Review of recent WEC-Sim (v6.1) advanced features

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Abstract—**WEC-Sim (Wave Energy Converter SIMulator) is an open-source software for modeling the motions, loads and power generation of wave energy converters. WEC-Sim performs simulations in the time domain using hydrodynamic coefficients calculated by boundary element method (BEM) frequency-domain potential flow solvers such as WAMIT, NEMOH, Capytaine, or Ansys AQWA. WEC-Sim development is ongoing, including various features, applications, and example cases used to demonstrate potential use-cases to meet the needs of the growing marine energy industry. Through input from a broad user base and an extensive team of developers and collaborators, new features of WEC-Sim are developed to expand the software's use cases and improve overall functionality. Three new WEC-Sim features highlighted in this paper include updating WEC-Sim to be compatible with MoorDyn Version 2, incorporation of second order excitation loads (quadratic transfer functions) and allowing for dynamically changing hydrodynamics.**

Keywords — **Linear Potential Flow Theory, Mooring, Hydrodynamics, Wave Energy**

I. INTRODUCTION

WEC-Sim is an open-source software tool for modeling wave energy converters built in the MATLAB/Simulink Environment. A key factor in the success of WEC-Sim is its ability to handle a wide range of design problems. This is particularly advantageous in the marine energy community for modeling the variety of wave energy converter types and applications. This paper details three new features of WEC-Sim which each expand the realm of capabilities to further improve WEC-Sim's range of applicability. These capabilities are to be included in WEC-Sim's v6.1 release and are demonstrated here to increase user awareness and familiarity with the concepts. The three new features are detailed below.

Compatibility with MoorDyn v2

- WEC-Sim's compatibility with MoorDyn is paramount as it supports the integration of detailed WEC models with complex mooring dynamics, an integral component to effective WEC design. The updates included in MoorDyn v2 allow for precise seabed conditions, bending stiffness, mooring lines between multiple dynamic bodies, and required reconfiguration of WEC-Sim's mooring blocks.

Quadratic Transfer Functions (QTF)

- Second order excitation loads are implemented into WEC-Sim through application of the quadratic transfer function (QTF) consisting of the wave drift (low frequency components) and sum frequency (high frequency components) loads.

Variable Hydrodynamics

- Lastly, WEC hydrodynamics may significantly change as the device state (operational depth, submerged volume, variable geometries, etc.) varies. WEC-Sim's dynamically changing hydrodynamics feature allows for multiple sets of BEM data to be loaded and applied to simulate a device with variable states.

Each of these features supports an expanded functionality of WEC-Sim, making the software more applicable to the wide range of wave energy technologies and applications. These features are described and demonstrated in more detail in the subsequent sections.

II. RECENT FEATURES OF WEC-SIM

A. *MoorDyn v2*

MoorDyn is an open-source software developed by the National Renewable Energy Laboratory (NREL) to model dynamic mooring systems for marine applications [1]. Developed in 2014, MoorDyn uses a lumped-mass approach for modeling the dynamics of mooring systems connected to floating bodies and accounts for forces from internal axial stiffness and damping, weight and

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buoyancy, Morison's equation, and stiffness and damping from contact with the sea floor. WEC-Sim has been compatible with MoorDyn Version 1 (v1) since 2016 and the combination of tools has been utilized for a variety of applications [2-3]. The coupling between the two open-source software tools allows WEC-Sim to solve the hydrodynamics and other device dynamics (PTO, controls, etc.) while MoorDyn is fed the outputs of WEC-Sim and called to solve the mooring dynamics.

MoorDyn Version 2 (v2) can handle additional dynamics when compared to v1, including simulation of 6 degree of freedom (dof) objects, non-linear tension, wave kinematics, bending stiffness, bathymetry, and seabed friction [4]. Each of these features enables a more comprehensive suite of mooring modeling tools to compliment WEC-Sim. Although some of the changes in MoorDyn v2 could be accessed with the pre-existing WEC-Sim + MoorDyn coupling, the ability to simulate 6 dof objects came with the ability to include mooring connections between two floating bodies, which WEC-Sim had not yet been setup to handle. Furthermore, changes in the input file style meant additional updates were needed to the WEC-Sim + MoorDyn applications case. These additional updates have now been incorporated into WEC-Sim v6.1.

The WEC-Sim joint-Lab Sandia and NREL team has developed a GitHub repository which houses the compiled MoorDyn library as well as the MoorDyn header files and a MATLAB-based caller script. This repository allows for WEC-Sim to access the MoorDyn source code without users needing to compile it themselves. For MoorDyn v2, the repository was updated with new compiled library and header files, and WEC-Sim users are directed to copy and paste the files from this repository into the main WEC-Sim source folder to gain the MoorDyn compatibility. In order to use MoorDyn with WEC-Sim, users must initialize the mooring system in the *wecSimInputFile.m* script, add the MoorDyn block(s) to the Simulink model, and include a "mooring" folder with a MoorDyn initialization file (e.g., "lines.txt").

Updates to the WEC-Sim source code itself are primarily related to the MoorDyn Simulink block(s). For MoorDyn v1, the block is set up to apply the mooring force based on the displacement of the connection point. This functionality is shown in Fig. 1. Since MoorDyn v2 can account for connections between bodies, the block needed to be updated to apply the mooring force based on the relative displacement between two connection points. This updated functionality can be seen in Fig. 2 where the 'MoorDyn Connection' block is placed in parallel to the constraint and measures the difference between the two connection points. With the current approach, only one instance of MoorDyn can be called at one time. Thus, to enable a model with multiple mooring connections, the 'MoorDyn Connection' block uses 'From' and 'GoTo' blocks to send the data to a 2nd block called 'MoorDyn Caller', which calls MoorDyn once for each timestep to calculate all mooring forces. Lastly, a few small changes to WEC-Sim's Mooring Class and other source functions were made to support the new and improved MoorDyn functionality. With the new input syntax and new Simulink blocks, these features are not backwards compatible meaning WEC-Sim models using MoorDyn v1 will need to be updated accordingly. The required updates are intended to be relatively simple and have been well documented for clarity.

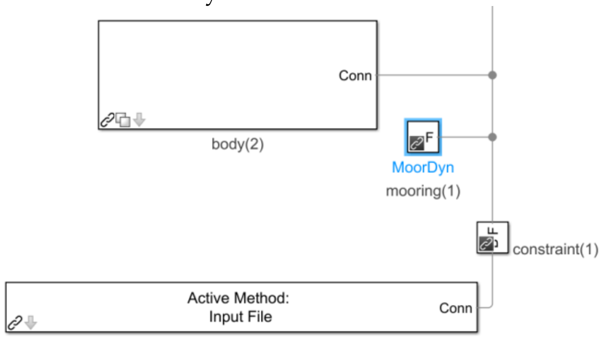

Fig 1. WEC-Sim block and connection for MoorDyn v1 coupling.

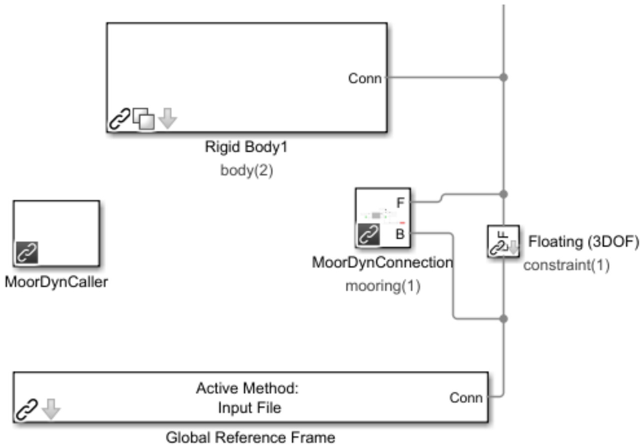

Fig. 2. WEC-Sim blocks and connections for MoorDyn v2 coupling.

Next, the WEC-Sim Applications case for MoorDyn also needed to be updated. This example adds mooring to the Reference Model 3 (RM3) setup as shown in Fig. 3. While the appropriate initialization in the *wecSimInputFile.m* did not need updates, the MoorDyn initialization file did require updates according to the v2 formatting. The differences between MoorDyn's version 1 and 2 formatting guidelines can be found in the MoorDyn documentation. These updates include both changes to input variable formatting and to the input coordinates to adjust to the differences in WEC-Sim's and MoorDyn's coordinate conventions. WEC-Sim defines the body motion with respect to the body's center of gravity while MoorDyn defines body motions with respect to the location specified in the MoorDyn input file. It is important for WEC-Sim users to specify the initial location of a body in the MoorDyn input file as equal to the body's center of gravity and any connection points on the body relative to that point. To ensure the WEC-Sim + MoorDyn coupling is functioning properly, the results using the updated applications case were compared to the results from v1 in Fig. 4. The extreme reduction in variation of fairlead tension for the first 20 seconds of the v2 results and slight offset in steady state are a factor of an improved initialization for MoorDyn v2. Despite a small offset, the two results are very close to lining up, suggesting the updates for WEC-Sim + MoorDyn v2 coupling are consistent with the v1 implementation.

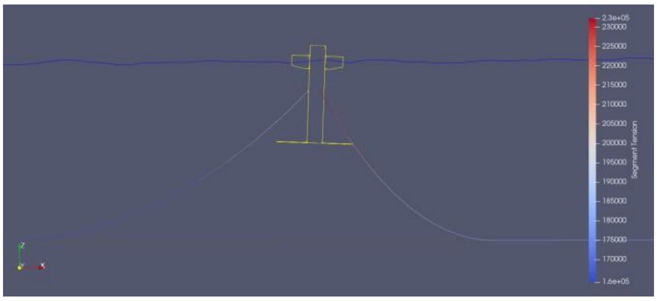

Fig. 3. WEC-Sim Applications MoorDyn example - Reference Model 3 with mooring lines (dynamics modeled by MoorDyn) shown using ParaView visualization software.

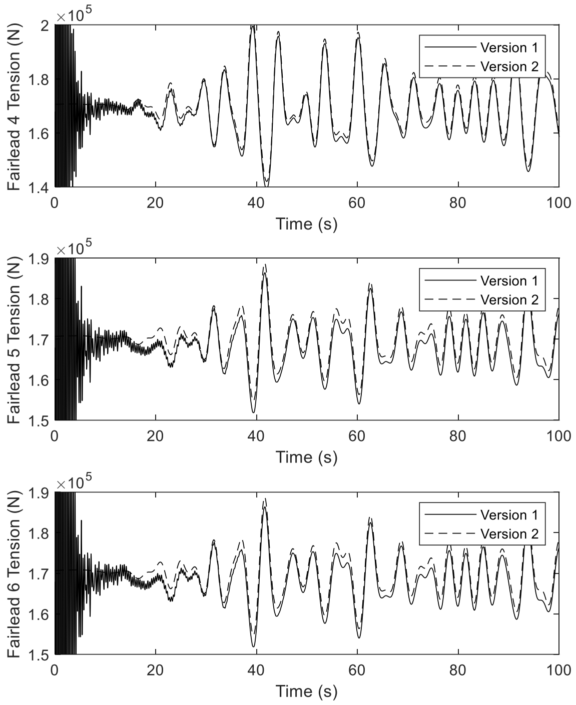

Fig. 4. Fairlead tension from WEC-Sim Applications case (RM3 with 3 mooring lines) for coupling between WEC-Sim and MoorDyn v1 vs. MoorDyn v2. MoorDyn v2 exhibits significantly improved initialization but matches relatively well after a settling period.

B. Quadratic Transfer Functions (QTF)

In potential flow problems, a perturbation series is applied to truncate the high order terms. BEM tools like WAMIT and NEMOH v3.0 can calculate the QTF coefficients. The QTFs calculated by BEM solvers consists of a quadratic expression and potential expression. The quadratic expression is calculated using a quadratic operation for the first order terms, while the potential part is calculated using a direct or an indirect method comparable to the first order Haskind relations and diffraction pressure [5]. The WEC-Sim team has implemented the QTFs in the time domain.

The first order excitation force for the i^{th}degree of freedom (dof) is calculated as in (1):

$$F_{ex\ i}^{(1)} = \Re\left(\sum_{k=1}^{N_\omega} A(\omega_k)X_i(\omega_k)e^{j\omega_k t}d\omega\right) \quad \forall\, i = 1,\dots,\text{dof} \quad (1)$$

which represent a single inverse Fourier transform, where the $F_{ex}^{(1)}$is the first order excitation force, $\Re$ is real number, N_ω is the number of waves in the wave spectrum, $A(\omega)$ is the complex wave amplitude of incident wave, and $X(\omega)$ is the frequency-domain first order excitation force coefficient. The second order excitation i^{th} dof force is expressed as (2):

$$F_{ex\ i}^{(2)} = F_{ex\ i}^{(+2)} + F_{ex\ i}^{(-2)} \quad (2)$$

where $F_{ex\ i}^{(+2)}$ is the fast-varying component, and $F_{ex\ i}^{(-2)}$ is the slow-varying component and they can be expressed as Full QTFs in (3):

$$F_{ex\ i}^{(2)} = \Re\left(\sum_{k=1}^{N_\omega}\sum_{l=1}^{N_\omega} A(\omega_k)A(\omega_l)X_i^{+}(\omega_k,\omega_l)e^{j(\omega_k+\omega_l)t} + A(\omega_k)A^{*}(\omega_l)X_i^{-}(\omega_k,\omega_l)e^{j(\omega_k-\omega_l)t}\right) \forall\, i = 1,\dots,\text{dof} \quad (3)$$

Where the first expression is related to the fast-varying component $F_{ex}^{(+2)}$ and the second expression is related to the slow varying component $F_{ex}^{(-2)}$, X^{+} and X^{-} are the fast and slow varying frequency-domain excitation coefficients respectively, the superscripts * represents the complex conjugate. The equation above requires a double inverse Fourier transform, which is computationally intensive. To reduce computation time, WEC-Sim employs the method proposed by Duarte et al. [6], leveraging the symmetry property of excitation force coefficients.

In WEC-Sim, the first order excitation force is calculated during the time-domain solution process. However, like FAST [7], the second order excitation force is computed in the frequency domain during the initialization step.

Fig. 5. WEC-Sim+ MOST (Matlab for Offshore Simulation Tool) model of a FOWT used to demonstrate the new QTF feature.

WAMIT was utilized to generate the QTF frequency domain coefficients for 100 frequencies for a tension-leg platform (TLP) of a Floating Offshore Wind Turbine (FOWT) (Fig. 5), implementing a JONSWAP wave spectrum with a significant wave height of 6 meters. Fig. 6 compares WEC-Sim results with those from OrcaFlex and FAST, showing that WEC-Sim calculations align well with the Full QTF results obtained from OrcaFlex and FAST. Similarly, Fig. 7 demonstrates the fast-varying component of WEC-Sim, indicating good agreement with the results from OrcaFlex and FAST. While small phase differences are present, these are mostly limited to the surge and heave directions which are both orders of magnitude less than the forces in the pitch direction.

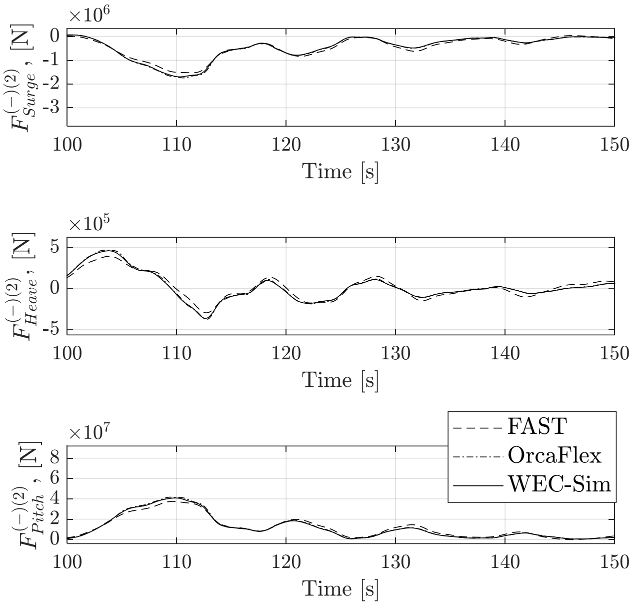

Fig. 6. Slow Varying Component comparison

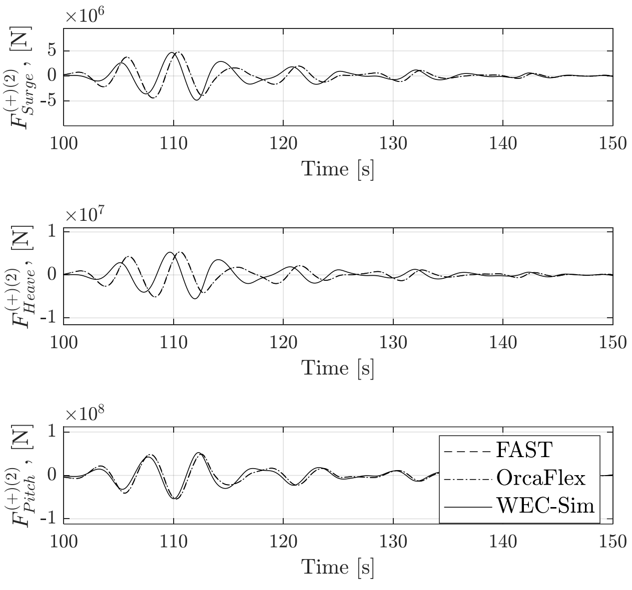

Fig. 7. Fast Varying Components Comparison

C. *Variable Hydrodynamics*

WEC-Sim's new variable hydrodynamics advanced feature allows users to extend their time-domain hydrodynamics simulations to model changes in the state of their device. This changing state could include a wide variety of scenarios. If the user can define their switching parameter during simulation and create sets of BEM coefficients across the state, they may implement variable hydrodynamics for that state. Examples of varying states include:

- Prescribed change in device orientation at a given time.
- Operational depth varying with time.
- Geometry varying with velocity (e.g., flaps opening and closing).
- Geometry changing to enable load shedding.
- Device submerging due to large loads.

The variable hydrodynamics feature enables modeling of states that are not easily modeled using other methods. For example, generalized body modes (e.g., flexible bending modes) in WEC-Sim are still best represented by BEM coefficients pertaining to that mode. Large horizontal displacements are best represented by a phase component in the excitation force. Passive yawing of a device is best represented by that feature because wave direction is already a dimension of BEM coefficients. However, a geometry that is varying significantly with time, like a variable geometry WEC [8] with flaps opening and closing under certain conditions, could theoretically be modeled with WEC-Sim's variable hydrodynamics feature.

WEC-Sim varies hydrodynamics by pre-processing a range of BEM coefficients across the state's transition space. For example, if one simulates a change in operational depth from 1m to 10m, WEC-Sim will select and apply BEM coefficients across that depth. The signal that indicates how the device depth should change is determined by the user.

Varying the state means varying hydrodynamics, which can be unstable when implemented suddenly. This can be rectified by supplying BEM coefficients of sufficiently discretized steps across the state's transition space. Using the example above, varying the operational depth so significantly could require new BEM coefficients every 1m or every 0.1m. Each varying state will have different impacts on the simulation depending on what state is changing, the range of the state, and how fast the state changes. It is the user's responsibility and of critical importance to discover the required discretization of the variable state and to obtain sufficient sets of BEM coefficients across the state.

Further publications and work on WEC-Sim's variable hydrodynamics will focus on the validation of the theoretical applications presented here and guidance on how to approach implementing a custom variable hydrodynamics simulation.

III. CONCLUSION

To stay up to date with advancements in the wave energy industry, the joint-Lab Sandia and NREL WEC-Sim development team is constantly enhancing the software tool with new features and applications. The three features detailed in this paper are all included in WEC-Sim's v6.1 release and support a greater range of capabilities and improvements in simulation fidelity for certain applications.

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