

Advanced Features and Recent Developments in the WEC-Sim Open-Source Design Tool

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I. INTRODUCTION

WEC-Sim is an open-source tool developed in Matlab/Simulink to simulate wave energy converters (WECs). WEC-Sim has been developed jointly by the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (Sandia) since its initial release in 2014 [1]. WEC-Sim simulations are performed in the time domain based on the radiation and diffraction method [2] using hydrodynamics coefficients derived from boundary element method (BEM)-based frequency-domain potential flow solvers (e.g., WAMIT, NEMOH, Capytaine, or ANSYS-AQWA). Within this level of modeling fidelity, WEC-Sim can handle floating body hydrodynamics [3], mechanical and electrical power generation methods, advanced control implementation [4], mooring systems, and other unique applications such as desalination [5]. WEC-Sim functionalities are developed using Simulink blocks and Matlab functions. WEC-Sim capabilities include simulation of different wave conditions, constraints and power take-offs (PTOs), body dynamics, mooring systems, among other advanced features such as nonlinear hydrodynamics, nonlinear PTOs, body-to-body interactions, etc. WEC-Sim functionalities are listed in Table I.

II. WEC-SIM USER BASE

WEC-Sim has become a popular tool for WEC numerical modeling for many different applications. The WEC-Sim user community has been continuously growing since the software release in 2014. WEC-Sim users have a crucial role for the software development and improvement because of their input through the issues board in the WEC-Sim repository on GitHub. As of May 2023, more than 1000 issues from users have been addressed and more

than 1000 pull requests have been developed to improve the source code. The WEC-Sim user community is spread around the world, with the majority of users from the United States, China, and the United Kingdom. A global map with the percentage of users from each country is presented in Fig. 1.

TABLE I
PREBUILT WEC-SIM BLOCKS AND FUNCTIONALITIES

Environment	Constraint/PTO	Body Dynamics	Mooring
Regular waves, Irregular waves	Rotational, Linear	Rigid body, Flexible body	Mooring matrix, MoorDyn
Other Functionalities			
Boundary element method functions		Morison elements	
Nonlinear hydrodynamics		Generalized body modes	
Mean drift force calculation		Run from Simulink	
Cable block		Multiple condition runs	
Constraint & power take-off end stops		Passive yaw implementation	
Body-to-body interactions		Nonhydrodynamic bodies	
Wave directional spreading		Ocean currents	
Parallel computing resources		Wave elevation surface markers	

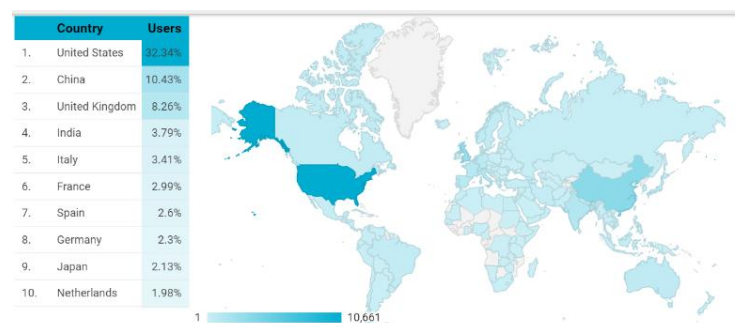


Fig. 1. Google Analytics WEC-Sim users from November 2016 to June 2023

WEC-Sim has been actively used to produce results for scientific publications. As of May 2023, approximately 144 scientific publications have been developed using WEC-Sim. During the first years after WEC-Sim was released, WEC-Sim publications were led by the WEC-Sim development team, but the number of publications developed by external users has been steadily increasing.

The number of known WEC-Sim publications by year and category is presented in Fig. 2.

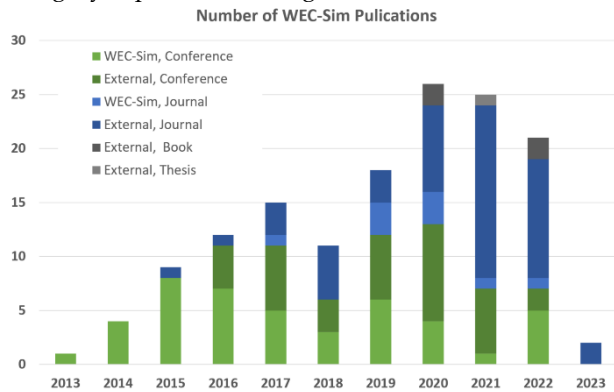


Fig. 2. Number of WEC-Sim publications by year and category.

III. TESTING EXPERTISE AND ACCESS FOR MARINE ENERGY RESEARCH (TEAMER)

This program was launched by the U.S. Department of Energy Water Power Technologies Office with three main goals: 1) improve access to testing infrastructure, 2) improve access to world-class expertise, and 3) provide consistent testing protocols [6]. The TEAMER program was established to facilitate collaboration between research institutions dedicated to study marine renewable energy. The TEAMER facility network covers expertise in 1) numerical modeling and analysis, 2) laboratory and bench testing, and 3) tank, flume, tunnel, and basin testing. There have been many different WEC-Sim TEAMER projects exploring various WEC technologies including point absorbers, oscillating surge wave energy converters, oscillating water columns, and an ever-growing list of unique concepts and applications. Since TEAMER’s first request for technical support in 2020, there have been 18 TEAMER awards focused on numerical model development in WEC-Sim, making up 16% of all TEAMER awards. Most TEAMER awards consist of WEC-Sim model building, model verification/validation, and model documentation to educate applicants on how to use the model for their own needs. Greater detail on the modeling efforts on a sub-set of these TEAMER awards are described in a recent European Wave and Tidal Energy Conference (EWTEC) 2023 paper [7].

IV. PTO-SIM

The PTO-Sim library was created to model PTO systems for WECs when a comprehensive model of the PTO is needed. PTO-Sim has a variety of blocks that can be used to simulate mechanical or hydraulic drivetrains commonly used in WEC applications. The current version of PTO-Sim is divided into three sub-libraries: Electric, Hydraulic, and Motion Conversion. The sub-libraries have blocks to model electric generators and hydraulic devices such as cylinders, rectifying valves, accumulators, and hydraulic motors, among others. PTO-Sim can be easily coupled with the other WEC-Sim blocks, which allows the user to develop complete wave-to-wire models of the WEC

systems. One of the main features of PTO-Sim is the versatility of the blocks, which can be used to simulate complex hydraulic or mechanical systems. Users can implement control algorithms using the PTO-Sim block inputs as control signals. Examples of using PTO-Sim can be found in the WEC-Sim Applications repository on GitHub [8]. A hydraulic PTO simulated with PTO-Sim for the RM3 WEC is presented in Fig. 3.

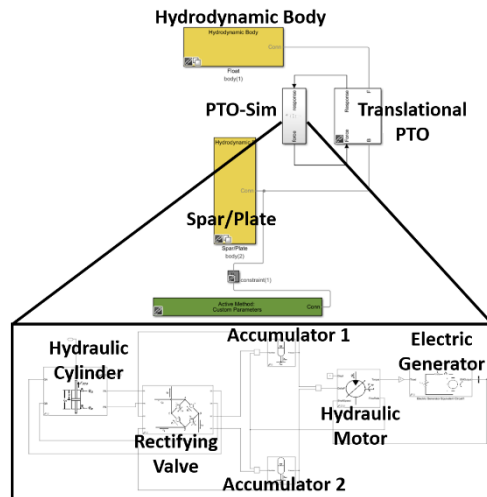


Fig. 3. Hydraulic PTO model using PTO-Sim library

TABLE II
WEC-SIM CONTROL EXAMPLES

Controller Application	Description
Passive (P)	Sphere with proportional (damping) control
Reactive (PI)	Sphere with proportional-integral (spring and damping) control
Latching	Sphere with latching (locking) control
Declutching	Sphere with declutching control
Model Predictive Control (MPC)	Sphere with model predictive control

V. CONTROL APPLICATIONS

The power generation performance of a WEC is highly dependent on the control algorithm used in the system. The WEC-Sim control applications were developed to provide examples of common high-level WEC control algorithms to users. High-level controls focus on controlling the applied power take-off force to maximize harvested mechanical energy. The control examples consist of the controllers outlined in Table II. The passive and reactive controllers are based on a simple mass-spring-damper system. The latching and declutching controllers operate by locking or releasing the device for a portion of each oscillation, respectively, while acting as a passive controller for the remainder of oscillation. Lastly, the model predictive controller completes an optimization routine using a state-space model to determine an optimal PTO force for each time step.

Complex conjugate control is detailed in WEC-Sim’s documentation as a method for understanding optimal control. The passive, reactive, latching, and declutching

examples demonstrate optimality through complex conjugate control in regular waves but can also be tuned to irregular waves using similar techniques. The model predictive control example presents a method for optimized, constrained control in realistic, irregular waves. Although it requires larger computation times, the model predictive controller is particularly beneficial because of its ability to predict future waves and maximize power accordingly as well as the ability to handle constraints. Currently, each of the controller examples focuses on mechanical power. Future work seeks to include power conversion methods using PTO-Sim to present a more practical control example that can maximize electrical power.

VI. CABLE BLOCK

WEC-Sim can model the connection between two dynamically active bodies via a tether, cable, or other flexible material that only transmits tensile coupling forces between the connected bodies in several ways. This can introduce significant numerical complexity to the time-domain solution because coupling forces are described via

$$F_{cable} = \begin{cases} Kx + C\dot{x}, & \text{if } x > 0 \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

Where the cable stiffness K is generally large, resulting in a significant change in coupling force for a small cable displacement x increasing the numerical stiffness of the problem. The WEC-Sim cable block is a direct implementation of the above equation, where the degrees of freedom of the cable attachment points are described by constraints also included in the WEC-Sim library: typically, a spherical constraint is appropriate, as it allows the cable to rotate relative to, but not translate from, its point of connection. While the cable block is not intended to model the kinematics of the cable itself, only the coupling forces it exerts, the cable block includes two drag bodies that can be used to model the quadratic drag and inertial forces exerted by a physical cable.

VII. CAPYTAINE

The WEC Modeling Project at NREL and Sandia is currently funding the development of the open-source linear potential flow BEM solver Capytaine [9] in order to improve open-source toolchains for the numerical modeling and simulation of WECs. Capytaine is a Python package with a Fortran core, based on the open-source solver NEMOH [10] from École Centrale de Nantes. Development started in 2017 at University College Dublin with the support of MaREI and version 1.0 was released in 2019 on Github. Since the beginning of the new funding by NREL and Sandia in April 2022, ~60 issues have been closed and ~130 pull requests have been merged. At the time of initiating funding for Capytaine development the only other predominant open-source BEM solver was NEMOH; however, from an external user perspective,

NEMOH's development and user support had stalled as of around 2019 with the WEC-Sim issues page receiving spillover request for support. The development for the recent release of NEMOH v3.0 [11] was unknown to the WEC Modeling Project at the time. Still, investment in an open-source BEM tool has been prioritized, as the ability to model WECs within WEC-Sim requires high-quality BEM linear hydrodynamic coefficients (i.e., radiation added mass, radiation wave damping, and wave excitation) and building a new or pulling in an existing BEM solver was outside the scope and budget of the WEC Modeling Project at this time. This collaboration has highlighted some of the challenges of supporting open-source software when development and maintenance is dependent on short-term grants when long-term continued support is required to prevent software from becoming outdated. A greater discussion of the current marine energy software landscape and future needs are highlighted in the Next-Generation Marine Energy Software Needs Assessment [12].

The highest priority task of the current development of Capytaine is the improvement of the performance and the precision of the core features of the code, that is the resolution of the radiation/diffraction problems. In particular, major issues in the evaluation of the Green function causing wrong results for high frequencies (mentioned for instance in [13]) have been solved. Performance has been improved by some optimizations in the Green function as well as a better choice of default linear solver (LU decomposition). The second highest priority goal for Capytaine is the improvement of the documentation and the support of the users. Several changes have been made to improve the internal consistency of the code, as well as its consistency with the documentation. The theory manual is still lacking, but has been expanded by 40%. Another high-priority goal for the future of Capytaine is ensuring its distribution on several platforms and its long-term preservation. For the latest release version, the build and packaging toolchain has also been updated to follow the recent changes in the Python packaging ecosystem and to offer more installation options to users. Finally, new features are under development. Hydrostatics have been added in version 1.4 of Capytaine. The prototype of approximate forward speed of Donatini et al. [14] is being merged into the code. Direct boundary integral equations ("source and dipole" method) as well as irregular frequencies removal techniques are considered to improve the accuracy of the code in the future.

VIII. MOST

MOST (acronym for Matlab for Offshore wind turbine Simulation Tool) is a Simscape library that offers additional Simulink blocks for the simulation of a floating wind turbine. MOST is developed by the Politecnico di Torino, and it is integrated within the WEC-Sim environment [15]. The capabilities of MOST are rooted in

its ability to effortlessly implement multibody dynamics: leveraging the libraries of MOST and WEC-Sim, it is possible to simulate, for example, WEC integrated with wind turbine platforms [16] or pendulum-type platforms [18] which are illustrated in Fig. 4; active control of water ballast; and multiple turbines mounted on a single platform.

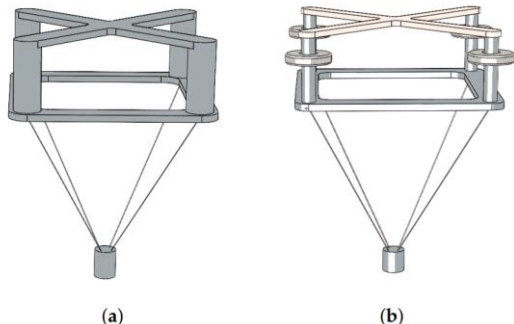


Fig. 4. Example of hybrid concepts a) of a semisubmersible-pendulum platform and b) of a platform with integrated WEC [16]

The additional blocks provided by MOST include the aerodynamics and wind turbine control system based on ROSCO, and it adds a new block to model the quasi-static nonlinear mooring system, based on the equation of the catenary.

The aerodynamic forces are implemented using look-up tables, based on the blade element momentum theory. The flapwise and edgewise loads generated by the distribution of aerodynamic pressure are obtained for each blade and applied as an external force at the blade root. The loads are discretised in function of the wind speed, rotor speed, and blade pitch. During the simulation, the wind speed along the blade span is averaged and used to evaluate the loads. The influence of the pitch and surge motion is taken into account by adding the wind speed with the velocity of the blade with respect to the global reference system.

MOST is validated with the results of OpenFAST (Fig. 5), where the platform cinematics is limited to the main degrees of freedom (surge, pitch, heave). The main difference between MOST and OpenFAST lies in the implementation of aerodynamic forces. MOST employs look-up tables, which significantly reduce computational time, making MOST 3-5 times faster. This efficiency makes MOST particularly well-suited for optimization purposes. In fact, two previous studies have explored the optimization of spar [17] and Hexafloat [18] concepts using the MOST and WEC-Sim environment.

However, the model does not account for important dynamic effects, particularly the flexibility of the blades, which can significantly impact load cycles. The incorporation of the aeroelasticity of the blade using modal analysis is a potential area for future development.

The WEC-Sim and MOST collaboration highlights the developers' desires to have a software suite that can model and simulate hybrid energy systems. Although no dedicated libraries exist to date, a user could also model the floating body interactions of offshore floating solar

systems. The renewable energy research community is quickly moving towards the evaluation and optimization of distributed hybrid energy systems and providing software tools that can assist in such analysis will help keep offshore renewables in the future energy mix.

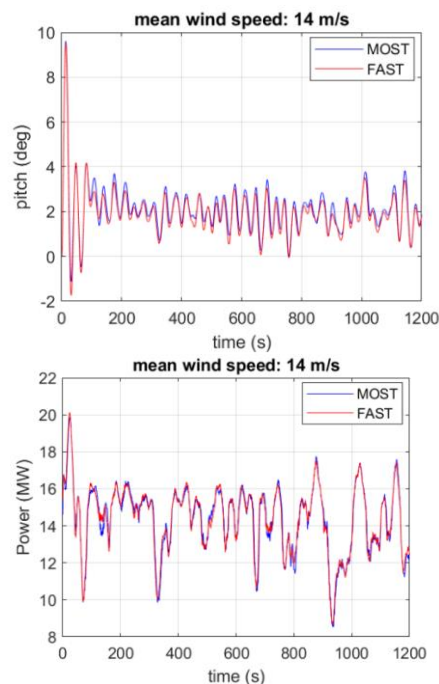


Fig. 5. Platform pitch and power output comparison between MOST and FAST for the IEA 15 MW wind turbine [13]

IX. FUTURE DEVELOPMENT GOALS

WEC-Sim is fortunate to have received sustained funding from the DOE Water Power Technologies Office that allows for continuous maintenance and development of the software. The WEC-Sim team at NREL and Sandia is continuously working on improving the software by adding new features based on the input received by the users through the GitHub issues board. WEC-Sim also has a development project board that is open to the public for review and comment to ensure new features are of value.

Among the future development goals for WEC-Sim is the possibility of having two separate wave trains, with different directions and spectrums, which can be used to follow a double peaked spectrum like Ochi-Hubble [19]. Another update to the software will be the implementation of Euler integration and a discrete finite impulse response to improve the speed of the calculation of the convolution integral for radiation which has been identified as one of the slowest computational components of the software. The new method will be compared with the currently available methods, convolution and state-space approximation, to validate the accuracy and estimate the speed improvement.

A body block to implement intrinsic impedance models will also be developed by the WEC-Sim team. This new body block will be useful for developers having experimental data or identified dynamic systems representing their WEC in the form of intrinsic impedance models. These models can be calculated from information

from the BEM output data and are effectively a summation of these constituent forces, but can also be derived in other ways that may not have resolved the individual terms (added mass, radiation damping, etc.) in a manner sufficient for a WEC-Sim input.

The identified development goals will be implemented in one of the next major releases of WEC-Sim, which currently happen on a yearly basis. All the new features will be documented in the WEC-Sim webpage.

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