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DEVELOPMENT AND DEMONSTRATION OF THE WEC-SIM WAVE ENERGY CONVERTER SIMULATION TOOL

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ABSTRACT

The National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (SNL) have developed WEC-Sim to provide the wave energy converter (WEC) design community with an open-source simulation tool. WEC-Sim models the system dynamics of WEC devices using multi-body dynamics methods and simulates hydrodynamic forces using coefficients predicted from potential flow models. In this paper we describe the methodology used in WEC-Sim and demonstrate the use of the code by simulating three WEC devices. Specifically, we model a two-body point absorber and two oscillating surge devices. For each device we describe how the WEC-Sim model was setup and present simulation results, such as predictions of device motions and power production. For verification and validation purposes, results are compared to corresponding results from other modeling tools and experimental data.

BACKGROUND AND MOTIVATION

Open-source numerical modeling tools have helped the wind energy industry achieve commercial viability by enabling the rapid development, analysis, and certification of wind turbine systems. The recent emergence of the WEC industry in the U.S. and across the globe has created a need for an equivalent set of WEC design and analysis tools to help advance WEC technologies. Device developers are currently relying heavily on commercial modeling tools, such as OrcaFlex, WaveDyn, and AQWA to meet their modeling needs. However, with the wide range of device archetypes currently being developed, and the fast pace of innovation in the WEC industry, there is a need for an open-source, WEC specific suite of tools that can be quickly modified to meet rapidly evolving modeling needs. Moreover, developing open-source modeling tools will help establish a collaborative research community that can play a role in accelerating the pace of technology development. To meet this need, the US Department of Energy (DOE) has funded NREL and SNL to initiate a wave energy converter modeling effort with the objective of providing a suite of open-source design and analysis tools to the WEC research and development community. Specific goals of the project are:

1. Develop WEC-Sim, an open-source, modular code for simulating WEC devices in operational wave conditions.
2. Perform a rigorous verification and validation of WEC-Sim through code-to-code comparisons and comparison with experimental data.
3. Develop an open-source boundary element method (BEM) hydrodynamics simulation tool by leveraging the TopCoder online coding competition platform [1] and the recently released Nemoh [2] BEM code.
4. Perform experimental tests to generate validation data that will be made freely available to the WEC community.

NREL and SNL recently developed the first version of the WEC-Sim code that will be publically released in Summer 2014. Herein we focus on WEC-Sim, beginning with a description of the theory used to develop the code. Next, we describe how the theory was implemented. Finally, we demonstrate WEC-Sim's capabilities by simulating a two-body point absorber and two oscillating surge devices. To verify and validate the accuracy of the WEC-Sim code, results are compared with corresponding results from other numerical models and experimental data.

THEORY

At its most basic, WEC-Sim solves the Cummins' Equation (Eq. 1) [3] in 6 degrees of freedom (DOF) to determine the motions and forces on a WEC device.

$$(m+m_\infty)\ddot{x} = -\int_{-\infty}^{t} f_r(t-\tau)\dot{x}(\tau)d\tau - F_{hs} + F_e + F_v + F_{ext}. \tag{1}$$

Here, m is the mass matrix and m_∞ is the added mass matrix. The term $-\int_{-\infty}^{t} f_r(t-\tau)\dot{x}(\tau)d\tau$ is the convolution integral that represents the resistive force on the body due to wave radiation, F_{hs}, F_e, F_v and F_{ext} are the hydrostatic force, the wave excitation force, the viscous drag force, and externally applied forces (e.g. the power-take-off system forces and mooring system forces), respectively.

Inviscid hydrodynamics are modeled using linear coefficients calculated using a potential flow boundary element method (BEM) solver. Viscous hydrodynamics (i.e. the viscous drag force) is estimated using quadratic damping term with drag coefficients from experimental data or computational fluid dynamics simulations [4]. Using the coefficients to model the hydrodynamic forces on the device allows WEC-Sim to use time-domain multi-body-dynamics methods to simulate device motions and loads in a computationally efficient manner. In the current version of WEC-Sim, external power-takeoff (PTO) forces are modeled as linear or rotational spring damper systems. A more realistic model that accounts for dynamic PTO system behaviors, such as generator inertia and hydraulic system dynamics, is currently being developed. Mooring system dynamics are modeled using a stiffness matrix, which can be generated using a quasi-static lumped mass mooring system model [5].

NUMERICAL IMPLEMENTATION

The numerical model was implemented in MATLAB [6] and its Toolboxes (SIMULINK and SimMechanics) using the modular structure shown in Figure 1. WEC-Sim modules are divided into three types:

1. Pre-processing modules are executed once at the beginning of a simulation to prepare user input data and perform calculations that are not time-dependent. (blue)
2. Time-domain modules simulate specific device components and solve the equation of motion (Eq. 1) to model the WEC system. (green)
3. Post-processing modules are responsible for visualization and simulation data analysis. (red)

Figure 2 illustrates the steps in creating a WEC-Sim simulation. The remainder of this section describes these basic steps and provides more details on how WEC-Sim was developed in the MATLAB framework. For completeness, Appendix A provides further details on each WEC-Sim module.

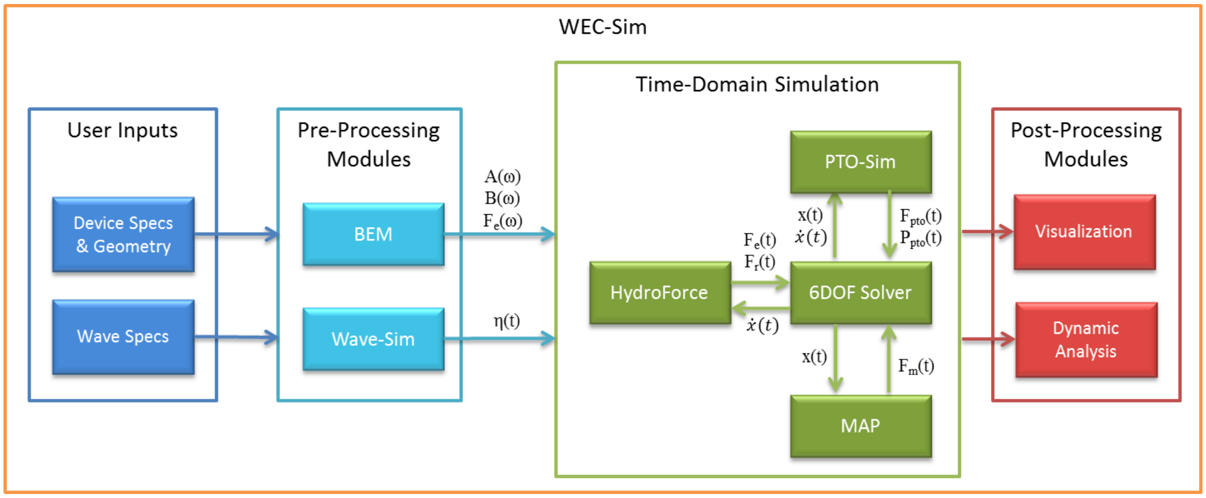

Figure 1 - The WEC-Sim code structure

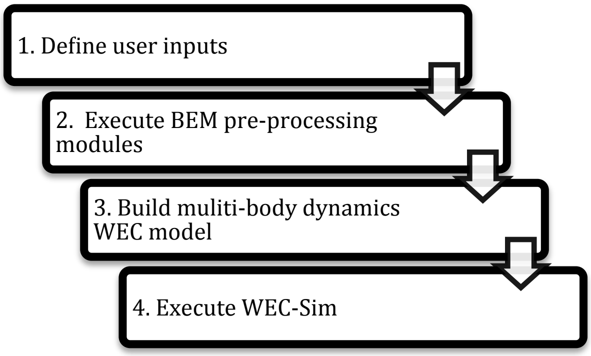

Figure 2 - The steps to build and run a WEC-Sim model

Step 1: The user first inputs the WEC geometry properties, such as mass, moments of inertia, and center of gravity, and the wave specifications, such as wave period and height or wave spectrum.

Step 2: The user's inputs are used to run the pre-processing modules. Specifically, the Wave-Sim module generates wave time-series, and a boundary element method (BEM) solver determines the WEC's hydrodynamic coefficients. Currently, WEC-Sim uses WAMIT [7] as its BEM solver. The WEC-Sim development team is currently working to switch to an open-source BEM code, which is being developed based on Nemoh [2].

Step 3: The user then creates a time-domain multi-body dynamics model of the device from a library of pre-built WEC components (Figure 3).

The user creates the model by dragging the appropriate number of bodies, joints and connections into the WEC-Sim model, and connecting them according to their physical layout. Each pre-built component contains time-domain modules that simulate the relevant physics for that component. For example, as Figure 4 shows, the body block that represents rigid WEC bodies contains the HydroForce module components that model hydrodynamic forces on the body.

Step 4: Once the WEC model is constructed, the SimMechanics 6DOF multi-body solver performs the simulation by summing forces from time-domain modules at each time-step and advancing the simulation in time using a 4th order Runge-Kutta integration scheme.

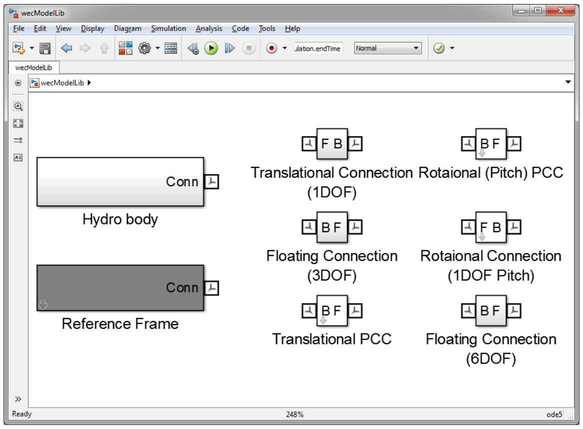

Figure 3 - WEC-Sim rigid body and joint connection library

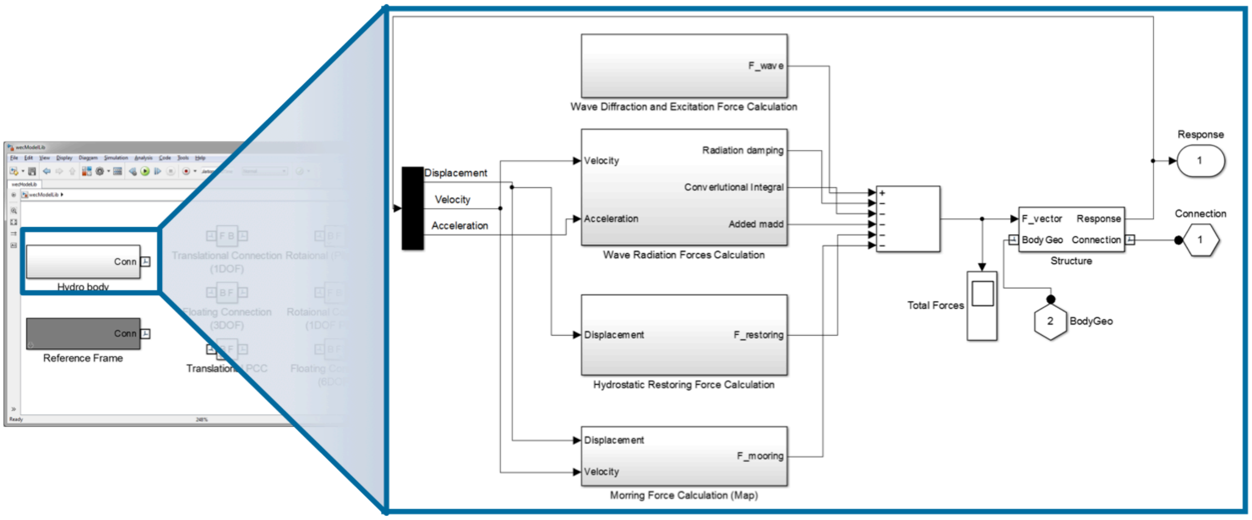

Figure 4 - The contents of the pre-built WEC-Sim body block used to model rigid bodies

CODE DEMONSTRATION

The following two sections demonstrate the use of WEC-Sim by describing simulations of a two-body point absorber a bottom-fixed oscillating surge device and a floating oscillating surge device.

Two-Body Floating Point Absorber Device

We used the WEC-Sim code to model the Reference Model 3 (RM3) WEC that was designed as part of the DOE Reference Model Project [8]. The RM3 geometry and mass properties are defined in Figure 5 and Table 1 respectively. More details on the RM3 device specifications, and its WEC-Sim model application can be found in [9].

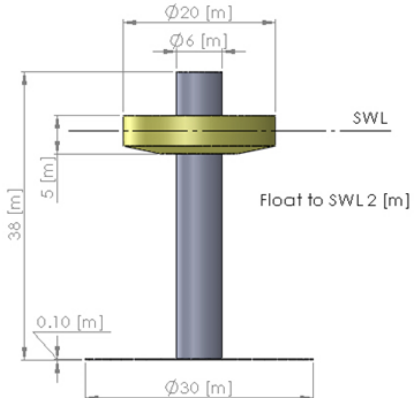

Figure 5 - Schematic of the RM3 floating point absorber

Table 1 - Mass properties and dimensions for the RM3 WEC.

	CG [m]	Mass [tonne]	Moment of Inertia [kg-m^2]		
Float	0.00	727.01	2.09E+07	0.00E+00	0.00E+00
	0.00		0.00E+00	2.13E+07	4.30E+03
	-0.72		0.00E+00	4.30E+03	3.71E+07
Spar/ Plate	0.00	878.30	9.44E+07	0.00E+00	0.00E+00
	0.00		0.00E+00	9.44E+07	2.18E+05
	-21.29		0.00E+00	2.18E+05	2.85E+07

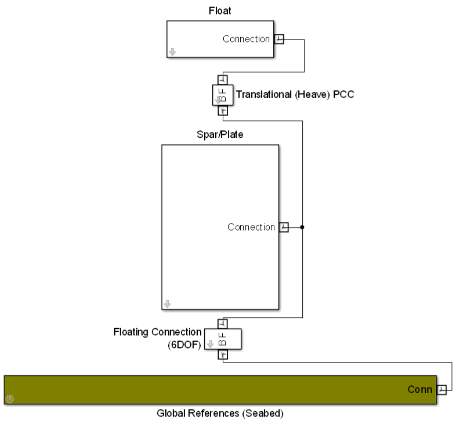

Figure 6 - WEC-Sim model for simulating The RM3 two-body point absorber

The RM3 WEC visualized in WEC-Sim's SimMechanics environment is shown in Figure 6. The float is connected to the spar/plate through a translational joint with a defined linear damping coefficient that simulates the PTO system, and the spar/plate is connected to the seabed through a 6DOF floating connection.

We modeled the RM3 device in WEC-Sim in 1DOF (heave), with PTO damping equal to 1200 kNs/m, and no mooring stiffness or viscous drag coefficients. Simulations were run for regular waves with T = 8 sec and H = 2m for 400s, with wave ramping for the first 100s of the simulation. Figure 8 shows a real-time visualization of WEC-Sim results within the SimMechanics environment.

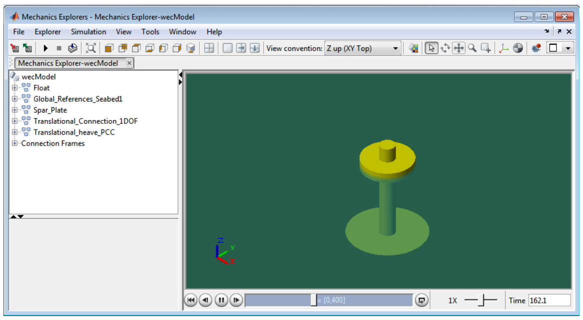

Figure 7 – Visualization GUI for the WEC-Sim RM3 Two-Body Point Absorber Model

The dynamic response of both the float and the spar/plate are shown in Figure 8 As shown in Figure 8, the RM3 WEC-Sim simulation has very good agreement with the commercial codes AQWA and WaveDyn. A similar code-to-code comparison was performed for the same WEC in 3DOF, results of which are shown in [9].

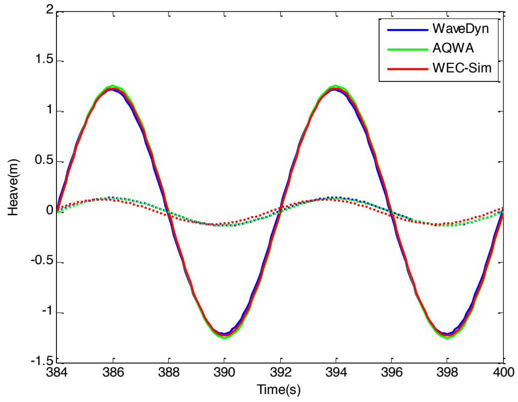

Figure 8 - 1DOF heave float and spar/plate response without PTO for the last 2 wave periods of the simulations

Oscillating Surge Device

Oscillating surge wave energy converters (OSWECs, Figure 9 and Figure 13) generate electrical power by utilizing the surge motion of waves to force a flap to rotate with respect to a reference point. Several designs have been proposed by the MHK industry, including Oyster, EB-Frond, WaveRoller and Langlee. This section presents the simulation results from modeling two OSWEC designs; a bottom-hinged design and a slack-moored floating design. The simulations were performed with different irregular sea states, which were characterized by significant wave height (H_s) and peak wave period (T_p), represented using a Brechtschneider spectrum.

Bottom-Hinged OSWEC

The schematic of the bottom-hinged OSWEC and the model setup in WEC-Sim are shown in Figure 9 and Figure 10, respectively. The device captures wave energy from the relative motion between the flap and the fixed base. In the WEC-Sim model the base was rigidly connected to the seabed, and the flap was connected to the base through a rotational joint. The joint contains a spring-damper system that represents the PTO system. The mass properties and device dimensions are listed in Table 2 and were determined based on the values given by van't Hoff [10].

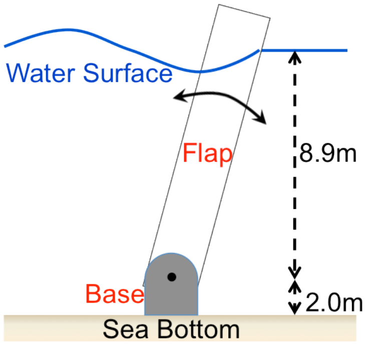

Figure 9 - Schematic of the bottom-hinged OSWEC device

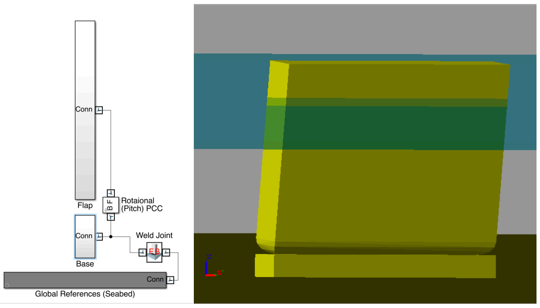

Figure 10 - WEC-Sim Model setup for the bottom-hinged OSWEC

Table 2. Mass properties and dimensions for the bottom-hinged OSWEC.

Parameters	Values (Unit)
Dimensions (width x thickness)	18 m x 1.8m
Hinge Depth (from water line)	8.9 m
Moment of Inertia (at Hinge)	1.85×10^6 kgm^2
Restoring Stiffness (at Hinge)	6.4 MNm/rad

We performed a WEC-Sim simulation at six selected sea states. The PTO damping coefficients were selected based on the values given in the experimental study. For each case, the simulation duration was $125 \times T_p$ long with a ramp time of $25 \times T_p$ and a time step size of $0.01 \times T_p$. A drag coefficient of 8 was selected for the flap motion [11]. Figure 11 shows an example of the flap response and power output from a WEC-Sim simulation with Hs=1.75 m and T_p=10.5 s.

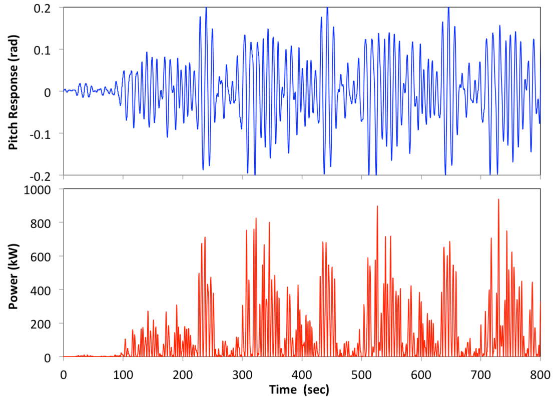

Figure 11 - Example of instantaneous flap pitch response (top) and power output (bottom) from Wec-Sim

To validate the WEC-Sim model, we compared the averaged mechanical power results to those reported in van't Hoff's experimental study [10]. The power production values are plotted against the energy period, T_e, in Figure 12, where T_e is approximately 1.16 times T_p [12]. The WEC-Sim simulations results agreed well with those from the wave tank test measurements.

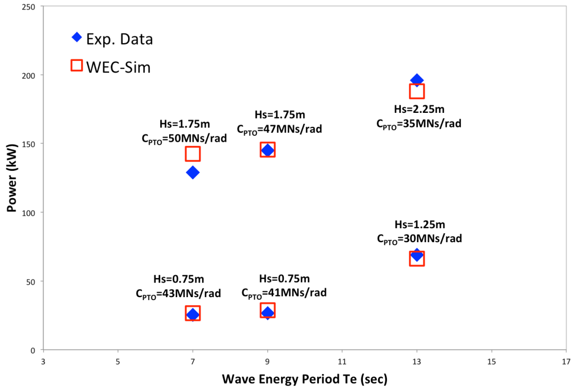

Figure 12 - Mechanical Power performance from WEC-Sim and experimental data (in full scale) [13]

Slack-Moored Floating OSWEC

The schematic of the slack-moored floating OSWEC is presented in Figure 13. The device contains two fore flaps and two aft flaps, which are both connected to a supporting frame. The device converts wave energy from the relative motion between the flaps and the frame.

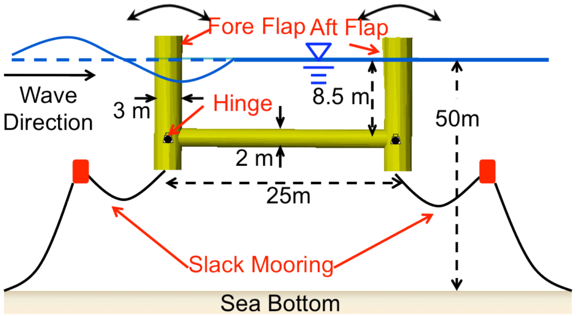

Figure 13 - Schematic of the floating OSWEC device

The mass properties and device dimensions were given based on Babarit's study [11], and the values are listed in Table 3. The listed values for the flaps only account for the mass properties of a single flap. To balance the net buoyance restoring force caused by the device displacement and gravity, additional ballast was included. For simplicity, we assumed the weight of the frame was equal to its displacement, and the weight of the mooring line was not considered in the simulations. The ballast was equal to the net force caused by the buoyance for of the flap and gravity and was added to the frame as point mass.

Table 3 - Mass properties and dimensions for the floating OSWEC

Flap	Width (m)	9.5
	Draft (m): WL to Hinge	8.5
	Thickness (m)	2
	Mass (Ton)	85
	Number of Flaps	4
	Center of Mass (m)	(±12.5,0,-3.5)
	MOI (Ton m^2)	1300
Supporting Frame	Width (m)	25
	Draft (m)	12
	Center of Mass (m)	(0,0,-8.5)
	MOI (Ton m^2)	76300
	Ballast (Ton)	200
	Number of Ballast	2
	Ballast location	(±12.5,0,-8.5)

WL: mean water line
MOI: moment of inertia at CG

The WEC-Sim OSWEC model setup is shown in Figure 14. Each flap is connected to the frame through a rotational spring-damper joint to represent the PTO system. Because the incoming wave was assumed to propagate normal to the flap, the simulation was simplified to a 3DOF problem, where the device was only allowed to move freely in surge, heave, and pitch. In addition, we assumed that the device was connected to a slack mooring system, and the mooring effect on the device power generation performance was negligible [11]. A small spring stiffness value of 40 kN/m was therefore specified in the horizontal direction only to keep the device in position.

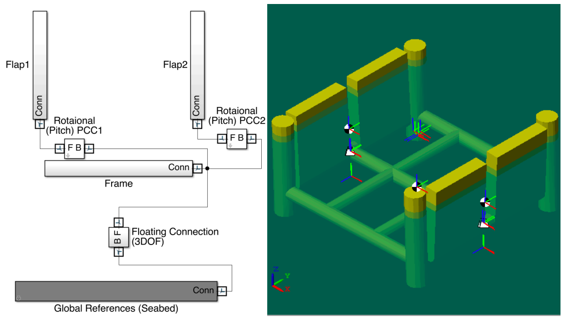

Figure 14 - WEC-Sim model setup for the Floating OSWEC.

A series of WEC-Sim simulations were performed with H_s equal to 2.5 m and a range of T_p between 6 s and 15 s. For each case, the simulation duration was 125×T_p long with a ramp time of 25×T_p and a time step size of 0.005×T_p. The drag coefficient was also assumed equal to 8, as in the previous simulations.

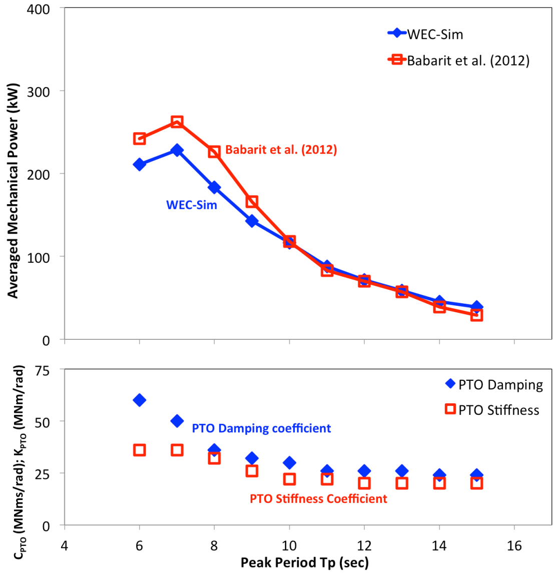

Figure 15 - Averaged mechanical power for the floating OSWEC and corresponding C_{PTO} and K_{PTO} values (H_s=2.5m)

The time-averaged mechanical power was calculated, and the results from WEC-Sim were compared to those numerical simulation results presented in [14]. The comparison of the time-averaged mechanical power is shown in Figure 15. The corresponding C_{PTO} and K_{PTO} for each case under different sea states were given based on [11] and are also plotted in Figure 15. Overall, the WEC-Sim results agreed well with those obtained from [14]. The slight difference could be attributed to the differences in the way that WEC-Sim and Babarit [14] modeled the viscous drag term and specified the mass distribution of the device in the simulations. Furthermore, the current version of WEC-Sim does not model off-diagonal radiation added-mass and damping terms from other bodies, whereas Babarit [14] considers these terms. Further studies are underway to develop the capability to model off-diagonal hydrodynamic forces from other bodies.

CONCLUSIONS

NREL and SNL have developed an open-source numerical modeling tool for design and analysis of a wide span of WEC devices. In this paper, we applied WEC-Sim to model a two-body floating-point absorber and two types of oscillating surge designs, a bottom-hinged system and a floating design. A preliminary verification and validation study was conducted by comparing the WEC-Sim simulation results to those obtained from other numerical models and existing experimental data. Overall, the WEC-Sim predictions agreed well with those numerical and experimental results.

The WEC-Sim is still under the development process. Further studies are being conducted to improve the WEC-Sim modeling capabilities, including the calculation of nonlinear restoring and wave excitation forces and off-diagonal hydrodynamic forces from other bodies. A PTO library module is also currently being developed for simulating different types of PTO systems, which considers a more realistic PTO system behaviors, including generator inertia and hydraulic system dynamics. In addition, experimental tests for generating validation data have been planed. These experimental studies are necessary to further validate WEC-Sim, and the experimental data that will be made freely available to the WEC community.

ACKNOWLEDGEMENTS

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APPENDIX A: DESCRIPTION OF WEC-SIM MODULES

Table A1. Description of WEC-Sim modules

Module	Code Type	Description
BEM	Commercial code: WAMIT	Determines hydrodynamic coefficients using boundary element method simulation methods.
WaveSim	In-house code developed in MATLAB	Generates simulated wave states using measured wave data and standard wave spectra.
HydroForce	In-house code developed in MATLAB	Calculates time dependent hydrodynamic forces using inviscid hydrodynamic coefficients (from BEM module), viscous drag coefficients, relative device motions, and the current sea state.
PTO-Sim	In-house code developed in SIMULINK	PTO-Sim will enable time dependent electrical power predictions from the calculated mechanical power. PTO-Sim will be broken into modules that allow for custom PTO-train configurations.
Multi-Body Solver	In-house code developed in SimMechanics	SimMechanics is a MATLAB Toolbox. WEC device is modeled in SimMechanics by connecting the appropriate number of bodies, joints and connections, according to their physical layout. The multi-body multi-degree-of-freedom system is then solved in the time domain by SimMechanics.
MAP	In-house code developed in Python and C++	A quasi-static mooring line module developed at NREL in collaboration with the NREL Wind Power Program.