Experimental Validation of a Spectral-Based Structural Analysis Model Implemented in the Design of the VolturnUS 6MW Floating Offshore Wind Turbine

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ABSTRACT

The following work presents a spectral-based structural analysis method implemented in the design of the VolturnUS 6MW Floating Offshore Wind Turbine hull developed to increase system optimization. To begin, a description of the methodology is provided which details how transfer functions relate the hull's structural response to first order wave kinematics and wind turbine aerodynamics. Following the model definition, focus is placed on model validation using results from an experimental 1:52 scale model test of the VolturnUS system (shown in Fig. 1) conducted at the University of Maine's Alfond W^2 Ocean Engineering Laboratory. Using data acquired from load cells installed at various locations in the hull the accuracy of the model is assessed through the use of power spectra and statistics. The performance of the structural model is considered over a range of environmental conditions representing design load cases prescribed by the American Bureau of Shipping for class certification of floating offshore wind turbines.

KEY WORDS:

offshore wind turbine; structural analysis; model testing

NOMENCLATURE

ABS- American Bureau of Shipping
DLC – Design Load Case
FE – finite element
FOWT – floating offshore wind turbine
NREL – National Renewable Energy Laboratory
PSD – Power spectral density
RAO – response amplitude operator

INTRODUCTION

Of the estimated 4,150 GW of renewable wind energy lying off the coast of the United States over 60% is located at depths requiring the use of deep-water floating platform technology(U.S. Department of Energy, U.S. Department of the Interior, 2016). In an effort to harness this abundant deep-water natural resource the technological development of floating offshore wind turbines (FOWTs) has seen considerable progress in the renewable energy engineering field.

Selected as a finalist in the Department of Energy's Offshore Wind Advanced Technology Demonstration Project in May 2016, the University of Maine has developed the VolturnUS 6MW FOWT. Slated for deployment off Northeast U.S. Coast in 2019, the VolturnUS system reduces the cost of offshore wind through the use of a concrete semi-submersible hull, designed for mass production using novel manufacturing and assembly processes, and innovative design methods, the latter of which is the focus of this paper (Viselli, Dagher, & Goupee, Model Test of a 1:8-scale Floating Wind Turbine Offshore in the Gulf of Maine, 2015), (Viselli, Dagher, Goupee, & Allen, Design and Model Confirmation of the Intermediate Scale VolturnUS Floating Wind Turbine Subjected to its Extreme Design Conditions, 2015).

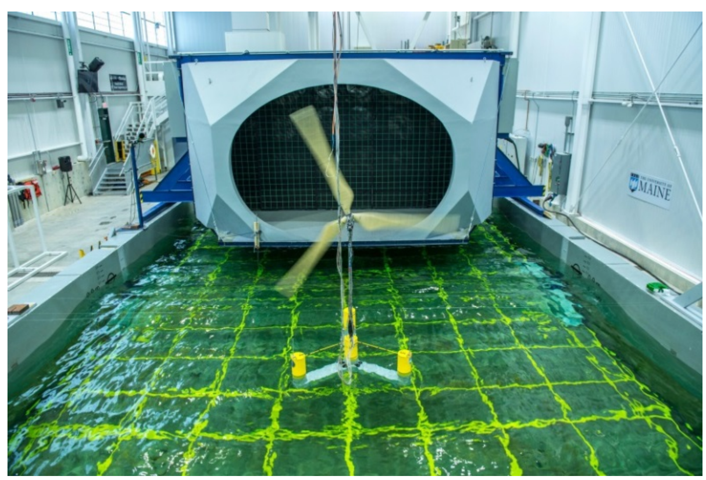

Fig. 1 VolturnUS 1:52 Scale Testing

At present many FOWT components are analyzed using proven numerical models, such as the software FAST developed by the National Renewable Energy Laboratory (NREL), which fully couples the response to aerodynamic and hydrodynamic loading in various components of the system (Coulling, Goupee, Robertson, Jason, & Dagher, 2013)(Allen, Goupee, Viselli, & Dagher, 2015). For the purpose of analyzing an FOWT's turbine, tower and mooring systems these numerical models provide adequate accuracy and resolution for engineering design (Allen, Goupee, Viselli, & Dagher, 2015). However, the fidelity in the discretization of the hull's elastic body needed to capture platform structural responses require that coupled numerical models simplify or negate the elasticity of the hull. As such, many aspects of the FOWT's hull are not currently addressed in the codes resulting in the need to develop a new analysis method.

ANALYSIS METHODOLOGY

The following section outlines the steps of the structural methodology. The output of the model is a time history of a unique structural response at a given point in the hull due to loads associated with the hydrodynamic s experienced by the hull and the aerodynamics imparted from the turbine. The analysis routine produces load time histories of various structural responses required for design. The inputs into the model are stochastic wind and wave environments and the outputs are specified structural responses (i.e. bending moment, axial load, stress, deformation, etc.) to the input environments. The structural response to these two external sources are computed independently of one another with the total load response being the superposition of each time history. As such, the following two sections separately described the method by which the hydrodynamic and aerodynamic loadings are calculated.

Hydrodynamic Structural Response

The first step in relating a particular structural responses to a stochastic wave environment is to derive the transfer function which relates a response to the various components of the wave field. The transfer functions implemented in this routine, known commonly as response amplitude operators (RAOs), relate the normalized magnitude and phase of a structural response with respect to a unique wave frequency and direction.

To produce these RAOs a potential flow model is used to derive the hydrodynamic pressures over the submerged body as well as the rigid body's dynamic response at each desired wave frequency and heading. Next the structural response is calculated using a finite element (FE) shell model, shown in Fig. 2. The hydrodynamic pressures and dynamic response calculated by the potential flow model are applied to the FE model. At each desired wave frequency the structural response is resolved at various wave phase angles, which when completed, indicate the peak normalized load response and its corresponding phase angle. As depicted in Fig. 4, this normalized structural response, $R^h(f,\theta)$, is defined by a magnitude and a phase as a function of wave frequency f and wave heading θ. $R^h(f,\theta)$ is the linear structural response and as such can easily be implemented in the frequency domain.

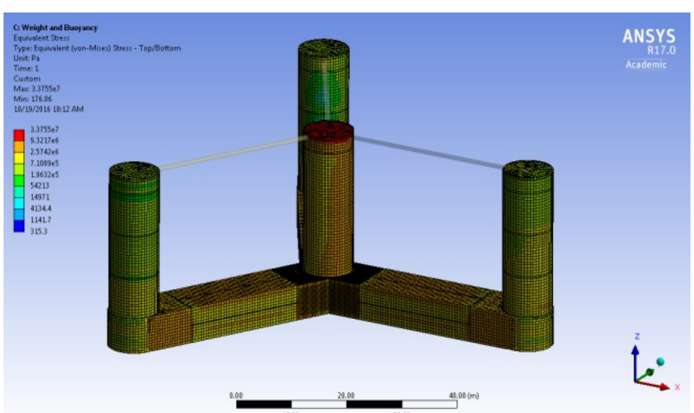

Fig. 2 Ansys Mechanical FEA Shell Model

The second step is to define the wave environment in the frequency domain so that it can be related to the hydrodynamic load transfer function $R^{wave}(f,\theta)$. A stochastic wave field is defined as $S^{wave}(f)$ in the frequency domain by taking the Fast Fourier Transform (FFT) of the wave elevation time series.

The third step is to define spectral response of the load. A load response spectrum $S^{load}(f)$ is derived by relating each frequency component of $S^{wave}(f)$ to its corresponding component of the load transfer function, $R^{wave}(f,\theta)$. $S^{load}(f)$ is defined by both the real and imaginary components of the response, and thus accurately represents the load in both magnitude and phase (with respect to the wave environment). Note that the frequency range considered by the model is bounded within the wave energy range of the sea state. Considering a JONSWAP spectrum, the model defines the wave energy range to be located between the points to the left and right of the peak period which correspond to 2.5% of the peak spectral value (Gueydon, Duarte, Jonkman, Bayati, & Sarmento, 2014).

Finally the load time history $F^{wave}(t)$ is derived by taking the Inverse Fast Fourier Transform (IFFT) of the spectral load response $S^{load}(f)$. $F^{wave}(t)$ is the linear hydrodynamic load response to the stochastic wave environment defined above.

Turbine Aerodynamic Structural Response

The load effects due to wind turbine aerodynamics are now presented. This transfer function is primarily intended to capture the peak, mean, and minimum turbine thrust loads imparted on the hull, as well as low frequency responses (up to approximately .01 Hz) due to stochastic wind fields and turbulence. It is not intended to capture high frequency responses due to turbine blade pass rates or structural frequency responses.

The first step involves applying maximum thrust load, as well as the system's reactions to the turbine thrust to the FE model shown in Fig. 2. In addition to the thrust load the FE model considers the resulting hydrostatic reactions, mooring reactions and gravity loads due the static heel angle caused by the turbine thrust. The load value from a still water condition with no turbine thrust load applied is then subtracted from the load response from this analysis. A unit load response is then derived by dividing the aforementioned difference by the maximum thrust load. By using this normalized value the system response to an increase in thrust load is assumed to be linear in this model which is valid if the model is used within the range of small angle assumptions (which is typically valid for angles less than 14 degrees).

The second step involves deriving the aerodynamic thrust load for a given design wind environment. A numerical simulation is conducted in NREL's FAST v8. From the FAST analysis the aerodynamic thrust's magnitude is derived by considering the response of the rotor thrust load at the low speed shaft and subtracting the components due to gravity and inertia. By doing this it is assumed that the dynamic load effects on the low speed shaft due to inertia and displacement are governed by the system's hydrodynamic response (Goupee, Koo, Kimball, Lambrakos, & Dagher, 2014).

Finally, the turbine aerodynamic thrust load time history in the hull is then generated by multiplying the aerodynamic thrust time history by the thrust load transfer function with respect to the wind heading. The total load time history is then computed as the sum of the wave load time history and the aerodynamic turbine thrust load time history.

MODEL VALIDATION

Model validation of the structural analysis method is now presented with the use of model scale test data of the VoltrunUS system at 1:52 scale generated in 2016. The validation study evaluates the performance and capabilities of the structural analysis model over a range of design conditions required by the American Bureau of Shipping (ABS) with emphasis placed on Design Load Cases (DLCs) which were found to govern various aspects of the VolturnUS design. The DLCs investigated in this work represent the design scenarios for floating offshore wind turbines required for classification by the ABS in *Guide for Building and Classing Floating Offshore Wind Turbine Installations*, 2014 (American Bureau of Shipping, 2014) with additional guidance from *Global Performance Analysis for Floating Offshore Wind Turbine Installations* (American Bureau of Shipping, 2014).

In August and September of 2016 a 1:52 scale model test campaign of the VolturnUS FOWT was conducted at the W2 Ocean Engineering Lab Wind-Wave Basin (shown in Fig. 1). The testing campaign was conducted successfully over the course of several weeks and subjected the model to ABS defined environmental conditions which, as previously mentioned, were found to be design-driving to various components of the full-scale VolturnUS system.

The test program followed Froude scaling as is customary for wave basin tests using a scale factor of 52 (Martin, Kinbak, Viselli, & Goupee, 2013). The prototype turbine for this test campaign was representative of a 6MW offshore wind turbine producing a full-scale hub height of 100 meters and a rotor radius of 75.5 meters. The test platform was a geometrically scaled version of the VolturnUS 100% design hull and the turbine implemented performance-matched wind blades attaining the turbine power and thrust behavior of the full-scale unit. The tower was designed to match its full-scale target with respect to mass and fundamental bending frequencies. Finally, the mooring system, consisting of three equi-spaced catenary lines, was sized to match the mass and geometry of the full scale system. Please note that all results and references are provided with respect to the full scale system. Also, all test data has processed by a low-pass filter to negate responses greater than .5 Hz.

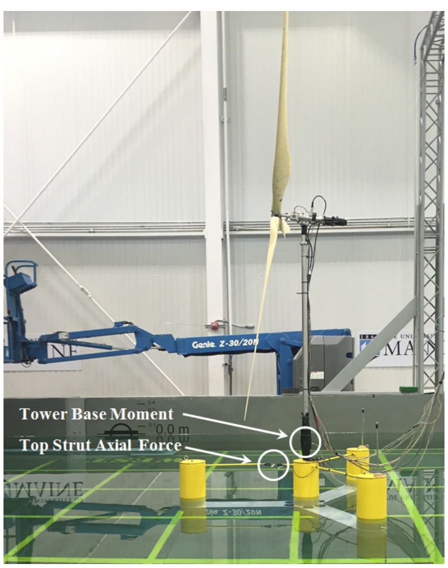

Fig. 3 Locations of Validation Measurements on VolturnUS 6MW 1:52 Scale Model

Model validation of the structural analysis method is now presented. Depicted in Fig. 3, the validation of the structural model was conducted using measured loads in the system during testing from recorded from (2) locations:

(1) A load cell which measured which measured axial force in the VolturnUS hull's top upwind horizontal axial member (strut)
(2) A strain gauge array which measured fore-aft tower base bending moment

Note that the stop strut load cell is located at a structural indeterminate location within the system. Thus, in order to replicate the RAOs of the structural response the structural analysis routine utilized a FE model which represented the stiffness of the VoturnUS 1:52 scale model.

Validation of Load Transfer Functions

In the following section the derivation of the hydrodynamic and aerodynamic load transfer functions are validated against data obtained during system characterization tests. The hydrodynamic RAOs for the top strut's axial force and tower base's bending moment were derived following the procedure outlined in the previous section. To validate this methodology the calculated RAO values are compared to the load responses recorded during a broad band simulation conducted during basin testing. The calculated values and recorded values for the top strut and the tower base are provided in Fig. 4 and Fig. 5, respectively.

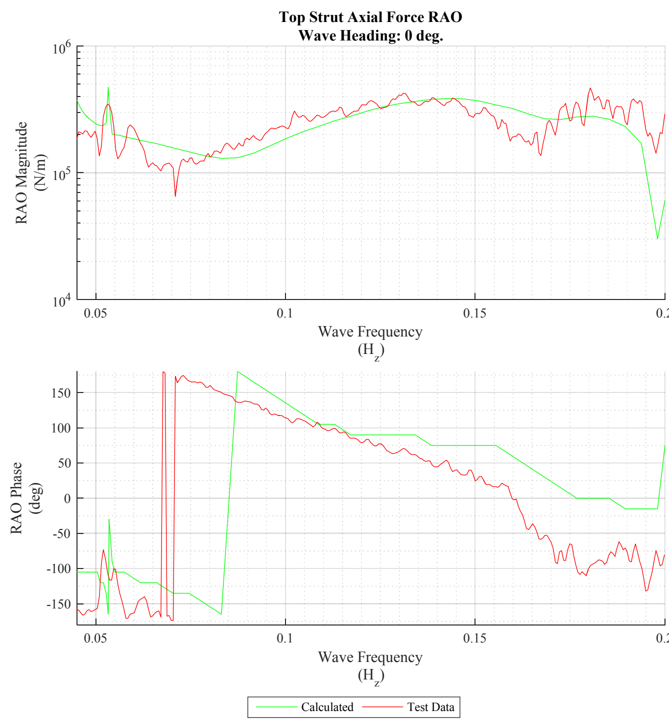

Fig. 4 Top Strut Axial Load RAO for a wave heading of 0 degrees

The strut's calculated axial load response agrees well in both magnitude and phase over majority of considered wave frequencies. The calculated RAO shows a significantly larger response at approximately .052 Hz. which corresponds the system's heave natural frequency. As shown in previous work, the system's dynamic behavior is typically overestimated near resonance when the effects of viscous damping are not considered (Robertson, et al., 2013). The nonlinear nature of this damping effect does not allow for its inclusion in the system's linear response and thus cannot be accounted for in the load analysis presented here. As such, the loads near system resonance are expected to be overestimated by the model due to the increase in system global dynamics.

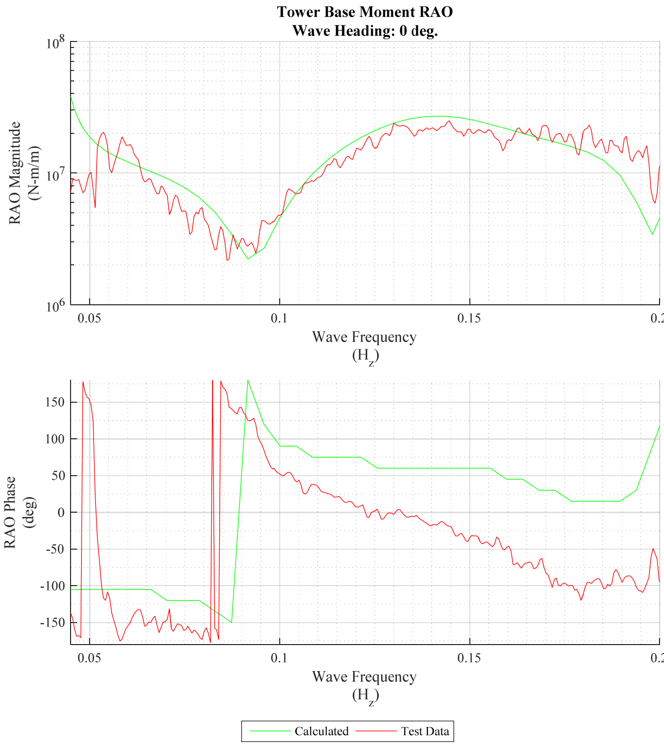

Fig. 5 Tower Base Moment RAO for a wave heading of 0 degrees

The calculated tower base moment RAO, shown in Fig. 5, also shows favorable agreement with the results from the broad band test. The magnitude of the RAO matches quite well with the calculated values matching the data's trend over the frequency range. The calculated magnitude can be seen increasing on the far left side of the figure as the response nears the system's pitch natural frequency. Similar to the heave response in the top strut near heave resonance, the tower's moment response near pitch resonance is significantly over predicted by the model. However, unlike the heave response, the pitch response is far outside of the energy range associated with the design sea states. This can be deduced from the JONSWAP spectrums of the ABS cases shown in Fig. 7.

Fig. 6 depicts data collected during a steady wind test conducted at the turbine's rated wind speed, the condition which elicits the maximum aerodynamic thrust on the turbine. The figure depicts the load and the corresponding load responses in the tower base and top strut. This condition is used to verify aerodynamic transfer functions whose calculated value can be seen in red in the figure. Note that despite a prescribed steady, uniform wind condition, the observed responses from the test data indicate a small amount of turbulence in the wind field as the values oscillate about the mean values.

In conclusion, the hydrodynamic RAO values for both locations compare very well with the broad band test. It was noted that that the model tends to overestimate the response near system heave and pitch resonance. However, considering that these frequencies lie outside of the design wave spectrums this overestimation will likely not impact the final results. The aerodynamic loads calculated by the model agree quite well with the recorded data. However, it was noted that the test data did not achieve a steady state response and was likely subjected to unwanted turbulence inherent in a physical test. This inclusion of turbulence in the test data may lead to greater low frequency responses in the results which are witnessed by the model.

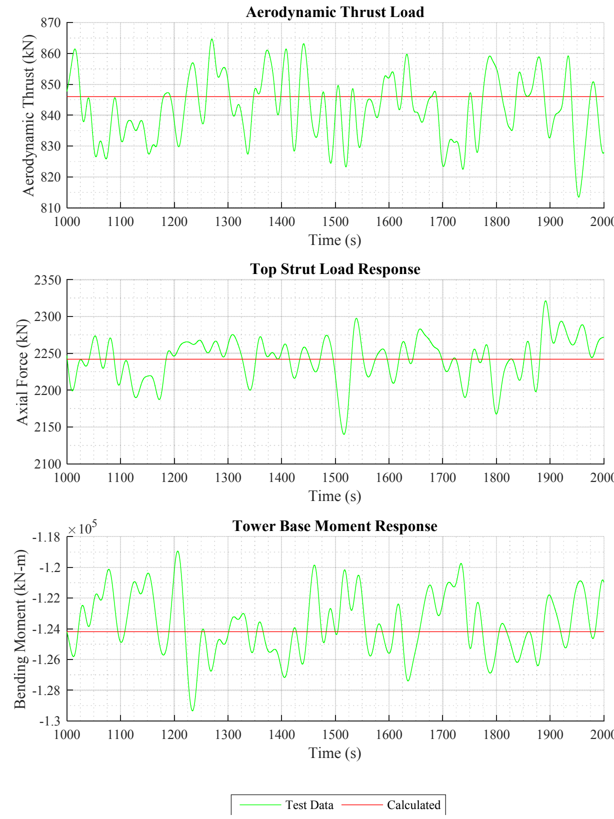

Fig. 6 System Response at Rated Wind Speed

Model Validation in ABS Design Sea States

The following validation study evaluates the performance and capabilities of the structural analysis model in two design-driving conditions required by ABS. These two DLCs have been selected for comparison since both were found to govern various aspects of the VolturnUS design. The first load case, ABS DLC 1.2, represents normal operational conditions and thus drives the fatigue design of many structural elements in the system. The second load case, ABS DLC 1.6, represents an extreme 50-year operational condition and has been found to govern the limit state of many elements. The DLC environmental conditions are provided in Table 1 and the JONSWAP spectrums for each condition have been plotted in Fig. 7.

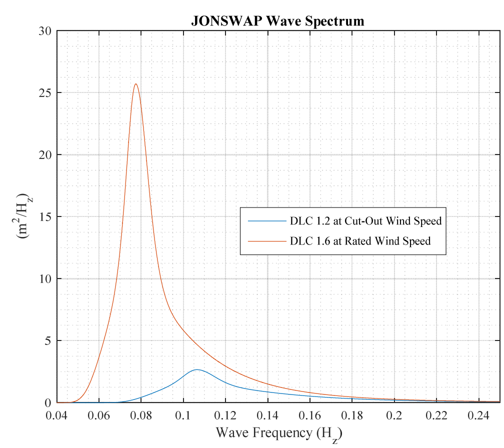

Fig. 7 ABS DLC Sea State JONSWAPs

Table 1 ABS DLC Environmental Conditions

ABS DLC	DLC 1.2 at Cut-Out Wind Speed	DLC 1.6 at Rated Wind Speed
Mean Wind Speed at Hub Height (m/s)	24.0	11.5
Significant Wave Height (m)	3.4	8.5
Peak Wave Period (s)	9.3	13.1
JONSWAP Shape Parameter	1.8	2.75
Simulation Time (s)	600	3600

DLC 1.2 – Normal Operation

ABS DLC 1.2 is an operational fatigue design load case which is representative of the wind turbine under normal operational conditions. The environment of DLC 1.2 consists of wind speeds varying over the wind turbine's operational range from cut-in to cut-out. Each wind speed coincides with a unique sea state sharing joint probability. The DLC 1.2 condition presented here represents the wind turbine at its cut-out wind speed. This maximum operational wind speed coincides with the largest normal operational sea state, as defined in Table 1.

Since this DLC represents the system under normal conditions it tends to generate the most fatigue damage for a number structural elements in the FOWT. A fatigue critical element is typically dependent upon the load amplitude and frequency (as opposed to the peak or mean) and as such a useful indicator of a model's ability to accurately capture fatigue loading is often the standard deviation of the response. As seen in Table 2, the model was able to capture the responses standard deviation to within 3.2% and 2.2% of the recorded data for the top strut and tower base moment, respectively.

The power spectral densities (PSDs) of the top strut and tower base moment's response during this event are provided in Fig. 8. As indicated by the JONSWAP in Fig. 7 the wave energy for this sea state is present from approximately .08-.18 Hz. Considering the calculated response with respect to the test data over this frequency range it can be deduced that the model is able to capture the hydrodynamic load response quite accurately for both the tower base and top strut.

Both PSDs indicate a greater low frequency response from the test data compared to the calculated response. This region between approximately .01 Hz to .06 Hz contains system responses primarily due to wind field turbulence and second order hydrodynamic response, the latter of which is not captured by the model's linear hydrodynamic capabilities. However, these responses are two orders of magnitude smaller than the first order hydrodynamic response and as such add little contribution to the overall design values. This is further evident in the statistics comparing the peak response in Table 2 which shows that the model was able to capture the peak load response to within 4.3% and 2.4% of the recorded data for the top strut axial force and tower base moment, respectively.

Overall, the model tends to accurately capture the fatigue loads associated with this DLC quite well. The model's agreement with the data in terms of its standard deviation is a good indication to a model's ability to capture fatigue loads. Additionally, the PSDs show that the majority of the response's energy is dominated by wave energy, a region very well captured in the model.

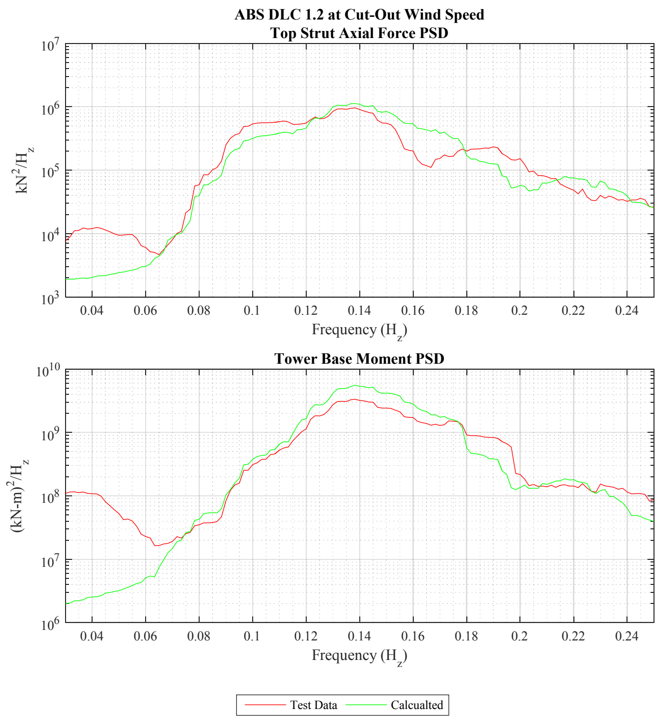

Fig. 8 DLC 1.2 Structural Response PSD

Table 2 ABS DLC 1.2 Structural Response Statistics

	Top Strut Axial Load		
	Calculated	**Test Data**	**% Diff.**
Mean Load (kN)	1.50E+03	1.43E+03	5.4%
Maximum Load Magnitude (kN)	2.21E+03	2.12E+03	4.3%
Standard Deviation (kN)	2.34E+02	2.26E+02	3.2%
	Tower Base Moment		
	Calculated	**Test Data**	**% Diff.**
Mean Moment (kN-m)	-3.87E+04	-3.55E+04	8.9%
Maximum Moment Magnitude (kN-m)	8.19E+04	8.39E+04	-2.4%
Standard Deviation (kN-m)	1.48E+04	1.45E+04	2.2%

DLC 1.6 – Extreme Operation

DLC 1.6 represents an extreme operational design load case. Events falling into this category consist of a 50-year return sea state associated with a particular wind speed over the turbine's operational range. Design experience has shown DLC 1.6 to govern many aspects of the system's structural design and dynamic response, particularly when the event occurs at the turbine's rated wind speed which subjects the system to the unfavorable combination of the turbine's peak aerodynamic thrust and an extreme sea state. The combination of the peak thrust load and severe wave environment produced an excellent representation of a significant design-driving event.

The statistics for this event, found in Table 3, indicate that the model was able to accurately capture the peak loads. The top strut peak load was captured to within 3.2% of the recorded value. Note however that the data and the model's mean value have approximately the same difference as the peak value and suggests that the model was able to capture the peak load amplitude. Similarly, the peak tower base load was found to be within 2.0% of the test data; however the difference is approximately that of the mean value and again indicates that the load amplitude was captured correctly by the model.

The PSDs of the top strut and tower base bending moment's structural response are provided in Fig. 9. As seen in the JONSWAP spectrum for DLC 1.6 in Fig. 7, the wave energy band for this case spans from approximately .05 Hz to .18 Hz. The strut data indicates a response near the heave natural frequency of .052 Hz, which is on the cusp of the wave energy band. This frequency, however, is outside of the range considered by the hydrodynamic load model and as such does not display a response at this location. However, the additional energy at the heave natural frequency does not seem to affect the response and, as was seen in the previous case, the total response is driven by the wave energy range.

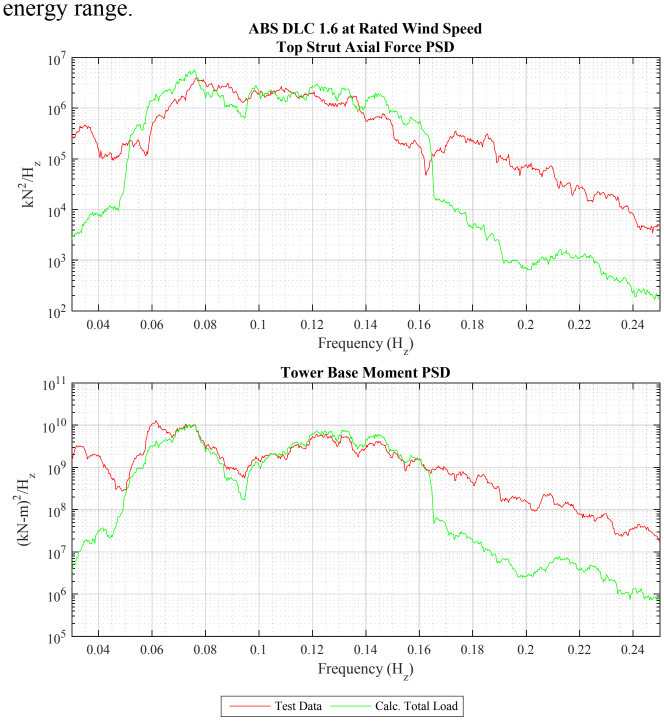

Fig. 9 DLC 1.6 Structural Response PSD

Overall DLC 1.6 is represented well by the load model. The predicted peak load values agreed well with the data. Additionally, it was shown that the small difference in the calculated and recorded peak values was likely attributed to the mean values which are very sensitive to the turbine's thrust load. The recorded data from the struts frequency response showed a response near the heave natural frequency. Since frequency was outside of the model's prescribed wave spectrum bounds it was not seen in the calculated response. However, this response was shown quite small compared to the first order hydrodynamic response, and did not show a meaningful difference in the design load values.

Table 3 ABS DLC 1.6 Structural Response Statistics

	Top Strut Axial Load		
	Calculated	**Test Data**	**% Diff.**
Mean Load (kN)	2.32E+03	2.25E+03	3.1%
Maximum Load Magnitude (kN)	4.02E+03	3.89E+03	3.2%
Standard Deviation (kN)	4.45E+02	4.16E+02	7.0%
	Tower Base Moment		
	Calculated	**Test Data**	**% Diff.**
Mean Moment (kN-m)	-1.43E+05	-1.48E+05	-3.6%
Maximum Moment Magnitude (kN-m)	2.16E+05	2.20E+05	-2.0%
Standard Deviation (kN-m)	1.98E+04	2.20E+04	-9.8%

CONCLUSIONS

In summary, a new method for resolving structural design loads in a FOWT's hull was presented. The model's methodology was presented and outlined the manor by which the hydrodynamic and aerodynamic loads can be resolved in the time domain with the use of load transfer function and stochastic environment inputs.

The structural model was then validated against experimental 1:52 scale basin test data of VolturnUS 6MW FOWT. This process began with validating the load transfer functions via system ID tests. The hydrodynamic RAOs were compared to load responses recorded during a broad band spectrum tests. The calculated RAO values showed excellent agreement with the data with the exception of values near heave and pitch resonance which were over predicated by the model. This was found to be an artifact of the linear potential flow analysis which typically overestimates system response near resonance. The aerodynamic transfer functions were then validation against a steady wind test. The calculated values showed good agreement to the test data's mean values. However, it was observed that the test data did not depict a steady state response and was likely influenced by turbulence in the wind field.

This was then followed by model validation during ABS defined DLC events. The events considered for the study were indicative of ABS DLCs found to govern certain areas of the FOWT's design. Thus, validation was conducted within regions which the models are intended for use. The study first considered ABS DLC 1.2, a fatigue driving load case. The model showed very good agreement with the data, especially with regard the standard deviation of the response, indicating its applicable use for fatigue design. The second load case considered was ABS DLC 1.6. When the event occurs at the turbine's rated wind speed the system is subject to the unfavorable combination of the turbine's peak aerodynamic thrust and an extreme sea state and as such tends to govern the limit state of many structural elements in the hull. The model showed excellent agreement with the data during this event and showed it was able to capture all peak loadings to within 3.2% of the test data.

Overall, structural model's ability to represent the system's response to design environments appeared to agree quite well with the measured data. The key design values appear to be in agreement with the responses witnessed during the model testing and should provide an overall confidence in models ability to represent the response of an FOWT during design conditions.

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