

OMAE2016-54984

WEC-SIM PHASE 1 VALIDATION TESTING - EXPERIMENTAL SETUP AND INITIAL RESULTS

**Bret Bosma, Asher Simmons
and Pedro Lomonaco**
Oregon State University
Corvallis, Oregon USA

Kelley Ruehl, Budi Gunawan
Sandia National Laboratories
Albuquerque, New Mexico USA

ABSTRACT

In the wave energy industry, there is a need for open source numerical codes and publicly available experimental data, both of which are being addressed through the development of WEC-Sim by Sandia National Laboratories and the National Renewable Energy Laboratory (NREL). WEC-Sim is an open source code used to model wave energy converters (WECs) when subject to incident waves. In order for the WEC-Sim code to be useful, code verification and physical model validation is necessary. This paper describes the wave tank testing for the 1:33 scale experiments of a Floating Oscillating Surge Wave Energy Converter (FOSWEC). The WEC-Sim experimental data set will help to advance the wave energy converter industry by providing a free, high-quality data set for researchers and developers. This paper describes the WEC-Sim open source wave energy converter simulation tool, experimental validation plan, and presents preliminary experimental results from the FOSWEC Phase 1 testing.

INTRODUCTION

The nascent wave energy industry includes many young researchers and new developers who are eager to make commercialization a reality. One roadblock preventing rapid evolution of a prevailing technology is the industries tendency to avoid freely and openly sharing data. In addition, developers often need to rely on expensive numerical modelling packages and lack the resources for physical model testing data in order to validate their prototypes.

WEC-Sim is an open source code, developed by Sandia and NREL, used to model wave energy converter (WEC) performance in operational and extreme waves. WEC-Sim code development is part of the US Department of Energy Wind and Water Power Technologies Office's initiative to promote and support the emerging wave energy industry. The WEC-Sim code is a time-domain modeling tool developed in MATLAB/Simulink using the multibody dynamics solver SimMechanics [1]. WEC-Sim solves the WEC's governing

equations of motion using the Cummins time-domain impulse response formulation in 6 degrees of freedom (DOF) [2].

The WEC-Sim code has undergone verification through code-to-code comparisons; however validation of the code has been limited to publicly available experimental data sets. While these data sets provide preliminary code validation, the experimental tests were not explicitly designed for code validation, and as a result are limited in their ability to validate the full functionality of the WEC-Sim code. Dedicated physical model tests for WEC-Sim validation are being performed in two phases.

This paper will provide an overview of the dedicated WEC-Sim validation experimental wave tank tests performed at the Oregon State University's (OSU) Directional Wave Basin (DWB) at Hinsdale Wave Research Laboratory (HWRL). Phase 1 of experimental testing was focused on the FOSWEC device characterization, and was completed in winter 2015. Phase 2 will be focused on characterization of the FOSWEC's dynamics and performance, and is scheduled for spring 2016. This phased approach allowed for initial data to be analyzed, refinements to the numerical and physical model, and evaluation of instrumentation and testing methods. The experiments have been designed explicitly to validate the performance of the WEC-Sim code and its new feature additions. Upon completion, the WEC-Sim validation data set will be made publicly available to the wave energy community, so that it can be used as a numerical benchmarking data set.

For the physical model testing, a highly sophisticated and controllable model of a floating wave energy converter, the FOSWEC, has been designed and constructed. FOSWEC instrumentation includes state-of-the-art devices to measure pressure fields, motions in 6 Degrees of Freedom (DOF), multi-axial load cells, torque transducers, position transducers, and encoders. Most of the collected data has redundancy from multiple types of instrumentation. The model also incorporates a fully programmable Power Take-Off (PTO) system which can be used to generate or absorb the hydrokinetic wave energy.

This paper will primarily focus on the experimental design and setup of the WEC-Sim validation testing, while a follow-on OMAE paper will focus on numerical simulations of the Phase 1 experiments using the WEC-Sim code [3].

WAVE ENERGY CONVERTER SIMULATOR (WEC-SIM)

The WEC-Sim code is a time domain simulation tool for modeling the system dynamics of Wave Energy Converters (WECs). It supports multi-body dynamics and simulates hydrodynamic forces using coefficients predicted from potential flow models. It is implemented in the MATLAB/Simulink environment. A detailed overview of the development and demonstration of the WEC-Sim simulation tool is given in [4] and [5].

Prior to WEC-Sim development, WEC device designers relied heavily on commercial modeling packages that were more general purpose, and not specifically targeted at WECs. Moreover, these commercial packages were developed for designing ships, stable off-shore structures, and other more static applications. WEC-Sim, on the other hand, is specifically targeted at modelling WECs and caters to the needs of the industry, such as close-proximity body-to-body interactions, motion constraints, and PTO forcing.

An online forum, hosted through GitHub, allows code users to interact with the developers and the open source community. Since WEC-Sim is open source, users can modify and add features on their own to improve functionality. The GitHub code release mechanism also allows for these features to be integrated in future releases of the code.

The backbone of WEC-Sim is its ability to efficiently solve the Cummins' equation. As inputs to this equation, linear hydrodynamic coefficients are calculated using a potential flow Boundary Element Method (BEM) solver (e.g. Nemoh, Wamit, or AQWA) and imported into WEC-Sim. Additionally, experimental data or Computational Fluid Dynamics (CFD) software can be used to estimate viscous drag forces to be included in the model as a quadratic damping term. PTO forces in WEC-Sim are modelled as linear or rotational spring damper systems, or can be coupled with PTO-Sim for more sophisticated PTO models [6]. Additionally, mass and inertia properties of each body in the model need to be specified. An overview of the general WEC modelling methodology is given in [7]. The ability of WEC-Sim to calculate instantaneous buoyancy and Froude-Krylov forces is presented in [8]. A preliminary WEC-Sim code-to-code comparison is presented in [9].

The WEC-Sim code is part of a larger effort that includes development of a BEM hydrodynamics simulation tool, and experimental tests to create validation data to be made available to the community at large [10]. This physical test data will be used with code-to-code comparisons to rigorously verify and validate the WEC-Sim code.

OPEN SOURCE DATA SETS AND CODES

As an emerging industry, WEC developers are understandably protective of their intellectual property. This is

especially the case for physical model testing data and results, as any edge in the rush to commercialization is desired. Because of this, however, there is very little sharing of knowledge regarding WEC prototyping and testing between developers. This seems to be changing slowly, as there has been talk of the need for sharing within the industry for it to be successful. In fact, industry partners were consulted for the project described in this paper, and valuable feedback was attained. The industry will benefit greatly from openly published test data which is starting to emerge. For instance, the project described in this paper is working toward making one such data set. Additionally, findings and best practices learned through the WEC-Sim experimental testing effort will be made publicly available.

There are several other ongoing efforts to make publicly available data sets and simulation codes. One such effort is the Northwest National Marine Renewable Energy Center (NNMREC) open data project [11]. The project aims to make publicly available test data sets intended for researchers and developers. Another open data resource is the OpenEI Marine and Hydrokinetic Technology Database, which highlights projects around the world [12]. Yet another resource is OpenORE, which builds on the practice of open science to provide information on open data [13]. Data from the project described in this paper will be made available on the NNMREC open data site and on the Marine and Hydrokinetic Data Repository [14].

VALIDATION TESTING OBJECTIVES

The experimental testing described in this paper has three main objectives. First, verification and validation of the numerical simulator, WEC-Sim. Motions and forces in operational waves will be compared between experimental and numerical results. Second, evaluation of new instrumentation and procedures for load characterization, with a goal of improving survivability testing. The final objective is to deliver a publicly available, high-quality data set along with the associated design and specifications. The FOSWEC architecture was chosen as the device to be tested. This geometry was chosen after a rigorous down select process involving the assessment of 11 geometries in order to find the most suitable given the desired objectives. This was accomplished using the decision matrix method. The results of the selection criteria for the FOSWEC are shown in Figure 1. For more information on the FOSWEC selection process, refer to the WEC-Sim validation testing report [15].

A total of ten weeks of physical model testing of the 1:33 scale FOSWEC is scheduled, split into two phases. Phase 1, completed in winter 2015, focused on system identification to characterize the FOSWEC, and was six weeks in duration. Phase 2, scheduled for another 4 weeks in spring 2016, will include further characterization and the addition of more advanced control system work as well as extreme conditions. The results of Phase 1 and Phase 2 testing will be a fully characterized system with sufficient data required for simulation and validation efforts.



Wave Energy Converter					
Example Image	Archetype	Industry Example	Operating DOF	PTO Type	
	Floating oscillating surge device	Langlee 	3: Surge, heave, pitch	Rotational	
Validation Ability					
WEC-Sim Modeling	DOF Testing	Wave Directionality	Body-to-Body Interaction	Nonlinear hydrostatics & hydrodynamics	Validation Ability Total
2	2	2	2	2	2
Testability					
Modularity of Testing	Performance Instrumentation	Ease of Deployment	Ease of Construction	Loads Instrumentation	Testability Total
2	2	1	1	2	1.63
Weighted Total					1.88

Figure 1. Results of the selection criteria showing the geometry chosen for the physical model testing

EXPERIMENTAL SETUP

Experimental Testing Facilities

All physical model testing is conducted at OSU in Corvallis, OR. PTO characterization and preliminary testing took place in OSU's Wallace Energy Systems Research Facility (WESRF). This preliminary work included the electrical setup, component checkout, and testing of the motor/generator, drive, and torque transducer. Bench testing to characterize losses in the PTO system and identification of desired data acquisition related to the PTO was also conducted at WESRF.

Complete device testing is performed at the HWRL. Dry tests were also conducted using the same data acquisition system used for the wave basin testing. One of the dry tests, the swing test used to characterize the model centers of mass and inertia, is shown in Figure 2.

The DWB itself, where all water testing is performed, is pictured in Figure 3. The basin dimensions are 48.8 m long, 26.5 m wide and a max depth of 1.37 m. The wavemaker is a piston type directional with 29 paddles 2.0 m high. It can create waves in a period range of 0.5 s to 10 s and can create a max wave height of 0.85 m.

Motion Constraint and FOSWEC Design

The FOSWEC captures wave energy by converting the relative rotary motion between a flap and a floating platform into electrical energy. To simplify the design requirements, the PTO is placed out of the water. The mechanical design of the FOSWEC for 1:33 scale physical model testing is shown in Figure 4, and Figure 5 includes its physical dimensions.



Figure 2. Swing test of the FOSWEC at HWRL to characterize mass and moments of inertia



Figure 3. DWB at OSU's HWRL

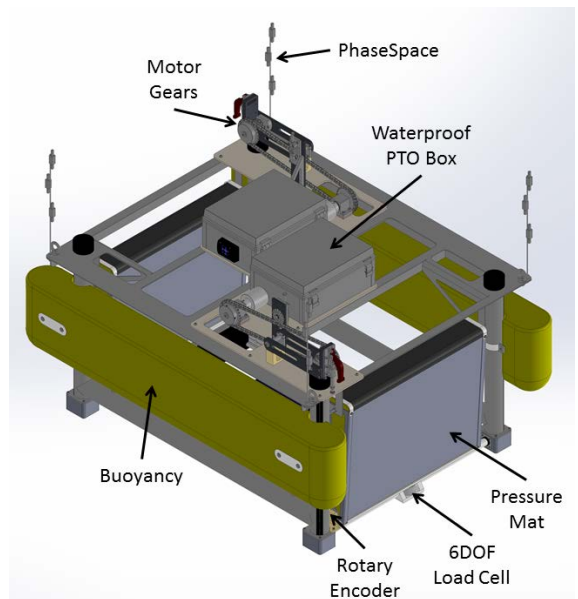


Figure 4. FOSWEC 1:33 scale design for wave basin testing at HWRL

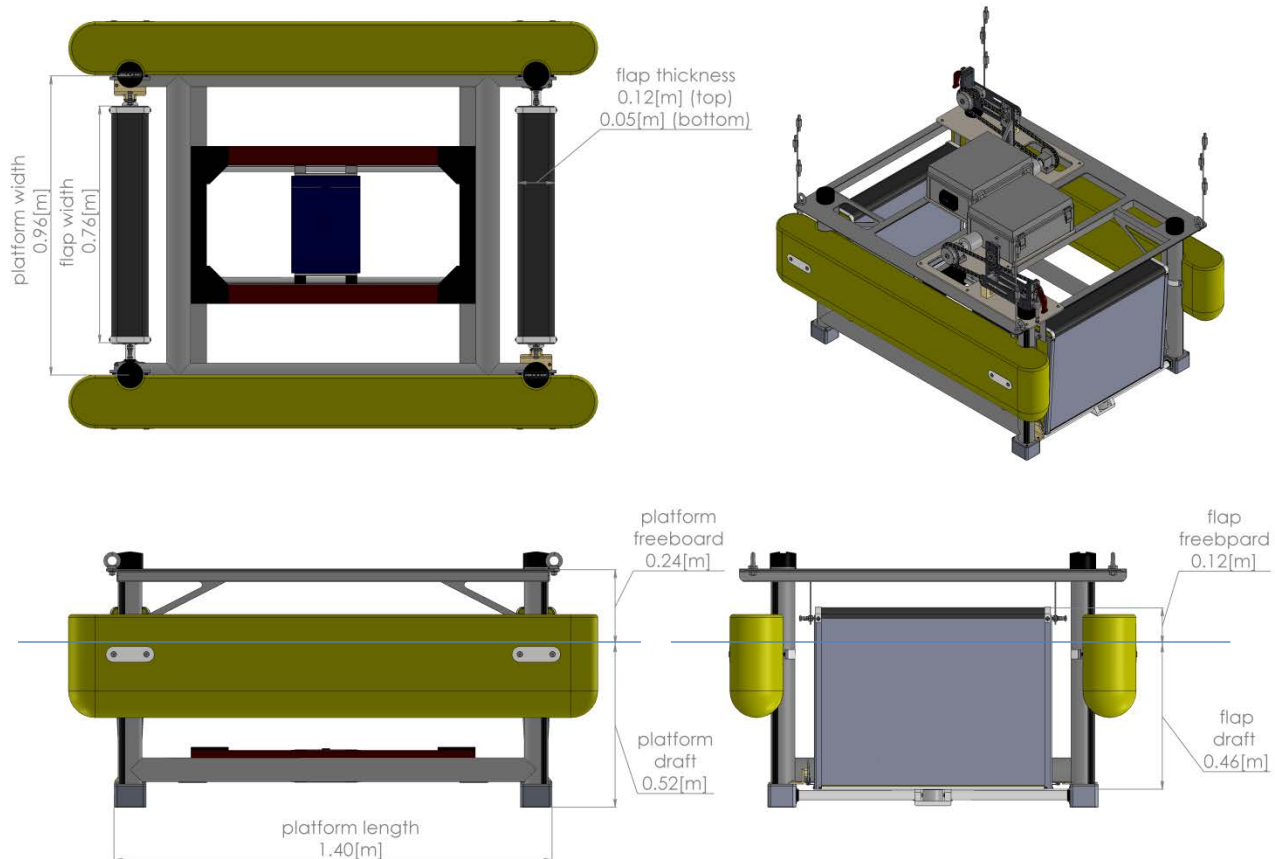


Figure 5. FOSWEC 1:33 scale dimensions

Because the focus of the study is to test the hydrodynamics of the FOSWEC without influence from nonlinear mooring forces, a motion constraint system was implemented instead of a traditional mooring system. The motion constraint system was designed with the ability to lock the platform in all DOFs of motion, and iteratively unlock certain DOF. The key modelling DOFs of interest for the platform are heave, pitch, and surge. Therefore, the motion constraint system will be able to unlock these DOFs and allow a range of motion. Furthermore, a restoring force was provided by four bungee cords for the surge motion, thus bringing the system to settle back to an equilibrium position after each test. This system is characterized in the results section. Heave, pitch, and surge motion are independently lockable, allowing for a focus on each mode, or combination of modes. This setup provides data for ever-increasing complexity of motion. Instrumentation is also included in the motion constraint system to monitor motion and forces as needed. A rendering of the motion constraint mechanical design is shown in Figure 6.

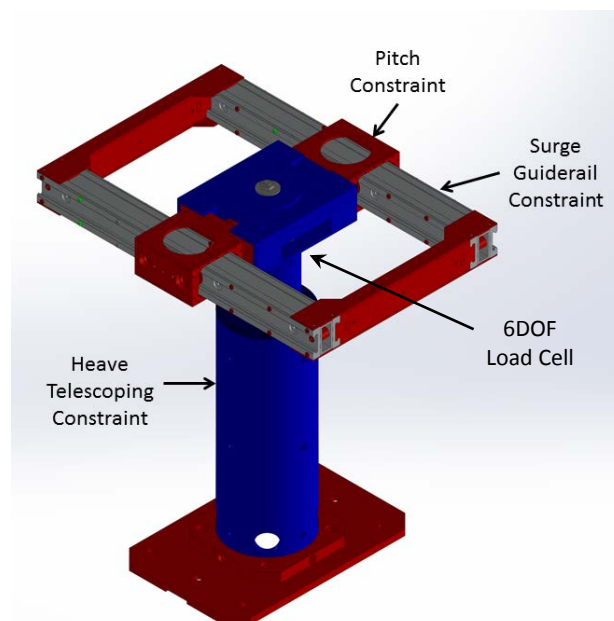


Figure 6. Motion constraint system mechanical design (view from bottom) to constrain FOSWEC motion to heave, pitch and surge. WEC is mounted on top of guiderail

PTO System

The PTO system for the experimental device was designed to provide a load to the system which is a representation of the full scale equivalent. Because of instrumentation considerations, cost constraints, and ease of operation, the PTO generator/gearbox and torque transducer were chosen to be out of the water, above the model. Figure 7 shows the PTO housing, gears and chain connecting the PTO box to the flap drive shaft. Two chains were used to transfer the motion from the primary drive shaft below the water to a motor/generator shaft above the water. The first chain is located inside the vertical pipe at the corner of the FOSWEC, while the second chain, located above the water, connects the first chain to the sprocket on the side of the waterproof box for PTO, shown in Figure 7. This provides an optional first stage of gear reduction. A torque transducer is mounted at the shaft that connects the sprocket and a gearbox with a 1:71 gear ratio. Finally, a brushed DC motor/generator is connected to the gearbox inside the waterproof box

A power electronics drive capable of providing position and torque control delivers bidirectional power flow to the motor/generator. The position control is used in the forced oscillation tests and fixed flap tests to monitor the position of the flaps. The torque control is used to provide a constant damping to the system for Phase 1 of testing. The drive system control was used in Phase 1 of testing for the forced oscillation tests, and it will be capable of implementing more advanced control schemes to be applied in Phase 2 of testing.

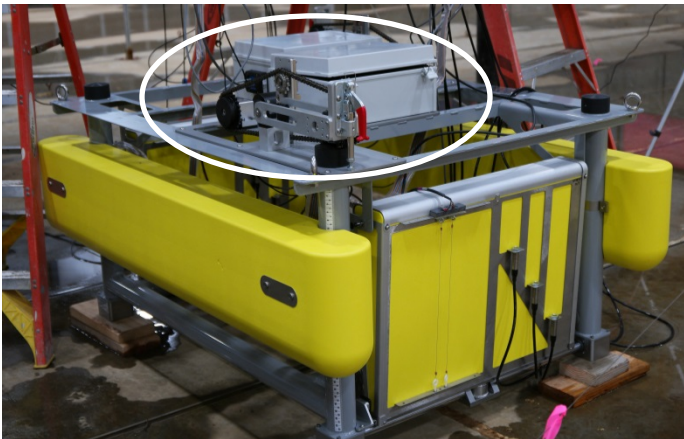


Figure 7. PTO installation in 1:33 scale FOSWEC

Instrumentation

The objective of the instrumentation is to characterize the pertinent motion, forces, and pressures related to the entire FOSWEC device. Where appropriate, redundant systems were put in place both as a check, and as a backup, in case any system fails.

In the wave basin, fourteen wave gauges were used to characterize the wave field and measure the incident waves on the model itself. Five sensors were surface piercing resistance type wave probes measuring the wave field across the basin as it approaches the model. Nine sensors were acoustic type and

were positioned around the model characterizing the wave field close to the FOSWEC.

Motion tracking of the FOSWEC platform was measured using the PHASESPACE 6 DOF motion tracking system, consisting of a set of 8 cameras attached to a rigid frame [16]. This was used to track the motion of the floating platform through LED markers attached to the upper deck of the model. Additionally, tape extension position sensors and an inclinometer were installed in order to measure the motion of the platform pitch, heave, and surge motion. This provided redundant measurements for the position of the platform, with the PHASESPACE motion tracking system being the primary measurement. To measure the motion constraint loads, a multi-axis load cell was installed at the connection between the motion constraint system and the model.

Each flap also has several sensors characterizing it. A submersible absolute encoder was placed at the end of each shaft, measuring the rotation of the flap. Six DOF load cells are used for measurement of the forces at the interface between the flap and the platform. A rotary torque transducer is also implemented, one for each flap within the PTO system. Rotary encoders attached to the generators in the PTO system will be used for providing feedback to the generators, and as a backup for the flap rotation measurement in the system. Individual pressure sensors were also installed on the flap surfaces (three for each flap), as well as a resistive wave gauge and an array of 32 x 32 sensors were placed on one side of each flap in the form of a waterproof pressure mat. Images taken of the FOSWEC instrumentation are shown in Figure 8.

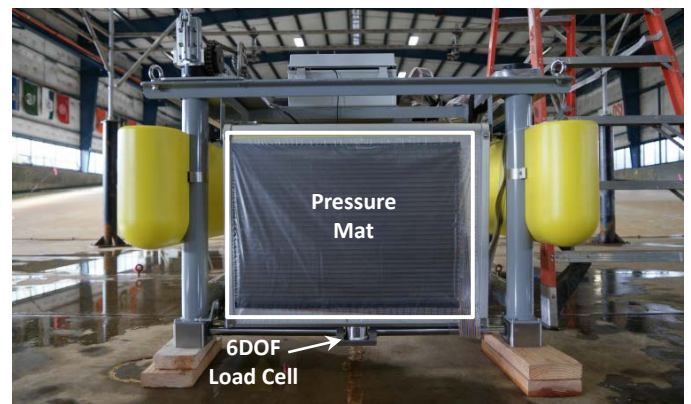


Figure 8. Pressure mat and 6DOF load cell installation on the FOSWEC flap

Experiments

Three types of experiments were conducted on the FOSWEC, namely dry tests, wet tests, and wave tests. Dry tests were performed at the WESRF lab for the PTO system and at HWRL for the overall model. Wet tests and wave tests were conducted at HWRL.

Characterization and checkout of the PTO system included the testing of the generator/gearbox combination and torque transducer. Testing of operational modes and estimates of electrical and mechanical system losses were performed.

The center of mass was estimated for each flap and the platform independently. Center of mass measurements for the flaps in y and z was done using a scale method as shown in Figure 9. Center of mass in x was assumed to be centered in the body. Center of mass for the platform in x and y was determined using the scale method and in z using the pendulum method.

For the pendulum method of determining the Center Of Gravity (COG) of the platform, an additional mass was placed at a known distance from the vertical axis of the object. The inclination angle was then measured. The elevation of the COG was then computed with equation (1) as outlined in [17]:

$$d_{COG} = \frac{Fd_1}{mgsin(\alpha)} \quad (1)$$

where d_{COG} is the distance from the pivot point to the center of mass of the object, F is the weight of the additional mass, d_1 is the distance from the additional mass to the vertical axis of the object, m is the mass of the object, g is the acceleration due to gravity, and α is the displaced angle from vertical due to the applied mass.

Moments of inertia were estimated using a pendulum method and the parallel axis theorem. The equation describing the moment of inertia at the COG is

$$I_{COG} = \left(\frac{T}{2\pi}\right)^2 mgd_{COG} - md_{COG}^2 \quad (2)$$

where I_{COG} is the moment of inertia at the COG, and T is the period of oscillation, which was measured using an acoustic range finder.

Wet tests are those that occur in the basin with no waves generated from the wavemaker. Wet tests included static offset, forced oscillation, and free decay tests.

Static offset tests are used to determine the restoring forces in the system. The tests focused on the heave, pitch and surge for restoring stiffness of the platform, and pitch for the restoring stiffness of the flaps. These were conducted by pulling in the direction of each DOF. Results of these are force vs displacement curves showing the restoring forces for the desired DOF [18].

Forced oscillation tests are used to determine the added mass and radiation damping coefficients for each flap. The PTO was used as a motor to excite the flap with a fixed stroke and period of oscillation. Recordings of position, velocity, acceleration, and force were taken. The linear hydrodynamic model shown here will be used to extract estimates for $A_{jj}(\omega)$ and $(B_{jj}(\omega) + jC_v)$ terms in (3).

$$F(t) = \left(m_j + A_{jj}(\omega)\right)\ddot{\xi}(t) + (B_{jj}(\omega) + jC_v)\dot{\xi}(t) + k_j\xi(t) \quad (3)$$

where $F_e(t)$ is the actuation force, t is time, m is the mass, j is the matrix element corresponding to the DOF of interest, A is

the added mass, ω is the angular frequency, ξ is the motion or rotation variable, B is the radiation damping, C_v is the linearized viscous drag, and k is the restoring stiffness (or hydrostatic coefficient) of the body as described in [19].

Free decay tests were conducted to determine the natural frequencies and damping ratios of the relevant DOFs of each body. For these tests, the body was pulled in the direction or rotation of the DOF of interest and then released. The motion of the free decay of the device for each DOF was recorded. The free decay tests trials were repeated for each initial displacement, and run for a range of different initial displacements in order to measure the impacts of nonlinearities such as quadratic damping.

Wave excitation tests were run to determine the excitation forces on the bodies. All DOFs for each body were fixed in place and waves were run and the corresponding forces/torques were measured. A fixed wave height and range of periods were run to obtain a frequency dependent approximation of the wave excitation force.

Additionally, a set of monochromatic waves were run for a range of wave heights and period. Wave heights ranged from 1.5 cm to 13.6 cm, and wave periods ranged from 0.87 s to 3.482 s.

PHASE 1 PRELIMINARY RESULTS

WEC-Sim phase 1 experimental testing was completed in winter 2015. Accordingly, the results presented in this section are preliminary.

Mass Properties Test Results

The mass properties tests were used to characterize the FOSWEC's mass, moment of inertia, and center of gravity. An overview of these results is shown in Table 1, and a definition sketch of the local coordinates is shown in Figure 9 and Figure 10 for the flap and the FOSWEC, respectively. The center of gravity is measured from the origin (green cross-hair in Figure 10) but relative to the still water line, and the moments of inertia are measured about the center of gravity (COG). Note that the mass properties in Table 1 include each Flap, and the Platform, but not the motion constraint (part of which moves with the FOSWEC in each DOF).

Table 1. FOSWEC mass properties from swing test

	Flap ₁	Flap ₂	Platform
Mass (kg)	23.14	23.19	153.8
X_{cog} (m)	-0.65	0.65	-0.0009
Y_{cog} (m)	0.0108	0.0017	-0.0044
Z_{cog} (m)	-0.29	-0.29	-0.063
I_{xx} (kg m²)	1.42	1.58	37.88
I_{yy} (kg m²)	1.19	1.62	29.63
I_{zz} (kg m²)	1.99	1.25	NA

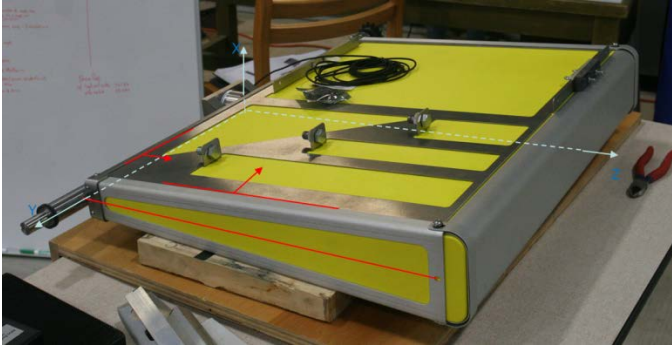


Figure 9. Flap COG measurement test

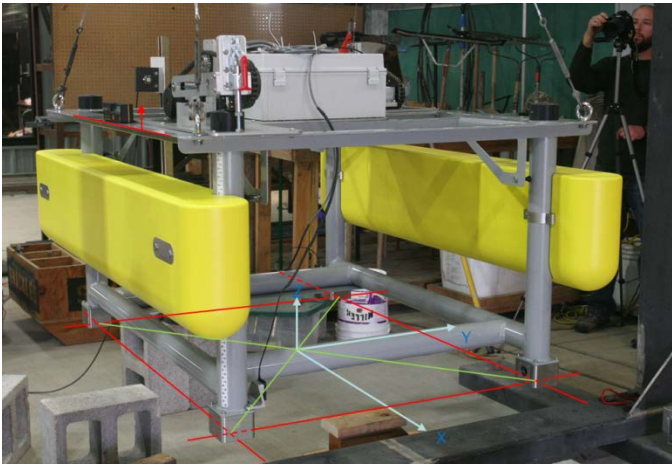


Figure 10. FOSWEC swing test without the flaps

FOSWEC Surge Decay and Static Offset

In order to characterize the surge restoring stiffness of the FOSWEC, the device was pulled horizontally by the overhead crane and a pulley to different displacements, shown in Figure 11, and the resulting force was measured. This static offset test was used to determine the stiffness of bungee cords which provide a restoring force to the FOSWEC in surge. Results from the static offset test are shown in Figure 12, and an overview of the results for all DOF static offset is shown in Table 2. The surge restoring stiffness is 962 N/m with a correlation coefficient (R^2) of 0.96.

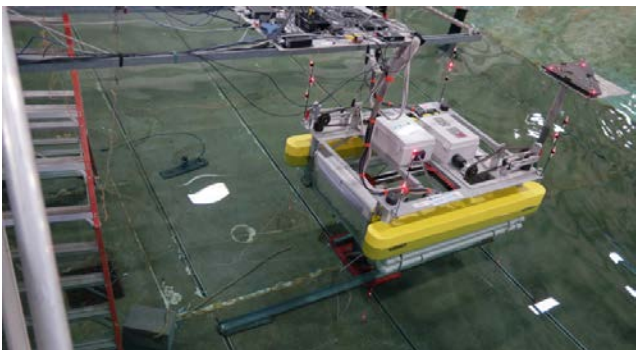


Figure 11. FOSWEC surge static offset and decay test setup

Then the FOSWEC was pulled to different initial displacements and released to characterize its surge decay. The decay tests were repeated for initial surge displacements of 7, 10, 15, and 20 cm. Results from the FOSWEC surge decay tests with the mean and the 90% confidence interval are shown in Figure 13. The results have been normalized by the initial displacement to demonstrate the nonlinearity of the FOSWEC's response in surge. Since the FOSWEC's decay rate varies as a function of the initial displacement, the surge motion must be modeled nonlinearly as a function of displacement. Additionally, it can be seen that the surge response is overdamped since there is little to no overshoot.

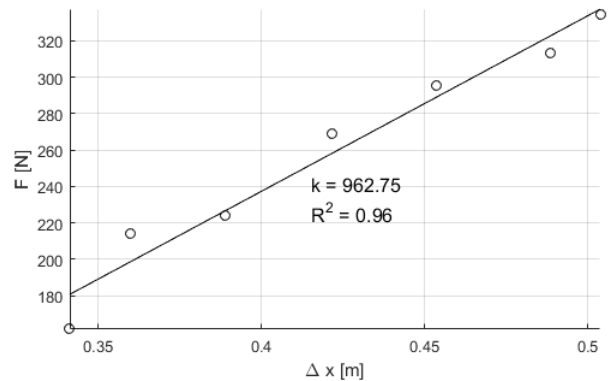


Figure 12. FOSWEC surge static offset test, force versus displacement slope, $k = 962 \text{ N/m}$ with $R^2 = 0.96$

Table 2. Results from static offset tests

	K	Units	R²
Surge	962.75	[N/m]	0.96
Heave	7,115	[N/m]	0.99
Pitch	47.06	[Nm/deg]	0.99
Flap	2.69	[Nm/deg]	0.96

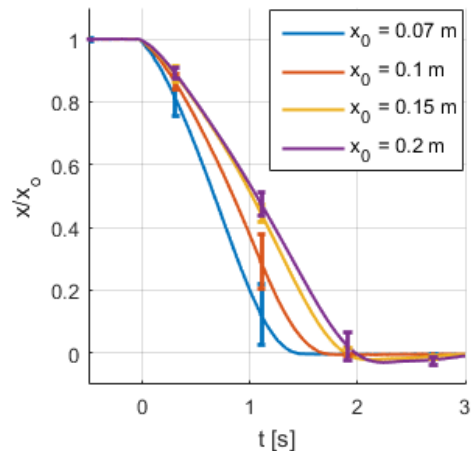


Figure 13. FOSWEC normalized surge decay experimental results for initial displacements of 7, 10, 15 and 20 cm

FOSWEC Heave Decay

In order to characterize the heave response of the FOSWEC, the device was lifted by the overhead crane to different initial displacements and released to characterize its heave decay response. All other DOFs were locked. An image from the experimental setup is shown in Figure 14.

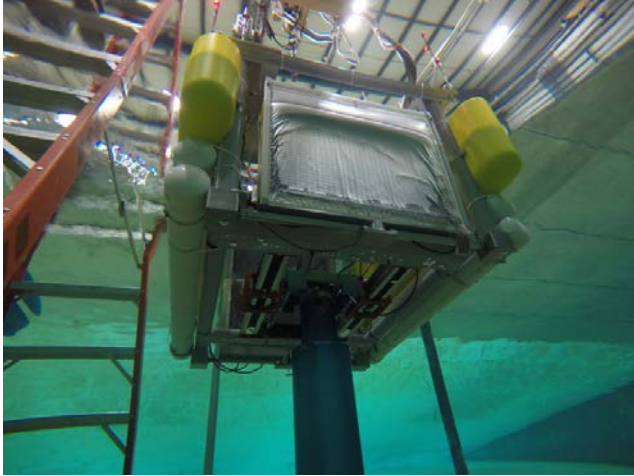


Figure 14. Underwater view of the FOSWEC during the heave decay test

The decay tests were run for initial heave displacements of 3, 5, 7, 10, and 15 cm, and were repeated for each initial displacement. Results from the FOSWEC heave decay tests are shown in Figure 15, with the mean and the 90% confidence interval. The results have been normalized by the initial displacement to demonstrate the nonlinearity of the FOSWEC's response in heave. Since the FOSWEC's decay rate varies as a function of the initial displacement, the heave motion response is highly nonlinear, a result which is expected because of the changing water-plane area. Based on the results of this test, the peak to peak damped natural period of the FOSWEC in heave is 1.56 s. Results from the heave static offset are shown in Table 2. The heave restoring stiffness is 7,115 N/m with a correlation coefficient (R^2) of 0.99.

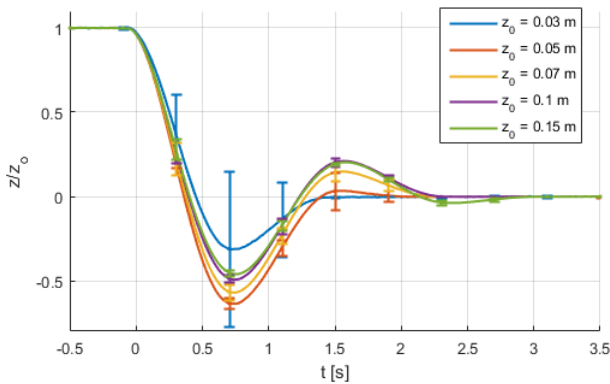


Figure 15. FOSWEC normalized heave decay experimental results for 5 initial displacements of 3, 5, 7, 10, and 15 cm

FOSWEC Pitch Decay

In order to characterize the pitch response of the FOSWEC, the device was lifted by the overhead crane to different initial pitch displacements, and released to characterize its pitch decay response, while all other DOFs were locked. An image from the experimental setup is shown in Figure 16.

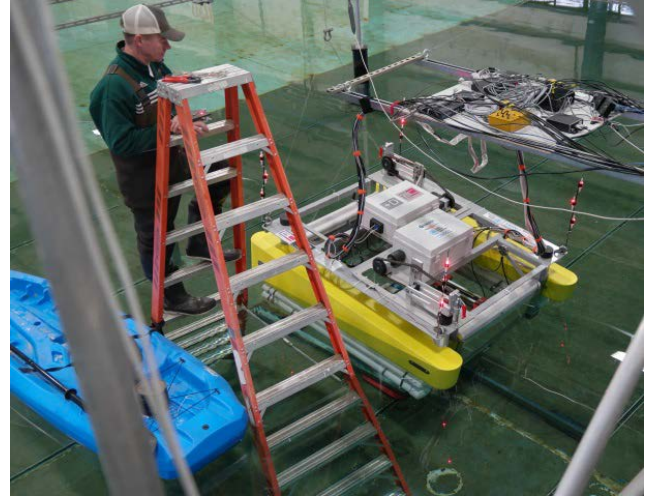


Figure 16. FOSWEC pitch decay test setup

The decay tests were repeated for initial pitch displacement angles of 2, 3, 5, 7, and 8.4 deg. Results from the FOSWEC pitch decay tests with the mean and the 90% confidence interval are shown in Figure 17. The results have been normalized by the initial displacement angle to demonstrate the linearity of the FOSWEC's response in pitch. Since the FOSWEC's decay rate is constant (within 90% CI range) as a function of the initial displacement angle, the pitch motion can be modeled linearly. Based on the results of this test, the damped natural period of the FOSWEC in pitch is 1.64 s. Results from the pitch static offset are shown in Table 2. The pitch restoring stiffness is 47.06 Nm/deg with a correlation coefficient (R^2) of 0.99.

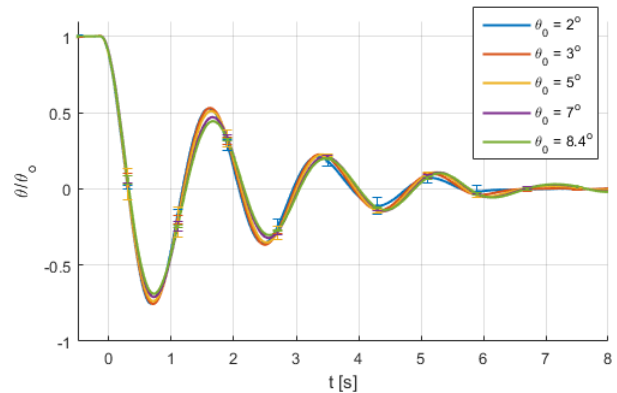


Figure 17. FOSWEC normalized pitch decay experimental results for initial displacements of 2, 3, 5, 7 and 8.4 deg

FOSWEC Flap Pitch Decay

In order to characterize the flap pitch response, the top part of the flap was pulled horizontally by the overhead crane and a pulley to different initial pitch displacements, and released to characterize its pitch decay response. The bottom part of the flap was attached to the FOSWEC, and only had a rotation movement around the shaft. The decay tests were repeated for initial pitch displacement angles of 5, 7, 10, 15, and 20 deg. Results from the flap pitch decay tests with the mean and the 90% confidence interval are shown in Figure 18. The results have been normalized by the initial displacement angle to demonstrate the highly nonlinear response of the flaps' response in pitch. A larger oscillation is generally observed for a larger initial angle, which is expected because a larger initial angle is also subjected to a larger hydrostatic force.

The flap's pitch response varies significantly as a function of the initial displacement angle. The flap's pitch decay can be characterized as an underdamped system, as shown by the oscillations past the initial overshoot, whose damped natural period also varies as a function of the displacement angle. Results from the flap static offset are shown in Table 2. The flap's pitch restoring stiffness is 2.69 Nm/deg with a correlation coefficient (R^2) of 0.96.

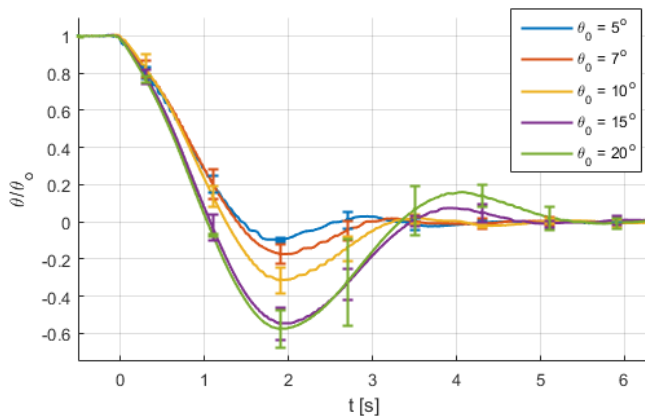


Figure 18. Flap1 normalized pitch decay experimental results for initial displacements of 5, 7, 10, 15 and 20 deg

CONCLUSIONS

This paper presents the Phase 1 WEC-Sim test plan and preliminary experimental results for the FOSWEC. The Phase 1 wave basin tests of the FOSWEC 1:33 scale model were completed over a period of six weeks OSU in winter 2015.

The overall objective of the WEC-Sim experimental testing is to generate a complete and accurate data set for validation of the WEC-Sim code, evaluating new instrumentation techniques for load characterization, and providing a free and publicly available set of test data to be used in the community at large. The Phase 1 wave basin tests of the FOSWEC 1:33 scale model focused on system identification to characterize the FOSWEC. The FOSWEC mass properties, center of gravity, and moments of inertia, critical components for FOSWEC system identification and WEC-Sim validation were characterized.

The static offset tests were used to characterize the restoring stiffness of the FOSWEC in each DOF. The free decay tests were used to determine the damped natural period of the FOSWEC in each DOF, along with its linearity. All DOFs except the FOSWEC pitch were highly nonlinear, a characteristic which will need to be accounted for numerically for accurate simulation results.

While this paper focused on presentation of the tests completed in Phase 1, physical testing of the FOSWEC will include a total of ten weeks at OSU's HWRL, where the remaining 4 weeks of Phase 2 testing will be completed in spring 2016. All data presented in this paper, and collected in Phase 2 will be released publicly in fall 2016. Additionally, comparison of this data set to WEC-Sim and AQWA time-domain simulations is presented in the follow-on OMAE 2016 publication [3].

FUTURE WORK

During Phase 2 of experimental testing, the flap added mass $A_{jj}(\omega)$ and the total damping $(B_{jj}(\omega) + jC_v)$ in Eq. (3) will be determined experimentally by means of forced oscillation tests. In these tests, a known oscillation of the flaps is imposed by reversing the PTO system, where the required force to introduce a given amplitude motion and its frequency is measured, yielding the necessary information to estimate added mass at peak accelerations, and total damping at peak velocities.

FOSWEC excitation forces in each DOF will be measured during the Phase 2 Wave Excitation tests, where all motions are locked and forces are measured in all DOF for a variety of regular waves with different frequencies and amplitudes.

Additionally, as part of the model characterization and testing program, a detailed representation of the PTO damping properties is necessary. PTO performance is estimated by the angular velocity of the Flap, and the torque transmitted to the drive shaft for a given constant damping. PTO Optimization of the torque damping is performed while all DOF of the platform are locked, and the flap is excited by waves with the natural pitch frequency of the flap, obtained during the Decay tests. PTO Optimization tests will be presented in Phase 2.

The final objective of Phase 2 testing is to characterize the FOSWEC's response when subject to incident waves of varying periods, amplitudes, and angles. The FOSWEC will be subject to both regular and irregular waves in order to develop a comprehensive numerical benchmarking dataset.

ACKNOWLEDGMENTS

This research was possible through support from the Department of Energy's EERE Office's Wind and Water Power Technologies Office. The work was supported 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.

This research was also supported in part by the Department of Energy's EERE Office's Wind and Water Power Technologies Office's Postdoctoral Research Awards administered by the Oak Ridge Institute for Science and Education (ORISE) for the DOE. ORISE is managed by Oak Ridge Associated Universities (ORAU) under DOE contract number DE-AC05-06OR23100. All opinions expressed in this paper are the author's and do not necessarily reflect the policies and views of DOE, ORAU, or ORISE.

The authors would also like to thank Christopher A. Kelley and Carlos Michelen from Sandia National Laboratories, Yi-Hsiang Yu and Michael Lawson from NREL, Andrews-Cooper for the design and fabrication of the FOSWEC, +D for design and fabrication of the motion constraint, and OSU HWRL for their part in supporting this research.

REFERENCES

- [1] *MathWorks - MATLAB and Simulink for Technical Computing*. Natick, Massachusetts, United States.
- [2] W. Cummins, "The impulse response function and ship motions," *Schiffstechnik*, vol. 9, pp. 101–109, 1962.
- [3] Kelley Ruehl, Carlos Michelen, Bret Bosma, and Yi-Hsiang Yu, "WEC-SIM PHASE 1 VALIDATION TESTING – NUMERICAL MODELING OF EXPERIMENTS - Article in Press," in *Proceedings of OMAE 2016*, Busan, South Korea, 2016.
- [4] "WEC-Sim Website." [Online]. Available: <http://wec-sim.github.io/WEC-Sim/>. [Accessed: 04-Jan-2016].
- [5] Y. Yu, Michael Lawson, Kelley Ruehl, and Carlos Michelen, "Development and Demonstration of the WEC-Sim Wave Energy Converter Simulation Tool," in *Proceedings of the 2nd Marine Energy Technology Symposium*, Seattle, WA, USA, 2014.
- [6] R. So, A. Simmons, T. Brekken, K. Ruehl, and C. Michelen, "Development of PTO-SIM: A Power Performance Module for the Open-Source Wave Energy Converter Code WEC-SIM," in *Proceedings of OMAE 2015*, St. John's, Newfoundland, Canada, 2015.
- [7] K. Ruehl, "Wave Energy Converter Design Tool for Point Absorbers with Arbitrary Device Geometry," in *Proceedings of ISOPE 2013*, 2013.
- [8] MJ Lawson, Y. Yu, Adam Nelessen, Kelley Ruehl, and Carlos Michelen, "Implementing Nonlinear Buoyancy and Excitation Forces in the WEC-Sim Wave Energy Converter Modeling Tool," in *Proceedings of OMAE 2014*, San Francisco, CA, 2014.
- [9] K. Ruehl, C. Michelen, S. Kanner, M. Lawson, and Y. Yu, "Preliminary Verification and Validation of WEC-Sim, an Open-Source Wave Energy Converter Design Tool," in *Proceedings of OMAE 2014*, San Francisco, CA, 2014.
- [10] A. LaBonte, Brooke White, Michael Lawson, Yi-Hsiang Yu, Kelley Ruehl, Diana Bull, Ye Li, Robert Thresher, and Daniel Laird, "Wave Energy Converter Simulation: Development, Code Competition, and Validation Efforts," presented at the EWTEC 2013, Aalborg, Denmark, 2013.
- [11] "Open Data | Northwest National Marine Renewable Energy Center | Oregon State University." [Online]. Available: <http://nmmrec.oregonstate.edu/industry-resources/open-data>. [Accessed: 04-Jan-2016].
- [12] "Marine and Hydrokinetic Technology Database | Open Energy Information." [Online]. Available: http://en.openei.org/wiki/Marine_and_Hydrokinetic_Technology_Database. [Accessed: 04-Jan-2016].
- [13] "OpenORE | Open source offshore renewable energy." [Online]. Available: <http://openore.org/>. [Accessed: 04-Jan-2016].
- [14] "Marine and Hydrokinetic Data Repository." [Online]. Available: <https://mhkdr.openei.org/>. [Accessed: 04-Jan-2016].
- [15] Kelley Ruehl, Carlos Michelen, Nathan Tom, Michael Lawson, Yi-Hsiang Yu, and Asher Simmons, "WEC-Sim Validation Testing Plan FY14 Q4," Sandia National Laboratories and National Renewable Energy Laboratory, SAND Report SAND2016-1339 R, Sep. 2014.
- [16] "PhaseSpace Motion Capture." [Online]. Available: <http://www.phasespace.com/>. [Accessed: 04-Jan-2016].
- [17] S. K. Chakrabarti, "Modeling laws," *Offshore Struct. Model. Adv. Ser. Ocean Eng. World Sci.*, pp. 12–37, 1994.
- [18] Y.-B. Kim, "Dynamic analysis of multiple-body floating platforms coupled with mooring lines and risers," Texas A&M University, 2004.
- [19] Y. Yu, Ye Li, Kathleen Hallett, and Chad Hotimsky, "Design and Analysis for a Floating Oscillating Surge Wave Energy Converter," in *Proceedings of OMAE 2014*, San Francisco, CA, 2014.