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Aeroelastic Modeling of Large Offshore Vertical-axis Wind Turbines: Development of the Offshore Wind Energy Simulation Toolkit

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The availability of offshore wind resources in coastal regions makes offshore wind energy an attractive opportunity. There are, however, significant challenges in realizing offshore wind energy with an acceptable cost of energy due to increased infrastructure, logistics, and operations and maintenance costs. Vertical-axis wind turbines (VAWTs) are potentially ideal candidates for offshore applications, with many apparent advantages over the horizontal-axis wind turbine configuration in the offshore arena. VAWTs, however, will need to undergo much development in the coming years. Thus, the Offshore Wind ENergy Simulation (OWENS) toolkit is being developed as a design tool for assessing innovative floating VAWT configurations. This paper presents an overview of the OWENS toolkit and provides an update on the development of the tool. Verification and validation exercises are discussed, and comparisons to experimental data for the Sandia National Laboratories 34-meter VAWT test bed are presented. A discussion and demonstration of a "loose" coupling approach to external loading modules, which allows a greater degree of modularity, is given. Results for a realistic VAWT structure on a floating platform under aerodynamic loads are shown and coupling between platform and turbine motions is demonstrated. Finally, future plans for development and use of the OWENS toolkit are discussed.

Nomenclature

θ	=	rotor azimuth
Ω	=	rotor speed
$\dot{\Omega}$	=	rotor acceleration
ω	=	platform angular velocity
$\dot{\omega}$	=	platform angular acceleration
h_i	=	co-rotating (hub) frame
n_i	=	inertial frame
p_i	=	platform fixed frame
Δt	=	time step size
t	=	time
F	=	force

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I. Introduction

THE availability of offshore wind resources in coastal regions makes offshore wind energy an attractive opportunity[1]. There are, however, significant challenges in realizing offshore wind energy with an acceptable cost of energy due to increased infrastructure, logistics, and operations and maintenance costs. As this paper will argue, the vertical-axis wind turbine (VAWT)[2] has the potential to alleviate many challenges encountered by the application of horizontal-axis wind turbines (HAWTs) to large offshore wind projects. Although tools exist for offshore[3] and vertical-axis[2,4,5] turbine design, offshore VAWTs require unique considerations better addressed through a new, customized design tool. Furthermore, this software can serve as an open-source, modular foundation for future offshore wind energy research.

This paper discusses motivation for exploring offshore wind energy through VAWT configurations and presents a modular analysis framework that is currently under development. The Offshore Wind ENergy Simulation (OWENS) framework allows for arbitrary VAWT configurations to be modeled, thereby allowing for innovative design concepts to be developed and computationally tested. The underlying finite element formulation allows for a higher level of modeling fidelity compared to previous VAWT tools both in terms of physical description of a VAWT configuration and analysis capabilities. Verification of the analysis tool is discussed, using a number of analytical and numerical verification exercises. Coupling strategies to external modules are discussed and a "loose" coupling approach, which allows for a greater degree of modularity, is presented. Analysis results for a realistic VAWT structure under aerodynamic loads for fixed and floating foundations are presented and the coupling between VAWT and platform motions is demonstrated. Finally, future plans for the development and use of OWENS are discussed.

II. Motivation

Although offshore wind resources make offshore wind energy an attractive opportunity, infrastructure costs and operation and maintenance (O&M) costs for offshore wind technology are significant obstacles that need to be overcome to make offshore wind a viable option. It has been estimated that a greater than 20% decrease in cost of energy (COE) will be required to ensure the viability of offshore wind energy. This reduction in COE is likely to come from decreases in installation and O&M costs, while increasing energy production. Rotor design has a significant impact on all three of these areas, and therefore is critical in reducing the COE. Whereas it is estimated that the entire turbine contributes nearly 28% of the lifecycle cost (see Figure 1), the actual rotor is only estimated to contribute about 7% of this cost. Therefore, it is more important to consider design configurations that lower the installation, logistics, and O&M costs while increasing energy capture rather than trying to decrease the cost of the rotor itself.

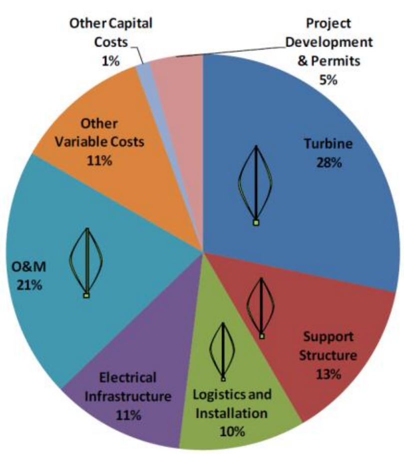


Figure 1. Lifecycle cost breakdown for an offshore wind project

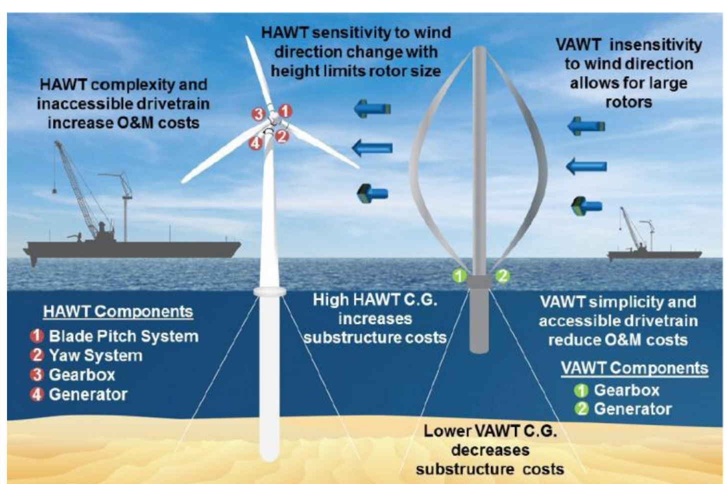


Figure 2. Comparison of VAWTs and HAWTs for offshore applications

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 center of gravity 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, these contributions to COE are often considered to have the greatest potential for lowering COE for off-shore wind.

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. The VAWT configuration, however, can significantly address the need for lower COE for offshore applications[6]. Figure 2 illustrates a comparison of VAWTs and HAWTs for offshore applications, whereas areas on Figure 1 with a VAWT symbol show aspects of lifecycle cost that can be potentially reduced by a VAWT configuration. 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 center of gravity of the turbine, but also reduces O&M costs by having components readily accessible near water level. The simplicity of the VAWT configuration compared to the HAWT can also lower rotor costs. 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. To remain a viable option for offshore wind energy, however, VAWT technology will need to undergo significant development in coming years. Further offshore VAWT development requires modular aero-hydro-elastic analysis software capable of accurately predicting design loads for a floating VAWT system.

III. Model Formulation

The fundamental requirements of the aeroelastic analysis tool for offshore VAWTs necessitates a flexible framework capable of considering arbitrary configuration geometries, arbitrary loading scenarios in the time or frequency domain, and the ability to interface with various modules that account for the interaction of the environment and power generation hardware with the turbine structure. The finite element method[7] provides a means to satisfy these general requirements. If a sufficiently robust element is developed, a mesh (collection of elements) of an arbitrary VAWT configuration may be constructed via a mesh generator. The ability to capture various couplings and provide an accurate representation of turbine behavior will depend on the robustness of the element formulation.

The finite element method requires boundary conditions to be imposed on the elements by specifying loads or displacements at discrete points (nodes) in the mesh. These boundary conditions provide a clear interface between aerodynamic and hydrodynamic modules that impart forces on the turbine. With boundary conditions specified, unspecified displacements and loads may be calculated. Next, displacement motions of the turbine may be provided to aerodynamic and hydrodynamic modules to calculate loads on the turbine. This gives rise to mutual causation because in reality loads and displacements are intricately connected. Practical solutions to this dilemma will be discussed in a subsequent section.

A. Analysis Framework

The OWENS analysis framework has been designed utilizing the robustness and flexibility of the finite element method. By utilizing boundary conditions, the interaction of loadings on the structure and platform will be considered along with generator effects to predict the motions of the turbine. Provisions will be made for a turbine controller as well. 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 resonance concerns.

Existing commercially available multi-body dynamics software could be adapted to enable the required VAWT analyses. There is a need, however, for a VAWT aero-elastic code that can serve the wind research community, one that is modular, open source, and can be run concurrently in a parallel batch processing setting without the need to purchase multiple software licenses. The modularity of the present approach will also allow re-use of many existing analysis code components, such as existing aerodynamics[8-10] and hydrodynamics[11,12] codes.

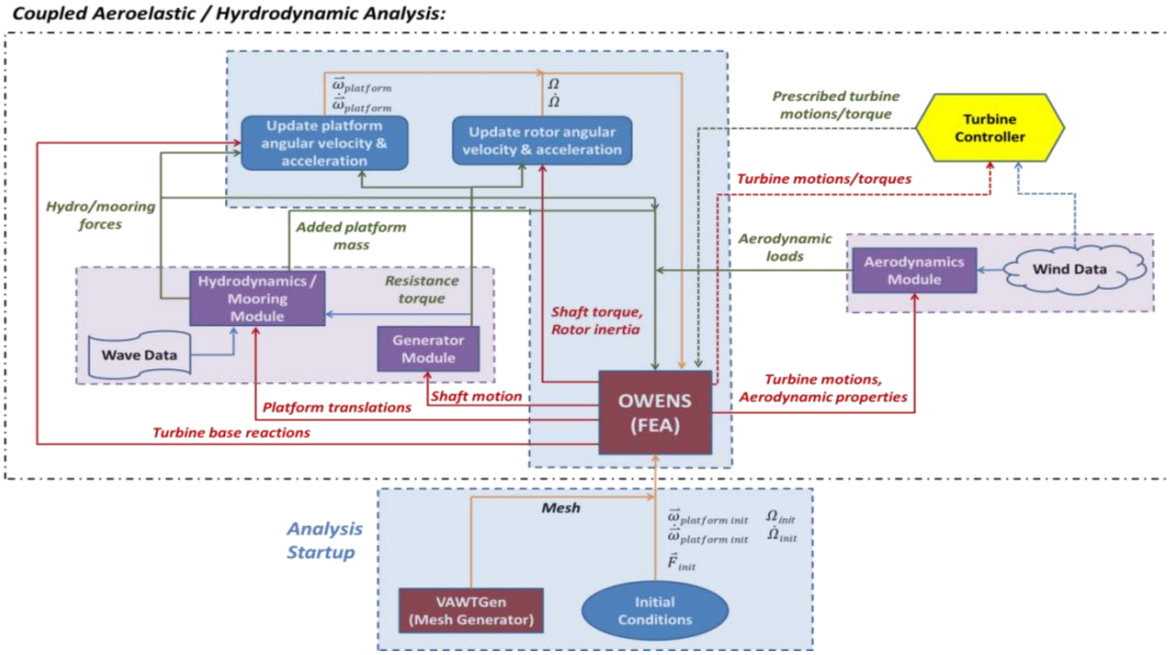


Figure 3. Analysis framework for the OWENS toolkit.

B. VAWT Mesh Generator

A VAWT rotor consists of a tower, blades, and possibly support members (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 that is capable of generating VAWTs of arbitrary geometry, including H, V, and Darrieus configurations. Any number of blades may be oriented arbitrarily about the tower, and configurations with swept blades may be considered. The VAWT configuration is discretized from continuous structural components into a finite number of beam elements. Figure 4 shows arbitrary Darrieus, V, and H-VAWTs VAWTGen is capable of generating. VAWTGen also allows for concentrated structural components to be considered, and constraints of various joints may be imposed between structural components.

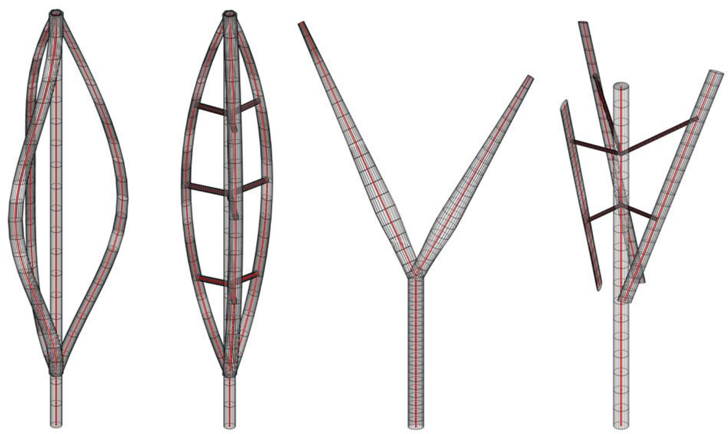


Figure 4. Arbitrary VAWT configurations produced by VAWT Gen

C. Finite Element Formulation and Implementation

To facilitate the aeroelastic analysis of a vertical axis wind turbine via a finite element approach, a three-dimensional Timoshenko beam element has been formulated. The beam is "three-dimensional" in the sense that it allows for deformations of the beam in all physical dimensions. Each node of the beam has three translational degrees of freedom and three rotational degrees of freedom. Retaining a torsional degree of freedom in the element allows passive aeroelastic tailoring concepts to be explored. Furthermore, the constitutive relations of the beam element have been developed in a manner that allows for coupling terms to be introduced for bend-twist and extension-twist couplings that may arise due to cross-sectional geometry or composite material usage. The equations of motion are developed for a beam element of arbitrary orientation in a co-rotating (hub) frame. Thus, rotational effects of Coriolis and spin softening phenomenon are included in the formulation. This reference frame is allowed to translate to account for platform or foundation effects. These considerations allow for formulations with couplings between platform and element motions. The various reference frames used to describe the motion of a point in the structure are shown in Figure 5.

The ability for the element to have arbitrary orientation in the hub frame allows for complex VAWT configurations to be constructed using the VAWTGen mesh generator. This also allows the investigation of passive aeroelastic couplings through swept configurations. Inherent in the beam formulation is that deformations of the elastic axis are being modeled. For proper dynamics modeling, mass center offsets from the elastic axis at each cross-section are introduced. The beam formulation also accounts for the ability to model concentrated masses and stiffness at any point along the element. Imposing concentrated masses allows for one to account for unsmooth mass distributions in the turbine, due to joints at tower/strut/blade connections or other hardware. Concentrated masses can also be used to model internal joints in a turbine blade that result in unsmooth mass distributions. Concentrated stiffness can model stiffness at component joints, or even at internal blade joints.

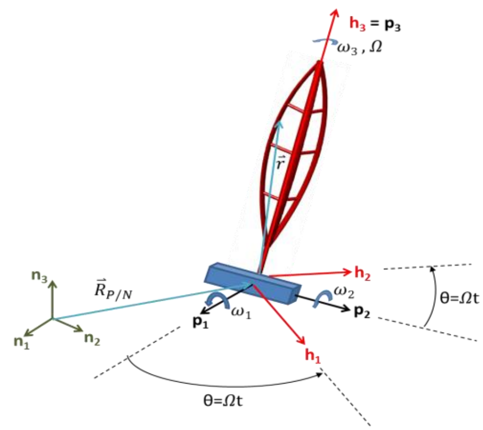


Figure 5. Illustration of reference frames, position vectors and angular velocities for a point on a VAWT

The beam formulation utilizes numerical integration to construct the element system matrices that will be assembled into a global system of equations. This allows flexibility in the shape functions that are used to describe the variation of a displacement along the length of an element. Simple linear shape functions can be used for piecewise representation of a structural component from many beam elements. Alternatively, more advanced shape functions can represent a structural component with a single beam element (comparable to an assumed modes approach, as utilized by National Renewable Energy Laboratory FAST dynamics code for HAWTs[3]). If one can construct mode shapes for the predominant motions of structural components (perhaps by performing finite element dynamics analysis on structural components with various boundary conditions), these mode shapes can be provided to the software implementation with relatively minimal changes to the core analysis framework.

Geometric nonlinearities have been included in the beam element formulation to include stress stiffening[13]. Such effects model the stiffening that occurs in a structure under load. Stress stiffening can be critical in the modal analysis of rotating structures to obtain appropriate predictions of system frequencies for a structure under rotational loads. A static analysis is typically performed considering loads at some equilibrium configuration (i.e. constant rotor speed of a VAWT). The nonlinear equations of motion are then linearized about this equilibrium solution and modal analysis of a pre-stressed configuration is considered. Future formulations of the beam element will consider large deformations of structures which may significantly alter load-displacement relationships. If necessary, more robust geometric nonlinearities will be included via a total or updated Lagrangian formulation[14].

IV. Verification Procedures

Verification and validation procedures were conducted on the finite element implementation of a beam element with rotational effects as well as the overall finite element framework of the OWENS toolkit. Both an Euler-Bernoulli and Timoshenko beam were developed and verified, although validation exercises showed the Timoshenko beam element proved to be better suited for the class of structures (VAWTs) the OWENS toolkit is being developed for. Analytical solutions for free vibration[15] (without rotational effects) were considered as well as an analytical solution for a "whirling shaft"[5] which introduced rotational effects into verification exercises.

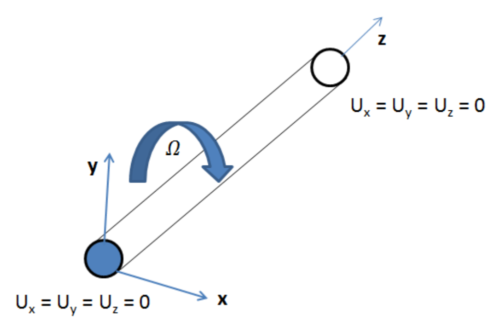


Figure 6. Schematic for whirling shaft

The whirling shaft configuration is shown in Figure 6. The configuration is a beam with pinned-pinned boundary conditions that is specified to rotate at constant angular velocity (Ω) about its flexural axis. Only transverse deflections of the beam are modeled and axial and torsional deformation modes are constrained in this verification exercise. The known analytical solution[5] for this configuration is shown below. At zero specified angular velocity the beam behavior is relatively simple with uncoupled transverse bending modes, and the natural frequency (ν_n) for a pinned-pinned beam is shown in Eq. (1). For the whirling shaft, the natural frequency of the beam is related to the parked natural frequency and the specified angular velocity as shown in Eq. (2). The mode shapes become coupled in transverse deflections with a 90 or 270 (-90) degrees phase offset as shown in Eqs. (3) and (4). Table 1 shows error of natural frequencies calculated using the OWENS analysis tool relative to the analytical solution for various angular velocities for n = 1,2,...5. Overall, outstanding agreement is seen using 20 uniform beam elements to describe the whirling shaft configuration. The mode shape amplitudes and phase for the 2nd bending mode (n=2) are shown in Figure 7. The correct mode shape amplitudes are observed, as well as the correct phase offsets. This exercise successfully verified the basic rotational effects present in the finite element formulation and implementation.

$$\nu_n = \left(\frac{n\pi}{L}\right)^2 \sqrt{\frac{EI}{\rho A}} \tag{1}$$

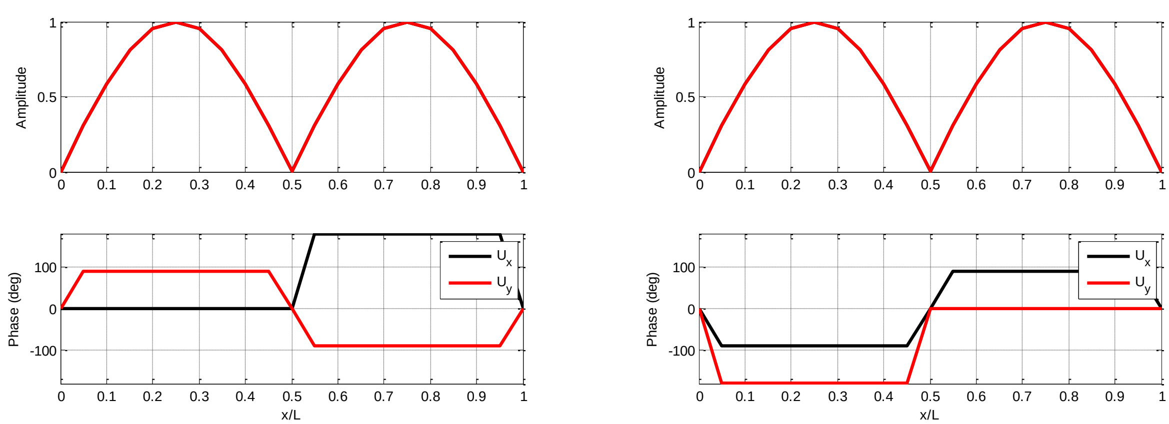
$$\omega_n = |\nu_n \pm \Omega| \tag{2}$$

$$\begin{Bmatrix} U_x \\ U_y \end{Bmatrix}_1 = \sin\frac{n\pi}{L}z \begin{Bmatrix} \cos\omega_n t \\ \cos\left(\omega_n t + \frac{\pi}{2}\right) \end{Bmatrix} \tag{3}$$

$$\begin{Bmatrix} U_x \\ U_y \end{Bmatrix}_2 = \sin\frac{n\pi}{L}z \begin{Bmatrix} \cos\omega_n t \\ \cos\left(\omega_n t + \frac{3\pi}{2}\right) \end{Bmatrix} \tag{4}$$

Table 1. Whirling shaft predicted frequencies percent error relative to analytical solution

	***Ω*(Hz)**	**0.0**		**0.5**		**1.0**		**2.0**		**5.0**
n=1	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.10	0.03
n=2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01
n=3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01
n=4	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
n=5	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03



a) Lower frequency (β= 90 deg) **b) Upper frequency (β= -90 deg)**

Figure 7. Whirling shaft coupled mode shapes (n=2)

Analytical solutions are difficult to obtain for all but the simplest configurations. Thus, an assumed modes approach was also considered to perform additional verification procedures beyond analytical solutions. The assumed modes approach provided a second numerical treatment of structural dynamics of a beam. This method is independent of the numerical finite element method, and may serve as another verification procedure to ensure the correctness of the finite element implementation.

Finally, ANSYS® finite element software was used in a code-to-code comparison with the OWENS finite element framework. ANSYS® is a well-verified commercial code, and a successful code-to-code comparison serves as a verification exercise for the OWENS toolkit. This code-to-code comparison allows for realistic structures to be modeled with each software tool and numerous features to be verified. Overall, a high degree of success was seen in the verification exercises performed on the OWENS toolkit and numerous results were documented. For brevity, the full report of verification exercises is not shown in this paper. Verification results for the aforementioned "whirling shaft" problem will be shown. Full verification procedures and results will be documented in a verification manual for the OWENS toolkit.

V. Validation Procedures

The OWENS toolkit has been validated using experimental test data for the Sandia National Laboratories (SNL) 34-meter VAWT test bed[2,16]. Validation procedures include comparison of parked modal analysis to experimentally observed natural frequencies and mode shapes. Furthermore, the availability of experimental data for the response of a rotating wind turbine was utilized to construct Campbell diagrams. Comparison of the experimental and predicted Campbell diagrams served as a validation exercise for the ability of OWENS to model a realistic, rotating VAWT structure. Figure 8 shows a photograph of the installed 34-meter VAWT as well as the wireframe visualization of the VAWT created using the VAWTGen mesh generator.

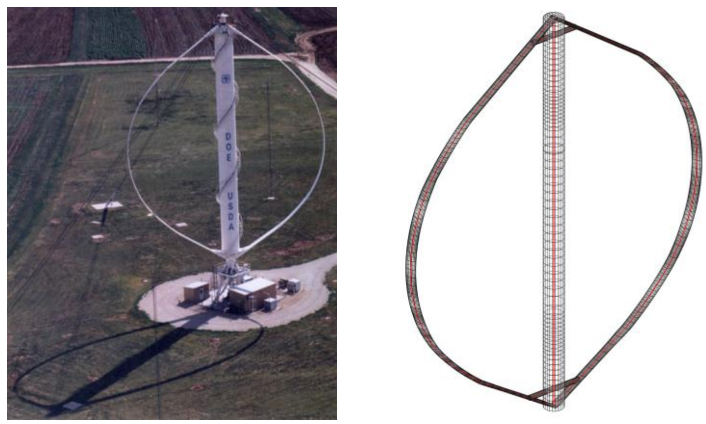


Figure 8. Sandia 34-meter VAWT test bed

This model was composed of a total of 208 elements and 215 nodes (1290 degrees of freedom). Blade profiles were modeled after original schematics for the 34-meter VAWT. Inspection of component schematics allowed the masses of concentrated joint hardware to be accounted for. Blade mechanical properties were calculated from cross-sectional geometries and aluminum material properties. Strut (tower to blade connection) components were modeled at the tower top and bottom. Although the actual turbine had a guy-wire system, approximate boundary conditions of a pinned tower top and base tower base were utilized in verification and validation procedures. The tower base torsional degree of freedom aligned with the tower axis (axis of rotor rotation) was also constrained to enforce that the tower base rotate with the hub frame.

A. Parked Modal Analysis

The predicted frequencies and mode shapes were compared to modal test results for the 34-meter VAWT as shown in Table 1. Mode shape abbreviations are: FA = flatwise anti-symmetric, FS = flatwise symmetric, PR = propeller, BE = blade edgewise/butterfly. Note that due to the prescribed boundary conditions, tower modes are not predicted in the analysis. Furthermore, more accurate specifications of mass/elastic axis offsets, concentrated mass terms, and boundary conditions are likely necessary to achieve better agreement with modal test results. Despite these likely missing refinements of the model, the OWENS Timoshenko implementation has a maximum difference of 7.6% for the first six modes, and the OWENS Euler-Bernoulli implementation has a maximum difference of 9.5%. Again, tower modes are not present in the comparison due to the approximate boundary conditions at the tower top eliminating tower modes from the analysis predictions. Timoshenko beam theory in general is more robust than Euler-Bernoulli beam theory, and appears to agree better with experimental results. The two beam theories have comparable computational costs, and future developments of OWENS will make use of the Timoshenko beam element implementation. Figure 9 presents predicted mode-shapes for the 34-meter VAWT test bed. The predicted mode shapes are in good agreement with those documented in experimental data[16].

Table 2 Comparison of OWENS modal analysis frequencies (Hz) to modal tests for parked SNL 34-meter VAWT

Mode	Modal Test[16]	OWENS (Timoshenko)	% Difference	OWENS (Euler-Bernoulli)	% Difference
1 FA	1.06	0.99	6.20	0.96	9.51
1 FS	1.06	1.00	5.58	0.97	8.78
1 PR	1.52	1.58	4.06	1.62	6.63
1 BE	1.81	1.67	7.57	1.67	7.68
2 FA	2.06	2.03	1.21	1.98	3.83
2 FS	2.16	2.08	3.70	2.01	6.78

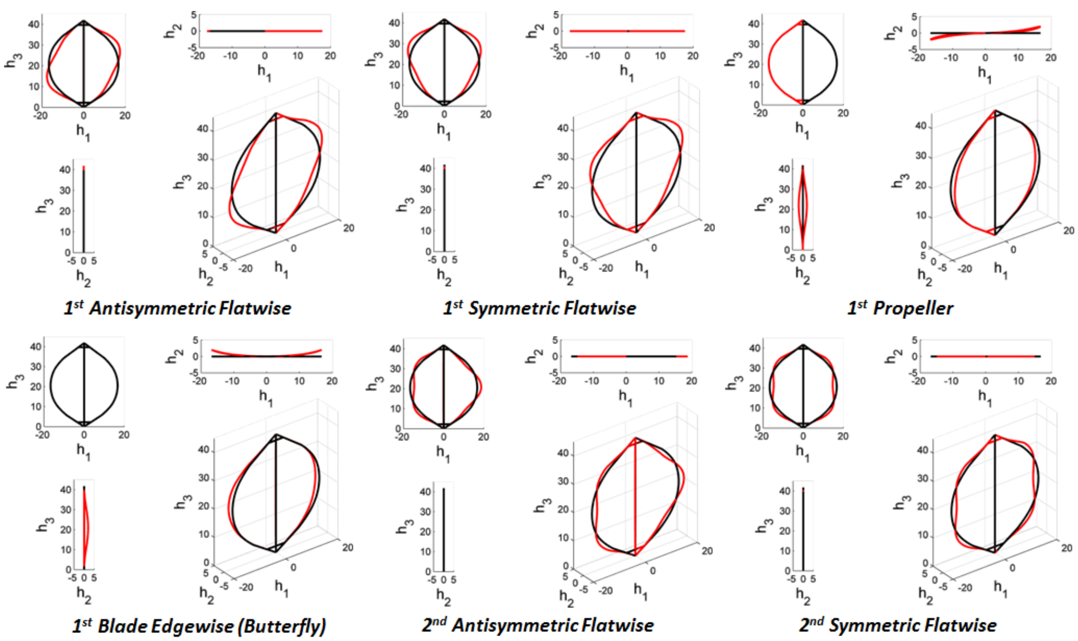


Figure 9. Visualization of predicted mode shapes for SNL 34-meter VAWT

B. Rotating Modal Analysis

Rotating modal analysis of the SNL 34-meter VAWT was conducted using the OWENS toolkit. Rotor speeds from 0 to 50 RPM were considered, and stress stiffening effects were included. A static analysis under gravitational and centrifugal loads was conducted to establish an equilibrium configuration about which modal analysis was performed. This "spin-up" procedure incorporates pre-stress effects that result in a stiffening of the structure. Spin softening and stress stiffening effects compete as rotor speed increases, but typically stress stiffening effects are more dominant. This results in an increase in most natural frequencies of the system as rotor speed increases. Thus, the inclusion of stress stiffening is critical in replicating behavior of actual flexible, rotating systems.

Figure 10 shows the predicted Campbell diagram for the first 12 modes of the 34-meter VAWT for the rotor speeds considered. Experimental data obtained from edgewise and flatwise gauges is also plotted. Overall, the predictions are in good agreement with the trends of the experimental data, especially if one considers the moderate resolution of the VAWT model. If one were to adjust the stiffness/ mass distributions, and boundary conditions of the modeled VAWT better agreement may be achieved. Nevertheless, the model appears to be more than adequate for preliminary design considerations. It is notable that the tower mode is not predicted, but this mode will not be present due to the approximate boundary condition at the top of the tower. As mentioned previously, this boundary condition was specified to avoid modeling the guy wires of the actual turbine for initial validation efforts.

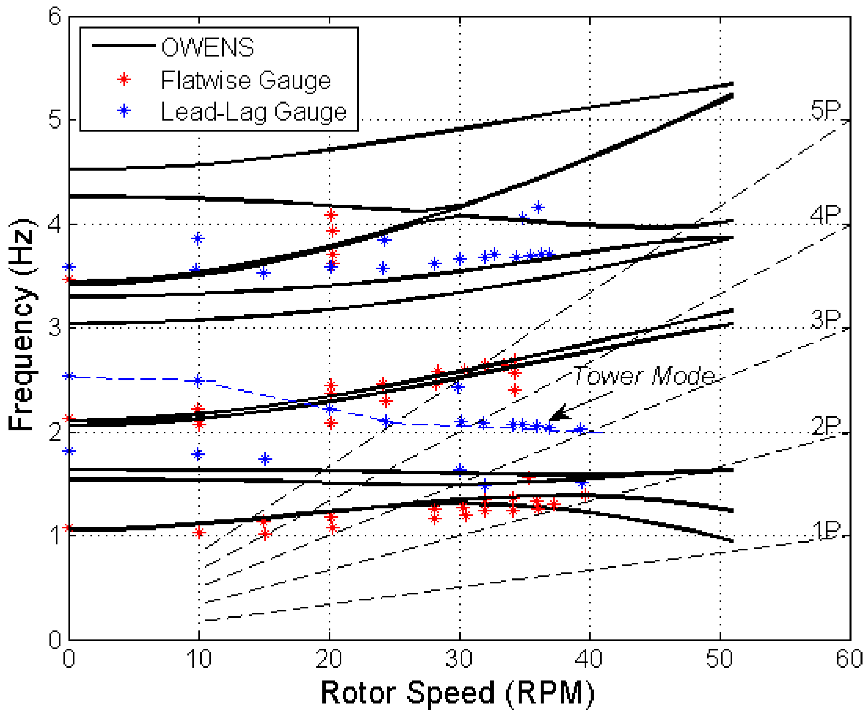


Figure 10. Campbell diagram for the SNL 34-meter VAWT (experimental data and numerical predictions)

VI. Module Interface Considerations

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",[17] 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. Furthermore, this approach potentially requires more overhead in code management and limits the ease of collaboration. A monolithic code not only requires developers to understand the details and implementation of particular external loading calculations, but also requires understanding the intricacies of the monolithic framework design and implementation. This can potentially limit code development and collaboration efforts. Therefore, a monolithic framework has not been considered for the OWENS toolkit.

Another approach considers "loose" coupling of modules and provides a greater degree of flexibility and modularity in the framework. The framework is no longer monolithic and knowledge of details of external loading 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 platform motions (displacements, velocities, and accelerations) will be provided to the hydrodynamics/mooring module without any knowledge of the calculations that are to be performed by this module. The analysis framework then receives restoring forces and moments in return that will be applied to the platform structure. The drawback of this approach is that analysis occurs in a staggered manner with motions at previous time steps being utilized to calculate external forces at a current time step. Future work will investigate techniques for iterating at each time step to reach a converged solution within a loosely coupled framework. Nevertheless, it is believed that the greater modularity of a loose coupling strategy outweighs this drawback. Furthermore, the stability limits of this approach are well understood[18] and consequences of the inherent approximations in this approach can be eliminated for all practical purposes with sufficiently small time steps.

A comparison of the monolithic (which will be referred to as a "tight" coupling approach) to the loose coupling approach will be considered by modeling the platform mooring/foundation as simple linear springs. In the tight coupling approach, the spring restoring force $F = -kx$ is modeled by directly modifying the equations of motion in the OWENS framework. This restoring force is modeled using an external module with the loose coupling approach. For all practical purposes, the OWENS framework doesn't have access to the spring force-displacement relations and the module is treated as a "black box". The module receives platform displacements from OWENS and provides restoring forces in return. The Sandia 34-meter VAWT was considered on an elastic foundation modeled by three linear, translational springs. A step relaxation was performed on the platform and the motion of the platform and VAWT structure were observed for a number of time step sizes.

First, the boundary conditions on the tower top of the 34-meter VAWT were removed to allow for tower modes to appear in structural response. The stiffness of the platform spring was tuned to result in a rigid body platform frequency of 0.1 Hz. This frequency is representative of low frequency motion encountered in mooring systems of floating structures. The first tower mode of the VAWT in the "flatwise" direction for a fixed foundation is 1.058 Hz. Modal analysis of the VAWT on the elastic foundation yielded corresponding coupled platform-tower modes of 0.125 Hz and 1.359 Hz. For a parked VAWT, the platform/turbine was displaced 1 meter in the flatwise direction and released at time t = 0. Motions in the flatwise platform and tower top displacements were examined for time step sizes of 0.01, 0.1, 0.25, 0.5, and 1.0 seconds. Time integration was performed using an energy preserving time integration method for Gyric systems.[18] At larger time step sizes, stability limits on the loose coupling approach ($\Delta t < 2/\omega_{max}$, such that ω_{max} is the maximum frequency of the motion being supplied to the external module) were encountered as documented by Belytchko[19]. Figure 11 and Figure 12 show the platform and tower top displacement respectively for the various time steps sizes. Results for Δt = 0.01 seconds are not plotted, but are shown in subsequent tables examining convergence of frequency content and motion amplitudes for loose and tight coupling approaches. Solid lines represent simulation results with a tight coupling approach whereas dashed lines represent those with a loose coupling approach. Due to the low frequency of the platform mode, all time steps agree reasonably well. Discrepancies are noticeable for time step sizes of 0.5 and 1.0 seconds, but this is true for both tightly and loosely coupled approaches. With regards to the tower top motions, the higher frequency content in the tower mode showed more noticeable discrepancies for 0.5 and 1.0 second time steps (tower motions for time steps size of 1.0 seconds are not visualized due to large discrepancies).

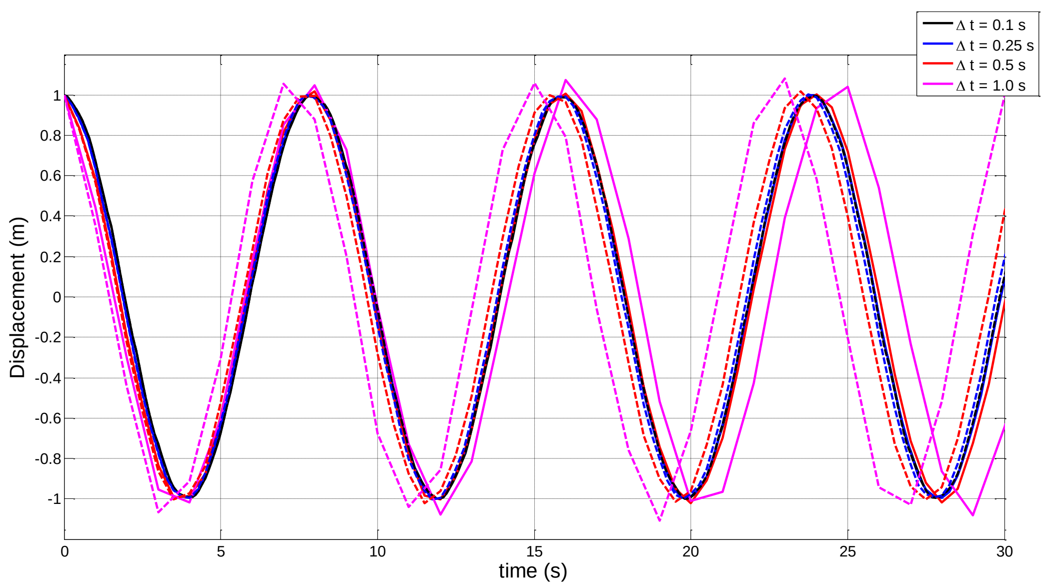


Figure 11. Platform motion for various time step sizes and tight/loose coupling approaches

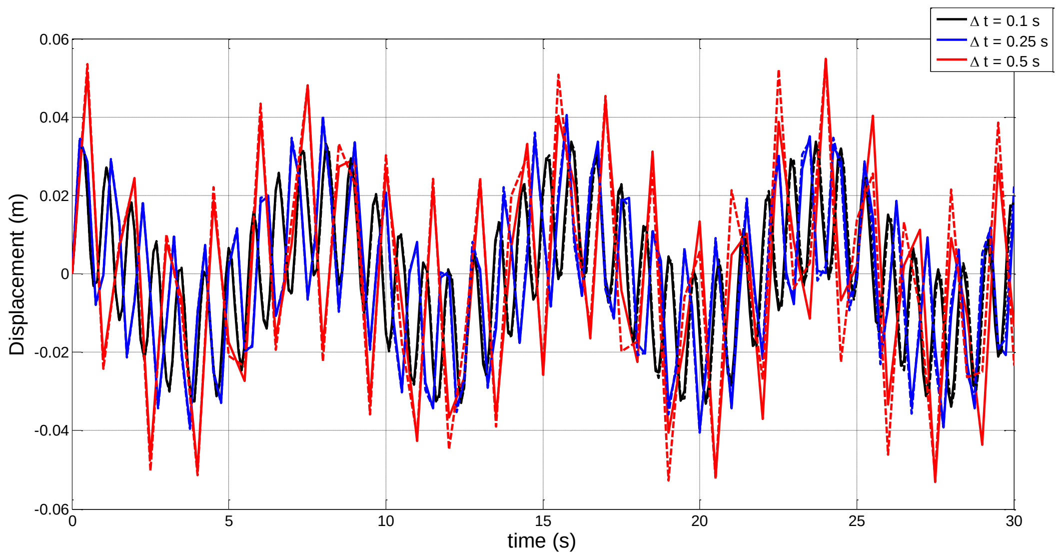


Figure 12. Tower top flatwise motion for various time step sizes and tight/loose coupling approaches

Tables 2 and 3 quantify the errors in motion of platform and tower respectively in terms of frequency content and extrema. These errors are calculated using the values for frequency from modal analysis and extrema from a tightly coupled 0.01 second time step solution as a reference. In terms of frequency content, both coupling strategies degrade in prediction at larger time step sizes. Nevertheless, it is notable that the loose coupling strategy performs comparable to the tight coupling approach with respect to frequency prediction for larger time steps. With regards to extrema, it was observed that the tightly coupled approach typically had lower errors, especially at large time step sizes. On the whole, this exercise not only demonstrates the concept of loose coupling, but also assures the approach can be applied with reasonable accuracy if appropriate time integration parameters are chosen. This study also indicates that moderately sized time steps may be utilized for initial design studies. Furthermore, for low frequency platform motions, accurate modeling of VAWT structural motions may require smaller time steps than needed to accurately resolve platform forcing via a loose coupling strategy.

Table 3. Percent errors of platform motion frequency content and extrema

	Platform Mode Frequency		Tower Mode Frequency		Minimum Displacement		Maximum Displacement	
Δt	**Tight**	**Loose**	**Tight**	**Loose**	**Tight**	**Loose**	**Tight**	**Loose**
0.01	0.00	0.00	0.59	0.66	-	-	-	-
0.10	0.00	0.00	5.00	5.00	0.01	0.06	0.08	0.04
0.25	0.00	0.00	22.81	22.66	0.12	0.61	0.09	0.46
0.50	0.00	1.36	46.53	46.23	2.41	2.32	1.82	2.57
1.00	4.32	3.52	67.68	68.26	8.14	11.05	7.51	11.43

Table 4. Percent errors of tower top motion frequency content and extrema

	Platform Mode Frequency		Tower Mode Frequency		Minimum Displacement		Maximum Displacement	
Δt	**Tight**	**Loose**	**Tight**	**Loose**	**Tight**	**Loose**	**Tight**	**Loose**
0.01	0.00	0.00	0.44	0.28	-	-	-	-
0.10	0.00	0.00	5.52	5.63	4.01	4.94	4.32	4.94
0.25	0.00	0.08	23.38	23.27	16.98	25.31	23.77	25.31
0.50	0.00	1.36	46.96	46.67	64.20	70.06	69.44	67.90
1.00	4.32	3.52	68.54	68.26	172.53	225.93	155.25	227.78

VII. Analysis of a VAWT with Aerodynamic and Platform Forcing

Previous sections explained the analysis framework for the OWENS toolkit along with loose coupling approach that was adopted to increase the modularity and flexibility of the tool. This approach was demonstrated on a realistic VAWT configuration with a simple foundation model. Results for a one-way coupling to the Sandia National Laboratories CACTUS[8] VAWT aerodynamics software are presented here. The coupling is one-way in the sense that only the rigid rotor rotation of the VAWT is considered in aerodynamics analysis. Blade deformations are not accounted for in aerodynamic force calculations, and thus the aeroelastic nature of the simulation is limited. Future developments will make use of two-way coupled aerodynamics model[9,10] that receives blade deformations and performs aeroelastic calculations.

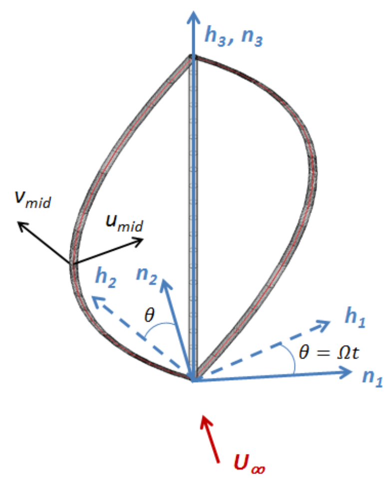


Figure 13. Illustration of idealized 34-meter VAWT with frames and wind direction.

An idealized version of the Sandia 34-meter VAWT was considered in this analysis. This configuration is very similar to the actual 34-meter VAWT test bed, but constant blade cross-sections and a parabolic blade profile are modeled. No struts or joint hardware are considered. A constant rotor speed of 30 revolutions-per-minute was specified and uniform wind speed of 8.9 m/s was considered. Both fixed and floating foundations were considered, and the floating foundation had frequencies identical to that specified in Section VI. Figure 13 illustrates the idealized VAWT along with reference frames and wind direction. The tower base is modeled using a fixed boundary condition at the foundation/platform and the tower top was left unconstrained. For this intial study, rigid motion of the platform/VAWT combination are not incorporated into aerodynamic calculations. Future work will address this interaction. Aerodynamic calculations were conducted for 16 seconds (8 rotor revolutions), as beyond this time periodicity in the aerodynamic forcing was observed. Aerodynamic loads, along with centrifugal forces, were applied to the rotating structure. No wave loadings or hydrodynamics were considered in this analysis, but the springs attached to the floating foundation serve as a simplified mooring system. Future work will implement more robust hydrodynamics/mooring modules into the OWENS framework.

Figure 14 shows the predicted flatwise and edgewise motion of the mid-blade span (see Figure 13) for the cases of fixed and floating foundations. For this configuration the floating foundation has a clear effect on amplitudes of blade motions. The lower frequency of the platform is also observed in the blade motion. Figure 15 shows the translational motion of the platform (U and V are platform translations aligned with n_1 and n_2 respectively as shown in Figure 13). This motion further illustrates the coupling of platform and VAWT modes by containing both lower(platform) and higher(tower) mode frequencies. Furthermore, the effect of the aerodynamic thrust loading along with inertial effects of structural vibrations on platform motions is apparent. This study has qualitatively examined the response of a representative ground-based VAWT under aerodynamic loading with fixed and floating foundations. Future work will examine more suitable VAWT and platform designs for offshore applications.

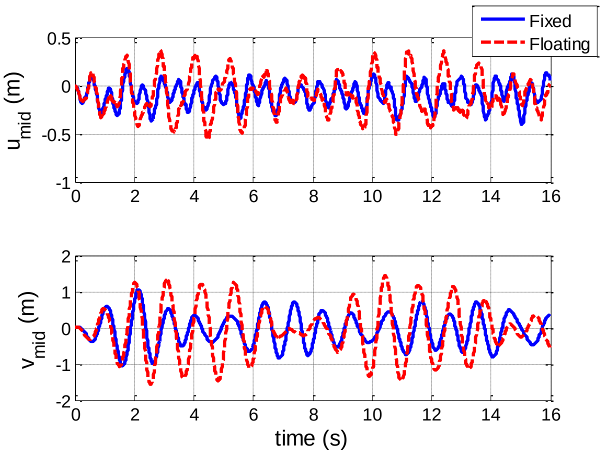


Figure 14. Blade mid-span motions of idealized 34-meter VAWT under aerodynamic loading with fixed/floating foundations

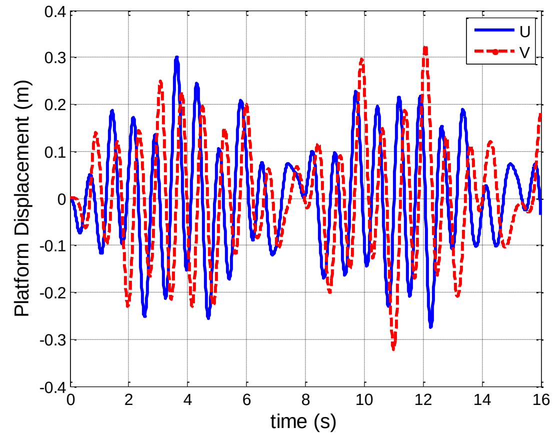


Figure 15. Platform motions of idealized 34-meter VAWT under aerodynamic loading

VIII. Conclusion

In summary, the viability of offshore wind energy depends on significant advancement of offshore wind technology. VAWTs are poised to lower cost of energy for offshore wind by providing a simpler design that is scalable to the large sizes required for increased energy capture. New robust design tools are required to advance the technology, and the analysis framework presented in this paper will satisfy this need. The Offshore Wind Energy Simulation toolkit will be a central framework for an efficient, portable software package that will be an invaluable resource for future offshore wind energy research. A flexible and modular finite element framework has been designed to allow a core analysis tool to interface with a variety of external loading modules. The OWENS modular framework, beam element with rotational effects, and VAWTGen mesh generator presented in this paper are key components in developing this robust finite element design tool.

The formulation and implementation behind the OWENS toolkit has been verified through a number of analytical and numerical verification studies. Full details of verification exercises will be provided in a separate verification manual for OWENS. The toolkit has also been validated against experimental data for the Sandia National Laboratories 34-meter VAWT test bed. Validation exercise confirmed the ability of OWENS to predict frequencies and mode shapes for both parked and rotating VAWTs. Studies indicated that including gyroscopic and stress stiffening effects were critical for predicting accurate Campbell diagrams for the 34-meter VAWT.

A loose coupling strategy for external loading modules, which facilitates the modularity of the OWENS framework, was discussed and demonstrated for the case of a simplified elastic foundation. Results indicated the loose coupling strategy could reasonably replicate results using a monolithic, or tightly coupled, approach. Finally, an example analysis of a VAWT under aerodynamic loads for both fixed and floating foundations was presented. This demonstrated the interaction of two external loading modules (aerodynamics and foundation/platform mooring) with the structural motions modeled using the OWENS toolkit. Future work will provide a two-way aeroelastic coupling and higher fidelity hydrodynamics/mooring module within the OWENS framework. Future applications of the OWENS toolkit will consider both practical design studies of innovative offshore VAWT configurations as well as fundamental investigations into the dynamics of offshore VAWTs.

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