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Hydrodynamic Module Coupling in the Offshore Wind Energy Simulation (OWENS) Toolkit

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ABSTRACT

When considering the future of offshore wind energy, developing cost effective methods of harnessing the offshore wind resource represents a significant challenge which must be overcome to make offshore wind a viable option. As the majority of the capital investment in offshore wind is in the form of infrastructure and operation and maintenance costs, reducing these expenditures could greatly reduce the cost of energy (COE) for an offshore wind project. Sandia National Laboratory and its partners (TU Delft, University of Maine, Iowa State, and TPI Composites) believe that vertical axis wind turbines (VAWTs) offer multiple advantages over other rotor configurations considering this new COE breakdown. The unique arrangement of a VAWT allows the heavy generator and related components to be located at the base of the tower as opposed to the top, as is typical of a horizontal axis wind turbine (HAWT). This configuration lowers the topside CG which reduces the platform stability requirements, leading to smaller and cheaper platforms. Additionally this locates high maintenance systems close to the ocean surface thus increasing maintainability. To support this project and the general wind research community, the Offshore Wind ENergy Simulation (OWENS) toolkit is being developed in conjunction with Texas A&M as an open source, modular aero-elastic analysis code with the capability to analyze floating VAWTS. The OWENS toolkit aims to establish a robust and flexible finite element framework and VAWT mesh generation utility, coupled with a modular interface that allows users to integrate easily with existing codes, such as aerodynamic and hydrodynamic codes.

Current efforts to include a hydrodynamic module are focused on coupling WavEC2Wire with OWENS. WavEC2Wire is a wave-to-wire numerical model developed by Marco Alves at the Insituto Superior Tecnico for the analysis of wave energy converter devices. It has been adapted from its original form and restructured for use as a hydrodynamic module capable of providing OWENS with necessary floating platform dynamics. Hence, WavEC2Wire functions as a rigid-body solver designed to calculate the platform motion due to wave loads, moorings, and the influence of the attached VAWT and tower. This paper presents the WavEC2Wire module and details the OWENS coupling method. Additionally, planned improvements in the WavEC2Wire module as well as future development in OWENS are presented.

INTRODUCTION

Although offshore wind resources make offshore wind energy an attractive opportunity, the cost of energy (COE) of offshore wind projects must be reduced to make offshore wind a viable option. As over half of the capital investment in offshore wind is in the balance of station costs (Figure 1), reducing these expenditures could greatly reduce the COE for these projects. For a land based wind farm the turbine contributes 68% of the installed cost, whereas it is only 32% of the total for an offshore wind project [15]. Therefore, it is more important to consider turbine designs that lower the balance of station costs rather than trying to decrease the cost of the turbine itself.

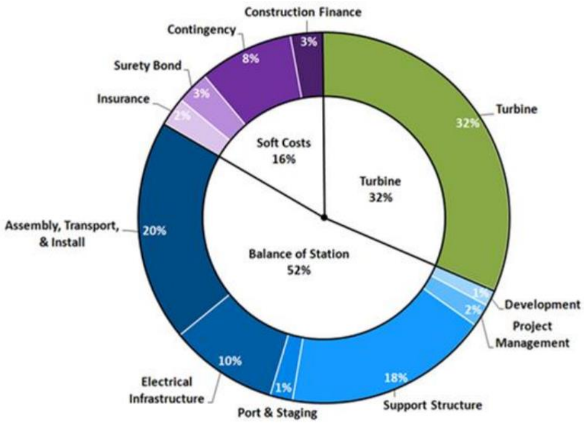

Figure 1 - Offshore wind farm, installed capital costs [15]

Horizontal-axis wind turbines have gained much popularity for land-based wind energy. Unlike VAWTs, HAWT designs have undergone much development over the past 20 years, which has led to lowered COE. As a result, further *significant* reduction in COE, which is necessary for future offshore wind energy, is not likely in the foreseeable future with HAWT configurations. Moreover, the high CG together with gearbox and generator placement at the top of the tower exacerbates installation, logistics, and other O&M cost concerns of offshore wind. Generally speaking, reducing these costs is often considered to have the greatest potential for lowering COE for off-shore wind.

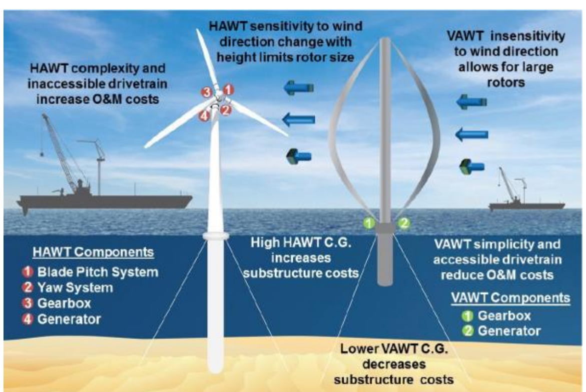

Figure 2 - Comparison of VAWTs and HAWTs for offshore applications [14]

Vertical-axis wind turbines held significant interest in the earlier days of wind energy technology during the 1980s. In the early 1990s, this configuration lost its popularity and the HAWT was adopted as the primary wind turbine configuration. However, when considering the primary COE drivers for offshore wind, the VAWT configuration offers some unique opportunities to significantly lower the support structure, installation, and O&M costs (Figure 2) [14]. These potentials for COE reduction are primarily due to the placement of the gearbox and generator at the bottom of the tower. This not only reduces platform cost by lowering the CG of the turbine, but also reduces O&M costs by having high maintenance components readily accessible near water level. The insensitivity of the VAWT to wind direction and the ability to scale the machines to large sizes will increase energy production and further reduce COE.

The advantages that VAWT technologies offer for offshore wind development are offset by the lack of development in the past years. Modular aero-hydro-elastic analysis software capable of accurately predicting design loads for a floating VAWT system need to be developed and validated. This paper details the development of a framework capable of predicting coupled loading on offshore wind structures.

OWENS FRAMEWORK

To facilitate the development of VAWT technology, robust design tools must be developed to assess innovative design concepts for offshore wind energy technology. Therefore, an aeroelastic design tool is being developed for modeling large offshore VAWT configurations [11], [12], [13]. The Offshore Wind ENergy Simulation toolkit will be able to explore a wide array of offshore VAWT configurations via modal and transient analysis. This tool is developed in MATLAB [8] and is a modular framework that will interface with aerodynamics, platform & mooring dynamics (hydrodynamics), and drivetrain/generator modules to predict the response of a VAWT of arbitrary configuration under a variety of conditions. The formulation also allows for stability analysis to identify potential resonance and flutter issues. The core of the analysis tool is a robust and flexible finite element framework capable of considering the dynamics of large, flexible, rotating structures.

The fundamental requirements of the aero-elastic analysis tool for offshore VAWTs necessitate a flexible framework capable of considering arbitrary configuration geometries, arbitrary loading scenarios, and the ability to interface with various modules that account for the interaction of the environment and power generation hardware with motions of the turbine. Figure 3 shows the analysis framework and the associated flow of information between the core OWENS analysis tool, aerodynamic, hydrodynamic, generator, and controller modules. The general finite element formulation is easily adaptable to transient analysis for investigation of start-up and shut-down procedures as well as turbulent wind and wave loadings. This implementation is also adaptable to modal analysis to assess stability of VAWT configurations and identify potential instabilities.

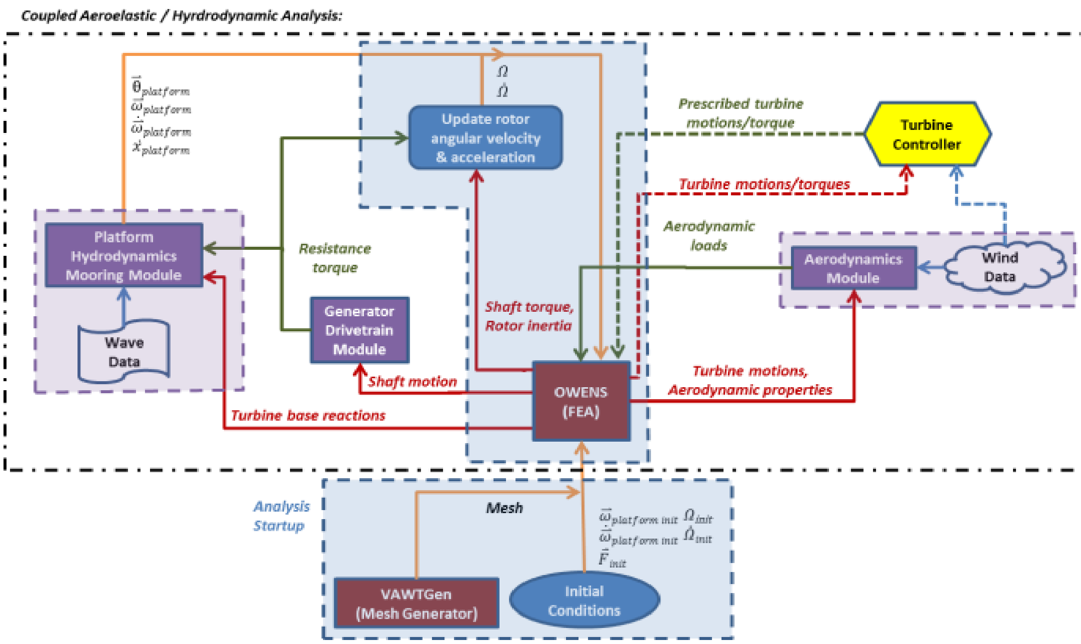

Figure 3 - Analysis framework for the OWENS toolkit

While existing commercially available multi-body dynamics software could be adapted for the required VAWT analyses, OWENS is developed to address the need for a modular, open source VAWT aero-elastic code to serve the wind research community. The modularity of the present approach also allows re-use of many existing analysis code components, such as existing aerodynamics and hydrodynamics codes.

VAWT MESH GENERATOR

A VAWT rotor consists of a tower, blades, and possibly support members (or struts). The blades may be affixed to the tower at their ends as in the Darrieus and V-VAWT configurations or via struts (H-VAWT). Struts may also provide a connection between the tower and blades at any position along the tower and blade spans. The *VAWTGen* mesh generator has been created and is capable of generating VAWTs of arbitrary geometry, including H-type, V-type, and Darrieus configurations (see Figure 4, from left to right: swept Darrieus, Darrieus with struts, V-VAWT, and H-VAWT).

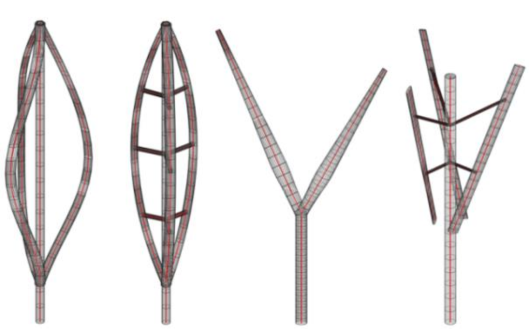
Figure 4 - VAWT configurations produced by VAWTGen

The blades may be rotated into an arbitrary orientation at arbitrary locations about the tower. Therefore configurations with swept blades may be considered. The VAWT configuration will be discretized from continuous structural components into a finite number of beam elements. The implementation also allows for concentrated structural components to be considered, and constraints of various joints may be imposed between structural components.

FINITE ELEMENT IMPLEMENTATION

VAWTs are typically constructed of relatively slender structural components. Accordingly, Timoshenko beam theory has been utilized to characterize the motions of structural component. The equations of motion are developed for a beam element of arbitrary orientation in a rotating reference frame. This reference frame is allowed to translate in order to account for platform or foundation effects. Rotational effects of Coriolis and spin softening phenomenon are included in the formulation. More details of the finite element implementation as well as initial verification efforts are discussed in References [10] and [12] respectively.

WAVEC2WIRE MODULE

For a floating VAWT, the overall system dynamics are significantly influenced by the interaction of the platform with the aquatic environment. To properly capture this interaction it is necessary to incorporate a hydrodynamic analysis code into the OWENS toolkit. With the goal being to develop an open-source and modular toolkit, WaveEC2Wire was used as the hydrodynamic module for this study. WaveEC2Wire is a MATLAB based numerical tool developed by Marco Alves at the Wave Energy Center for the analysis of wave energy converters (WECs) **Error! Reference source not found.**. In order to interface with OWENS, WaveEC2Wire has been modified and restructured such that it functions as the platform hydrodynamics/mooring module shown in Figure 3. Additionally, to use WaveEC2Wire, results from a 3D radiation-diffraction analysis are required for many of the analysis steps. In this study WAMIT was used but any sufficiently capable analysis code is acceptable.

As the hydrodynamic module of OWENS, WavEC2Wire calculates the platform dynamics of the floating VAWT. This is done by applying Newton's second law and equating the body inertial force with the forces acting on the device (Eq. 1).

$$M\ddot{\xi} = F_{pe}(t) + F_{pto}(t) + F_m(t) + F_f(t) + F_{app}(t) \qquad (1)$$

where M is the platform inertia matrix, $\ddot{\xi}$ the platform accelerations, F_{pe} are forces due to pressure differences on the rigid body platform (i.e. purely wave-structure interaction forces), F_{pto} are forces from the power take-off conversion chain (PTO) which interact with the structure to produce electrical power, F_m are mooring forces, F_f are friction forces, and F_{app} are user defined applied forces. For use with OWENS, the PTO terms are removed and F_{app} is defined as the VAWT tower reaction forces which are provided from OWENS through the coupling interface. WaveEC2Wire implements a rigid body assumption for the platform and retains only DOF relating to rigid body motion. This is consistent with other analysis codes [5] and considered adequate as the turbine tower is significantly more flexible than the platform, rendering platform deformations negligible. The user defines the active DOF (eg. surge, sway, heave, roll, pitch, yaw) to be considered in the analysis.

WaveEC2Wire utilizes a fully linear approach to determine the wave-structure interaction forces. For offshore platforms in operating conditions, meaning non-storm sea states with low to medium amplitude waves, the linear assumption holds true and is consistent with other platform analysis codes [5]. Utilizing the linear assumption, the complex amplitudes of the hydrodynamic diffraction (wave excitation) and radiation forces are determined due to a unitary amplitude incident wave as a function of frequency using a 3D radiation-diffraction solver (WAMIT [16]). The excitation complex amplitude is then applied to the wave time history for the desired incident environment to obtain the excitation force time history. WaveEC2Wire can calculate wave time histories for definitions of regular waves, JONSWAP or Pierson-Moskowitz spectrums (directional or non-directional), and sea wave measurements.

The radiation force is calculated using a state-space approach and is represented by a small number of first order linear differential equations with constant coefficients. This approach uses the frequency dependent added mass and damping coefficients as well as the infinite added mass computed from WAMIT to calculate the frequency dependent radiation transfer function K(ω), (Eq. 2).

$$K(\omega) = \frac{2}{\pi}\int_0^\infty K(t)e^{-i\omega t}dt = B(\omega) + i\omega[A(\omega) - A_\infty] \qquad (2)$$

Then, a parametric model of the transfer function is calculated using the least squares method. This model is computed in the frequency domain to eliminate additional errors introduced in calculation of the impulse response functions. For each convolution in the convolution integral, a state-space representation is created using Eq. 3. These states are used in the global state space system defined later.

$$y = \int_0^t K(t-\tau)\dot{\xi}(\tau)dt \cong \left| \begin{matrix} \dot{x} = Ax(t) + B\dot{\xi}(t) \\ y = Cx(t) \end{matrix} \right. \qquad (3)$$

The buoyancy force is calculated through the use of the hydrostatic coefficients which are provided by a 3D radiation diffraction code (WAMIT). The inertia matrix is defined as shown in Eq. 4 below and can be either calculated by WAMIT or input by the user.

$$M = \begin{bmatrix} m & 0 & 0 & 0 & mz_g & -my_g \\ 0 & m & 0 & -mz_g & 0 & mx_g \\ 0 & 0 & m & my_g & -mx_g & 0 \\ 0 & -mz_g & my_g & I_{11} & I_{12} & I_{13} \\ mz_g & 0 & -mx_g & I_{21} & I_{22} & I_{23} \\ -my_g & mx_g & 0 & I_{31} & I_{32} & I_{33} \end{bmatrix} \qquad (4)$$

where m is the mass of the platform; x_g, y_g, and z_g coordinates of the platform CG, and $I_{\#\#}$ the moments of inertia of the platform. All quantities are calculated for the platform only and contributions from the attached VAWT and tower are introduced through the coupling interface.

Other force terms consist of forces imposed by the PTO equipment, mooring system, and friction/drag. As mentioned earlier, the PTO system is deactivated and will not be discussed here. Mooring forces and drag forces are calculated using user defined polynomial functions of platform position and velocity. For this study, simple linear springs were used to simulate the mooring stiffness as a function of platform displacement and drag was neglected. The mooring and drag force calculations are currently an area of improvement and more robust modules are being developed, as discussed in the Future Work section.

To solve the equation of motion, a global state-space model is created. The size of the model depends on the number of convolution states and the number of active DOF in the solution as shown below (Eq. 5).

$$\begin{aligned} &M'\dot{X}(t) = AX(t) + BF_{app}(t) \\ &y(t) = CX(t) \\ &X(t) = \left[[x_{r1}] \ldots [x_{rn}]\ [\xi]\ [\dot{\xi}]\right]^T \end{aligned} \qquad (5)$$

where $x_{r1\text{-}m}$ are the convolution states, ξ and $\dot{\xi}$ are the displacement and velocity vectors respectively and F_{app} are applied forces. M' is the mass matrix (Eq. 6).

$$
M' = \begin{bmatrix} 1 & 0 & \ldots & 0 & 0 \\ 0 & \ddots & \vdots & \vdots & \vdots \\ \vdots & & 1 & 0 & 0 \\ 0 & \ldots & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & [M + A_\infty] \end{bmatrix} \quad (6)
$$

where M is the mass matrix defined in Eq. 4 and $A_\infty$is the infinite added mass from WAMIT. A, B, and C are the state-space coefficient matrices (Eq. 7).

$$
A = \begin{bmatrix} [A_{r1}] & 0 & \ldots & 0 & [B_{r1}] \\ 0 & \ddots & \vdots & \vdots & \vdots \\ \vdots & & [A_{rn}] & 0 & [B_{rn}] \\ 0 & \ldots & 0 & 0 & [1] \\ [C_{r1}] & 0 & [C_{rn}] & [f_f(\xi) + f_m(\xi)] & [f_m(\dot{\xi})] \end{bmatrix}, \quad (7)
$$

$$
B = \begin{bmatrix} 0 \\ \vdots \\ 0 \\ [-1] \end{bmatrix}, \ C = \begin{bmatrix} 0 \\ \vdots \\ 0 \\ [1] \end{bmatrix}^T
$$

where f_f and f_m are the coefficients for the friction drag and mooring forces respectively. The system of ODEs represented in Eq. 5 is then solved using the MATLAB explicit ODE45 Runge-Kutta ODE solver with initial conditions and time steps defined by OWENS. The solution contains state-space terms, as well as platform position, velocity, and acceleration which are output from the WaveEC2Wire module to OWENS. All results are calculated in the platform body coordinate system and transformed to the tower base in order to send to OWENS. Similarly, the external force from OWENS is transformed from the tower base to the platform CG for inclusion in the platform equation of motion. As the transformation capability was under development at the time of this study, it was chosen to attach the tower to the platform CG, thus requiring no transformation. This was adequate to demonstrate the coupling between codes and a finalized transformation routine has been developed for future work. Results for each time step are computed and sent to OWENS according to the coupling methodology, described in the next section.

COUPLING METHODOLOGY

The OWENS toolkit has been designed with ability to interface with arbitrary modules that provide forcing during a structural dynamics simulation. There are a number of ways to consider incorporating external forcing in the analysis framework. One approach, which has been termed “monolithic” [4] incorporates the solution for both the external loads and the structural responses into a single system of equations to be solved at each time step. Whereas this potentially allows for structural dynamics and loading calculations to be performed simultaneously, the modularity of the framework is severely limited. This approach requires all details of loading calculations be implemented alongside the structural dynamics code under a single framework, which can potentially limit code development and collaboration efforts.

Another approach considers “loose” coupling of modules or sub-systems and provides a greater degree of flexibility and modularity in the framework. The framework is no longer monolithic and knowledge of details of external modules is not required by the core analysis framework. Instead, only the data flow between the module and core analysis framework must be defined. This approach has been illustrated in Figure 3 for the OWENS toolkit. A specific example is that reaction force at the base of a turbine will be provided to a platform/hydrodynamics module that calculates the rigid body motions (translational and rotational) of a floating platform under the influence of an attached, flexible turbine structure. The core analysis has no knowledge of the hydrodynamics calculations being performed, and only requires the rigid body motions of the platform system to perform the coupled simulation.

The drawback of the loosely coupled approach is that analysis occurs in a staggered manner with motions/forces at previous time steps being utilized to calculate solutions at a current time step. This can lead to potential stability concerns in the coupling procedure, and critical time step sizes must be considered to maintain a stable solution procedure. Furthermore, a loose coupling approach may have significant stability concerns for modules coupled through acceleration (mass matrix coupling).

An improvement over the loose coupling procedure considers iteration at each time step, using a “predictor-corrector” approach. A popular approach is the Gauss-Seidel iterative method [9], which is used to integrate WavEC2Wire with OWENS. In this implementation, OWENS operates as a driver code and requests solutions from WavEC2Wire at specified time increments. To maintain the modular environment, even though both codes are written in MATLAB, they are run in separate instances. To pass information between the two MATLAB instances, network sockets are used as this approach is straight-forward and efficient for the transmission of small amounts of data. Upon start-up OWENS launches WavEC2Wire with appropriate inputs (platform details, environment, file locations, etc) for WavEC2Wire to define the problem and pre-process any required information. Once initialized, WavEC2Wire waits for a request from OWENS to solve an increment of the hydrodynamics problem. To request a solution, OWENS writes the required input parameters (requested time step and initial conditions) to the network socket, which is then read by WavEC2Wire. For each call, WavEC2Wire solves the system of equations over the requested time step (Eq. 5) and reports back the platform motions and accelerations to OWENS using a similar network socket call. In OWENS, this information is compared with the predicted results using a convergence tolerance to determine if iteration is required. If so, WavEC2Wire is called with a corrected set of inputs and the process repeats. If not, the solution is stored and OWENS moves to the next time increment.

PLATFORM AND MOORING DESIGN

To perform an initial platform design, topside characteristics for a non-optimized 5MW Darrieus VAWT are calculated by scaling existing Darrieus designs. The topside mass is determined to be 973 mt, with a CG of 54.9m above the still water line. The roll and pitch moments of inertia about the CG are 1.35 x 10^9 kg-m^2. The operating thrust load on the turbine is 550.0 kN with a center of pressure 67.0 m above the still water line. With these topside specifications, the following considerations are taken into account to size the initial platform.

1) The desired mean pitch angle is to be <5 deg
2) The desired roll/pitch natural period is to be greater than 20 sec and less than 40 sec

Using the OC3 Hywind spar as a baseline, a platform was scaled to meet the desired performance criteria [3].

Table 1 – Spar-buoy design

Spar-Buoy Design	
Mass (with ballast)	9050 mt
Draft	80 m
Major/Minor Diameter	8.0/13.0 m
CG below SWL	63.5 m
Pitch/Roll Inertia about CG	3.4 x 10^9 kg-m^2
Yaw Inertia about CG	2.0 x 10^8 kg-m^2

With the given topside information, the performance of the unmoored spar-buoy is as follows. The mean pitch under the 550 kN aerodynamic load is 4.4 deg. As the natural periods are influenced by the addition of a mooring system, they are described later.

To perform the WAMIT analysis for this spar design, a quarter symmetric surface model mesh was prepared in MultiSurf [1] and is shown in Figure 5. The model was created using low-order geometry representation with 672 waterline panels and 64 free surface panels to remove irregular frequencies.

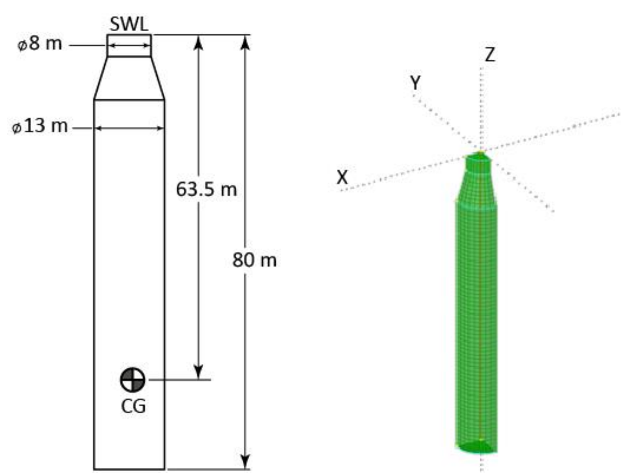

Figure 5 - Spar geometry and surface mesh for WAMIT analysis

The preliminary mooring design is based on the mooring for the OC3 Hywind spar [6]. This system uses three equally spaced catenary lines attached using a delta connection (Figure 6) to increase the mooring yaw stiffness. Each line is made of varied segments and a clump weight.

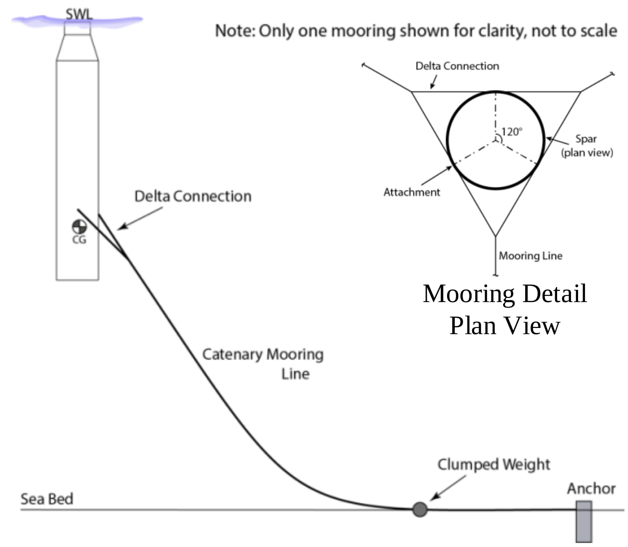

Figure 6 – Spar-buoy mooring attachments

The mooring system was linearized using a mooring model in FAST by independently exciting a platform DOF and measuring the resulting mooring loads [6]. Results for all 6 DOF are presented as the matrix of coefficients below.

$$KM = \begin{bmatrix} 4.1e4 & 0 & 0 & 0 & -2.8e6 & 0 \\ 0 & 4.1e4 & 0 & 2.8e6 & 0 & 0 \\ 0 & 0 & 1.2e4 & 0 & 0 & 0 \\ 0 & 2.8e6 & 0 & 3.1e8 & 0 & 0 \\ -2.8e6 & 0 & 0 & 0 & 3.1e8 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1.1e8 \end{bmatrix} \quad (8)$$

In WavEC2Wire this matrix is multiplied by the platform DOF to determine the mooring forces for a given position displacement. The inclusion of the mooring stiffness influences the natural periods of the system, most notably due to the strong coupling in surge/pitch and sway/roll. For the moored floating platform, the rigid body natural period in pitch/roll is 22.8 sec (0.044 Hz) and 29.0 sec (0.034 Hz) in heave.

This linear mooring model represents a baseline for initial platform design. More advanced mooring representations are currently under development including catenary equation and finite element models. These capabilities will be integrated into WavEC2Wire and allow more realistic simulations of the platform and mooring configurations. Additionally, the mooring system will be updated and tailored to the specific platform and environmental conditions as detailed in Future Work.

PLATFORM DYNAMICS SIMULATION

The topside is represented by a flexible tower structure with the aforementioned rigid body properties (Figure 7). For simplicity, the tower is assumed to be mounted at the center of mass of the platform via a fixed/clamped connection. The flexibility of the tower will also influence the natural periods of the system. In particular, the pitch/roll period will shorten slightly, as demonstrated in the next section.

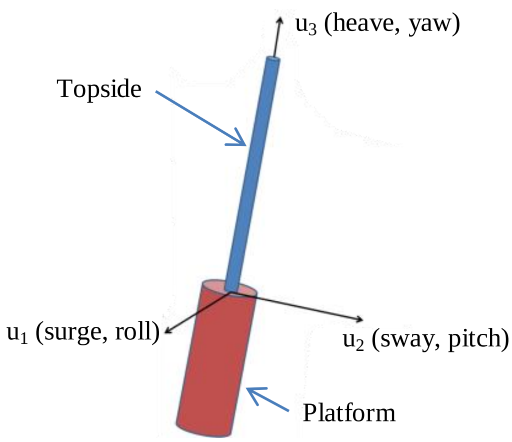

Figure 7 - Representative system for verification procedures

A Newmark-Beta implicit time integration method was considered in the structural dynamics simulation with a time step size of 0.1 seconds. To expedite the analysis, nonlinear effects were deactivated in the structural dynamics simulation. Furthermore, a reduced order model was employed in the structural dynamics simulation which included only the first 10 flexible modes of the tower structure. Although, the linear nature and reduced order of this structural model introduce certain approximations, the goal of this exercise is to verify coupling between a structural dynamics module and platform hydrodynamics module regardless of the fidelity of the individual modules.

VERIFICATION PROCEDURES

Verification procedures considered the isolated motion of individual platform surge, sway, heave, roll, pitch, and yaw rigid body degrees of freedom. First, step relaxations of each platform mode were considered and the influence of platform motion on the response of the flexible structure attached to the platform was observed. Next, an excitation force was applied to the flexible structure, and the response of the platform was observed. Fast Fourier Transforms (FFTs) of the platform and structural response were observed in each case and the frequency content of platform and structure were checked for consistency. Furthermore, all damping mechanisms were deactivated from the platform module (radiation damping, drag, etc.) and no structural damping was applied to the flexible structure. This verified energy was not being dissipated by the numerical time integration schemes or the coupling procedure. The Gauss-Seidel iterative method was employed to couple the two simulations together, and a convergence criterion of 1e-8 was enforced at each time step for iterations of the coupled structural dynamics and platform analysis. Gravity was deactivated in these initial verification procedures.

Additional tests were conducted that examined the combined sway/roll (surge/pitch) response of the coupled platform and structural dynamics analysis. Buoyancy effects were verified by examining a coupled platform/structural dynamics analysis under gravity and buoyant loads to confirm the platform design behaved as intended under self-weight and weight of the attached structure. Finally, a full six-degree of freedom platform analysis was also considered with wave loading active. This exercise sought to verify the effect of hydrodynamic forcing on the platform was also evident in the tower motion. Selected results are shown in the next sections.

PLATFORM ROLL/PITCH

The roll and pitch motions of the platform were isolated and all other rigid body motions of the turbine were constrained. Due to the axisymmetric nature of the platform and attached representative topside, roll and pitch verification tests are identical. First, the platform step relaxation in roll/pitch was considered. Second, an excitation force was applied in the sway/surge direction (u_2/u_1) to the tower top for a configuration with an initially stationary platform. The platform and structural motions were inspected for consistency in frequency content as well as periodicity, indicating energy is being conserved during the coupling scheme.

To perform the step relaxation, the platform was displaced at a roll angle of 0.1 radians with all other rigid body modes of the platform deactivated. The attached flexible turbine structure was initially at rest. At $t=0$ the platform was released and hydrodynamic restoring/mooring forces resulted in harmonic motion of the platform as well as the attached tower structure. The response of the simulation is simulated for two minutes. Figure 8 shows the time history and FFT of platform roll motion and tower tip displacement in the u_2 direction.

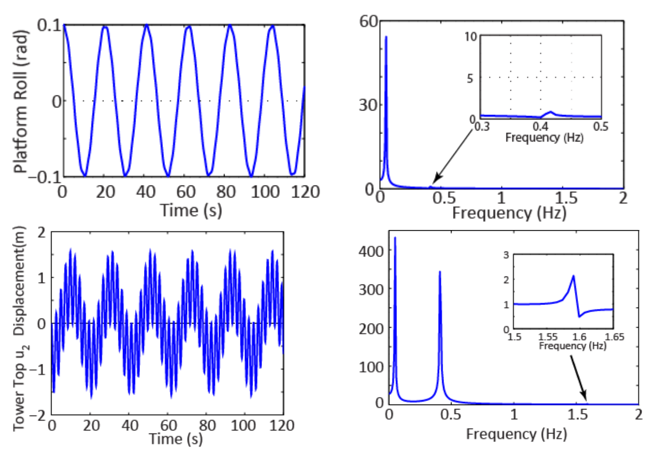

Figure 8 - Roll/Pitch Step Relaxation Results

Periodicity of the platform motion as well as the tower motion is observed, indicating the coupling scheme and numerical integration schemes are not spuriously dissipating energy. Frequencies of 0.050 and 0.41 Hz are observed in the tower motion, the former being representative of the low frequency platform motion and the latter being representative of the tower structural vibration. Furthermore, a frequency of the 0.050 Hz is observed in the platform motion. Closer inspection of the FFT of platform motion reveals a small irregularity in the smooth FFT distribution around 0.41 and 1.59 Hz. This suggests there is some impact of the structural motion on the frequency content of the tower although the forcing as a result of structural vibration is minimal compared to restoring forces acting on the platform.

For the second test the tower structure was excited by applying a force of 1e7 N for 1 second to the tower top in the sway direction to excite a roll rotation of the platform. The platform was initially stationary in this verification exercise. After 1 second, the excitation force was removed and the natural response of the system was observed. Figure 9 shows the time history and FFT of platform roll motion and tower tip displacement in the u_2 direction.

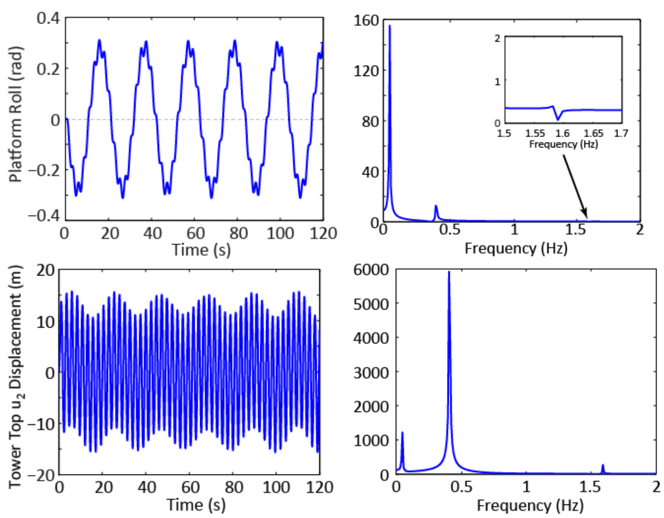

Figure 9 – Roll/pitch tower forcing results

Again, periodicity of the platform motion as well as the tower motion is observed, indicating the coupling scheme and numerical integration schemes are not spuriously dissipating energy. Frequencies of 0.050, 0.41, and 1.59 Hz are observed in the tower motion, the former being representative of the low frequency platform motion and the latter two being representative of the tower structural motion. Furthermore, dominant frequencies of 0.050 and 0.41 Hz are observed in the platform motion. Closer inspection of the FFT of platform motion reveals a small irregularity in the smooth FFT distribution around 1.59 Hz. This suggests there is some impact of the higher frequency structural motion on the frequency content of the tower although the forcing as a result of higher modes of structural vibration is minimal compared to restoring forces acting on the platform and the lower frequency platform motion.

COMBINED SWAY AND ROLL

The combined sway/roll and surge/pitch motions of the platform were isolated and all other rigid body motions of the turbine were constrained. First, a platform step relaxation in sway was considered. Second, an excitation force being applied in the sway/surge direction (u_2/u_1) to the tower top for a configuration with an initially stationary platform. Results from the step relaxation test are shown below.

The platform was displaced in sway/surge a distance of 1 meter with all other rigid body modes of the platform constrained to zero. The attached flexible tower was initially at rest. At $t=0$ the platform was released and hydrodynamic restoring/mooring forces resulted in harmonic motion of the platform sway and roll (surge and pitch) as well as the attached tower structure. The simulation was run for two minutes. Figure 10 shows the time history and FFT of platform sway and roll motion as well as the tower tip displacement in the u_2 direction.

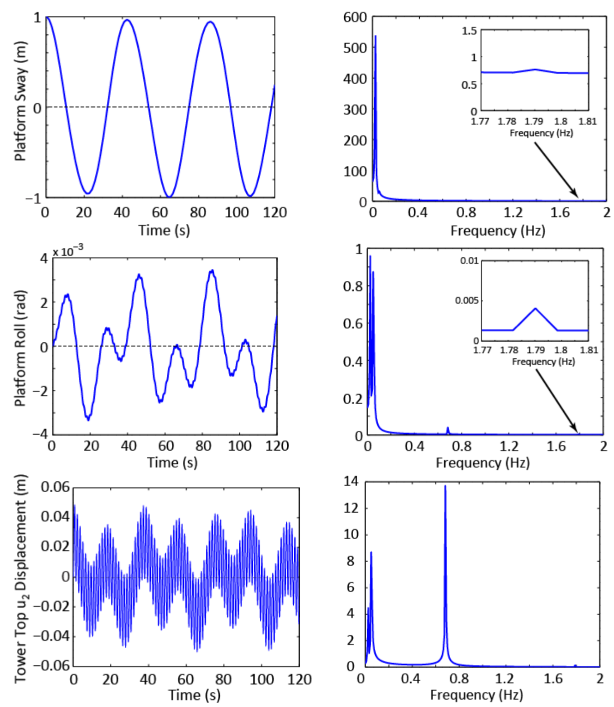

Figure 10 - Combined sway and roll results

Frequencies of 0.025, 0.05, 0.68, and 1.79 Hz are observed in the tower motion, the lowest two being representative of the low frequency platform motion and the higher two being representative of the tower structural vibration. Furthermore, a frequency of the 0.025 Hz is observed in the platform sway motion. Frequencies of 0.025, 0.05, and 0.68 Hz are apparent in the platform roll motion. Closer inspection of the FFTs of platform motion reveals small irregularities in the smooth FFT distribution around

0.05, 0.68, and 1.79 Hz for sway and 1.79 Hz for roll. This suggests there is some impact of the structural vibration on the frequency content of the tower although the forcing as a result of structural vibration is minimal compared to restoring forces acting on the platform.

WAVE EXCITATION

The floating system was subjected to regular wave excitation with a period of 7 seconds (0.143 Hz) and wave height of 2 meters using the wave excitation functionality in WavEC2Wire. All six platform degrees of freedom were active in the simulation, as well as gravity, buoyancy, and damping. 1 minute of simulation time was considered. Figure 11 shows the time history and FFT of platform surge motion and tower tip displacement in the u_1 direction. The regular wave frequency is evident as a peak in both the platform surge and tower top motion FFTs at approximately 0.14 Hz. This indicates that the regular wave excitation of the platform is manifesting itself in the structural motion of the attached flexible structure.

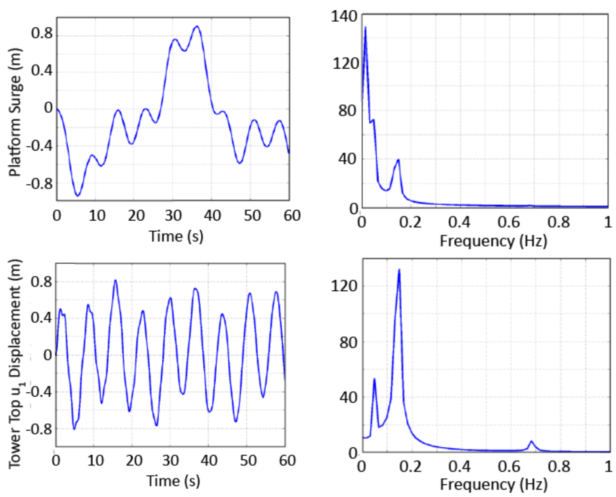

Figure 11 - Wave excitation results

BUOYANCY EFFECTS

This exercise seeks to verify correct buoyancy behavior in the analysis. When coupled with OWENS, the weight of the topside is accounted for in the reaction force passed through the coupling interaction and balances the buoyant force calculated by WavEC2Wire based on the platform position. For this test, the topside mass was reduced slightly in OWENS, resulting in a positive vertical force as the system was initially defined in equilibrium. Figure 12 shows the heave displacement of the platform as the system seeks the new equilibrium point. After ten minutes of simulation, the platform approaches a steady state value of approximately 0.1 meters. This heave displacement results in the correct buoyant force for static equilibrium and is consistent with the desired behavior of the platform under self-weight and a reduced weight of the attached structure.

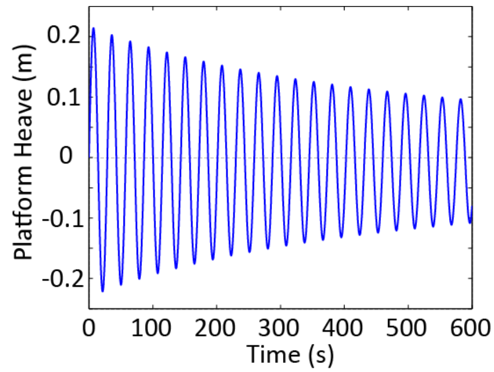

Figure 12 - Heave displacement results

CONCLUSIONS AND FUTURE WORK

This study demonstrates an approach for coupling the hydrodynamic code WavEC2Wire with the OWENS framework. The methods presented are capable of capturing the coupled behavior of the platform and topside motion and system natural frequencies as evidenced by the FFT analysis. The loose coupling scheme with predictor-corrector approach and use of network sockets is proven adequate for the dynamic simulation of a floating VAWT and establishes the groundwork for more robust testing. In addition to coupling a hydrodynamics code with OWENS, efforts are also being made to develop an aerodynamic module which will enable the analysis of wind loading on the floating VAWT system.

This initial coupling verification work will be augmented with future work that exercises the coupled aero-hydro-elastic software in more realistic environments and compares results with existing codes (platform dynamics with simplified topsides using FAST, etc). Damping mechanisms will be activated in these studies as well as appropriate coordinate transformations. The device will be subject to environmental conditions of increasing complexity (regular, irregular, and short-crested waves from the hydro end and steady, gusted, directionally gusted winds from the aero end).

While the current version of the WavEC2Wire module has been tested, there are various areas of improvement which are planned. Primarily, these improvements are aimed at increasing the capability of the WavEC2Wire module to model phenomena more applicable to floating VAWT design and represent areas somewhat outside the initial goals of the development of WavEC2Wire as a wave energy converter analysis code. All of these upgrades are intended to be transparent to the OWENS toolkit and will be completed solely within the WavEC2Wire module.

The first area of improvement will be the development of a mooring system that is tailored to the deployment environment and the specific operating requirements of the VAWT. This will require the use of non-linear mooring analysis code capable of capturing the large displacements typical of floating offshore wind turbine platforms. Instead of using a linear function based on platform displacement, a non-linear mooring module will be developed that more adequately models the larger and more sophisticated moorings required for a floating VAWT. Additionally, a finite element mooring model is also being considered. Similarly, a more sophisticated drag module is being developed. The exact structure of this module is still to be determined, but the intent is to include a Morrison's equation implementation as well as ocean current modeling capability.

Implementation of the mean drift force is also being investigated. The current plan is to use WAMIT to compute the drift frequency dependent quadratic transfer function. The transfer function will then be used in conjunction with the wave time history to create the mean drift force, much in the same way the diffraction force was calculated.

As the design progresses, efforts are being made to create a more accurate representation of the deployment environment. This includes characterizing the operating conditions as well as extreme events and survival cases. These analyses will be used to define applicable wave based loading scenarios and support the design of a wind/wave basin test matrix.

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