Journal of Physics: Conference Series

Stochastic load effect characterization of floating wind turbine support structures

View the article online for updates and enhancements.

IOP ebooks™

Bringing you innovative digital publishing with leading voices to create your essential collection of books in STEM research.

Start exploring the collection - download the first chapter of every title for free.

Stochastic load effect characterization of floating wind turbine support structures

Salem Okpokparoro[1,2] **and Srinivas Sriramula**[1]

[1] Lloyd's Register Foundation (LRF) Centre for Safety and Reliability Engineering, School of Engineering, University of Aberdeen, Aberdeen, AB24 3UE, UK

[2] Petroleum Technology Development Fund (PTDF), 2 Memorial Close, Central Business District, Abuja. Nigeria

E-mail: `s.okpokparoro@abdn.ac.uk`

Abstract. Achieving substantial reductions in Levelized Cost of Energy (LCOE) of floating wind turbines (FWTs) requires robust reliability assessment that accounts for inherent design uncertainties. A key aspect of such reliability assessment is the definition of limit states. In this regard, load effects need to be evaluated accurately. This paper presents a computational framework for evaluating load effects on FWT support structures. The computed load effect is subsequently characterized. A high fidelity finite element model of the National Renewable Energy Laboratory (NREL) 5MW reference turbine mounted on the OC3-Hywind spar buoy was developed and validated for this purpose. The loads from fully coupled time domain aero-hydro-servo-elastic simulations are transferred for detailed finite element (FE) load effect computation in Abaqus. Matlab® and Python are used as the computational tools for automating the whole analysis from start to finish. The initial part of this study addresses the amount of run-in-time to be excluded from response statistics. Based on convergence studies carried out, recommendations are made for run-in-time to be excluded from response statistics. The maximum von Mises stress in the tower as a measure of yielding is the load effect investigated in this study.

1. Introduction

Floating support structures are indeed the most viable option for deep water deployment of wind turbines. These structures are subjected to random excitation from both wind and waves as well as other loading sources. Designing floating wind turbine systems to withstand these loads throughout their service life at minimal cost requires robust engineering design that ensures the system is neither over-designed nor under-designed but just designed at the optimal level leading to substantial reductions in their LCOE.

Support structure design drivers for an ultimate limit state (ULS) design are usually the absolute maximum of key parameters such as tower top/base shear forces and moments and tension at the fairleads and anchors obtained from dynamic simulations. From a reliability standpoint, the load effects in terms of excessive yielding and buckling, deformations, loss of stability etc., which result from the interaction of such loads as computed from coupled dynamic simulations are essential for defining realistic limit state functions. High fidelity finite element analysis (FEA) is very much suited for such robust load effect computation and is used in this study. The maximum observed von Mises stress throughout the tower is taken as the measure of yielding. The computation and subsequent characterization of this load effect is presented in

section 4. High fidelity 3-D FEA models have also been employed by various researchers [1-3], in obtaining stresses on parts of wind turbines.

Part of this study throws light on the time to be excluded from response statistics in an ULS design where short 10 minutes simulations are carried out. This is crucial as the loads transferred from the aero-hydro-servo-elastic tool to the FEA model should not be characterized by start-up transients. Research findings on fully-coupled stochastic load effect computation and subsequent characterization are then presented. This work can be extended for developing uncertainty models towards more refined reliability assessment and partial safety factor calibration, leading to significant cost reductions in floating support structure design.

The wind turbine used for this study is the NREL offshore 5MW reference wind turbine [4] mounted on OC3-Hywind spar buoy [5]. The time series of von Mises stress is obtained using an interface between NREL aero-hydro-servo-elastic tool, OpenFAST (formerly known as FAST [6]) and FEA solver Abaqus with Matlab® and Python as the computational environment. Given the high computational cost of numerous FE simulations, High Performance Computing (HPC) cluster is used for this work.

2. Numerical model and tools

2.1. Coupled aero-hydro-servo-elastic time domain solver

Dynamic simulations of the floating turbine are performed using the NREL aero-hydro-servo-elastic code OpenFAST, which incorporates various modules like AeroDyn [7] for calculation of aerodynamic loads, a hydrodynamics module called HydroDyn [8], mooring dynamics modules (MoorDyn [9] is used in this study), structural dynamics modules SubDyn/ElastoDyn, and control/electrical system dynamics module ServoDyn. The wind loads acting over the rotor, gravitational loading as well as acceleration forces resulting from the contribution of the Rotor and Nacelle Assembly (RNA) in the full turbine system dynamics are reduced to 3 forces and moments at the tower top. The coupled turbine system structural dynamics are solved in OpenFAST which employs Kanes dynamics for solving the turbine system equations of motion. Details of the structural dynamics model employed by OpenFAST can be found in [10-12] and are not repeated here for sake of brevity.

2.2. FEA model

2.2.1. Creation of geometry and parts.
Based on material properties and geometric dimensions in [5], a 3-D geometry of the OC3-Hywind is generated using Abaqus Python scripting. The model however is a reduced model without mooring system, transition piece and turbine blades. The RNA and platform are represented as rigid bodies with appropriate masses and rotary inertias assigned to their reference points. Only the tower (the part spanning 77.6 m i.e. from the tower top to 10m above the mean water level) is modelled as a deformable body.

2.2.2. Mesh generation and model validation.
Few elements are generated for the rigid parts (mesh sizes greater than 2 m) while the flexible tower has a mesh size of 0.5 m. The tower mesh size of 0.5 m is chosen based on good agreement between the tower natural frequencies extracted in Abaqus modal analysis and results obtained using BModes [13]. BModes is chosen for validation of the FEA model because data from BModes modal analysis is used in calculating polynomial coefficients needed in OpenFAST input files. The tower can be classed as a thin-walled structural member and therefore shell elements are used as the tower mesh element type. The shell thickness is represented by an analytical field defined by a simple mathematical expression of thickness as a function of the distance from the tower top.

It is imperative that the modal dynamics of the finite element (FE) model is similar to the model used in OpenFAST simulations from which loads are to be transferred. The loads or displacements outputted by OpenFAST already account for the effect of hydrodynamic

loading, aerodynamic loads as well as inertia loads from structural dynamics of the full turbine system. Capturing these same dynamics within the FE-based model is therefore not needed. For simplicity of comparison, one can therefore neglect the hydrodynamic and hydrostatic effects on the platform as well as contributions from the mooring system. In the modal analysis carried out in Abaqus and BModes, the 6×6 inertia (added mass) and 6×6 hydrodynamic restoring (stiffness) matrices as well as the 6×6 mooring system matrix are neglected. Table 1 shows the results obtained. The tower is cantilevered to the top of the platform.

Table 1. Modal analysis.

Mode Type	Frequency (Hz)		
	Abaqus	BModes	%Diff
1st Side-Side	0.3678	0.3706	-0.756
1st Fore-Aft	0.3727	0.3756	-0.772
1st Torsion	1.4438	1.4584	-1.001
2nd Side-Side	1.9614	1.9962	-1.743
2nd Fore-Aft	2.4462	2.4926	-1.862

From the modal analysis results presented in table 1, there is good agreement between the natural frequencies obtained by Abaqus and BModes. The highest absolute percentage difference was 1.862%, confirming the validity of the FEA model. The first three mode shapes of the flexible tower are shown in figure 1. The tower mode shapes are plotted against the undeformed tower.
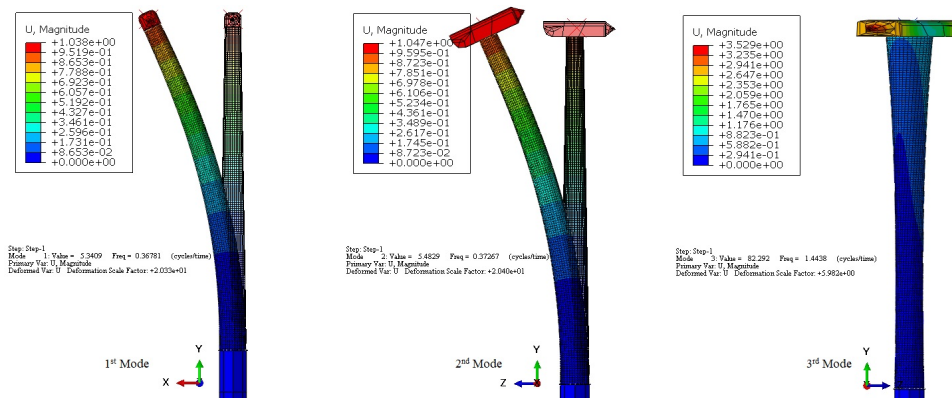

Figure 1. Tower mode shapes

2.3. Computational framework.

Matlab® environment is used for automatically transferring OpenFAST outputs to Abaqus. Python scripting is employed in creating the FEA model and executing the Abaqus jobs cyclically leveraging on the computational power of HPC clusters in executing numerous Abaqus jobs. The tower top forces directed along the x, y and z axes and moments about these axes which are outputs from OpenFAST, account for both the wind thrust force, rotor torque, gravitational load of the RNA together with inertial forces from the FWT dynamics. These tower top forces and moments are distributed to the FE tower top nodes by means of a tie connection between

the rigid RNA base plate and the tower top nodes. The tower base is assigned a fixed boundary condition. To account for the weight of the tower along with the tower inertial forces, the tower translational and rotational accelerations from OpenFAST together with gravitational acceleration of 9.80665 m/s^2 is applied to the tower as body forces in Abaqus. Similar analysis methodology was employed by Andrew *et al* [2] for evaluating stress utilization and buckling constraints using FEA in the optimization of composite towers for floating wind turbine concepts. Since the dynamics of the FWT system is already captured by OpenFAST, the problem is reduced to solving the equilibrium of all forces acting on the tower as represented by equation 1.

$$\left[\mathbf{K}\right]\{\mathbf{D}\} = \{\mathbf{F}\} \tag{1}$$

where $\left[\mathbf{K}\right]$ is the tower stiffness matrix, $\{\mathbf{D}\}$ is the vector of tower displacements and $\{\mathbf{F}\}$ is the vector of the forces acting on the tower. The displacements can then be calculated followed by strains and stresses. If tower displacements are known from aero-hydro-servo-elastic simulations, equation 1 can also be solved by specifying displacement boundary conditions.

3. Time domain stochastic aero-hydro-servo-elastic simulations

3.1. Reference site and metocean conditions

The site chosen for this study is the East Coast of the United States of America. The realistic metocean data was created by Stewart *et al* [14]. Water depth at this site is assumed to be 320 m. The expected values of significant wave height (H_s) and median peak-spectral period (T_p) for each average wind speed is used as published in [15].

3.2. Eliminating Start-up transients

The initial part of dynamic simulations is often characterized by start-up transients especially for floating platforms. These transients exist due to the influence of gravity and rotor rotation on the structural displacements (assumed to be undisplaced at start-up) [16]. However, with structural damping, these start-up transients die out over time. It is pertinent to ensure that the response statistics are truly representative of the structural behaviour of the FWT before they are transferred to Abaqus for load effect computation or as such any other post-processing. IEC 61400-3 [17] recommends the removal of the first 5 s or longer from the simulation statistics to reduce the impact of start-up transients. This 5 s run-in-time clearly would not suffice considering the long natural periods of floating support structures. Although 60 s was suggested by Haid *et al* [15] if proper initial conditions (ICs) are set, no explanation or backing was given. Guzmn *et al* [18] investigated the use of moving average and backwards analysis of standard deviation with the later recommended for checking converged statistics. The simulations carried out in [18] were long simulations of more than 3600 s with a recommendation of 600 s as the run-in-time to be expunged. For ULS simulations that require short simulations of 600 s and where the averages of the time series are of less importance than the absolute maximum values, it becomes quite challenging to ascertain the amount of run-in-time to be discarded. To investigate this, simulations based on Design Load Case 1.2 (DLC 1.2) from IEC 61400-3 are performed. The turbine control systems are active for all simulations. The wind turbine is assumed to be class II as described in IEC 61400-1 [19]. A total of 11 wind bins are simulated (4 m/s to 24 m/s wind and associated sea states conditioned on mean wind speed). IEC Kaimal spectral model and a turbulence intensity of 0.14 is used for generation of turbulent wind realizations with TurbSim [20] and JONSWAP spectrum for generation of random seas. The TurbSim input files were modified to output 700 s turbulent wind time series comprised of repeated 100 s realization. The wave elevation time series also comprised repeated 100 s wave elevation realizations. This

divides a $700\ s$ simulation into 7 windows of which corresponding wind and wave inputs are equal. This enables convergence towards stationarity of responses within short $700\ s$ simulations. The last window is used as the reference window for paired comparison as described by equation 2.

$$d = \frac{x^n_{(n-1)100+i} - x^7_{(n-1)100+i}}{x^7_{(n-1)100+i}} \times 100 \tag{2}$$

where d is the percentage difference between response x of window n, $(n=1,2,...6)$ at time $[(n-1) \times 100s + i]$ for $i = 0, dt, ..100s$ and the corresponding reference window response; dt is the simulation time step of $0.0125\ s$.

Two sets of results are presented: (a) simulations run without proper ICs for all wind bins, which would be referred to as zero ICs and (b) simulations run with proper ICs for all wind bins. The first simulations are run with all ICs set to zero (except the rotor speed which is set to the rated speed of $11.4\ rpm$). On completion of this simulation, a Matlab® script is called which automatically calculates the average of selected OpenFAST outputs in the reference window. Using these averages, new ICs are written for out-of-plane and in-plane blade tip displacements, blade pitch angles, rotor speed, platform surge, heave and pitch. This procedure is carried out for 11 wind bins. The results of convergence of chosen responses as described by equation 2 are presented in figures 2-4.
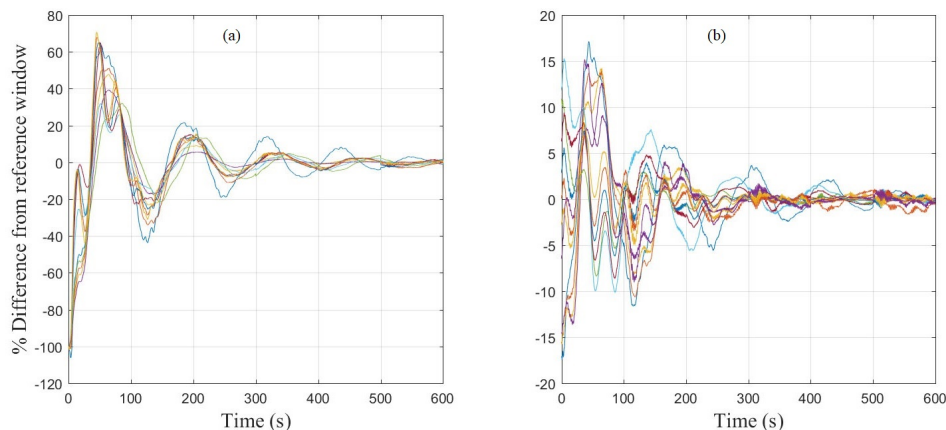

Figure 2. Platform surge convergence for (a) zero ICs and (b) proper ICs

From figure 2a, it takes about $200\ s$ for the 11 wind bins surge values to converge to less than $\pm 20\%$ of the reference window values. Whereas with proper ICs as seen in figure 2b, the surge response converges to less than $\pm 15\%$ in less than $60\ s$. Similarly, for pitch response shown in figures 3a & 3b, more than $150\ s$ is required for convergence within $\pm 20\%$ of the reference window for zero ICs simulations as opposed to proper ICs case of around $54\ s$ (if the spikes caused by controller action in simulations of wind speed bins greater than the rated wind speed are ignored). Although the tensions in the fairleads converge quicker, the effect of proper ICs is very visible as seen in figures 4a & 4b.

Using $\pm 20\%$ as the convergence criterion, 50-60 s would suffice as the amount of run-in-time to be excluded from response statistics if proper ICs are set. The effect of second-order waves was neglected in this study considering second-order forces do not greatly influence the response of the OC3-Hywind spar platform [21]. For other floating support structures where second-order hydrodynamics cannot be neglected, longer window length should be used for setting ICs and more than $60\ s$ run-in-time is suggested.
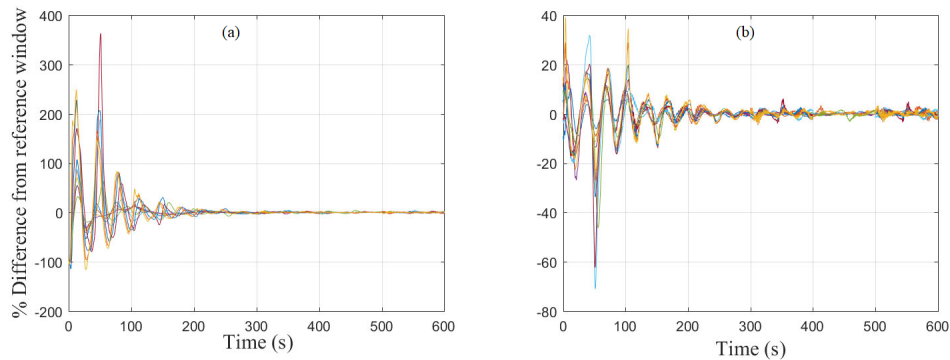
Figure 3. Platform pitch convergence for (a) zero ICs and (b) proper ICs
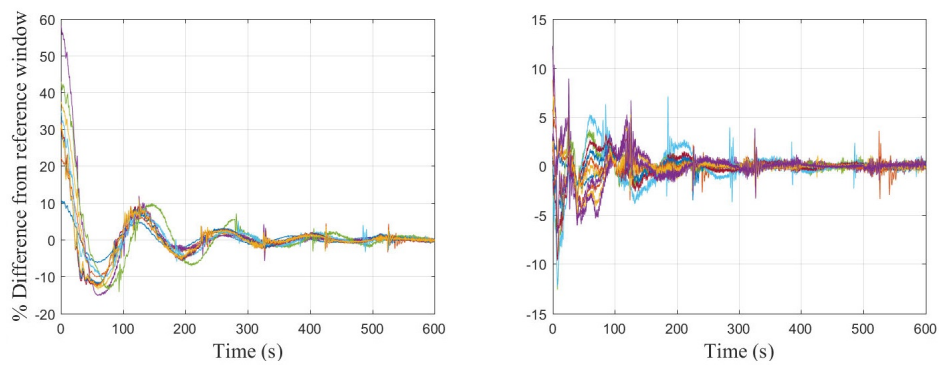

Figure 4. Fairlead tension convergence for (a) zero ICs and (b) proper ICs

4. Statistics of load effect and characterization

For every time step in the OpenFAST simulations, loads and accelerations are transferred to Abaqus for von Mises stress computation based on the analysis model described in subsection 2.3. The maximum von Mises stress in the deformable tower for every time step is extracted using a Python subroutine. Results presented here are for DLC 1.2, mean wind speed, $U = 12m/s$, $Tp = 10s$, and $Hs = 6m$. In accordance with IEC 61400-3 guidelines, 6 unique $600\ s$ realizations of wind and wave are used, making up 1 hr long simulation time. The statistics of the von Mises stress for the 6 realizations are presented in table 2. Figure 5 shows the time series of maximum von Mises stress on the tower at each time step for realization 1.

Table 2. Statistics of von Mises stress (MPa)

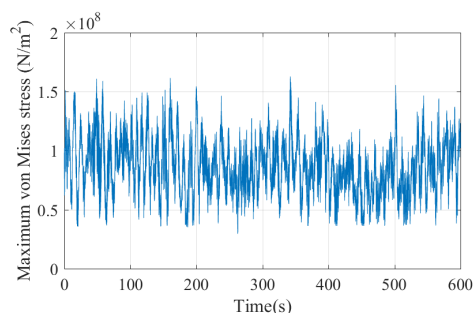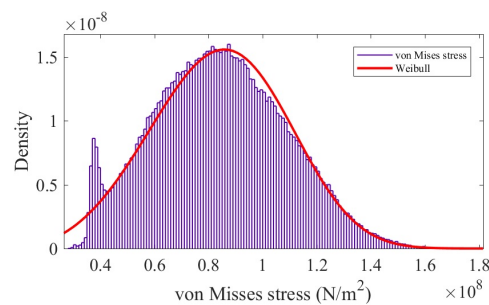| Realization	Min	Mean	Max	SD
1	29.5590	86.4498	162.8700	23.2917
2	29.4820	83.1068	172.0600	23.8721
3	28.6200	83.0719	178.0100	26.4151
4	29.0920	83.7572	179.5100	24.9498
5	32.4400	83.5242	168.5200	24.8681
6	31.1600	84.2366	159.6000	22.4549

Figure 5. Time series of load effect

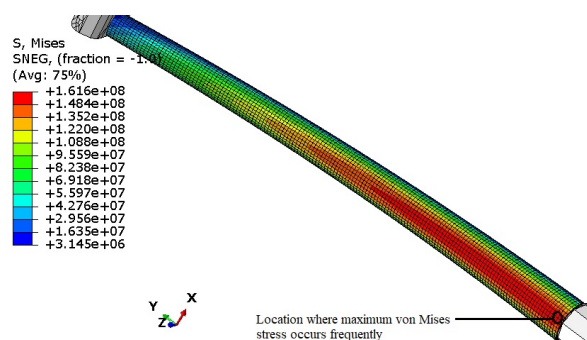**Figure 6.** Probability Density of load effect

Figure 7. Contour plot of von Mises stress (N/m^2)

The von Mises stress distribution on the tower at one time step can be seen in figure 7 with an indication on the location where this maximum value occurred. The aft region of the tower base experiences the most extreme von Mises stresses. It must be noted that the simulations in this work was for 0° wind and wave direction.

The load effect is treated as a stochastic variable characterized by a Weibull distribution as shown in figure 6. For 6 realizations of 48001 time steps, a total of 288,006 Abaqus jobs were performed in this study. The highest observed von Mises stress in 1 hr simulation was 179.51 MPa corresponding to a stress utilization of 0.5716 if the tower allowable stress is taken as 314 MPa.

5. Conclusions

In this paper, fully coupled dynamic load effect computation was carried out using a validated high fidelity FE representation of the OC3-Hywind FWT. The initial part of this work focused on developing a methodology for automatically setting ICs for aero-hydro-servo-elastic time domain simulations for floating support structure concepts. Paired comparison with a reference window was used to check for convergence towards stationarity. It was found that with proper ICs, the chosen periodic output channels converged to less than ±20% of the reference values in less than 60 s. Consequently, about 50-60s can be considered sufficient run-in-time to be excluded from response statistics if proper ICs are set. Setting ICs for tower-top FA and SS initial displacements and the effect of second-order hydrodynamics was not part of this study and will be investigated in future.

With the computational interface presented in this paper, load effect comprising 288,006 data points was computed and fitted with a Weibull distribution. From a reliability standpoint, this study presents an approach that treats load effects as stochastic variables and could be

used in establishing uncertainty models for robust reliability assessment leading to calibration of currently used partial safety factors and cost reduction.

Acknowledgements

References

[1] Gentils T, Wang L, Kolios A. Integrated structural optimisation of offshore wind turbine support structures based on finite element analysis and genetic algorithm. *Applied Energy* 2017; **199**: 187-204.

[2] Young AC, Goupee AJ, Dagher HJ, Viselli AM. Methodology for optimizing composite towers for use on floating wind turbines. *Journal of Renewable and Sustainable Energy.* 2017 May 24;**9**(3):033305.

[3] Wu K, Chen R, Li S. Finite element modeling of horizontally loaded monopile foundation of large scale offshore wind turbine in non-homogeneity clay. *World Congress on Software Engineering* 2009 (pp. 329-333). IEEE.

[4] Jonkman J, Butterfield S, Musial W, Scott G. Definition of a 5-MW reference wind turbine for offshore system development. *National Renewable Energy Laboratory, Golden, CO*, Technical Report No. NREL/TP-500-38060 2009.

[5] Jonkman JM. Definition of the floating system for Phase IV of OC3. *National Renewable Energy Laboratory* Technical Report NREL/TP-500-47535, Golden, Colorado, USA, 2010.

[6] Jonkman B, Jonkman J. FAST v8. 16.00 abjj. *National Renewable Energy Laboratory* 2016.

[7] Jonkman J, Hayman G, Jonkman B, Damiani R. AeroDyn v15 Users Guide and Theory Manual. NREL Draft Report 2015.

[8] Jonkman J, Robertson A, Hayman G. HydroDyn users guide and theory manual.

[9] Hall M. MoorDyn User's Guide. Department of Mechanical Engineering, University of Maine: Orono, ME, USA 2015.

[10] Jonkman J, Buhl M. New developments for the NWTC's fast aeroelastic HAWT simulator. In *42nd AIAA Aerospace Sciences Meeting and Exhibit* 2004 Jan 5 (p. 504).

[11] Jonkman JM. Modeling of the UAE wind turbine for refinement of FAST AD. *National Renewable Energy Lab., Golden, CO (US)*; 2003 Dec 1.

[12] Jonkman JM. Dynamics modeling and loads analysis of an offshore floating wind turbine. *National Renewable Energy Lab.(NREL), Golden, CO* (United States); 2007 Dec 1.

[13] Bir GS. User's guide to BModes (software for computing rotating beam coupled modes). *National Renewable Energy Laboratory Golden, CO*; 2005.

[14] Stewart GM, Amy R, Jason J, Lackner MA. The creation of a comprehensive metocean data set for offshore wind turbine simulations. *Wind Energ* 2016 06/01; 2018/06; **19**(6): 1151-9.

[15] Haid L, Stewart G, Jonkman J, Robertson A, Lackner M, Matha D. Simulation-Length Requirements in the Loads Analysis of Offshore Floating Wind Turbines. In *ASME 2013 32nd International Conference on Ocean, Offshore and Arctic Engineering* pp. V008T09A091-V008T09A091. American Society of Mechanical Engineers.

[16] Jonkman JM, Jonkman BJ. Fast modularization framework for wind turbine simulation: Full-system linearization. In *Journal of Physics*: Conference Series 2016 Sep Vol. 753, No. 8, p. 082010. IOP Publishing.

[17] International Electrotechnical Commission. Wind turbines - part 3: Design requirements for offshore wind turbines. *International standard IEC 61400-3*, 2009

[18] Guzmn RF, Mller K, Vita L, Cheng PW. Simulation Requirements and Relevant Load Conditions in the Design of Floating Offshore Wind Turbines. In *ASME 2018 37th International Conference on Ocean, Offshore and Arctic Engineering* pp. V010T09A066-V010T09A066. American Society of Mechanical Engineers.

[19] International Electrotechnical Commission. Wind turbines-Part 1: design requirements. IEC 614001 Ed. 3. 2006.

[20] Jonkman BJ. TurbSim user's guide: Version 1.50. 2009.

[21] Roald L, Jonkman J, Robertson A, Chokani N. The effect of second-order hydrodynamics on floating offshore wind turbines. *Energy Procedia.* 2013 Jan 1;35:253-64.