

OMAE2014-24445

IMPLEMENTING NONLINEAR BUOYANCY AND EXCITATION FORCES IN THE WEC-SIM WAVE ENERGY CONVERTER MODELING TOOL

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ABSTRACT

Wave energy converters (WECs) are commonly designed and analyzed using numerical models that combine multibody dynamics with hydrodynamic models based on the Cummins equation and linearized hydrodynamic coefficients. These modeling methods are attractive design tools because they are computationally inexpensive and do not require the use of high-performance computing resources necessitated by high-fidelity methods, such as Navier-Stokes computational fluid dynamics. Modeling hydrodynamics using linear coefficients assumes that the device undergoes small motions and that the wetted surface area of the devices is approximately constant. WEC devices, however, are typically designed to undergo large motions to maximize power extraction, calling into question the validity of assuming that linear hydrodynamic models accurately capture the relevant fluid-structure interactions.

In this paper, we study how calculating buoyancy and Froude-Krylov forces from the instantaneous position of a WEC device changes WEC simulation results compared to simulations that use linear hydrodynamic coefficients. First, we describe the WEC-Sim tool used to perform simulations and how the ability to model instantaneous forces was incorporated into WEC-Sim. We then use a simplified one-body WEC device to validate the model and to demonstrate how accounting for these instantaneously calculated forces affects the accuracy of simulation results, such as device motions, hydrodynamic forces, and power generation.

Other aspects of WEC-Sim code development and verification are presented in a companion paper [1] that is also being presented at OMAE2014.

INTRODUCTION

Wave energy is the most abundant source of marine hydrokinetic energy in the United States and is a plentiful resource around the globe [2]. Recent estimates indicate that the U.S. wave energy resource is 2,600 TWh/year [3]. If it is possible to extract even a small fraction of this energy, there is potential to satisfy a significant amount of U.S. electricity demand [4]. This finding has stimulated commercial and governmental interest in developing wave energy converter (WEC) technologies, and indicates that wave energy could play a significant role in the world's renewable energy portfolio for years to come. Nevertheless, WEC devices are at an early stage of development, corresponding to technology readiness levels (TRLs) 3 through 5, and are not yet a commercially viable technology.

Over the past several decades, open-source numerical modeling tools have helped the wind turbine industry achieve commercial viability by enabling the rapid development, analysis, and certification of system designs. The recent emergence of the WEC industry has created a need for a similar set of WEC design and analysis tools that enable the advancement of WEC technologies. Several companies have developed WEC modeling tools, such as WaveDyn, OrcaFlex, and AQWA, that meet many of the needs of the WEC research and development community. Previous experience at the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (SNL) in developing wind energy technology has shown that open-source device modeling tools help accelerate the pace of technology development by allowing users to modify or improve modeling tools as needed.

Currently, no comprehensive open-source WEC modeling tools are available.

To meet this need, NREL and SNL initiated the WEC-Sim code development effort, with the goal of producing an open-source WEC simulation software suite. WEC-Sim models devices by combining potential-flow hydrodynamics and multibody dynamics simulation methods. The development, verification, and use of the WEC-Sim code is described in our companion paper that will be presented at OMAE2014 [1] and in [5].

In this paper we describe the implementation of buoyancy and Froude-Krylov forces calculated at the instantaneous position of the body with respect to the free surface (referred to as instantaneous buoyancy and Froude-Krylov forces from this point forward). First, we present the numerical methods used in the WEC-Sim code. Verification of the methods is also discussed. Next, we use WEC-Sim to simulate a simple WEC device using a standard linearized hydrodynamics model and the instantaneous calculation method described herein. Finally, we present our conclusions and plans for future research.



FIGURE 1. OCEAN POWER TECHNOLOGIES' POWER BUOY OPERATING OFF THE COAST OF SCOTLAND. THE WETTED SURFACE AREA AND ORIENTATION OF THE DEVICE REMAIN APPROXIMATELY CONSTANT AS THE BUOY REACTS TO ONCOMING WAVES, ALLOWING THE POWER BUOY TO BE EFFECTIVELY MODELED USING LINEAR HYDRODYNAMICS METHODS. PHOTO FROM OCEAN POWER TECHNOLOGIES, NREL 22857

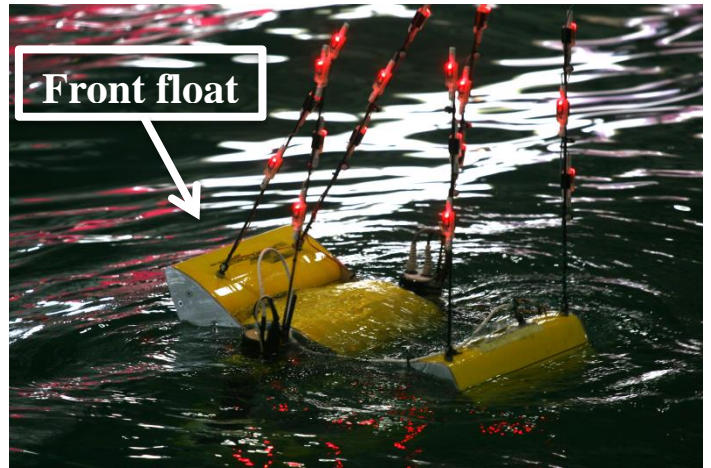


FIGURE 2. A 1:33 SCALE MODEL OF COLUMBIA POWER TECHNOLOGIES' 3-BODY STINGRAY WEC DEVICE UNDERGOING TESTING AT THE OREGON STATE UNIVERSITY'S TSUNAMI WAVE BASIN. IN THE PICTURE THE HIGHLY ASYMMETRIC FRONT FLOAT CAN BE SEEN LIFTING OUT OF THE WATER DURING OPERATION. IT MAY BE IMPORTANT TO CONSIDER NONLINEAR HYDRODYNAMIC EXCITATION AND BUOYANCY TO ACCURATELY MODEL THIS TYPE OF MOTION. PHOTO FROM COLUMBIA POWER TECHNOLOGIES, NREL 24535

NUMERICAL METHODS

WECs are commonly designed and analyzed by modeling fluid-structure interactions using hydrodynamic coefficients determined using a boundary element method (BEM) code such as WAMIT or AQWA. Originally formulated for analyzing the motions of ships, the BEM method assumes that all the hydrodynamic forces on a floating body can be modeled using a set of linear hydrodynamics coefficients. In operational conditions (i.e., calm to moderate seas), some WEC devices can be modeled using linear methods because the motions of the device are small and also because the wetted surface area of the device remains approximately constant.

Figure 1 is a photo of Ocean Power Technologies' PowerBuoy point-absorber WEC. It lends itself to being accurately modeled using linear methods under operational conditions because the buoyancy and excitation forces can be effectively modeled with linear coefficients as the buoy heaves and pitches.

Other WEC devices use highly asymmetric float shapes to maximize power capture from the wave environment. For example, Columbia Power Technologies' StingRay device (Figure 2) uses different float shapes for front and rear floats. The front float has a triangular shape, and small movements in the float's position with respect to the free surface cause the wetted surface area to change dramatically. This behavior does not allow the buoyancy and Froude-Krylov force acting on the float to be modeled using linearized hydrodynamic coefficients.

The WEC-Sim Code

WEC-Sim is a numerical tool for modeling wave energy devices in operational wave conditions. The code is not

intended to model devices in extreme conditions, where phenomena such as wave slamming or overtopping occur. WEC-Sim is based on a time-domain multibody dynamics solver implemented using MATLAB [1]. The multibody solver is coupled with custom-written code to compute hydrodynamic loads. Fully coupled numerical models of WECs are constructed by connecting device building blocks that model different WEC elements. For example, Figure 3 shows a tension-moored oscillating pitch device modeled within the WEC-Sim framework.

At its most basic, WEC-Sim solves the following equation:

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

where m and m_{∞} are the body mass and infinite frequency added mass, respectively, and x is position. The first term on the right-hand side of the equation is the convolution integral that models the wave radiation forces. F_{hs} , F_e , and F_{ext} are the hydrostatic, wave excitation, and external (e.g., power takeoff [PTO] and mooring) forces, respectively. Note that wave forces, F_e , comprise both the Froude–Krylov force and the wave diffraction force. Ruehl et al. [1] and McComb and Lawson [5] give more thorough descriptions of the numerical methods and their implementation in WEC-Sim.

In the initial version of WEC-Sim, all hydrodynamic forces were calculated using linear coefficients derived from potential-flow solvers, such as WAMIT. As discussed previously, however, not all devices and operating conditions can be accurately simulated using linear hydrodynamics approximations. To address this shortcoming, we have implemented buoyancy and Froude-Krylov forces calculated from the instantaneous position of the body with respect to the mean free surface. In this preliminary work, we continued to model radiation damping and diffraction forces using linear hydrodynamic coefficients.

Implementing Instantaneous Hydrodynamic Forces

Buoyancy and Froude–Krylov forces and moments were calculated by tracking the position of bodies within WEC-Sim and integrating the hydrostatic pressure force (Equation 2) and the hydrodynamic pressure (Equation 3) over the wetted surface of the body during each simulation time step:

$$p_{hs} = \rho g x_3 \quad (2)$$

$$p_{hd} = \frac{1}{2} \rho g H \frac{\cosh(ks)}{\cosh(kd)} \cos(\theta). \quad (3)$$

Here, ρ is the fluid density, g is acceleration resulting from gravity, d is the water depth, $k = 2\pi/T$, $s = z + d$, θ is the wave phase angle, and T is the wave period.

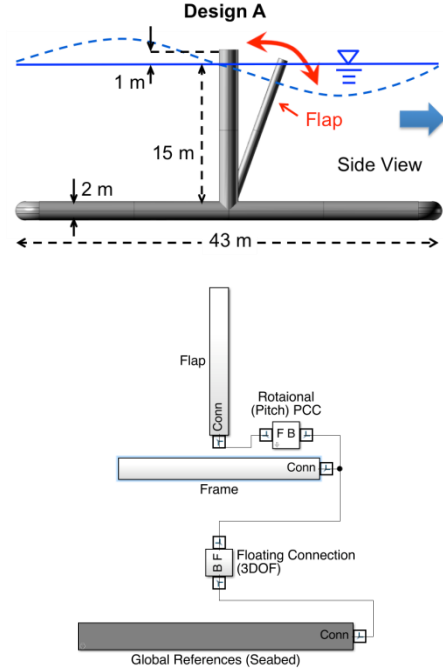


FIGURE 3. (TOP) SCHEMATIC OF A TENSION-MOORED OSCILLATING PITCH WEC BEING DEVELOPED AS PART OF THE U.S. DEPARTMENT OF ENERGY REFERENCE MODEL PROJECT. (BOTTOM) REPRESENTATION OF THE WEC DEVICE WITHIN THE WEC-SIM MODELING ENVIRONMENT. NOTES: PCC, POWER CONVERSION CHAINS; DOF, DEGREE OF FREEDOM

Numerically, forces and moments are calculated by discretizing body geometries into triangular elements (see Figure 4), tracking their displacement as the body moves, and then summing the resulting forces and moments on each element about the center of mass of the body. Because these forces depend only on the body position and predetermined wave conditions, we were able to incorporate the buoyancy and Froude–Krylov force calculations in an implicit fashion that uses the body’s position and wave conditions at the current solution time step (i.e., it was not necessary to lag the calculation in time).

Note that both the hydrostatic and hydrodynamic forces were calculated assuming first-order wave theory. We chose not to use higher-order wave theories so that all wave forces on the body were calculated in a consistent manner. The possibility of using second- or higher-order waves in future calculations will be explored as part of future code development efforts.

To verify the accuracy of the numerical integration techniques used to calculate the buoyancy and Froude–Krylov excitation forces, we compared the results from WEC-Sim calculations with analytical solutions. Specifically, we used a spherical geometry to exactly calculate buoyancy and Froude–Krylov forces through analytical integration and then performed the same calculation in WEC-Sim. Figure 4 presents the results of the buoyancy force comparison as a 20-m-diameter sphere goes from being completely submerged

(displacement = -10 m) to completely above the free surface (displacement = 10 m). The results match well, and the small discrepancy (<<1%) is due to discretization error of the spherical surface.

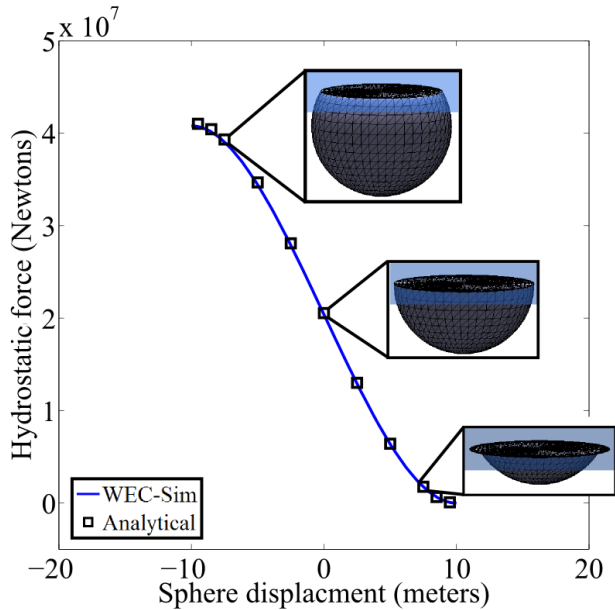


FIGURE 4. EXAMPLE OF A DISCRETIZED SPHERICAL GEOMETRY USED TO CALCULATE INSTANTANEOUS FROUDE-KRYLOV AND HYDROSTATIC FORCES. THE PLOT SHOWS HOW THE BUOYANCY VARIES AS A 20 METER DIAMETER SPHERE IS LOWERED INTO THE WATER. NOTE THAT THE BODY IS CUT BY THE BLUE PLANE, REPRESENTING THE FREE SURFACE.

Performing a similar comparison of the analytical and Froude-Krylov forces showed equally good results, resulting in confidence that the numerical techniques described previously were implemented correctly.

CODE DEMONSTRATION

We performed two test cases to demonstrate WEC-Sim’s capability to model instantaneous buoyancy and Froude-Krylov forces:

Case I: Heave decay of a 20-m-diameter ellipsoid-shaped float was simulated using both the linear and instantaneous calculation methods.

Case II: The same float used in Case I was connected to the seabed with a linear PTO element and the resulting device was simulated in a monochromatic wave field.

Case I: Heave Decay Test

The heave decay of an ellipsoid described by the equation

$$\frac{x^2}{10^2} + \frac{y^2}{10^2} + \frac{z^2}{4^2} = 0 \tag{4}$$

was simulated in WEC-Sim using the linear and instantaneous hydrodynamics calculation methods (Figure 5). The mass of the sphere (263,730 kg) was selected so that ellipsoid was in

equilibrium when its centroid is 2 m above the mean free surface. We chose this ellipsoid shape for the heave decay tests because the buoyancy force changes significantly as the buoy heaves.

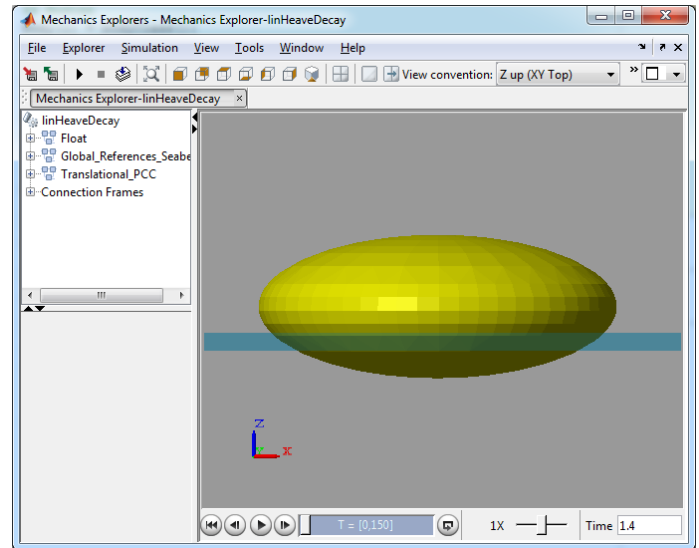


FIGURE 5. REPRESENTATION OF THE HEAVE DECAY TEST IN THE WEC-SIM ENVIRONMENT. NOTE THAT THE BLUE PLANE IS AT THE NEUTRALLY BUOYANT POSITION OF THE ELLIPSOID.

The sphere was displaced by 0.5 m, 1.5 m, and 2 m in the +z-direction (Fig. 5). Note that displacing the sphere by 2 m corresponds to the case where the ellipsoid is completely out of the water with the bottom of the buoy just touching the free surface. Figure 6 and Figure 7 present displacement and buoyant forces that act on the sphere after it is released. No viscous drag force was modeled for these decay tests, and all decay in motion results from radiation damping. Comparing the results in Figure 6 and Figure 7 indicates that for small displacements (0.5 m), the assumption of linear buoyancy accurately models the motion of the buoy, and there is little difference between the linear and nonlinear solutions. As the displacement of the sphere is increased, however, the sharp decrease in the wetted surface area decreases the buoyance force, and the linear and nonlinear solutions begin to diverge. This suggests that when buoy motion causes a significant change in the wetted surface area of a floating body, nonlinear hydrostatic (and likely hydrodynamic) effects must be considered to enable accurate simulation of the motion of the body.

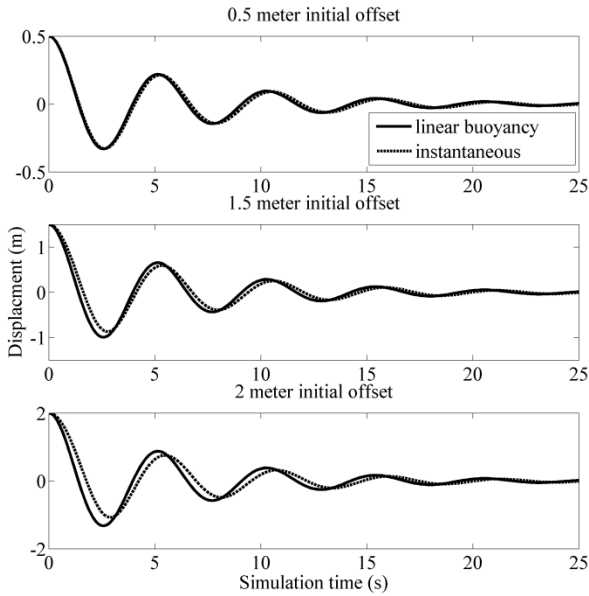


FIGURE 6. MOTION OF THE ELLIPSOID BUOY FOR INITIAL Z-DISPLACEMENTS OF (TOP) 0.5 M, (CENTER) 1.5 M, AND (BOTTOM) 2 METERS. NOTE THAT THE Z-COORDINATE SYSTEM IS DEFINED IN FIGURE 5.

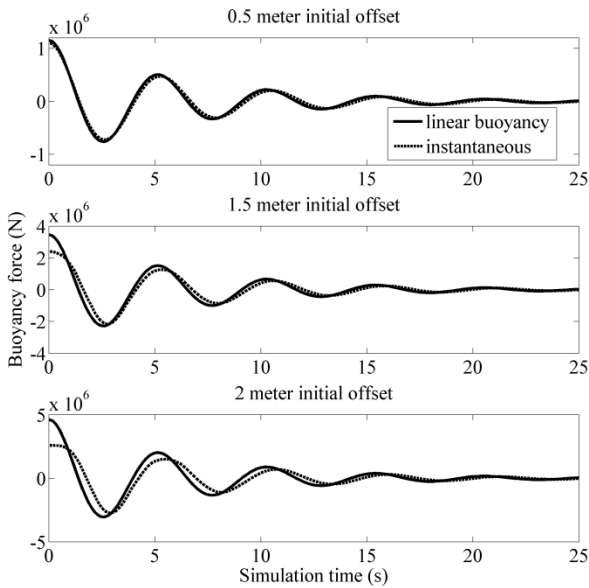


FIGURE 7. BUOYANCY FORCE ON THE ELLIPSOID BUOY FOR INITIAL z-DISPLACEMENTS OF (TOP) 0.5 m, (CENTER) 1.5 m, AND (BOTTOM) 2 m.

Case II: Modeling a Simple Wave Energy Converter Device

A WEC device consisting of the ellipsoid buoy described previously and a PTO system connected to the seafloor was modeled. The PTO system only allowed the buoy to move in the heave direction (z-direction). Based on experience, we selected the damping coefficient for the PTO system to be

1,000 kN-s/m. WEC-Sim was used to simulate the motion of the buoy and the PTO system in a monochromatic wave field with a period of 8 s and a wave height of 1.75 m. Figure 8 compares the power output of the device when linear and instantaneous force calculations are used. The results indicate that there is a significant difference in the power computed using the different modeling methods. The most noticeable difference is that the power generation is different on the upstroke and the downstroke for the instantaneous case. This is because the hydrodynamic restoring force is greater on the upstroke than on the downstroke. Modeling hydrodynamics with linear coefficients does not capture this effect, which could lead to incorrect predictions of device power in some circumstances. Yu and Li [6] observed this same behavior using Navier-Stokes computational fluid dynamics simulations of a two-body heave-only point absorber (see Figure 9). These high-fidelity simulations inherently capture the same non-linear phenomena that are described in this paper. Although the devices simulated are not identical, it is encouraging that WEC-Sim, which uses comparatively simplified simulation methods, predicts a similar power performance behavior.

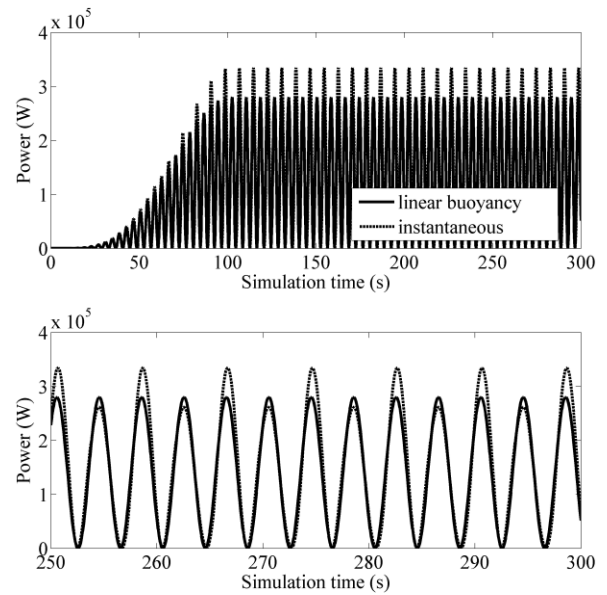


FIGURE 8. POWER OUTPUT OF THE SIMPLIFIED WEC DEVICE. THE INCREASE IN POWER BETWEEN 0 AND 100 SECONDS IS DUE TO A RAMP FUNCTION IN THE WAVE EXCITATION FORCE THAT IS USED TO STABILIZE THE SOLUTION.

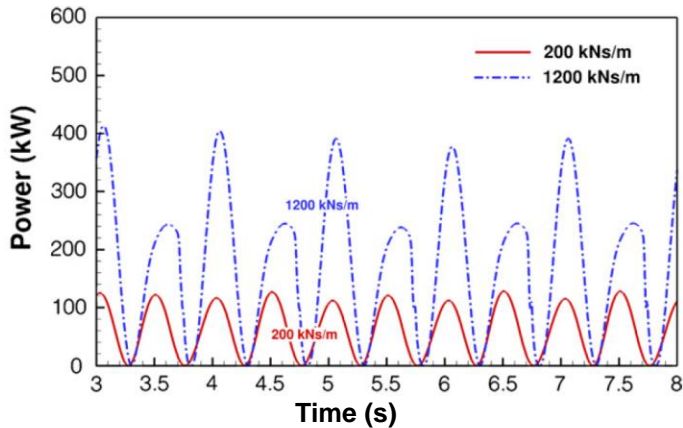


FIGURE 9. POWER PRODUCTION OF A TWO-BODY POINT ABSORBER AS PREDICTED BY YU AND LI. ADAPTED FROM [6].

CONCLUSIONS AND FUTURE WORK

This paper describes how the ability to calculate instantaneous buoyancy and Froude-Krylov forces was implemented in WEC-Sim. First, we discuss why this capability is needed in WEC-Sim and describe the numerical methods that were implemented. A validation of the numerical method is then presented, where hydrodynamic forces computed with the instantaneous method are compared to analytically calculated values. The good agreement between the WEC-Sim and analytic results engenders confidence that the numerical methods were correctly implemented. Finally, we use the WEC-Sim code to study the heave decay and power performance of a simple WEC device consisting of an ellipsoid-shaped float and a simple PTO system. The results from these simulations show that as the float undergoes large amplitude motions, the instantaneous force calculations are necessary to capture relevant physics.

Our future work on this topic will be to further develop, test, and validate the instantaneous hydrodynamics force calculation capability described in this paper. We also plan to use WEC-Sim to study how the annual average power production of wave energy devices predicted by numerical simulations is affected by including instantaneous force calculations.

Finally, we would like to note that WEC-Sim will be released to the public through the OpenEI (openei.org) Web portal and on GitHub (nrel.github.io/WEC-Sim) in June 2014 just before the OMAE2014 conference.

ACKNOWLEDGMENTS

Special thanks to Chad Hotimsky and Sam Kanner for their support on the development of WEC-Sim and data analysis.

This research was made possible with support from the Wind and Water Power Technologies Office within the DOE Office of Energy Efficiency & Renewable Energy. The work was supported by the National Renewable Energy Laboratory under contract number 26833 and by Sandia National Laboratories. Sandia National Laboratories is 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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