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Modal Dynamics and Stability of Large Multi-megawatt Deepwater Offshore Vertical-axis Wind Turbines: Initial Support Structure and Rotor Design Impact Studies

Brian C. Owens* and D. Todd Griffith†
Sandia National Laboratories‡, Albuquerque, New Mexico, 87185, USA

John E. Hurtado§
Texas A&M University, College Station, Texas, 77843, USA

The availability of offshore wind resources in coastal regions, along with a high concentration of load centers in these areas, makes offshore wind energy an attractive opportunity for clean renewable electricity production. High infrastructure costs such as the offshore support structure and operation and maintenance costs for offshore wind technology, however, are significant obstacles that need to be overcome to make offshore wind a more cost-effective option. A vertical-axis wind turbine (VAWT) rotor configuration offers a potential transformative technology solution that significantly lowers cost of energy for offshore wind due to its inherent advantages for the offshore market. This paper presents an initial design impact study for assessing the dynamic stability of large multi-megawatt deepwater offshore VAWTs. The analysis and understanding of very large, highly flexible VAWT structures is further complicated by the rigid body modes of a floating support structure. A newly developed design tool for offshore VAWTs is employed to assess the stability of very large multi-megawatt VAWT configurations in a deepwater environment. To gain a fundamental understanding of tower resonance in VAWTs, an analytical expression for characterizing critical per-rev excitations for VAWT configurations is developed and presented. The influence of various support condition on structural modes of a VAWT is also investigated. For offshore deployment, a monopile support condition may exacerbate resonance concerns while floating platform supports may provide a means to alleviate resonance concerns. The effect of the large rotating structure on the rigid body modes of the turbine/platform system is also examined.

I. Introduction

The availability of offshore wind resources in coastal regions, along with a high concentration of load centers in these areas, makes offshore wind energy an attractive opportunity for clean renewable electricity production. High infrastructure costs such as the offshore support structure and operation and maintenance (O&M) costs for offshore wind technology, however, are significant obstacles that need to be overcome to make offshore wind a more cost-effective option. Reductions in cost of energy (COE) are likely to come from decreases in costs across the board but especially the installation costs, support structure, and O&M, while maintaining or increasing energy production. A vertical-axis wind turbine (VAWT) rotor configuration offers a potential transformative technology solution that significantly lowers COE for offshore wind due to

*Graduate Student Intern, Wind Energy Technologies Department, P.O. Box 5800, and AIAA Member
†Principal Member of Technical Staff, Wind Energy Technologies Department, P.O. Box 5800, and AIAA Associate Fellow
‡Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.
§Associate Professor, Department of Aerospace Engineering, TAMU 3141, and AIAA Associate Fellow

its inherent advantages for the offshore market. For example, placement of the drive train components near the water level reduces support structure requirements (and costs) and improves accessibility for maintenance. The potential of scaling to much larger offshore VAWT rotors is an intriguing possibility as well. To remain a viable option for offshore wind energy, however, VAWT technology will need to undergo significant development in coming years. In particular, development of a better understanding of fundamental dynamic behavior is needed for all of the VAWT configurations being considered. Resonance is a common concern in rotating structures and a known issue in previous VAWT designs.[1–4] Thus, analysis and design to avoid structural dynamic resonance conditions is a key issue to be addressed in initial design studies. The design requirements and analysis techniques are well established for the conventional 3-bladed horizontal-axis wind turbine (HAWT), but these issues are not well-addressed for the range of VAWT rotor configurations and support structure options being considered by designers.

This paper presents an initial design impact study for assessing the dynamic stability of large multi-megawatt deepwater offshore VAWTs. Understanding the modal dynamics of a system is useful for gaining insight into the fundamental behavior of a system before a large number of loading scenarios are considered. Furthermore, identification of potential instabilities at the initial design stage is critical for proactively mediating undesirable response of a system. The analysis and understanding of very large, highly flexible VAWT structures is further complicated by the rigid body modes of a floating support structure. Previous research investigated smaller scale land-based VAWTs and resonance concerns were identified. The support conditions or boundary conditions, however, are known to dramatically influence the modal behavior (natural frequencies and mode shapes) of the structural dynamic system.[4–6] Thus, it is imperative to understand the behavior of a deepwater offshore turbine affixed to a platform (floating condition) relative to a land-based turbine (fixed condition). In addition, the presence and stability of additional rigid body modes for the floating case should be assessed along with elastic modes. Previous investigations have studied the effects of support condition on the tower modes of offshore HAWTs,[7] nevertheless, the fundamental difference between VAWT and HAWT configurations require unique design considerations and design analysis techniques.

Initial designs studies to investigate the stability of floating VAWT configurations are conducted using a newly developed design tool for offshore VAWTs. Validation procedures of the Offshore Wind Energy Simulation (OWENS) Toolkit for VAWTs have demonstrated the ability of the tool to predict the modal response of a rotating land-based Darrieus-type VAWT.[8] Herein, the OWENS toolkit is used to assess the stability of very large multi-megawatt VAWT configurations in a deepwater environment, and the influence of a floating platform configuration on the structural modes of a VAWT is investigated. The goal of such an investigation is to obtain a fundamental understanding of the interplay of platform support structure and the structural modes of a rotating VAWT. Furthermore, the effect of the large rotating structure on the rigid body modes of the turbine/platform system has been analyzed. Resonance concerns for rotating structures are commonly identified by inspecting the natural frequencies of a system for coincidence with per-rev excitations. For a VAWT, the sensitivity of resonance to a particular per-rev excitation is closely tied to the number of blades employed in a configuration. Therefore, a fundamental understanding of per-rev resonance sensitivities as related to the number of blades has been developed in this work. Parametric studies are performed across various turbine configurations, including the effect of scale: from a utility scale 500 kW turbine to very large 5 MW turbines (2 and 3 bladed designs), as well as a variety of support configurations including land-based, monopile, and floating configurations.

To summarize, this investigation of modal dynamics and stability in large offshore VAWTs presented in this paper provides the following contributions:

- A greater understanding of tower resonance in VAWT structures is gained by developing an analytical expression for critical per-rev excitations related to the number of blades employed in a VAWT configuration.
- Modal analysis shows large scale multi-megawatt VAWT designs exhibit very low frequency, interacting modes. Interpretation of modal analysis results for multi-megawatt VAWT configurations requires greater care than conventional VAWT configurations.
- A support condition study was conducted for VAWTs of different scale and number of blades. Overall, results indicated that a monopile support had the detrimental effect of lowering tower mode frequencies as well as lowering rotor speeds at which resonance may occur relative to a land-based support condition.
- Investigations revealed floating support conditions may alleviate resonance concerns, but with varying

degree depending on the platform design. Furthermore, care should be taken to ensure rigid body modes are not adversely affected by the supported turbine structure.

- Investigations revealed "rules of thumb" for estimating the evolution of a VAWT tower mode frequency with respect to rotor speed are less applicable to both floating configurations and larger VAWT structures.

II. Overview of Offshore Wind Energy Simulation Toolkit for VAWTs

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 under development for modeling large offshore VAWT configurations. 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 modular and interfaces with aerodynamics, platform & mooring dynamics (hydrodynamics), and drive-train/generator modules to predict the response of a VAWT of arbitrary configuration under a variety of conditions. The formulation will also allow for stability analysis to identify potential resonance and aeroelastic stability issues. The core of the analysis tool is a robust and flexible finite element formulation capable of considering the dynamics of large, flexible, rotating structures.

II.A. Analysis Framework

The fundamental requirements of the aeroelastic 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. 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 1 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.

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 and hydrodynamics codes.

II.B. 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 that is capable of generating VAWTs of arbitrary geometry, including H-type, V-type, and Darrieus configurations. 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. Figure 2 shows representative VAWT configurations generated with VAWTGen (from left to right: swept Darrieus, Darrieus with struts, V-VAWT, and H-VAWT). The implementation also allows for concentrated structural components to be considered, and constraints of various joints may be imposed between structural components.

II.C. Modeling approach for modal analysis of VAWT with a floating support

Although the OWENS toolkit was developed to interface with an external platform dynamics/hydrodynamics module, a limited platform dynamic capability was implemented in OWENS for the floating support studies

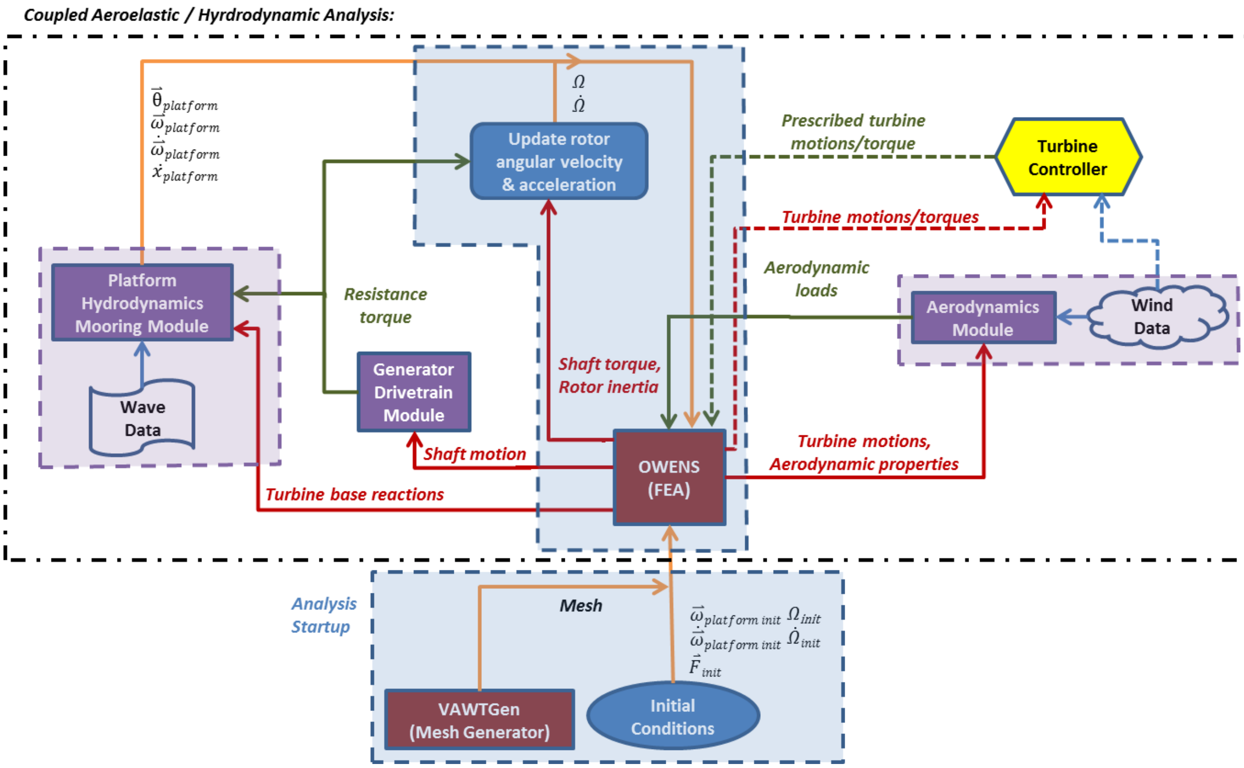

Figure 1. Analysis framework for the OWENS toolkit

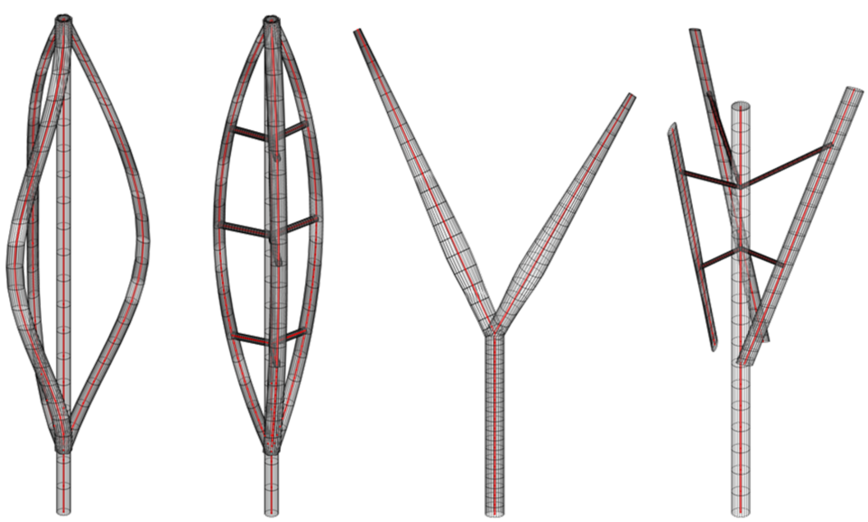

Figure 2. Arbitrary VAWT configurations produced by VAWTGen

conducted in this paper. Equations of motion were developed for a finite element representation of a VAWT configuration affixed to a platform modeled as a rigid body with six degrees of freedom. Small angular motions of the platform were assumed, and linearized equations of motion about an equilibrium configuration were employed in modal analysis of the combined platform/turbine system. The equilibrium solution from a nonlinear static analysis at a constant rotor speed (the structure under the influence of centrifugal and gravitational loadings) is used to apply pre-stress effects to the flexible VAWT structure as well as couplings between the flexible turbine structure and rigid body platform in the linearized representation. This modal analysis seeks to examine structural response and stability of this configuration linearized about a particular equilibrium condition. Analysis is performed in a co-rotating frame affixed to the rotating VAWT. Since the platform is naturally represented in a non-rotating frame, the combined system is potentially periodic in nature. In general, techniques for examining the response of periodic systems, such as Floquet theory[9] would be required. The mass/inertia and stiffness(mooring) of platform configurations employed in this paper, however, are axi-symmetric about the rotor axis and analysis of the entire system may be considered in the rotating frame without periodicity.

III. Understanding critical per-rev excitations for tower resonance

Historically, tower resonance has been a concern for vertical-axis wind turbines.[1,4] Tower mode frequencies vary with respect to rotor speed and sensitivities to certain "per-rev" excitations may exist. The sensitivity of a VAWT structure to certain per-rev excitations is strongly dependent on the number of blades employed in a VAWT configuration because tower excitation is primarily due to forcing on the attached blades. Previous work developed "rules of thumb"[10] based off of experimental observations[1] of a limited number of VAWT configurations. Herein, a more fundamental understanding of tower forcing frequency content for a VAWT with an arbitrary number of blades is considered.

An analytical expression for frequency content is developed for tower forcing represented in both a rotor-fixed, rotating frame as well as an inertially fixed frame. An important realization is that a harmonic force represented in an inertially fixed frame will have different frequency content than that represented in a rotating frame. Thus, care must be taken to ensure the per-rev excitation is expressed in a frame that is consistent with that used in modal analysis of a rotating structure. The analytical expressions for per-rev excitations are "numerically validated" using the CACTUS[11] aerodynamics software by examining the effective (collective) tower forcing for VAWT configurations with various numbers of blades.

III.A. Development of an analytical expression for tower forcing frequency content for a VAWT with an arbitrary number of blades

The effective harmonic forcing on a single blade may be expressed as

$$F_i^{(m)}(\Theta) = \sum_{n=0}^{N_p} \bar{F}_i^{(n)} \cos(n\Theta)\, \hat{b}_i \tag{1}$$

$$\Theta = \Omega t + \bar{\phi}^{(m)} \tag{2}$$

Such that $F_i^{(m)}$ is the i^{th} component of forcing on the m_{th} blade. $\bar{F}_i^{(n)}$ is the amplitude of forcing associated with an n per-rev excitation, N_p is the number of per-rev excitations considered in constructing the harmonic forcing on a single blade, Θ is the azimuth of blade m, and $\hat{b}_i$ represents a blade fixed frame. Furthermore, Ω is the rotor speed, t is time, and $\bar{\phi}^{(m)}$ is the azimuth of blade m at $t = 0$. This n per-rev harmonics present in this forcing term are due to changes in blade angle of attack as rotor spins at some angular velocity. Indeed, nonlinear system (such as the aerodynamic system representing the flow around a rotating VAWT) are known to have a response with frequencies as multiples of input frequency (such as rotor speed in this case).

Figure 3 illustrates the various frames considered in this development including a blade fixed frame ($\hat{b}_i$), a co-rotating/hub fixed frame ($\hat{h}_i$), and an inertially fixed frame ($\hat{n}_i$). The excitation frequency on a single blade may be monitored by a sensor placed on the blade (the blue dot in Figure 3) and measured in a local blade frame ($\hat{b}_i$) as shown in the expressions above.

For convenience, let the time be normalized by the period of rotor revolution $\left(\tilde{t} = \frac{t}{T}\right)$. Such that $T = \frac{2\pi}{\Omega}$.

$$F_i^{(m)}\left(\tilde{t}\right) = \sum_{n=0}^{N_p} \bar{F}_i^{(n)} \cos\left(n\left[2\pi\tilde{t} + \bar{\phi}^{(m)}\right]\right) \hat{b}_i \tag{3}$$

The contribution of forcing on blade m to the forcing on the tower may be accounted for by transforming the effective force on the blade to account for the azimuth of the blade in the co-rotating/hub frame. The transformation from the co-rotating frame to the blade frame is described by a single-axis rotation matrix

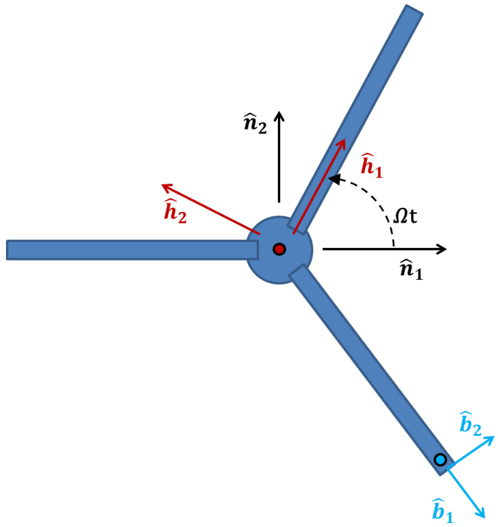

Figure 3. Illustration of various coordinate systems considered in blade/tower forcing

about the rotor angular velocity axis ($\hat{h}_3/\hat{n}_3$ axis). This frame is illustrated in Figure 3 as the $\hat{h}_i$ frame.

$$\left[C_H^B\left(\bar{\phi}^{(m)}\right)\right] = \begin{bmatrix} \cos\bar{\phi}^{(m)} & \sin\bar{\phi}^{(m)} & 0 \\ -\sin\bar{\phi}^{(m)} & \cos\bar{\phi}^{(m)} & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{4}$$

$$F_{Hi}^{(m)}\left(\tilde{t}\right) = C_H^{B^T} F_i^{(m)}\left(\tilde{t}\right) \tag{5}$$

The contribution of forcing on a blade may also be coordinatized in a fixed frame by transforming the effective force to account for the instantaneous position of the blade in the rotor azimuth. This frame is illustrated in Figure 3 as the $\hat{n}_i$ frame.

$$\left[C_N^B\left(2\pi\tilde{t}+\bar{\phi}^{(m)}\right)\right] = \begin{bmatrix} \cos\left(2\pi\tilde{t}+\bar{\phi}^{(m)}\right) & \sin\left(2\pi\tilde{t}+\bar{\phi}^{(m)}\right) & 0 \\ -\sin\left(2\pi\tilde{t}+\bar{\phi}^{(m)}\right) & \cos\left(2\pi\tilde{t}+\bar{\phi}^{(m)}\right) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{6}$$

$$F_{Ni}^{(m)}\left(\tilde{t}\right) = C_N^{B^T}\left(\tilde{t}\right) F_i^{(m)}\left(\tilde{t}\right) \tag{7}$$

The effect of all blade loadings on the overall tower forcing is simply a summation of the previous equations over the total number of blades. The effective tower loading measured by a sensor on the rotating VAWT tower (such as that shown in the red dot on Figure 3) can be expressed as:

$$F_{Hi}\left(\tilde{t}\right) = \sum_{m=1}^{N_{blades}} F_{Hi}^{(m)}\left(\tilde{t}\right) \tag{8}$$

Furthermore, the effective tower loading in a fixed frame can be expressed as:

$$F_{Ni}\left(\tilde{t}\right) = \sum_{m=1}^{N_{blades}} F_{Ni}^{(m)}\left(\tilde{t}\right) \tag{9}$$

A Fourier transform of these expressions is employed to examine the frequency content of tower forcing as a result of aerodynamic forces on blades.

For the tower forcing components coordinatized in the co-rotating frame the Fourier transform (only considering positive frequencies) is:

$$\begin{aligned} F_{H1}(\tilde{n}_t) &= \mathscr{F}\left[F_{H1}\left(\tilde{t}\right)\right] \\ &= \sum_{m=1}^{N_{blades}} \sum_{n=0}^{N_p} \frac{1}{2}\left(\bar{F}_1\cos\bar{\phi}^{(m)} - \bar{F}_2\sin\bar{\phi}^{(m)}\right) e^{in\bar{\phi}^{(m)}}\delta\left(\tilde{n}_t - n\right) \end{aligned} \tag{10}$$

$$F_{H2}(\tilde{n}_t) = \mathscr{F}\left[F_{H2}\left(\tilde{t}\right)\right] \tag{11}$$

$$= \sum_{m=1}^{N_{blades}} \sum_{n=0}^{N_p} \frac{1}{2}\left(\bar{F}_1 \sin\bar{\phi}^{(m)} + \bar{F}_2 \cos\bar{\phi}^{(m)}\right) e^{in\bar{\phi}^{(m)}} \delta\left(\tilde{n}_t - n\right)$$

$$F_{H3}(\tilde{n}_t) = \mathscr{F}\left[F_{H3}\left(\tilde{t}\right)\right] = \sum_{m=1}^{N_{blades}} \sum_{n=0}^{N_p} \frac{1}{2}\bar{F}_3 e^{in\bar{\phi}^{(m)}} \delta\left(\tilde{n}_t - n\right) \tag{12}$$

Such that $\tilde{n}_t$ is the per-rev frequency of tower excitation as viewed in the rotating hub frame, and n is a per-rev excitation experienced by a blade.

For the tower forcing coordinatized in a fixed frame the Fourier transform (only considering positive frequencies) is:

$$F_{N1}(\bar{n}_t) = \mathscr{F}\left[F_{N1}\left(\tilde{t}\right)\right] \tag{13}$$

$$= \sum_{m=1}^{N_{blades}} \sum_{n=0}^{N_p} \frac{1}{4}\left[\left(\bar{F}_1 - i\bar{F}_2\right) e^{i(n-1)\bar{\phi}^{(m)}} \delta\left(\bar{n}_t - (n-1)\right)\right.$$

$$\left. + \left(\bar{F}_1 + i\bar{F}_2\right) e^{i(n+1)\bar{\phi}^{(m)}} \delta\left(\bar{n}_t - (n+1)\right)\right]$$

$$F_{N2}(\bar{n}_t) = \mathscr{F}\left[F_{N2}\left(\tilde{t}\right)\right] \tag{14}$$

$$= \sum_{m=1}^{N_{blades}} \sum_{n=0}^{N_p} \frac{1}{4}\left[\left(\bar{F}_2 + i\bar{F}_1\right) e^{i(n-1)\bar{\phi}^{(m)}} \delta\left(\bar{n}_t - (n-1)\right)\right.$$

$$\left. + \left(\bar{F}_2 - i\bar{F}_1\right) e^{i(n+1)\bar{\phi}^{(m)}} \delta\left(\bar{n}_t - (n+1)\right)\right]$$

$$F_{N3}(\bar{n}_t) = \mathscr{F}\left[F_{N3}\left(\tilde{t}\right)\right] = \sum_{m=1}^{N_{blades}} \sum_{n=0}^{N_p} \frac{1}{2}\bar{F}_3 e^{in\bar{\phi}^{(m)}} \delta\left(\bar{n}_t - n\right) \tag{15}$$

Such that $\bar{n}_t$ is the per-rev frequency of tower excitation as viewed in a fixed frame.

III.B. Validation of analytical per-rev tower excitation expression using CACTUS aerodynamics software

The analytical expressions for per-rev tower excitations as a function of number of blades were employed to predict per-rev excitations in both a fixed and rotating frame for VAWTs with 1 to 7 blades. To numerically validate these predictions, the CACTUS[11] aerodynamics software was employed to calculate blade loads that were processed to calculate effective tower loads. These loads were expressed in both rotating and fixed frames and a Fast-Fourier Transform (FFT) was employed to extract frequency content for comparison of numerically predicted per-revs to those predicted by the analytical expression. Note that only the transverse tower excitations (both fore-aft and side-to-side) were considered in this study as these are of most significant concern in tower resonance.

The VAWT configurations modeled in CACTUS were of the Darrieus type. A constant wind speed and rotor speed were specified. A single blade geometry was chosen and VAWTs with various number of blades were modeled using uniform azimuth spacing of blades. No attempt was made to maintain constant rotor solidity across the various configurations. Thus, the magnitude of forcing and power output of the turbines varied with respect to number of blades. Nevertheless, the frequency content of forcing (which is being validated in this study) is independent of rotor solidity and directly related to the number of blades employed in a turbine configuration.

First, the assumed per-rev blade forcing frequency is verified through comparison to forcing on a single blade as predicted via a CACTUS simulation. Figure 4 shows the effective radial blade load vs. azimuth for a single blade. Figure 5 presents the FFT of the blade effective radial load, with peaks at the per-rev frequencies of 0,1,2,3,4,5,...,N. The same trends are seen in Figures 6 and 7 for the effective edgewise loading on a single blade.

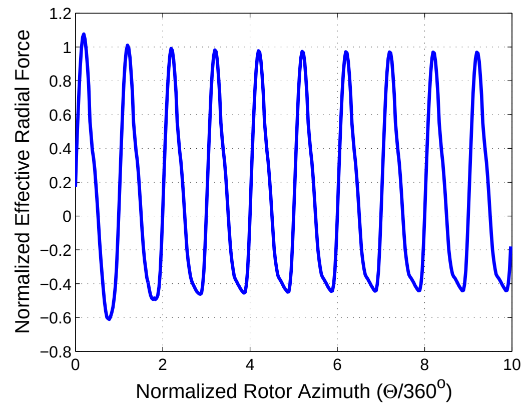

Figure 4. Effective radial force on a single blade vs. normalized azimuth

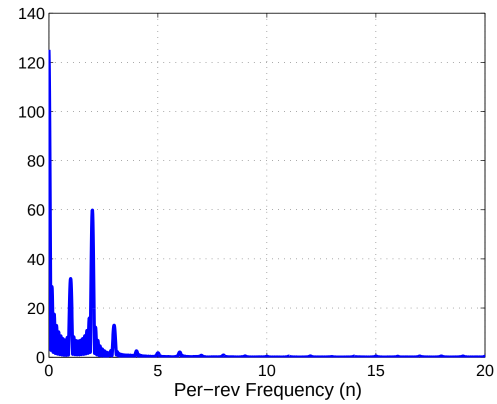

Figure 5. FFT of effective axial force on a single blade vs. normalized azimuth

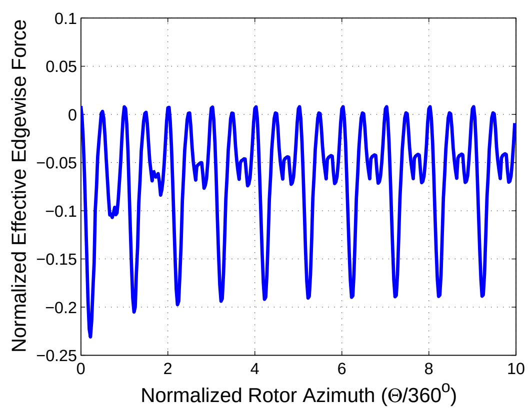

Figure 6. Effective edgewise force on a single blade vs. normalized azimuth

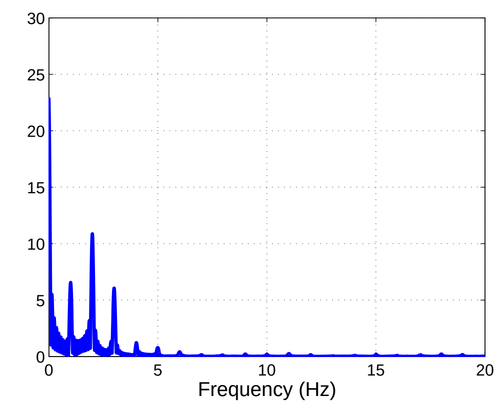

Figure 7. FFT of effective edgewise force on a single blade vs. normalized azimuth

Table 1 shows the analytical and numerical predictions for per-rev tower excitation for both fixed and rotating frames for VAWT configurations with various numbers of blades. The results of the numerical predictions validate the results of the analytical model. Furthermore, it is noteworthy that for certain configurations a 1 per-rev excitation measured in the hub frame is manifested as a 0 per-rev or constant excitation in the hub-frame. In this case, the 1 per-rev excitation viewed in the rotating frame is an artifact of the coordinate transformation and is not a true harmonic excitation from which resonance could result. For example, for a two-bladed VAWT a 1 per-rev excitation in the rotating frame manifests as a constant and 2 per-rev excitation in the fixed frame. Thus, for this configuration a 1 per-rev excitation in the rotating hub-frame could drive tower resonance. The analytical expressions also reveal that for VAWTs with 3 or more blades, a 1 per-rev excitation in the hub-frame will only manifest as a constant force in the fixed-frame. Thus, the 1 per-rev excitation in the hub-frame for these configurations will not drive resonance. The understanding of the difference in frequency content between the fixed and rotating frame is very important, particularly for experimentalists as instrumentation may be in different frames.

Inspection of Table 1 shows certain patterns in the fixed and hub frame per-rev excitations with respect to number of blades. A recursive formula for the i-th critical per-rev excitation as a function of number of blades may be developed as shown below.

For $N_{blades} \leq 2$, the i^{th} per-rev tower excitation in the hub-frame ($\tilde{n}_{t_i}$) is:

$$\begin{aligned} \tilde{n}_{t_1} &= 1 \\ \tilde{n}_{t_i} &= \tilde{n}_{t_{i-1}} + N_{blades} \end{aligned} \quad (16)$$

Table 1. Numerical validation of per-rev tower forcing

# of Blades	Fixed-frame (analytical)	Fixed-frame (CACTUS)	Hub-frame (analytical)	Hub-frame (CACTUS)
1	0,1,2,3,4,5	0,1,2,3,4,5	1,2,3,4,5	1,2,3,4,5
2	0,2,4,6,8,10	0,2,4,6,8,10	1,3,5,7,9	1,3,5,7,9
3	0,3,6,9,12,15	0,3,6,9,12,15	1,2,4,5,7	1,2,4,5,7
4	0,4,8,12,16,20	0,4,8,12,16,20	1,3,5,7,9	1,3,5,7,9
5	0,5,10,15,20,25	0,5,10,15	1,4,6,9,11	1,4,6,9,11
6	0,6,12,18,24,30	0,6,12	1,5,7,11,13	1,5,7,11,13
7	0,7,14,21,28,35	0,7,14	1,6,8,13,15	1,6,8,13,15

For $N_{blades} > 2$, the i^{th} per-rev tower excitation in the hub-frame ($\tilde{n}_{t_i}$) is:

$$\begin{aligned} \tilde{n}_{t_1} &= 1 \\ \tilde{n}_{t_i} &= \begin{cases} n_{t_{i-1}} + N_{blades} - 2 & i \text{ odd} \\ n_{t_{i-1}} + 2 & i \text{ even} \end{cases} \end{aligned} \tag{17}$$

Furthermore, the i^{th} per-rev tower excitation in the fixed frame ($\bar{n}_{t_i}$) is:

$$\bar{n}_{t_i} = (i-1)\, N_{blades} \quad i = 1, 2, ..., N \tag{18}$$

III.C. Interpretation of critical per-rev excitations

These analytical expressions for per-rev tower excitations due to blade loads are useful for understanding the sensitivity of certain VAWT configurations to tower resonance. Modal analysis of a VAWT structure is typically conducted within a co-rotating frame. Thus, the excitation frequencies should also be considered in this frame for consistency to ensure meaningful resonance predictions. Typically, one constructs a Campbell diagram and inspects the various system modes for per-rev crossings. As shown in this section, the effective tower excitation is sensitive to the number of blades and not all per-rev tower mode crossings can drive resonance. Furthermore, certain configurations show 1 per-rev tower forcing in the co-rotating frame which is not true harmonic forcing, and is merely an artifact of transformations between a co-rotating and fixed frame. With these considerations in mind, Table 2 shows the critical hub-frame per-rev excitations for VAWTs with various numbers of blades. Typically, lower per-rev excitations pose a more significant resonance concern than higher per-revs. Nevertheless, the first 4 per-rev excitations for each VAWT configuration (1-10 blades) are shown. Note that this work has sought to characterize the effects of blade forcing on tower excitation. Other forces acting on the system may give rise to other resonance concerns.

Table 2. Critical per-rev tower resonance design sensitivities (hub-frame)

# of Blades	Per-Rev Sensitivity	Example Configuration
1	1,2,3,4	
2	1,3,5,7	SNL 17-m,[1] SNL 34-m,[1] DeepWind[2,3]
3	2,4,5,7	VAWTPower VP60[4]
4	3,5,7,9	
5	4,6,9,11	
6	5,7,11,13	Lux[12]
7	6,8,13,15	
8	7,9,15,17	
9	8,10,17,19	
10	9,11,19,21	

IV. Turbine and Support Structure Configuration Descriptions

To gain a better understanding of modal dynamics of offshore VAWTs, various VAWT configurations and support conditions were considered. The VAWT configurations considered in this study include the Sandia National Laboratories (SNL) 34-meter VAWT,[1,13,14] which was a utility scale 500 kW design that served as an experimental test bed. To explore the effect of scale, two variants of an initial 5 MW VAWT design employing 2 and 3 blades are also considered. The basic specifications of these VAWT configurations are given in Table 3. Note that the 5 MW VAWT configurations have the same height and height to diameter ratios. To maintain rotor solidity, the chord of the two-bladed design was increased by 50% relative to the 3 bladed design. Initial design studies have employed an operational rotor speed between 6 and 8 RPM for these 5 MW VAWT designs. This estimated rotor speed is similar to those for other large multi-megawatt VAWT designs.[3]

Various support conditions were also considered for the turbine designs considered in this study. A land-based support conditions was considered by simply specifying a cantilevered boundary condition at the base of the turbine. For offshore deployment, 20 and 30-meter monopile support conditions were also considered. For this initial design study the tower properties were simply extended from the base of the turbine, and a fixed-base cantilevered boundary condition was specified at the monopile base. More detailed design studies could make use of more accurate monopile properties and base conditions.[7,15] For deepwater offshore deployment, two platform configurations were also considered. An initial spar buoy configuration designed for the 5 MW VAWT configuration was considered with physical and hydrodynamic added mass properties shown in Table 4. The ITI energy barge designed for a 5 MW HAWT[7] configuration is also considered in this support condition study. Although this platform was not designed specifically for the 5 MW VAWT configuration, the rigid body mass properties of the 5 MW VAWT and HAWT configurations are similar. This platform provides a distinctly different platform condition from the spar buoy configuration and is useful in initial design studies on support condition. The last column in Table 4 provides the ratio of spar buoy to barge platform properties. Perhaps most noticeable is the increased pitch/roll moments of inertia (physical and added) as well as the significant mass center offset from the still water level (SWL) for the spar buoy platform. In this initial support condition study, translational and rotational spring were attached to the rigid body platform and stiffness values were tuned to the platform/turbine rigid body frequencies shown in Table 5. Figure 8 shows schematics SNL 34-meter and 2 and 3 bladed 5 MW VAWT configurations on the 30-meter monopile support.

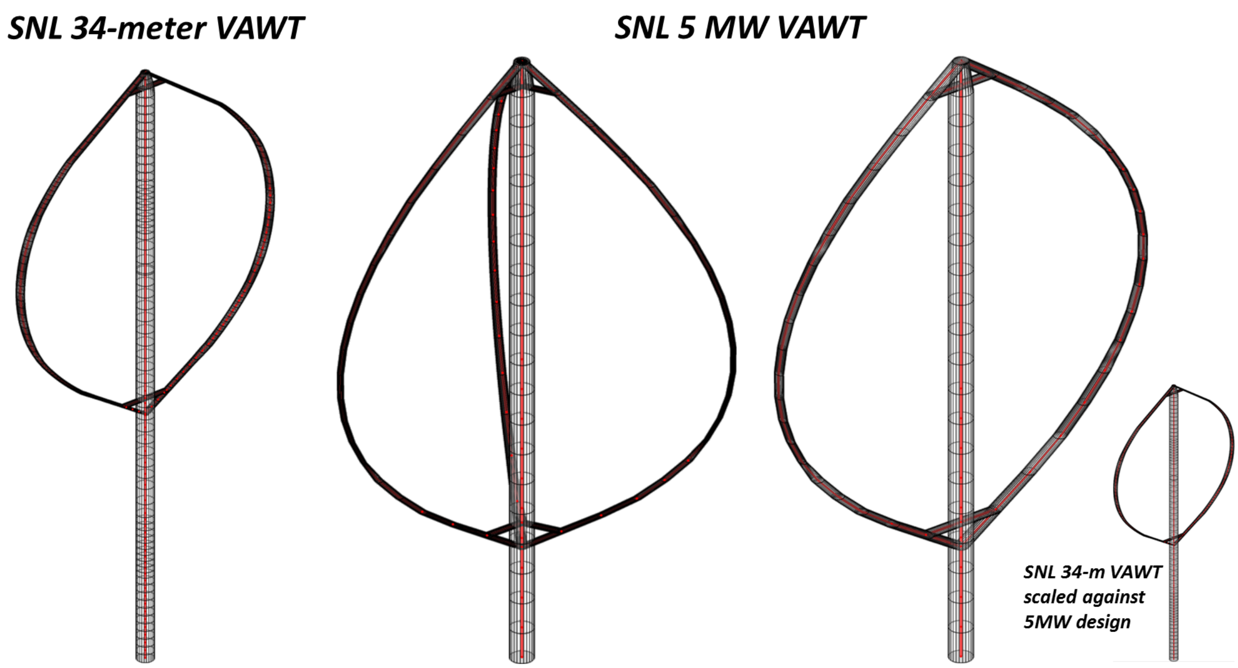

Figure 8. VAWT configurations on 30-meter monopile support

Table 3. Specifications for VAWT configurations

	SNL 34-meter	SNL 3 blade 5 MW	SNL 2 blade 5 MW
Rating	500 kW	5 MW	5 MW
Configuration type	Darrieus	Darrieus	Darrieus
Height (m)	42.5	132.1	132.1
Height to diameter ratio	1.25	1.22	1.22
Operating speed (RPM)	37.5	6-8	6-8
Mass (kg)	3.06×10^4	6.49×10^5	6.50×10^5
Mass center above base (m)	21.1	65.8	65.8
In-plane MOI about c.m. ($kg-m^2$)	7.28×10^6	1.20×10^9	1.30×10^9
Out-of-plane MOI about c.m. ($kg-m^2$)	5.88×10^6	1.20×10^9	1.09×10^9
Polar MOI about c.m. ($kg-m^2$)	1.43×10^6	2.11×10^8	2.23×10^8
Minimum chord (m)	0.91	1.92	2.88
Maximum chord (m)	1.22	2.57	3.86
Blade material	6063-T5 Al	Fiberglass	Fiberglass

Table 4. Mass property specifications for platform configurations

	Spar Buoy	ITI Energy Barge[7]	Ratio (Spar to Barge)
Mass (kg)	5.47×10^6	5.45×10^6	1.003
Mass center above still water level (m)	-68.40	0.28	-242.55
Pitch MOI about c.m. ($kg-m^2$)	2.32×10^9	7.27×10^8	3.19
Roll MOI about c.m. ($kg-m^2$)	2.32×10^9	7.27×10^8	3.19
Yaw MOI about c.m. ($kg-m^2$)	6.52×10^7	1.45×10^9	0.05
Surge added mass (kg)	6.00×10^6	7.49×10^5	8.01
Sway added mass (kg)	6.00×10^6	7.49×10^5	8.01
Heave added mass (kg)	2.26×10^5	1.86×10^7	0.01
Pitch added MOI ($kg-m^2$)	7.18×10^9	1.26×10^9	5.70
Roll added MOI ($kg-m^2$)	7.18×10^9	1.26×10^9	5.70
Yaw added MOI ($kg-m^2$)	0	1.18×10^8	0

Table 5. Platform/turbine system rigid body frequencies (Hz)

	Spar Buoy	ITI Energy Barge[7]
Sway	0.0084	0.0076
Surge	0.0084	0.0076
Heave	0.0330	0.1283
Pitch	0.0241	0.0980
Roll	0.0241	0.0980
Yaw	0.0270	0.0198

V. SNL 34-meter VAWT Support Condition Study

This section presents structural dynamics analysis of a representative, utility scale VAWT turbine for various offshore support conditions. First the Campbell diagram for the Sandia National Laboratories (SNL) 34-meter VAWT is presented. This can serve as a reference for a Campbell diagram of a conventional VAWT of moderate size. Next, various support conditions are considered and the influence of support conditions on the Campbell diagrams are explored. First a ground fixed scenario is considered, followed by a 20 and 30-meter monopile support condition, and a floating platform configuration. Overall, blade modes were found to not be significantly affected by support conditions. The Campbell diagrams of the tower modes of each support configuration are generated and the effect of the support type on the modal response of a rotating turbine is considered.

V.A. Reference SNL 34-meter VAWT configuration

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 loadings was conducted to establish an equilibrium configuration about which modal analysis was conducted. This "spin-up" procedure incorporates pre-stress effects that result in a stiffening of the structure. Spin softening and spin stiffening effects compete as rotor speed increases, but typically spin stiffening effects are more dominant resulting 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 rotating, flexible systems. Modeling of guy-wires was considered by attaching two linear springs to the top of the tower transverse to the tower axis. Although these springs are in the rotating hub-frame, the guy wires provide axi-symmetric stiffening about the axis of rotor rotation. Thus, the associated stiffness is the same regardless of rotor azimuth, and this modeling approach is acceptable.

The Campbell diagram of the 34-meter VAWT with guy wires is shown in Figure 9. Experimental data obtained from edgewise and flatwise gauges are 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 and mass distributions in the modeled VAWT better agreement may be achieved. Nevertheless, the model appears to be more than adequate for preliminary design considerations. The modes are assigned labels based off of the parked mode shapes. For example "1FA" corresponds to the first anti-symmetric flatwise mode. Other mode shape labels are as follows: FS = symmetric flatwise, PR = "propeller", BE = "butterfly"/blade edgewise, TI = tower in-plane, and TO = tower out-of-plane. The lower mode shapes for the 34-meter VAWT are shown in Figure 10.

V.B. Support structure influence on tower modes of SNL 34-meter VAWT

This section presents structural dynamics analysis of the Sandia 34-meter VAWT for various offshore support conditions. The Sandia 34-meter VAWT (without guy wires) is considered as the baseline VAWT configuration in this initial study. This baseline configuration is chosen since guy wires are not likely to be employed in offshore applications. First, a ground fixed scenario is considered, followed by a 20 and 30-meter monopile support condition, and a floating platform configuration. The monopile configurations were modeled as described in Section IV of this paper. A scaled version of the ITI Energy Barge (as discussed in Section IV) was considered for an initial design study of an existing VAWT design on a floating support structure. This barge was designed for use with the NREL offshore 5 MW turbine,[7] and power laws were used to scale platform mass and inertia properties for use with the Sandia 34-meter VAWT for initial support condition studies. Linear translational and rotational springs were attached to the platform, and the parked rigid body frequencies of the platform/turbine configuration were tuned to those from the ITI Energy Barge/5 MW turbine configuration[7] as shown in Table 5.

The Campbell diagrams of each support configuration are generated and the effect of the support type on the modal response of a rotating turbine was considered. In each case, the impact of support structure on tower resonance concerns was assessed. Results showed that blade modes were not significantly affected by support conditions and herein tower modes are discussed. Figure 11 shows a compilation of tower mode Campbell diagrams for the various support conditions. The red per-rev excitation lines correspond to critical per-rev excitations for tower modes of a 2 bladed VAWT design as determined in Section III. The land-based configuration has parked lower and upper tower mode frequencies of about 1.12 and 1.2 Hz respectively. As

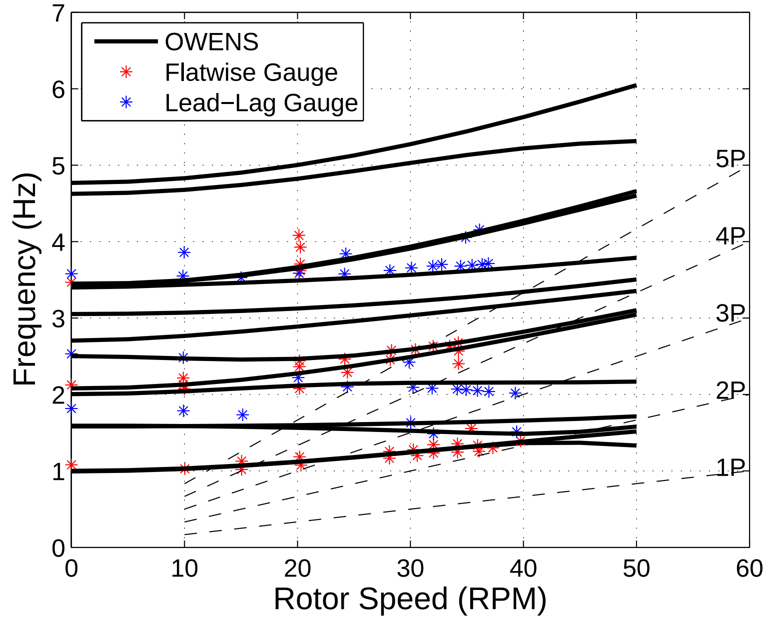

Figure 9. Campbell diagram of land-based SNL 34-meter VAWT (w/ guy wires)

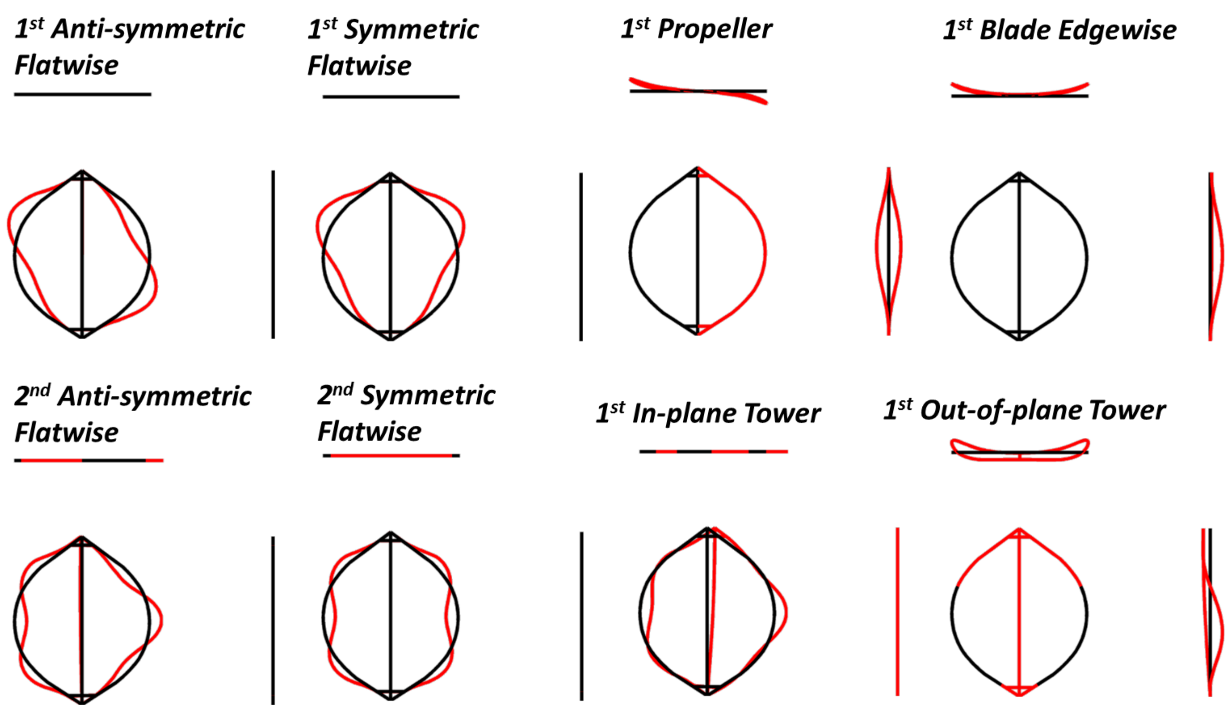

Figure 10. Lower mode shapes for SNL 34-meter VAWT

can be seen by examining the tower modes of the land-based VAWT with guy wires, removal of the guy wires approximately halves the frequencies of the tower modes. The monopile support significantly reduces the tower mode frequencies to approximately 0.55 Hz (a 57% reduction) for the 20-meter monopile and to approximately 0.42 Hz (a 65% reduction) for the 30-meter monopile. This reduction in parked tower mode frequencies results in critical per-rev crossings at much lower rotor speeds than the land-based or floating configurations. Thus, the monopile support appears to exacerbate resonance concerns for tower modes in

VAWTs for offshore deployment.

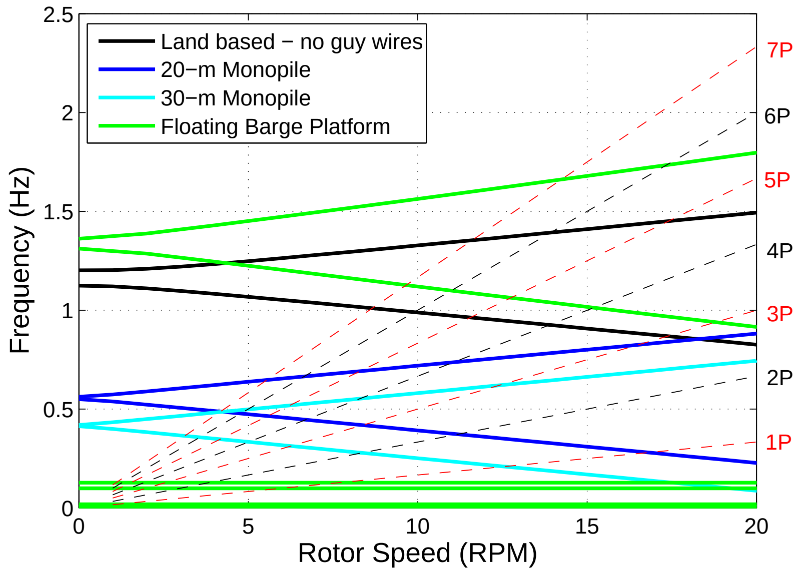

Figure 11. Campbell diagram of SNL 34-meter VAWT tower modes for various support conditions

The floating platform support increases the lower and upper first tower modes of the system from about 1.12 and 1.2 Hz to about 1.31 and 1.36 Hz respectively (a 13 and 17% increase) for the parked configuration. This increase in natural frequency is due to the floating platform providing a boundary condition to the turbine base that is more like a free boundary condition. Indeed, this may be qualitatively verified by comparing the increased modal frequencies of a "free-free" beam compared to a "fixed-free" beam.[16] Another interesting trend of the floating support condition is that the slope of the tower mode with respect to rotor speed has a higher magnitude than that of the land-based and monopile supports. For the upper tower mode, the increase in parked frequency and slope is beneficial in delaying upper tower mode critical per-rev crossings until higher rotor speeds. For the lower tower mode, however, these two trends serve to counteract each other. The low frequency rigid body modes of the platform/turbine system are also plotted on 11. For this configuration, the platform/rigid body modes are virtually unaffected by the rotating turbine.

The effect of support condition on parked first tower mode frequencies of the SNL 34-meter VAWT configuration is summarized graphically in Figure 12. This clearly emphasizes the detrimental effect of a monopile support in lowering tower mode frequencies, while the floating configuration may serve to increase tower mode frequencies. The effect of the support condition on the slope of the tower mode (with respect to rotor speed) is summarized graphically in Figure 13. Often a "rule of thumb" is used in preliminary design that estimates the tower mode slope magnitude of unity (modal frequency (Hz) / rotor speed (Hz)). Thus, only the parked tower mode frequencies need to be known for tower mode frequencies and the associated critical per-rev crossings may also be estimated. Results show the land-based and monopile support configurations are well approximated by this "rule of thumb" while the floating support configuration is not as well characterized by such an approximation.

VI. SNL 5 MW VAWT Support Condition Study

To explore the effect of machine size, a similar support condition study was performed with a larger 5 MW VAWT design. 2 and 3 bladed 5 MW VAWT designs were examined with land-based, monopile, and two floating platform supports. As shown in Section III, 2 and 3 bladed VAWT designs have different tower resonance per-rev sensitivities and it is important to explore the impact of this in design studies. First, the Campbell diagrams for the land-based configurations are presented, and the effect of scale as well as number of blades is discussed. Next, the effect of support condition on tower mode resonance is discussed. Monopile and floating support conditions are considered and different platform designs are found to have a profoundly different impact on the turbine structural response. The effect of the rotating turbine on rigid body modes of

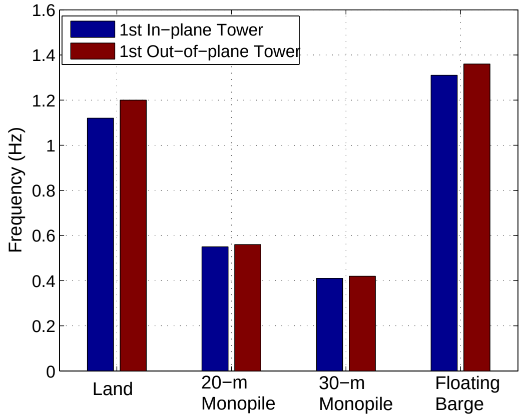

Figure 12. SNL 34-meter VAWT parked tower mode frequencies for various support conditions

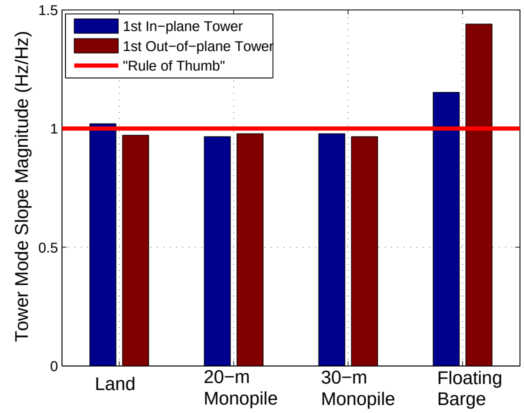

Figure 13. SNL 34-meter VAWT tower mode slopes for various support conditions

a platform supported system is also investigated. As with the smaller scale VAWT support study, commonly employed “rules of thumb” are examined for applicability to very large VAWT designs with various support conditions.

VI.A. Land-based configuration

Before examining the effect of support condition on a large multi-megawatt VAWT design, the land-based configuration is considered. The Campbell diagrams of the 3 and 2 bladed 5 MW VAWT designs from 0 to 10 RPM are shown in Figures 14 and 15 respectively. The 3 bladed design makes mode labeling difficult, and modes are simply labeled as tower modes (T), flatwise modes (F), or edgewise modes (E) in Figure 14. Mode labeling in the 2 bladed design uses the convention described in the previous section for the SNL 34-meter VAWT. Comparisons of these diagrams with the SNL 34-meter VAWT in Figure 9 shows that the larger scale of the 5 MW machines results in much lower modal frequencies. These lower modal frequencies are potential causes for concern as critical per-rev crossings on the Campbell diagrams will occur at lower rotor speeds. Such issues may limit the operating speed of the turbine configurations or require innovative solutions to mediate resonance concerns. Furthermore, comparison of Figures 14 and 15 show that the larger blade in the 2 bladed design (with a 50% larger chord compared to the 3 bladed design) affords the opportunity to provide higher bending stiffness in the blades and elevate blade mode frequencies. This may be useful in alleviating stability concerns (resonant or aeroelastic) in the two bladed design.

Comparison of tower modes in Figures 14 and 15 shows that both 2 and 3 bladed designs have similar parked tower frequencies. The upper tower mode behavior with respect to rotor speed is similar between the two designs. The lower tower mode of the 3 bladed design, however, interacts with lower frequency blade modes. As a rotor speed of 5 RPM is approached, the lower tower and flatwise modes begin to interplay and a “hybrid” mode develops that is a combination of tower and flatwise modes. Beyond 5 RPM the mode shapes “swap” and once again become more distinct mode shapes. This phenomenon has been termed “frequency veering” and “mode localization”[17,18] and typically occurs when two modes have similar frequencies, common mode shape attributes, and are varying with some parameter (such as rotor speed in the current study). The combination of low frequency modes, coupled modes due to rotational effects, and frequency veering complicate the structural dynamics analysis of VAWT configurations and require more careful interpretation of modal analysis results compared to conventional VAWT configurations.

VI.B. Monopile support

As with the previous support condition study for the 34-meter VAWT, 20 and 30-meter monopile support conditions were considered for the 5 MW VAWT designs. As before, the blade modes were not significantly affected by support condition and the tower modes are considered herein. Figures 16 and 17 show the tower mode Campbell diagrams for the 3 and 2 bladed 5 MW VAWTs respectively for land and monopile support conditions. Qualitatively, many of the trends from the 34-meter VAWT support condition study are echoed

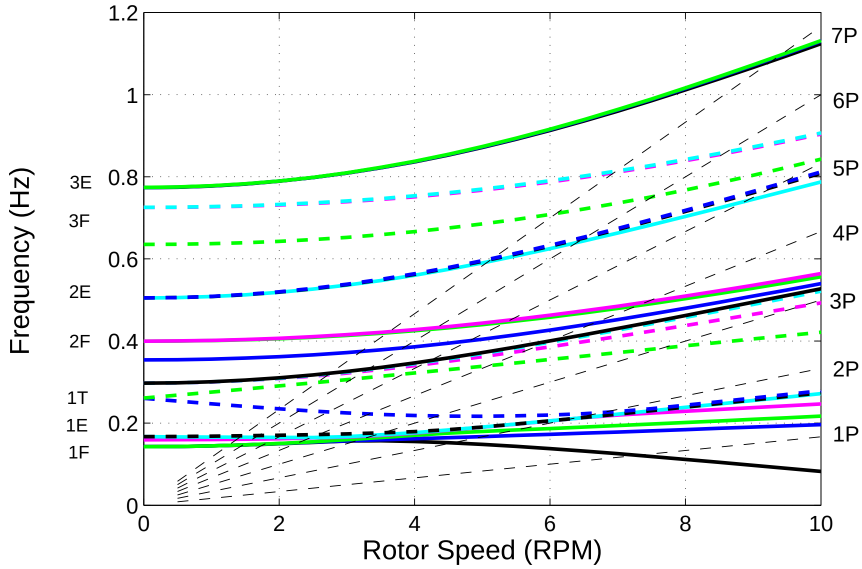

Figure 14. Campbell diagram of land-based 3 bladed SNL 5 MW VAWT

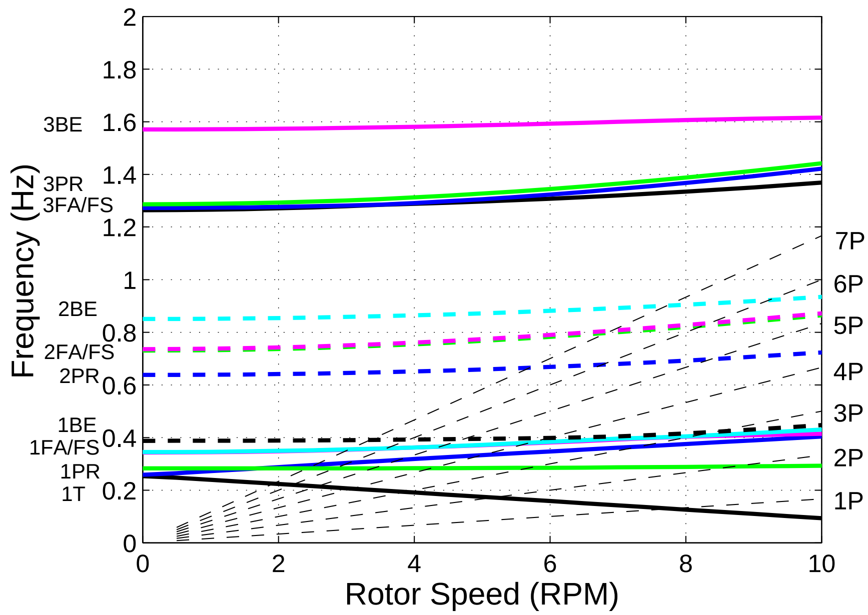

Figure 15. Campbell diagram of land-based 2 bladed SNL 5 MW VAWT

in this study. The monopile serves to reduce the parked tower mode frequencies and results in critical per-rev crossings at lower rotor speeds. For the 3 bladed configuration the 20 and 30-meter monopile reduce parked tower mode frequencies approximately 20 and 27% respectively relative to the land-based turbine. For the 2 bladed configuration the 20 and 30-meter monopile reduce parked tower mode frequencies approximately 24 and 33% respectively relative to the land-based turbine. Furthermore, the low frequency blade modes of the 3 bladed design result in noticeable frequency veering behavior in the lower tower and flatwise modes. Mode shapes of the lower modes undergoing frequency veering were examined in an attempt to identify which of the modes was associated with a dominant tower mode. The thicker line on Figure 16 shows the mode with a dominant tower mode while thinner lines show the evolution of the modes experience frequency veering as rotor speed increases. Inspection of Figure 17 shows an absence of frequency veering phenomenon in tower modes, which can be explained by the stiffer blade of the 2 bladed design resulting in higher blade mode frequencies above those of the tower modes.

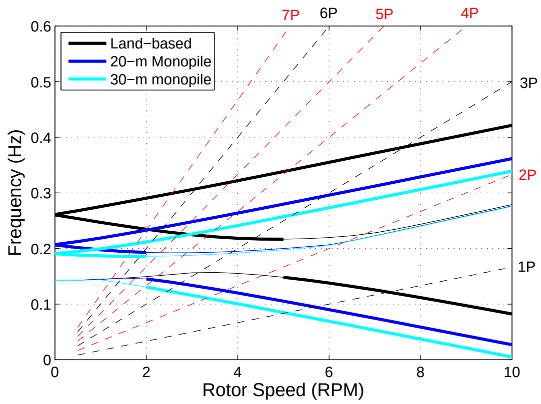

Figure 16. Tower mode Campbell diagram of 3 bladed 5 MW VAWT for land and monopile support conditions

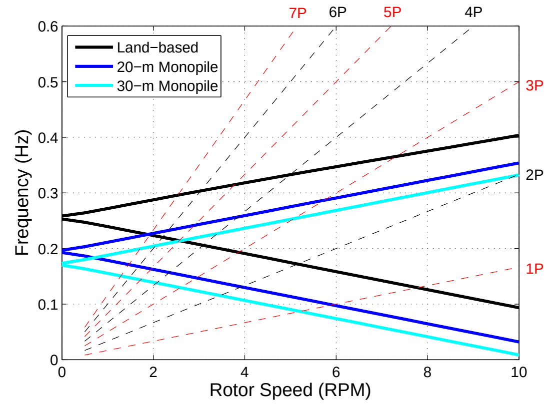

Figure 17. Tower mode Campbell diagram of 2 bladed 5 MW VAWT for land and monopile support conditions

Critical tower mode per-rev excitations for the 2 and 3 bladed configurations(as determined in Section III) are denoted by red lines on the Campbell diagrams. Figure 16 shows the monopile supported 3 bladed design has 2 per-rev crossings of the lower tower modes below a rotor speed of 4 RPM. This is a relatively significant decrease compared to the crossing around 5 RPM for the land-based support. For the upper tower mode, higher per-rev crossings occur below a rotor speed of 4 RPM as well. These lower per-rev crossings are below the estimated operating speed of 6-8 RPM for these initial turbine designs. Figure 17 shows the monopile supported 2 bladed design has 1 per-rev crossings of lower tower modes below 6 RPM, while the land-based configuration crosses the 1 per-rev excitation closer to 8 RPM. The 3 per-rev excitation crossings occur before 3 RPM for the lower tower mode and before 6 RPM for the upper tower modes of the monopile supported configurations. Thus, for each 5 MW design, the land-based support potentially has significant limitations on operating speed, and such limitations are only made more severe by the consideration of a monopile support.

VI.C. Floating support

Floating support conditions on the 5 MW designs were also considered using the spar buoy and barge platforms described in Section IV. As with the 34-meter VAWT support study, blade modes were not significantly affected by the floating support and Figures 18 and 19 show the tower mode Campbell diagrams for the 3 and 2 bladed 5 MW VAWT designs respectively with land-based and floating support condition. For the 3 bladed configuration, the spar buoy and barge platform support conditions elevate tower modes approximately 5 and 94% respectively relative to the land-based support. For the 2 bladed configuration, the spar buoy and barge platform support conditions elevate tower modes approximately 4 and 100% respectively relative to the land-based support. There is a striking difference on the effect of platform support on tower modes for the spar and barge supports. The last column of Table 3 compares the properties of the two platform configurations. A noticeable difference is the much larger moment of inertia (physical and added) for the spar buoy design as well as a significant mass center offset. These characteristics of the spar buoy platform result in a much higher effective moment of inertia compared to the barge platform. This results in a support condition closer to the land-based (fixed boundary condition) support than the “free” boundary condition[16] and the increase in frequency is not as pronounced. Thus, the lower effective moment of inertia associated with barge design allows for a more significant increase in tower mode frequencies.

As before, critical tower mode per-rev excitations for the 2 and 3 bladed configurations(as determined in Section III) are denoted by red lines on the Campbell diagrams. The spar buoy platform support does not result in any significant difference from a land-based configuration, with respect to critical per-rev crossings of tower modes. The barge support, however, provides some noticeable advantage in eliminating upper tower mode critical per-rev crossings due to the increased frequency and slope of tower modes for both 2 and 3 bladed configurations. For the 3 bladed configuration the 2 per-rev crossing of the lower tower mode is delayed until a rotor speed of 8 RPM and a 4 per-rev crossing at a rotor speed of approximately 4.5 RPM.

For the 2 bladed configuration the 1 per-rev crossing of the lower tower mode is delayed until a rotor speed of approximately 9.5 RPM and the 3 per-rev crossing is delayed until a rotor speed of approximately 5.5 RPM. The rotor speeds at these crossings are noticeably higher than the corresponding crossing in the land-based and spar buoy supported configuration.

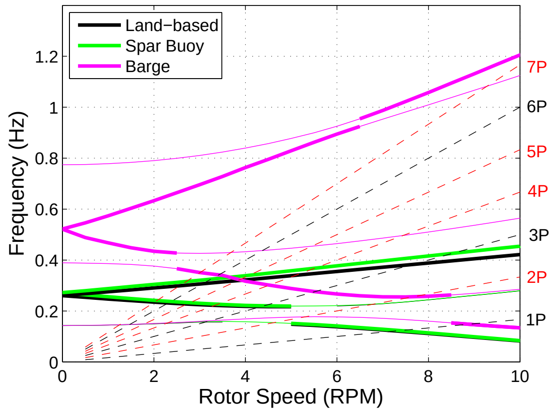

Figure 18. Tower mode Campbell diagram of 3 bladed 5 MW VAWT for land and floating support conditions

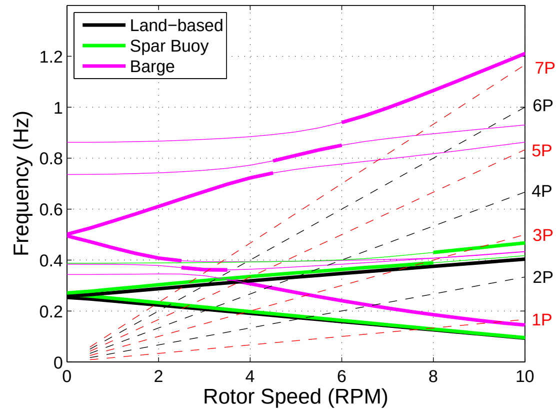

Figure 19. Tower mode Campbell diagram of 2 bladed 5 MW VAWT for land and floating support conditions

The rigid body modes of the spar buoy and barge platform supported 2 bladed 5 MW configuration are shown in Figures 20 and 21 respectively. The rigid body mode trends for the platform supported 3 bladed design are similar to 2 bladed design and are not discussed here. As seen in the Campbell diagram in Figure 19, the spar buoy platform has minimal interaction with structural modes of the turbine, and Figure 20 shows that the structural modes of the turbine have no perceivable interaction with the rigid body modes of the spar buoy supported system. Different trends are seen for the rigid body modes of the barge platform supported configuration in Figure 21 with the rotating structure having noticeable interaction with the pitch/roll rigid body modes. Indeed, the lower moment inertia of the barge platform relative to the rotating turbine allows more interaction between rigid body modes and structural modes. Thus, while such a platform type can be employed to improve structural response of the turbine, care should be taken to ensure rigid body modes are not adversely affected. Note that since the analysis has been performed in the rotating frame, the pitch/roll modes as viewed in an inertial frame will be a combination of the "pitch/roll" modes characterized in Figure 21 transformed from the rotating frame to the inertial frame.

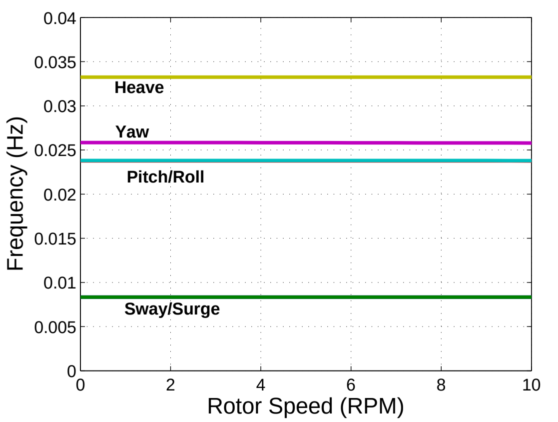

Figure 20. Rigid body mode Campbell diagram of 2 bladed 5 MW VAWT on spar buoy platform

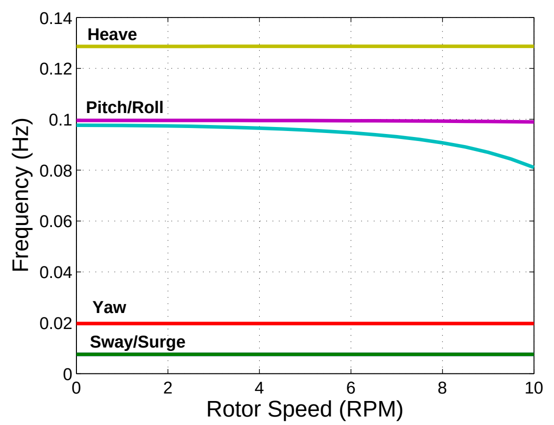

Figure 21. Rigid body mode Campbell diagram of 2 bladed 5 MW VAWT on barge platform

Figure 22 summarizes the effect of support condition on the parked tower mode frequencies of the 5 MW VAWT designs. Qualitatively, many of the trends observed in the support condition study for the SNL 34-meter VAWT (shown in Figure 12) are observed for the larger 5 MW configurations. Due to the scale of the 5 MW machine, the addition of a 20 or 30-meter monopile support has a less profound decrease in

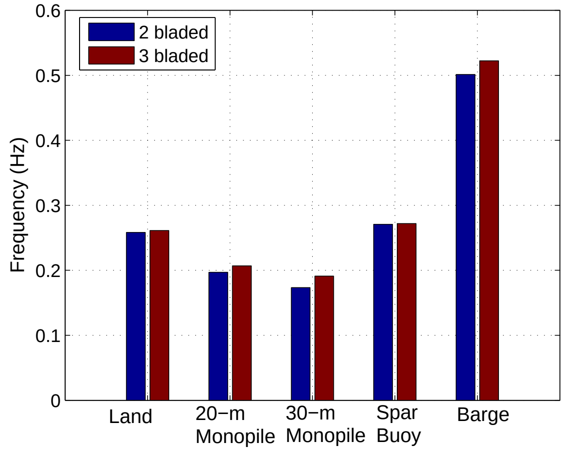

Figure 22. Parked tower mode frequencies for 2 and 3 bladed SNL 5 MW VAWT on various support conditions

parked tower mode frequencies, but further decrease from the already low tower mode frequencies of the land-based configuration is undesirable. Similarly, the spar buoy support provides a negligible increase in parked tower mode frequencies while the barge support provides a significant increase in parked tower mode frequencies. Figures 23 and 24 show the tower mode frequency slope magnitudes for the 3 and 2 bladed 5 MW designs. The slope is estimated using the tower mode frequencies at 0 and 10 RPM rotor speed. The tower mode slopes of the land-based, monopile supported, and spar buoy supported configurations characterized decently by the "rule of thumb" and differences are mostly due to frequency veering that results from the frequency veering interaction of low frequency modes. As seen in the 34-meter VAWT study, the barge platform supported configuration results in much higher tower mode frequency slopes that are not captured well by the "rule of thumb" approximation typically employed in initial design studies.

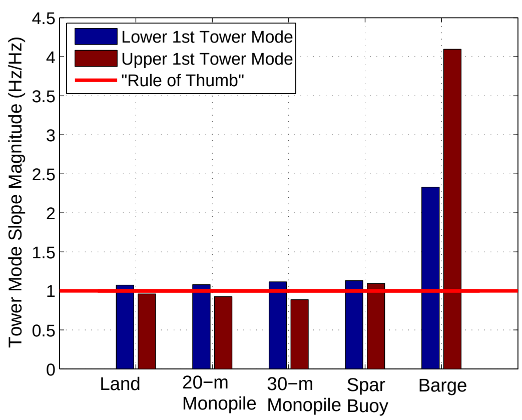

Figure 23. Tower mode slope for 3 bladed SNL 5 MW VAWT on various support conditions

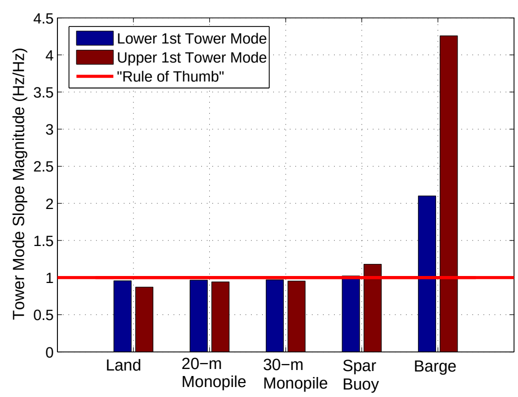

Figure 24. Tower mode slope for 2 bladed SNL 5 MW VAWT on various support conditions

VII. Conclusion and Future Work

The availability of offshore wind resources in coastal regions, along with a high concentration of load centers in these areas, makes offshore wind energy an attractive opportunity for clean renewable electricity production. High infrastructure costs such as the offshore support structure and operation and maintenance costs for offshore wind technology, however, are significant obstacles that need to be overcome to make offshore wind a more cost-effective option. A VAWT rotor configuration offers a potential transformative technology solution that significantly lowers COE for offshore wind due to its inherent advantages for the offshore market. This paper, has resulted in a better understanding of fundamental dynamic behavior of

VAWTs for offshore deployment with various support conditions through an initial design impact study for assessing the dynamic stability of large multi-megawatt deepwater offshore VAWTs.

This study of modal dynamics and stability in large offshore VAWTs has provided the following contributions:

- This work has developed a greater understanding of tower resonance in VAWT structures by developing an analytical expression for critical per-rev excitations related to the number of blades employed in a VAWT configuration. This greater understanding of tower mode resonance in VAWT design is an invaluable resource that may be employed by VAWT designers and analysts.
- The large scale of multi-megawatt VAWT designs results in very low frequency modes, and noticeable interplay between the tower and blade modes was observed in the form of frequency veering. Thus, the interpretation of modal analysis results for multi-megawatt VAWT configurations requires greater care than conventional VAWT configurations.
- A support condition study was conducted for VAWTs of different scale and number of blades. Overall, results indicated that a monopile support had the detrimental effect of lowering tower mode frequencies as well as lowering rotor speeds at which resonance may occur relative to a land-based support condition.
- Investigations revealed floating support conditions may alleviate resonance concerns, but with varying degree depending on the platform design. This study also showed that the influence of support structure on the turbine structural modes can come at the expense of turbine modes interacting with the rigid body modes of the platform/turbine system. Thus, care should be taken to ensure rigid body modes are not adversely affected by the attached flexible turbine structure.
- Consideration of different platform designs showed that spar and barge platform designs provide a range of influence on turbine structural response, and demonstrate an opportunity to design the platform in a way to mitigate tower resonance. System-level design studies with cost modeling, however, will determine the best solutions for rotor configuration, rotor operating conditions, and platform configuration.
- Investigations revealed "rules of thumb" for estimating the evolution of a VAWT tower mode frequency with respect to rotor speed are found to be less applicable to both floating configurations and larger VAWT structures with modes undergoing "frequency veering" as rotor speed varies. Therefore, more detailed analysis may be necessary than those previously employed for smaller scale, land-based VAWTs.

Future work should seek to characterize the severity of resonance concerns for large multi-megawatt VAWT configurations. Support condition design may remedy resonance concerns in tower modes to a certain degree, but low frequency modes of these large machines suggest avoiding all lower critical per-rev crossings may be unavoidable. Innovative control strategies may be required to operate through resonant conditions and alleviate constraints on operating speed. Furthermore, dynamic aeroelastic instability or flutter can be a concern for lift-generating structures under aerodynamic loads, and flutter has been observed in smaller-scale VAWT designs.[19] Recent studies have shown that flutter is a potential issue in very large HAWT blades[20–23] and may be a concern for very flexible multi-megawatt VAWT structures under large aerodynamic loads as well, but this issue has not been explored for large-scale offshore VAWT systems. Indeed, for an equivalent power rating, a VAWT design must have much larger (and likely more flexible) blades than a HAWT design. This detail accentuates the concerns for flutter instabilities.

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