Wave Energy Convertor Simulation: Development, Code Competition, and Validation Efforts

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Abstract— **The U.S. Department of Energy Wind and Water Power Technologies Office launched an initiative to develop a Wave Energy Convertor Simulation (WEC-Sim) tool in the fall of 2012. As demonstrated through wind industry experience, WEC developers, who are typically start-ups with devices in the prototype phase, can accelerate development, analysis, and certification of system designs using a verified and validated suite of numerical modeling tools. Accordingly, to assist the nascent WEC industry, the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (SNL) are developing an open-source WEC simulation tool that will be capable of modeling the dynamic response and power performance of WEC devices in operational wave climates. This paper will present the computational framework that will be used to develop the WEC-Sim code and will describe how online coding competitions will be used to assist in the development effort. The WEC-Sim validation and verification plan and external partnership opportunities will also be discussed.**

***Keywords*: Wave Energy, Numerical Simulation, Coding Competition**

I. Introduction

Recently completed studies [1] show that the maximum technically recoverable energy from U.S. waves and tidal currents is approximately 1,420 terawatt-hours per year (TWh/yr). Of this amount, the total recoverable wave resource is estimated to be 1,170 TWh/yr along the outer continental shelf of the United States. This finding has renewed commercial and governmental interest in WEC technologies and indicates that wave energy could play a significant role in the US renewable energy portfolio in the years to come. Nevertheless, despite decades of research and development, wave energy converters (WECs) are not yet a commercially viable renewable energy generation technology. Experience from the wind energy industry has demonstrated that developing an open-source suite of simulation tools that can be used in the device design and optimization process has the effect of accelerating the pace of technology development.

There are currently several commercial modeling tools available for purchase that are capable of modeling WECs. However, these tools are expensive, and are not entirely customizable because the source code is proprietary. While these barriers do not necessarily affect established companies that can easily afford commercial modeling tools, they often preclude small startups, academic researchers, and students from performing WEC research and development. There are also several European efforts to produce ocean energy modeling tools (e.g. the MARINA Platform and Structural Design of Wave Energy Devices projects). However, the resulting modelling tools from these projects are not yet freely available and it is not clear that they will be freely available to the public and open source. Thus, to date no open-source tool exists, hampering the pace of WEC technology development [2]. Development of the open-source WEC-Sim modeling tool will reduce the cost burden that commercial modeling tools place on WEC researchers, and will encourage the development of new and innovative design concepts.

In 2012, the U.S. Department of Energy (DOE), NREL, and SNL initiated the WEC-Sim project, which has the goal of developing an open-source simulation capability that satisfies the unmet needs of the WEC research and development community. The WEC-Sim team (DOE, NREL, and SNL) recently developed a project plan that identified the numerical methods that WEC-Sim will use and defined the capabilities that the WEC-Sim tool will have. Specifically, WEC-Sim will combine a multi-body simulation code and potential flow hydrodynamics models to develop a simulation tool that can model most WEC devices in operational sea states, where the fluid-interactions between the WEC and the wave field can be modeled under linear assumptions. Modeling WECs in extreme conditions where non-linear phenomena, such as wave slamming and overtopping, are prominent is beyond the scope of the current effort.

WEC-Sim development will be performed in-house by NREL and SNL researchers and through the use of code competitions, which leverage the expertise of the worldwide programming community. The following sections describe the WEC-Sim project. First, we briefly describe the modular structure and numerical methods that WEC-Sim will use. We will then focus on the use and the structure of coding competitions that the WEC-Sim team is using to speed the pace of code development. Finally we will discuss possible verification and validation efforts. The intent of this paper is two fold. (1) Inform the international WEC research community on the WEC-Sim project and receive feedback and constructive criticism on the project. (2) Encourage mutually beneficial collaborative partnerships between the WEC-Sim team and the research community in the areas of code development, verification, and application.

II. WEC-SIM MODULAR STRUCTURE

WEC-Sim is being developed using a modular structure, where separate code modules are responsible for simulating the physical phenomena relevant to WEC device performance, e.g. hydrodynamics, multi-body dynamics, etc. The modules will combine to create a comprehensive capability to simulate WEC devices that extract energy from the wave induced motion between floating bodies, or floating bodies and a fixed reference point (e.g. the seabed). The base module will be the multi-body solver that will gather forces from other modules and advance the simulation in time. To model more complex or atypical WEC devices, additional physics and device component modules can be developed or modified, as necessary, to add functionality to simulate different types of WEC devices. For example, additional modules could be developed to model an oscillating water column, which uses an air turbine to generate energy. Most of WEC-Sim will be developed at NREL and SNL, though at least one module will be developed using an online code competition as described later in this manuscript.

WEC-Sim is a quick-running code for design and optimization of wave energy converters operating in the time domain. As Fig. 1 illustrates, WEC-Sim is a loosely coupled code (i.e. explicit coupling between modules) that will consist of pre-processing, time-domain simulation, and post-processing environments. Pre-processing modules are executed only once at the beginning of the simulation based on user inputs, and provide information needed by the simulation modules (e.g. hydrodynamic coefficients). User inputs, shown in Figure 1 include wave energy converter device specifications and geometry, frequency dependent wave spectra ($S(\omega)$), and ocean current speed time series ($c(t)$, [m/s]). Simulation modules model specific device components and are typically executed each time-step in the simulation to update forces and motions of the various components. Module inputs and outputs include time-series wave surface elevation ($\eta(t)$, [m]), frequency-domain added mass ([kg]), frequency-domain radiation damping ($B(\omega)$, [Ns/m]), and frequency-domain wave excitation ($F_e(\omega)$, [N/m]), WEC displacement and velocity ($x(t)$ and $x(t)$) and the forces passed to the multi-body solver including the time-domain wave excitation force ($F_e(t)$, [N]), time-domain wave radiation force ($F_r(t)$, [N]), time-domain mooring force ($F_m(t)$, [N]), time-domain PTO force ($F_{PTO}(t)$, [N]), and time-domain PTO power ($P_{PTO}(t)$, [Nm/s]). Post-processing modules perform analysis and visualization of simulation results and are only executed after the simulation is complete. Proposed capabilities of WEC-Sim include: WEC simulation in regular and irregular wave environments; rigid body representation of device components in early code development to be replaced by deformable bodies in later development phases; a mooring system simulated as linear springs and dampers or finite element models; a Simulink interface for the PTO system model; operational load output for further structural and fatigue analysis. WEC-Sim will not be capable of simulating complex, non-linear phenomena (e.g. wave-slamming and overtopping) as linear frequency-domain potential flow simulations will be used to determine hydrodynamic coefficients. WEC-Sim also will not utilize computationally intensive simulations (e.g. FEA and CFD) and hence can be run on a standard PC.

Details on the function of the different modules and coupling of the data inputs and outputs (I/O) between modules are shown in Fig. 1.

III. THE USE OF CODING COMPETITIONS

Online code competitions are a method of outsourcing code development projects to a large community of coding experts from around the world. Specifically, a code development problem is defined and a cash prize is provided to the coder or coding team that produces the best solution, as defined by a set of pre-defined grading criteria. Because coding competitions leverage a large body of coding experts, they have been shown to provide code quality superior to what can be developed “in-house”, while simultaneously increasing the speed and reducing the cost of code development projects. NASA, DARPA, and Harvard Medical School, just to name a few, have recently demonstrated that code competitions are an effective mechanism for scientific research. The project described herein is the first that is funded by the U.S. Department of Energy to use coding competitions.

For this pilot competition DOE is leveraging best practices in collaborative and distributed innovation from the collected experience of the NASA Center of Excellence for

Collaborative Innovation (CoECI). The CoECI is a NASA-led virtual Center of Excellence that advances the use of open and distributed innovation models to improve government missions. It is collaboration between NASA and Harvard Business School.

The WEC-Sim team has identified the potential flow hydrodynamics module (see Figure 1) as the one best suited for a coding competition. Specifically, the code competition will be used to develop an open-source boundary element method frequency domain potential flow solver, referred to as OpenBEM from here on in. Developing this module will remove the need to use commercial codes, such as WAMIT and AQWA, to generate hydrodynamic coefficients needed to estimate the hydrodynamic forces on WEC devices in a computationally efficient manner. The BEM module was selected as an attractive candidate for a code competition for the following reasons:

1. Removing the need to purchase a commercial BEM code, such as WAMIT or AQWA, will significantly reduce the cost of using WEC-Sim. The commercial BEM code is the most expensive part of the WEC-Sim code. WAMIT is $20,000-$40,000 for a perpetual license and AQWA is as much as $40,000 per year. For comparison, the other commercial components of WEC-Sim cost less than $10,000 (SimMechanics is $4,000 and SimScape is $4,000).
2. Running a coding competition to replace the commercial BEM code is low risk to the WEC-Sim development project because the successful completion of the WEC-Sim code is not dependent on developing OpenBEM.
3. The OpenBEM code will allow users of the WEC-Sim simulation tool and researchers at the National Labs to modify the code to meet future modeling needs.

DOE will be carefully evaluating the progress and outcome of the coding competition to determine the usefulness of coding for future code development projects. One of the particular elements of uncertainty is that typically the members of online code competition communities are not technical experts in the scientific area that the code is being developed to study. Accordingly, to allow the most coders to compete in the competition, the physics of the problem is removed from the problem definition and the problems must be presented as pure mathematical or algorithmic problems.

The steps involved in running a coding competition include developing the concept of the code competition, selecting a code competition platform, breaking complicated problems into multiple competitions, determining the criteria for judging the resulting code, launching the competition, and selecting a winner. The following sections provide more detail on these steps.

A. Selecting a Code Competition Platform

There are several online platforms that facilitate the development and execution of code competitions. The WEC-Sim team and CoECI held meetings with several of these organizations in an effort to select the best platform for hosting the OpenBEM coding competition. The TopCoder [3] platform was identified as the most promising for developing OpenBEM. The TopCoder Community is a body of over 450,000 members representing an enormous span of cultural backgrounds, fields of study, and disciplines. This diversity provides a valuable benefit to TopCoder customers in the form of novel but appropriate contributions in design, concept, analysis, and mathematics to a solution. There are typically cash prizes awarded for winning the coding competitions to provide an incentive for participating in the competitions. The WEC-Sim team and CoECI are in the process of finalizing a contract with TopCoder to provide guidance, administrative support, and the coding competition platform to support the planned OpenBEM code competition.

B. Planning the Code Competition

TopCoder staff, CoECI, and the WEC-Sim team will collaborate over the next several months to develop the code competition to develop OpenBEM. TopCoder staff will provide guidance and invaluable experience on the most effective way to execute a code competition. NASA COECI will provide process integration assistance and guidance for selecting appropriate coding sub-challenges, which are discussed later in this document. Harvard Business School studies the incentives and motivation that drives communities to participate in challenges, and provides suggestions for the most effective prize designs.

Developing OpenBEM using a single code competition is difficult due to the complexity of the problem. Instead, the development process will be broken down into several small problems. Each problem will be converted into one or more problem statements and run as separate competitions within the TopCoder community. Software developers, algorithmists, and mathematicians will compete with each other to create a winning solution as described in more detail in the following section.

C. Separating OpenBEM Development into Many Competitions

Scientific code development competitions are typically broken down into small well-defined problems, or challenges and each challenge is solved in a series of several contests. The complete code is assembled from the products of the individual contests. Within each challenge, it is necessary to create a purely mathematical challenge problem statement. Effectively, this step removes the physics from the problem and restates the problem in purely mathematical terms. This will allow coders who are not experts in the fluid mechanics of boundary element methods to compete, thus significantly increasing the size of the pool of coders who will compete for the prize. In addition, the National Labs and DOE will work with TopCoder to provide the data sets and ensure the grading criteria and requirements for each problem result in code that can be assembled together to produce a functional end product.

Development of OpenBEM will be broken into four main challenges. Each challenge will be comprised of several code competitions:

Challenge 1: Geometry Preparation and Mesh Generator. Frequency domain boundary element simulations solve the inviscid Navier Stokes (Euler) equations across a computational mesh (a discretized geometric representation) of the geometry that is being simulated. The objective of this competition is to develop the capability to import (or read) CAD geometry of the WEC device and output a computational mesh that can be used by the frequency domain solver that will be developed in Challenge 2.

Challenge 2: Frequency Domain Potential Flow Solution. Solving the inviscid Navier-Stokes equations on the computational mesh using the BEM method provides the ability to calculate hydrodynamic coefficients (e.g. added mass and radiation damping) and wave excitation forces of floating and submerged bodies that comprise WEC devices. The objective of this competition is to develop an open-source BEM code.

Challenge 3: Improve Code Efficiency and Speed. It is possible to significantly improve the speed of BEM simulations by taking advantage of parallel computing capabilities and by using advanced BEM numerical solution methods (e.g. sphere of influence weighting and advanced matrix solvers). Improving the speed of OpenBEM will facilitate parametric studies of buoy shapes for device performance optimization purposes. Accordingly, it is the objective of this competition to develop and implement numerical methods that significantly improve the performance of OpenBEM.

Challenge 4: Visualization, Post Processing Capabilities, and GUI. The objective of this competition is to improve the usability of the OpenBEM tool by developing robust visualization, post processing, and GUI interfaces that streamline the process of setting up and post-processing OpenBEM simulations. There are numerous open-source code libraries that can be leveraged to develop these capabilities. The WEC-Sim development team will determine how these resources should be used before proceeding with this competition.

D. Game Plan

TopCoder has developed a comprehensive methodology for running code competitions. Before the competition is initiated, an expert developer, or "copilot" is assigned to help plan and administer the competition. Copilots are experienced members of the TopCoder community who have demonstrated expertise in managing the technical and logistical aspects of code competitions. A co-pilot to help develop Test and Scoring criteria will be selected from the TopCoder Community. This is typically accomplished with a contest, which involves one or more candidates submitting their approach to the challenge in writing. A winner is selected to support the mesh scoring software throughout the remainder of the Challenge.

A typical TopCoder project runs for 10 to 14 days. This includes a 2-6 day registration and submission phase, followed by screening, review, and fix phases. Fig. 2 illustrates an approximate timeline for Phase One of the code competition effort.

We anticipate finalizing the criteria for judging competitions, launching initial competition, and it is possible some competitions may be completed by the time of this EWTEC presentation. Success in this effort may grow in the future use of code competitions in the U.S. federal government. We will discuss anticipated challenges in the code competition process and present our preliminary evaluation of the efficiency of using online code competitions for code development.

IV. Verification; Validation

It is anticipated that WEC-Sim will be used by the WEC industry to develop and optimize new WEC designs. Accordingly, in order to produce a simulation tool in which the WEC industry will have sufficient confidence, WEC-Sim must be thoroughly verified and validated. Numerical verification and, pending budget appropriations, experimental validation tests will determine the validity of assumptions and simplifications used in the code development process. These efforts will help identify the operating conditions (e.g. sea states) within which WEC-Sim is accurate. Furthermore, an experimental validation testing campaign will provide a high quality, publicly available data set that can be used by the wave energy community at large.

A. Plan for Verification

Here, we define verification as a process of comparing WEC-Sim predictions to predictions from other numerical simulation codes (i.e. code-to-code comparisons) and comparing with analytical solutions to simplified problems (e.g. an analytical solution to a two body point absorber in heave only). Verification demonstrates that WEC-Sim is correctly solving the governing equations that are assumed to describe the physics of WEC performance. We will perform verification activities as part of the code development using code-to-code comparison methods and comparison with analytical solutions as described above.

B. Plan for Validation

Validation of the WEC-Sim tool is defined as the process of comparing WEC-Sim predictions to results from experimental tests. Validation demonstrates both that the correct governing equations are modeled by WEC-Sim and the accuracy of the code.

The WEC-Sim validation effort is two-pronged. The WEC-Sim team will first work with partners to obtain available data from device developers, academic partners, and literature that can be used for WEC-Sim validation. Once available data has been catalogued, data gaps will be assessed and plans for generating new high-quality data through a set of well-controlled wave tank tests will be developed.

V. Plan for Dissemination of Code and Validation Data

WEC-Sim source code and executables will be distributed on the NREL and SNL websites and via the OpenEI webpage: Water Gateway on Open Energy Info (OpenEI) web portal by the Spring of 2014. OpenEI (www.openei.org) is an online knowledge-sharing platform that connects individuals and stakeholders with one another, and with the latest energy information and data. The Water Power page—or Gateway—contains links to critical public data sets, up-to-date information on technologies and events, a community forum to discuss topics of interest, links to major research and industry reports, and more.

Newly collected data for the WECSim validation effort will be made publically available. Again, providing public validation data will serve two purposes. First, it will demonstrate WEC-Sim's capabilities and accuracy to developers, researchers, and investors. Second, the testing campaign will results in the first publically available device design and corresponding data sets. This information can be used by the WEC industry to validate and improve in-house design tools, thus further assisting in the development of the WEC-industry.

VI. CONCLUSIONS

The WEC-Sim project was recently initiated by the U.S. DOE with the goal of developing an open-source WEC design and optimization numerical modeling tool. This project will leverage expertise within the U.S. National Laboratories and will use new coding competition platforms to quickly develop the WEC simulation capability

A. Opportunities for Collaboration

There are a number of partnership opportunities in the WEC-Sim initiative. Specifically, the WEC-Sim project could benefit greatly from partners willing to participate in the code comparison/verification and validation phases. DOE welcomes discussion of partnership opportunities such as:

- Once the WEC-Sim beta version is released in early 2014, a developer or university may be interested in running the code for comparison of code performance prediction with privately held tank test data
- Feedback on user-friendly nature, or suggested improvements, to the beta code
- Contribution of existing data sets (public or privately held) for code validation and access to facilities and instrumentation for controlled tests to provide validation data sets
- Participation in experimental tests to provide validation data

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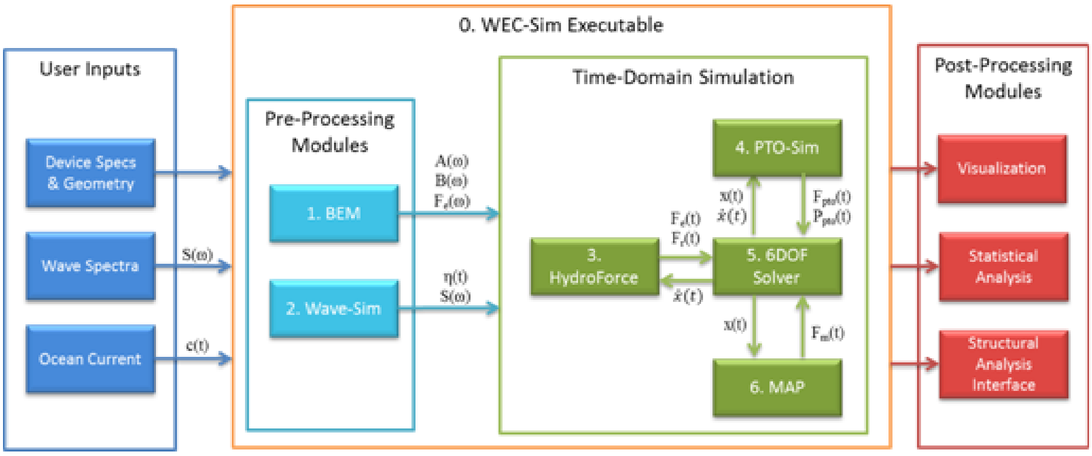

Figure 1 Schematic of the WEC-Sim code structure. Module descriptions provided in Table 1.

Contest	Count	Month 1				2				3				4				5				6				7				8				9			
Phase One Challenge One																																					
Scoring Software Copilot Solicitation Contest	1			X	X																																
Solution Test/Scoring Software	2					X	X	X																													
Analytics Challenge Draft Contest	1								X	X																											
Mesh Model Visualizer	2							X	X	X	X																										
Geometry Samples Test Contest	1									X	X																										
Contest Tester	1											X	X																								
CAD to Mesh Model Contest	1													X	X	X																					
Productization & Math Package Updates	3																	X	X	X	X	X	X														
Bug Hunt	1																			X																	
	0																																				
Phase One Challenge Two																																					
Gateway Decision for Challenge Two	0																G																				
Scoring Software Copilot Solicitation Contest	1																	X	X																		
BEM Solution Test/Scoring Software	1																			X	X																
Contest Tester	1																					X	X														
BEM Inviscid Navier-Stokes Equation Solver	1																							X	X	X											
Math Package Scoring Software	1																							X	X												
Contest Tester	1																										X	X									
Math Package Contest	1																												X	X							
Code Productization & Refinements	3																															X	X		X	X	
Bug Hunt	1																																	X			
Solution Architecture Documentation	1																																	X	X		
Fix and Change Cycle Iteration																																					
Bug Races	8																																				

Figure 2 Approximate timeline for code competition Phase One.

Module Numbe	Module Name		Code Type	Description and Status
0	WEC-Sim Executive Code		In-House	The executive code facilitates communication and information exchange between modules to perform the dynamic simulation of WEC devices. Development work on this module will begin in FY13
1	Pre-Processing Modules	Linear BEM	Commercial (WAMIT)	Hydrodynamic coefficients will be determined using the commercial code WAMIT. There is no work to be done on this task because NREL and SNL currently own the code and have significant experience using it. A codeing comeptition is being initiated to develop an open-source boundary element code.
2		WaveSim	In-House	This module generates simulated wave states using measured wave data and standard wave spectra. NREL and SNL have independently developed versions of this tool over the past several years for other numerical modeling projects. These existing tools will be built upon to create the WaveSim module.
3	Time Domain Simulation Modules	HydroDyn-WEC	In-House	HydroDyn-WEC calculates time dependent hydrodynamic forces using inviscid hydrodynamic coefficients (from WAMIT), viscous drag coefficients, relative device motions, and the current sea state. These forces are used to drive the mulit-body dynamics simulation of a WEC device. NREL has developed this capibility as part of the FAST wind turbine simulation tool. SNL has also developed a tool with a similar capability as part of other numerical modeling projects. These existing tools will be built upon to create the HydroDyn-WEC module.
4		PTO-Sim	In-House	PTO-Sim will enable time dependent electrical power predictions from the calculated mechanical power. PTO-Sim will be broken into modules that allow for custom PTO-train configurations. The following main modules will be considered: prime-mover (i.e. hydraulic cylinders, rack and pinon, ball-screw, etc), generators (specifications obtained from manufacturers), storage (capacitor banks, batteries, etc), and power electronics necessary for grid connection.
5		6DOF Solver	Commercial (SimMecahncis)	SimMecanics is a multi-body-dynamics simulation engine that simulates multi-body multi-degree-of-freedom systems in the time domain. This tool will be used to model the motions of the bodies that comprise the WEC. Forces generated by other modules (e.g. HydroDyn-WEC) are used to drive SimMechanics simulations. Development of SimMechanics device models will begin in FY13
6		MAP	In-House	MAP (Mooring Analysis Program) is a mid to high fidelity mooring line dynamics modeling tool that is under development at NREL. An alpha version of MAP is being released at the end of Q1 in FY13.
7	Post-Processing Modules		In-House and Commercial	NREL and SNL use a variety of methods to post-process and visiuialize data. Custom written MATLAB and Python scripts are used for data processin and verrification. Commercial visiuilization tools (e.g. Paraview and TecPlot) are used for visiuilizing complex data sets. Because many of the required capibilities exist, little effort will be dedicated to developing new post-processing capibilities in year 1 of the development effort with one exception. The ability to output operational hydrodynamic loads to FEA analysis codes for detailed structural analysis will be developed.

Table 1 The WEC-Sim modules and their state of development.