A Novel Simulation Toolbox for Wave Energy Converters

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Abstract— **To design a wave energy conversion system, time domain numerical modelling is required. This is due to the nonlinearities present in the system from different sources, including hydrodynamic forces, device dynamics, control mechanisms, and mooring lines. Combining model accuracy with the efficient calculation of hydrodynamic forces in the time domain can be challenging and time consuming to implement. This paper describes unified computational framework that handles those challenges efficiently for different types of wave energy converters. The framework is implemented as a toolbox that contains the key components of a wave-to-wire model. Finally, a short validation of the model and comparison with wave tank experiments is shown.**

Keywords— **wave power, simulation, toolbox, nonlinear, fully-coupled, Simulink, flexible, robust**

I. Introduction

Since the early 1970s, it has been known that time domain simulation of wave energy converters (WECs) is essential for studying the power production and dynamics of these systems [1]. Time domain modelling is required to study the temporal transient responses of WECs with nonlinearities that originate from different sources (e.g., large wave amplitudes, viscous drag forces, nonlinear power take-off responses, or time-varying active-control mechanisms).

In general, WECs are required to be designed for three different operational regimes: (1) operational conditions in which the device should be designed to produce maximum power, (2) operational conditions where large waves are present or motion amplitudes are large enough to push the hydrodynamic response into a nonlinear regime, and (3) survival conditions, in which nonlinear forces and Morrison-type loads become important.

Among the tools presently used by WEC developers are AQWA, OrcaFlex, and WaveDyn. The current numerical tool (RE-WEC) was developed to address the shortcomings of current commercially available simulation packages and provide a more-comprehensive, modular, and flexible design tool. A summary of high-level capabilities includes:

- Use of a “building blocks” based approach that can be used to represent the WEC device. Building blocks include: (1) linear and nonlinear wave models, (2) linear and nonlinear wave-force computation, (3) multi-body dynamic code consisting of bodies, linear joints and rotary joints, (4) linear and nonlinear mooring system models, (5) parametric shape definition, and (6) post-processing and motion visualization.
- Seamless transition from a simple linearized analysis to a complex nonlinear analysis.
- Computational efficiency to allow for complex multi-dimensional parametric optimizations to be completed rapidly. Such optimizations often require thousands of dynamic simulation runs.
- The use of a unified and standardized modelling framework and ability to expand the model using the widely used Matlab/Simulink environment and ability to leverage a wide range of commercial toolboxes to extend capabilities.
- The ability to utilize the model to create an equivalent plant model that can be used for control systems optimization.
- Built-in pre-processing/post-processing tools to simplify model creation as well as running large optimization problems.
- Unified access to all force, motion and wave data within the modelling framework to allow for easy expansion of the modelling capabilities to meet specific needs such as the detailed representation of the PTO subsystem or custom control system.

Table 1 shows a capability matrix and compares RE-WEC to AQWA and WaveDyn.

TABLE 1. COMPARISON BETWEEN CAPABILITIES OF THE CURRENT TOOL AND OTHER SIMULATION SOFTWARE USED IN DESIGN OF WEC SYSTEMS.

	RE-WEC	AQWA	WaveDyn
Pre-processing			
Mesh Generation	x	x	
Parametric Shape Representation	x		
Wave Structure Interaction			
1st Order Wave Forces	x	x	x
2nd Order Wave Forces	x	x	x
Multi-body Hydro Coupling	x	x	x
Global Drag Forces	x	x	x
Custom Distributed Drag Elements	x		
Nonlinear Froude Krylov Force	x	x	
Wave Resource			
Standard Spectral Models	x	x	x
Specific Time-Series	x		x
Nonlinear higher order waves	x		
Mooring System			
Static	x	x	x
Dynamic	x	x	
Multi-Body Dynamics			
Linearized		x	
Fully Nonlinear	x	x	x
Interoperability			
Matlab/Simulink Integration	x		
Batch Optimization	x		
Controls Optimization Plant Model	x		
Parallel Computing Capable	x		
Post Processing			
Data Transparency	x		
3-D Motion Visualization	x	x	
Movie Creation	x		

The common technique when modelling WEC devices in operational conditions is to use integral-differential equations to represent the motions, and convolution integrals to represent the wave radiation forces. However, the direct calculation of the convolution integral is very time consuming, especially with variable time-step solvers. Therefore, different techniques in time domain or frequency domain have been proposed in the literature to eliminate the need to save a large amount of data and re-evaluate the integral at every time step [3,4]. Depending on the WEC system, these techniques can be more efficient and/or more accurate [5].

When the device is actuated near its resonance frequency or if the wave height increases, the linear approach will not be able to capture all dynamic characteristics of the system. In most cases, significant differences are often observed between the results obtained by these linear numerical analytical results and experiments [6]. In order to address this issue, it is important to include nonlinear wave loads in the numerical model of the system. Hereafter, this condition is referred to as an operational condition with a weakly nonlinear free surface. Often, wave energy converters are also required to be designed to maximize the converted wave energy by operating near their principle natural frequency. This results in large amplitude motions of the device and its corresponding nonlinear responses. Previous studies [7,8] showed that in these cases the nonlinear Froude-Krylov force is the main contributor to the hydrodynamic loads. Therefore, a better model of Froude-Krylov force (i.e., the sum of the incident wave force plus the static pressure force) is required to improve the accuracy of the model. This is done by calculation of Froude-Krylov force over the exact instantaneous wetted surface of a device at each time step. A few models based on this theory have been applied in wave energy [9], with promising results. Several previous studies show that the hydrodynamic loads calculated with this method are very similar to predictions by fully nonlinear methods, simulation time is several orders of magnitude faster. From a practical point of the view, nonlinear effects start to play a significant role when the wave amplitude or the oscillating amplitude of the body get large. In these conditions, however, the device is taken out of power production mode and is put in "survival" mode.

In survival condition, the viscous effects are important and need special attention. In most practical systems, the survival condition happens when the wave length is much larger than the characteristic size of the device. In these conditions, the Morrison equation can be utilized to calculate of wave radiation and viscous forces, while the Froude-Krylov forces are calculated based on the instantaneous position of the device [10].

The main contribution of the present paper is to describe the capabilities of a recently developed wave energy converter simulation tool.

II. DESCRIPTION OF TOOLBOX CAPABILITIES

RE-WEC is a multi-body, time-domain simulation tool which has been developed to evaluate WEC performance, optimize power-capture efficiency, determining hydrodynamic loads in extreme conditions, studying the system stability in survival wave conditions, and designing control systems.

RE-WEC provides an easy-to-use platform for building computational WEC models. This is done either in a graphical user interface (GUI) or using a more-generalized input file. The GUI system includes a graphical representation of well-known device types (Fig.3). A user needs to provide the high-level characteristics of the device, such as mass properties, dimensions of different pieces, and power take-off parameters, while the tool chooses the best numerical parameters by searching the previously analysed cases with similar range of parameters to ensure the accuracy of the results.

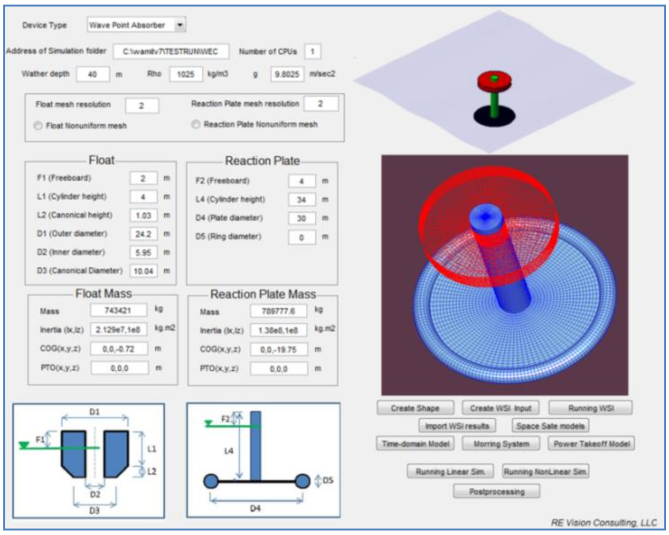

Fig. 1. The GUI interface of the WEC simulation package.

Another approach to model a system, is to provide the input file of the device. The user provides conventional part systems, such as device dimensions, mass properties, PTO, mooring lines, etc. The built-in parametric mesh generator creates the mesh for hydrodynamic analyses. The pre-processing tool creates the required input files and runs WAMIT, to calculate the wave diffraction, radiation, and nonlinear/linear hydrostatic effects. It also provides the required data files needed for calculation of viscous forces during the simulation stage.

RE-WEC is designed to be general. In fact, no assumption is made a priori about the topology of the model. Rather, one can assemble the model by connecting elements from a library that includes body models, mechanical joints, actuators, and different cable models. The model is built on a unified modelling approach using nonlinear ordinary differential equations.

The built-in wave-body interaction module includes wave diffraction, radiation, and the resulting hydrodynamic forces acting on the submerged parts of the WEC. In this model, we solve the potential flow problem using the boundary-integral approach [19]. This approach includes the potential incompressible equation inside the fluid domain, the kinematic and dynamic free-surface conditions, the no-flux condition at the solid boundaries (on the body surface and the sea floor), and the radiation condition in the far field.

A major shortcoming of conventional linearized wave-body interaction approaches is that they neglect the higher-order effects. RE-WEC solves this issue using weakly nonlinear time-domain formulation. To be specific, the basic simulation procedures are (1) Solve a scattering and radiation problem at the initial stage based on the linear free surface and on the mean location of the WEC device. (2) Assuming the flow is potential, disregarding the presence of the structure, solve the boundary-value problem based on the exact instantaneous location of the free surface and obtain its velocity at each time step. This two-step approach is essential in the accurate and numerically tractable modelling of the large (nonlinear) motions of the WEC device when the device oscillates near its operational limits to extract the maximum energy possible from each wave.

The dynamics of the WEC are solved in the time domain using a fixed or variable time-step integrator implementation. Different control actions can be used either through the component-based PTO modelling or at the system level by adjusting the PTO forces. The Simulink platform is used as the high-level interface of the model. The model consists of five primary blocks and many other axillary blocks. For most of the blocks, a user can choose between different options, depending on the simulation type (e.g., operational condition, weakly nonlinear condition, or survival condition). The four primary top-level building blocks of the model, shown in Fig.4, are as follows:

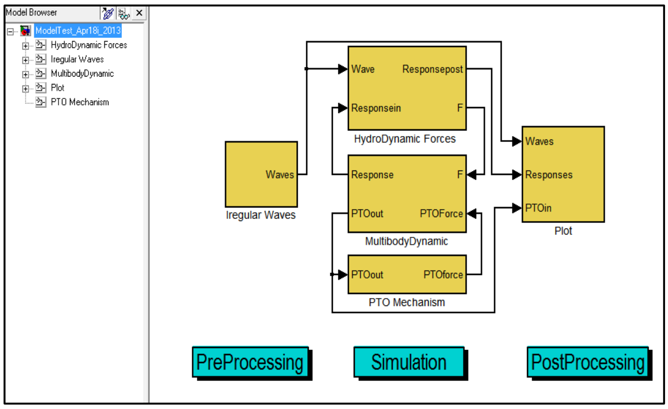

Fig. 2. High-level Simulink model of a WEC system.

Wave and Environmental effects block: Time realizations of the wave and other environmental loads are obtained from the wave and environmental effects block. The wave field can be defined as: (1) a regular sinusoidal wave, (2) a irregular unidirectional, (3) or directional waves obtained from measured data, or (4) from standard spectrums (Fig 5a). In the case of weakly nonlinear and fully nonlinear wave-field simulations, the wave field is calculated from either Stokes wave theory, or Fourier approximation wave theory [20] (Fig 5b). In addition, other environmental effects, such as wind and current, are also presented, either from their standard models [23] or from the input file/Matlab function provided by the user. Finally the wave frequencies are adjusted based on the current speed to allow for the Doppler effects [16].

Hydrodynamic Load Calculation: In this block, the first-order and second-order hydrodynamic loads acting on subsystems are calculated. In particular, the time histories of the wave forces, viscous force, and radiation forces are calculated, depending on the type of the simulation. The magnitude and direction of hydrodynamic loads depend not only on the characteristics of the incident waves and environmental effects, but also on the position and orientation of the device at each time-step.

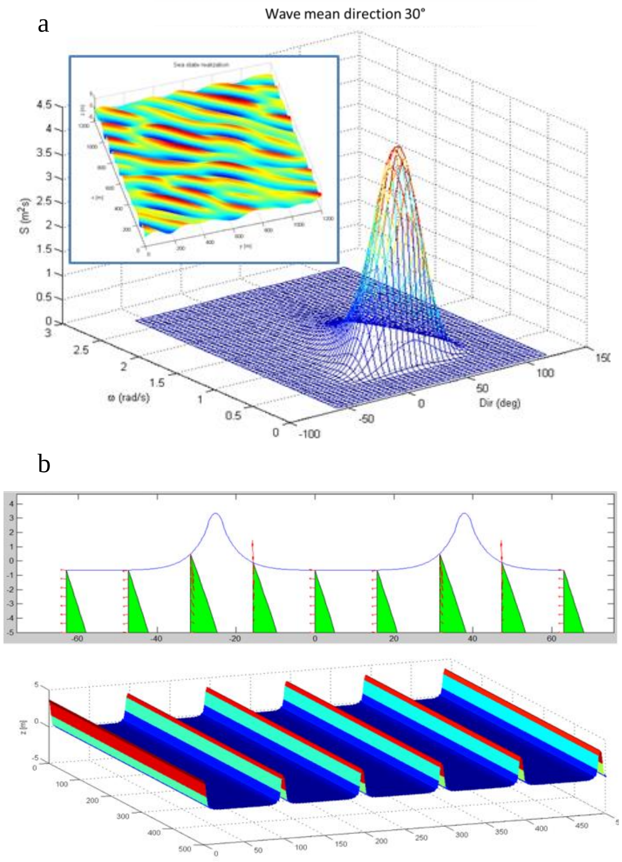

Fig. 3.a) Irregular sea state realization and wave spectra, and b) Nonlinear, steady, shallow-water Stokes wave.

Multi-Body Dynamics: A flexible multi-body system forms part of the code to simulate a WEC system with interconnected rigid components. The device multi-body representation then is constructed, based on the users inputs. In, this includes the topology of the system and the description of each component, including type and characteristic of their interconnections. The model then transforms the user inputs into a mathematical description of the system. Each body of the model in the mathematical model is denoted as a link with the reference position in the global coordinate system. A link connects to the other links through a node, which represent the connection point between interconnecting subsystems. Each node is assigned a joint element, in which the characteristics of the connection is defined (i.e. rotational power take-off, translational power take-off, passive damper-spring, or active motors). Efficient forward and backward recursive algorithms are employed to combine the individual component formulations into a global system of equations for the device.

PTO Mechanism:

The PTO mechanism is represented either by reduced linear and nonlinear models or by sets of ordinary differential equations that model various parts of the power take off system (including hydraulic systems, generator, and rectification-smoothing systems).

The PTO block includes the general description of commonly used models. Among the models are linear and nonlinear damper models and dynamic model templates for different types of PTOs. The primary blocks are pistons, pipes, check valves, accumulators and hydraulic motor, generators, and the rectification and smoothing system. The template can be used for building the customized representation of the user's PTO. Moreover, these models can easily be expanded or adapted to fit any particular requirement.

Mooring System: A mooring system is made up of a number of cables that are attached to a wave converter device at fairlead, with the other ends anchored to the seabed or attached to floating buoys. Cables can be made up of chain, steel, or synthetic fibres. In general, the mooring system dynamics is nonlinear, which is evident in their force-displacement relationships. The mooring dynamics also often include nonlinear hysteresis effects, where energy is dissipated in the lines as they oscillate with the device around their mean position [16]. Two mooring system models can be used to represent the mooring system – a static and a dynamic model. The static model simply represents the mooring system as a catenary system. The cable dynamic module enables fully-nonlinear time-domain simulations of mooring lines. The dynamic cable model can be used to model nonlinear stress-strain relationships of the synthetic cable made out of nylon, polyester or polypropylene, and model rapid transitions from taught to low-tension modes.

Post-Processing: The model provides the user with different options for the outputs. In addition to global responses, it also provides the capability to obtain intermediate responses, too. (for example structural forces at the interconnections of components, motion and forces in mooring lines, different components of hydrodynamic forces, such FK pressure forces, diffraction forces, viscous forces, etc.)

Motion Visualization: Being able to visualize the systems dynamic behavior is an important step to develop an intuitive understanding of the systems dynamic response. It also allows for rapid debugging of a simulation setup. Motions can be visualized in a graphical viewer during run-time or as a post-processing step. The system response can also be exported as a movie file for viewing/demo purposes.

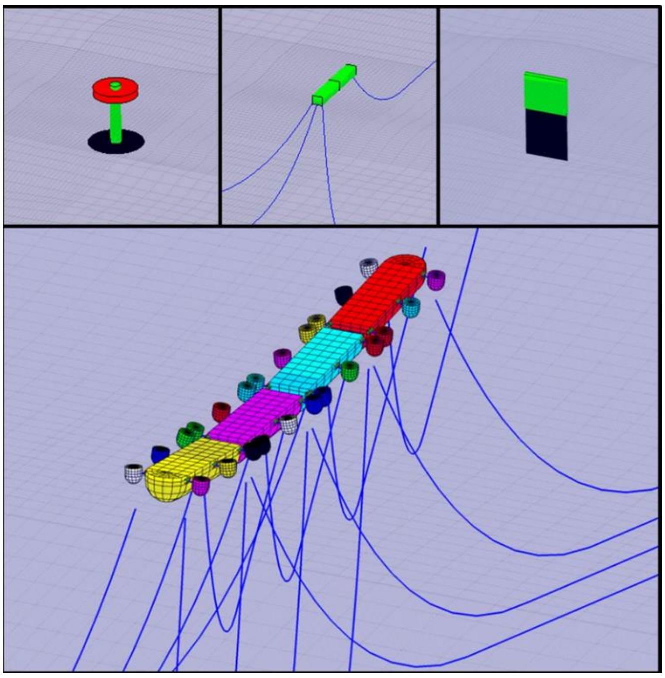

Fig. 4 3-D Motion Visualization of different types of devices

III. VALIDATION

The numerical tool has been used in a significant number of commercial WEC design efforts and results have shown excellent agreement between model testing and theoretical model results. The following validation provides a representative example of the correlation between the theoretical model and a set of wave tank tests. The systems chosen for validation is a heaving point absorber working against a submerged reaction plate (Fig 8a). This type of device has been pursued by a number of companies and is therefore relevant as a benchmark for future efforts on similar devices. During the preprocessing step, the cable configuration of the device and the surface meshes for different bodies are calculated. The resultant configuration is shown in Fig 8.

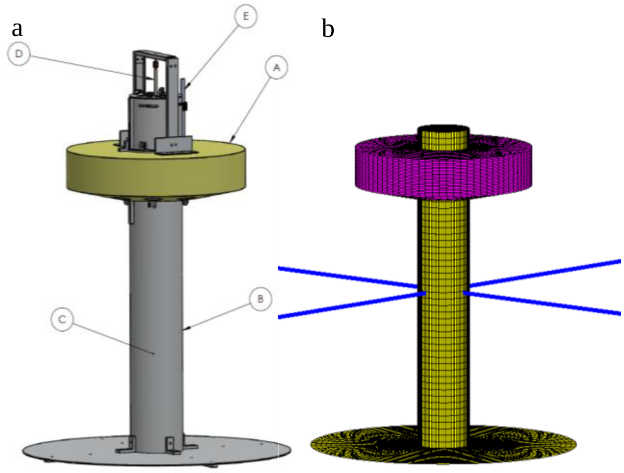

Fig. 5. The Solidwork model of the small-scale PTO device and its numerical representation in the model.

A set of model tests were carried out at 1:33 scale in the hydraulic laboratory at Scripps Institute of Oceanography. Wave periods between 5 and 20 seconds were selected to test the response of the model to sinusoidal waves. This corresponds roughly to the range of wave periods encountered at most deployment sites of interest globally. The wave tank is 30 meters long, 2.4 meters wide, and 2.5 meters deep. The tank features glass-walls, allowing users to observe device motion. An analog signal was used to control the hydraulic piston-type wave maker and generate the test waves. A carriage travels the length of the tank and was locked at 14 meters from the wave maker for the testing and as an observation platform. The major dimensions of the wave tank are shown in Fig. 9.

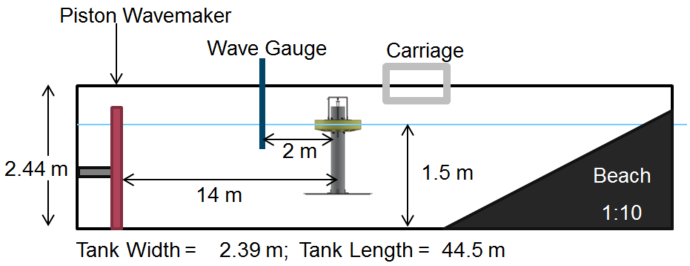

Fig. 6. Wave tank dimensions (not to scale).

Motions of the model were recorded using an OptiTrack camera tracking system (Fig. 10). The model was equipped with a linear potentiometer and load cell to measure the relative motion and force between the vertical column and float and to compute mechanical power absorbed. Mooring line loads were measured using a load cell on one of the mooring lines. An inductance wave probe located 2 meters up-wave of the model measured the incoming wave profile. The signals were recorded and scaled using LabVIEW, and the time records have been transferred into a Matlab data file to simplify the analysis of the signals.

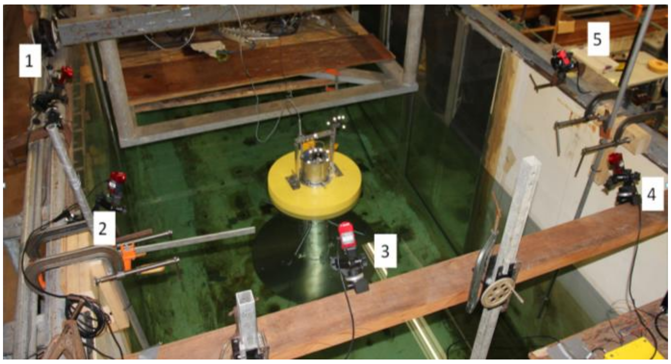

Fig. 7. Camera layout for testing. Camera 6 not shown.

To compare the experimental and numerical results, the key characteristics of the experiments are used as input parameters for the numerical model. In particular, to validate the current model based on the DNV Recommended Practice [23], the following items are calibrated and validated: (1) model characteristics (geometry, mass, mass distribution, metacentric heights, and waterline), (2) restoring force, stiffness, and damping forces, (3) natural periods in heave, surge, and pitch degrees of freedom (in water), and (4) instrumentation, sensor characteristics, and accuracy levels. The drag coefficient in oscillatory flow was considered to be related to the drag coefficient in steady unidirectional flow. Based on the DNV recommended practice [23] and previous studies [24], a function of the KC number is chosen for modelling this unsteady variability. The numerical results (mean energy and statistics of time histories) match well with experimental observations, especially for the case with larger contribution on the mean power (T = 8 to 12 sec). As an example, Fig. 11 shows a comparison of the mean powers calculated from the RE-WEC tool and observed in the experiment as function of PTO linearized damping value. There are small deviations from the measurements, mostly due to the nonlinear characteristics in the PTO and the small variability in the wave generating system.

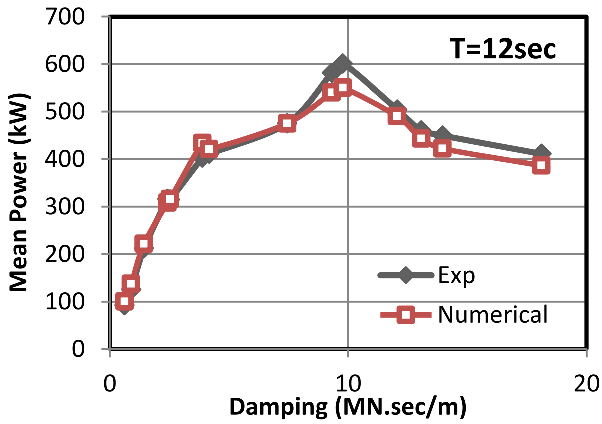

Fig. 8. Numerical model and experimental mean power vs. PTO damping value at T = 12 sec.

IV. Conclusions

This paper describes the new WEC modeling tool, RE-WEC, developed by Re Vision Consulting used in the analysis of wave energy converters. In particular, we pointed out the simulation requirement for studies of wave energy converters and the capabilities required for such analyses. RE-WEC provides a unified modelling framework to carry out linear operational analyses, operational analyses with weakly nonlinear free surface, and survival analysis in extreme regular and irregular waves. It also addresses the main shortcoming of current tools used in the study of WEC systems. RE-WEC has a flexible interface in Simulink and provides required functionalities for analyses and optimization of different WECs. In summary, the modelling approach presented in this paper is:

- Useful for simulation: It is implemented in Simulink and various WEC configurations can be conveniently tested. The ability to parametrically define all system properties allows the system to be used in parametric optimization studies. Simulation of both linear and non-linear wave structure interaction can be accessed within the same framework, making the tool useful for the assessment of device performance as well as extreme load conditions required for structural design purposes.

- Useful for control design: The formulation chosen as the basis of RE-WEC is very suitable for system analysis and control design. The process-plant model can be systematically shortened to obtain a simplified mathematical description of the system for control design purposes.

RE-WEC provides significant 'capabilities-enhancements over similar types of tools used in the simulation of wave energy converters and will serve as a valuable tool in the design and development of different types of wave energy conversion systems. Present efforts are focused on incorporating an advanced wave-prediction and controls optimization framework under funding from the National Science Foundation (NSF).

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