9) and Eq. (10) to determine the coupling radiation force between the buoy and then the spar/plate.

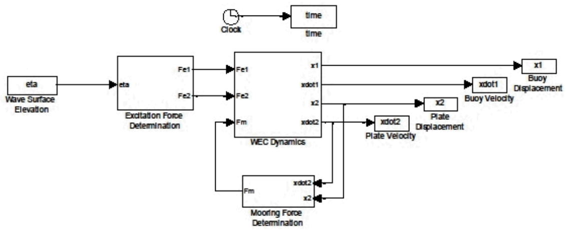

Fig. 12 - Simulink Two-Body Point Absorber Model: Top Level

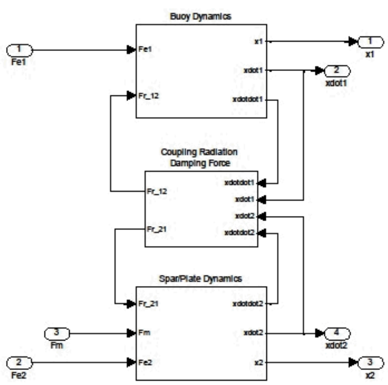

Fig. 13 - Simulink Single-Body Point Absorber Model: WEC Dynamics Subsystem

WEC Dynamics Model Output

The two-body WEC Dynamics Model developed in MATLAB/Simulink is then used to estimate the L10's response when subject to real ocean waves collected by NDBC buoy 46229. Before running the model, the viscous damping terms defined in Eq. (8) and Eq. (9), b_{v1} and b_{v2} , must be determined. These terms are constants included in the two-body point absorber EOM to account for viscous effects that are otherwise ignored in this modeling methodology. Ideally, appropriate viscous damping terms would be determined by matching experimental RAOs with the model's RAOs, however unlike the single-body point absorber geometry, there is no experimental wave tank data available for the L10 (or any other two-body point absorber).

Since the WEC modeling methodology presented in this paper is intended for use as an initial design tool, it is not uncommon that a geometry will be modeled prior to experimental wave tank testing. Because of this, it is recommended that initial viscous damping terms are chosen based on the following criteria. The viscous damping term should be chosen so that the model converges to a stable solution near resonance and eliminates high-frequency vibration; otherwise, the model is an underdamped system with RAOs spiking near resonance. For the L10, these criteria were met with viscous damping terms b_{v1} = 5,000 [N/m/s] and b_{v2} = 50,000 [N/m/s]. Furthermore, it is recommended that once experimental data is collected, the viscous damping terms should be refined using the process described in the single-body point absorber section.

Once the viscous damping terms for two-body point absorber model are determined, the WEC Dynamics Model can be used to estimate the WEC's response to irregular waves. The wave surface elevation is plotted with the buoy and spar/plate's heave displacement response on the top of Fig. 14, and the velocity of the buoy relative to the spar/plate, $\dot{x}_2 - \dot{x}_1$, is plotted on the bottom. For the relatively low energy wave climate of June, the WEC's relative velocity typically ranges from +/- 2 [m/s], a term that is especially important term because it drives the PTO system.

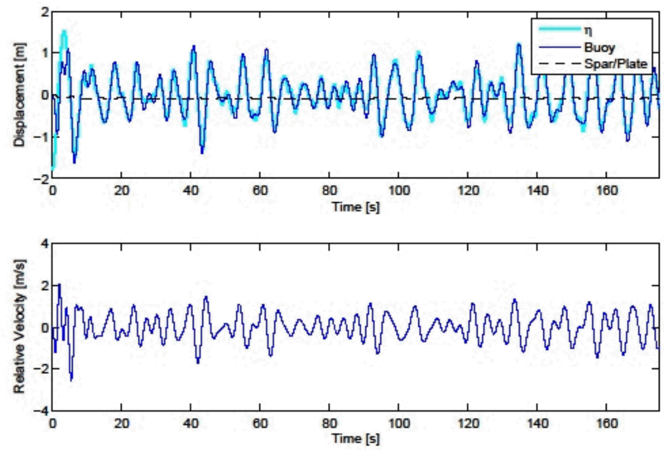

Fig. 14 - Two-Body Point Absorber Irregular Wave Response: (top) Wave and WEC Displacement, (bottom) Relative Velocity

CONCLUSIONS

As an effort to promote and support development of the wave energy industry, a modeling methodology was developed than can be used to estimate the performance of point absorber WECs for a given wave climate. This modeling methodology is presented as a flowchart in Fig. 1, and is applicable for modeling both single-body and two-body point absorbers with arbitrary geometry. The first step is to determine the frequency-domain response of a point absorber's 3D geometry. Impulse response functions are then calculated from the point absorber's frequency-domain response, and they are used to define the governing time-domain equations of motion. Time-series wave surface elevation is then used as the input to the WEC Dynamics Model developed in MATLAB/Simulink that solves for the point absorber's response.

The modeling methodology was first applied to a single-body point absorber geometry representative of designs currently being pursued. Then experimental wave tank data for the same geometry was used to determine a viscous damping term appropriate for the Oregon wave climate. This value was determined by averaging the tuned viscous damping terms for Oregon's dominant wave periods, 9 to 13 [s]. Using this viscous damping term, the response amplitude operators from the single-body WEC Dynamics Model were compared to experimental response and results from a RANS simulation for the same single-body point absorber geometry. For the dominant wave periods of interest, the response determined from the single-body WEC Dynamics Model is very good, typically with less than 10% error by comparison with experimental data.

The modeling methodology was then applied to model Oregon State University's L10 two-body point absorber. Unlike the single-body geometry, there is currently no experimental wave tank data publicly available for two-body point absorbers even though they are a common design. Viscous damping terms for the two-body model were determined by two criteria: eliminate high frequency vibration and converge to a stable solution near resonance. Since the modeling methodology is intended for use as a fast solving design tool, it is not uncommon that experimental data will not be available for a particular geometry. However, it is recommended that once experimental data is available, it should be used to refine the model similar to what was done for the single-body geometry.

A benefit of modeling in MATLAB/Simulink is its modular nature which allows the WEC Dynamics Model to be extended to include a power PTO subsystem on the top level that can be used to estimate the device's power output. A hydraulic PTO model is under development to be incorporated into the WEC Dynamics Model (Ruehl 2010). The modularity of this model makes it well suited for comparing WEC performance with different PTO systems by simply using a different subsystem. Additionally, since MATLAB/Simulink is often used to develop control strategies, thus another possible extension of the WEC Dynamics model is to implement and evaluate different methods of control. The work presented in this paper demonstrates preliminary results towards the development of WEC-Sim, an open source DOE funded WEC design tool. When complete, WEC-Sim will be capable of modeling many different WEC archetypes with multiple degrees of freedom that will include modules for mooring, PTO and control.

ACKNOWLEDGEMENTS

This research was made possible by support from the Department of Energy's EERE Office's Wind and Water Power Program. The work was supported by the Northwest National Marine Renewable Energy Center (NNMREC) under Department of Energy Award Number DE-FG36-08GO18179, and by Sandia National Laboratories, a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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