Sensitivity of Modal Parameters of an Offshore Wind Turbine to Operational and Environmental Factors: A Numerical Study

Preprint

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Sensitivity of Modal Parameters of an Offshore Wind Turbine to Operational and Environmental Factors: a Numerical Study

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ABSTRACT
The dynamics and performance of offshore wind turbines are sensitive to their structural properties, and in particular their modal parameters, i.e., natural frequencies, damping ratios, and mode shapes. In this work, the sensitivity of the modal parameters of a 6-MW fixed-bottom jacket-supported offshore wind turbine to different operational and environmental conditions including wind speed and rotor speed is investigated. Effect of blade flexibility on the modal parameters of the system is also studied. A multiphysics model of the wind turbine is created for the OpenFAST open-source aero-hydro-servo-elastic wind turbine simulation tool. Local sensitivity analysis is performed to investigate the sensitivity of turbine modal parameters; mainly first tower fore-aft and side-to-side natural frequencies and damping ratios. Because the tower frequencies and damping ratios vary with different operational and environmental conditions, as seen in many researchers' studies with data measurements of offshore wind turbines, this study focuses on the determination of the modal parameters especially for the larger turbines being used today. Results show that blade flexibility reduces the first fore-aft and side-to-side tower frequencies in comparison with the case that blades are assumed rigid. Increase in the rotor speed causes stiffening in the wind turbine system and the first fore-aft tower frequency grows as the rotor spins faster. The first fore-aft tower damping ratio increases as a result of growth in the wind speed, which is caused by aerodynamic damping.

Keywords: Offshore wind turbine, modal parameters, aerodynamic damping, OpenFAST, Campbell diagram

INTRODUCTION

The dynamics and performance of offshore wind turbines are sensitive to their structural properties, and in particular their modal parameters, i.e., natural frequencies, damping ratios, and mode shapes. Modal parameters play a key role in the design of wind turbines. They are also key parameters in damage detection and model updating of structures [1, 2]. Different operational conditions, e.g., rotor speed, blade pitch, and different environmental conditions including wind speed, yaw angle, rotor rpm, mean sea level, blades pitch, and wind and wave loads affect the wind turbine's modal parameters. Dong et al. [3] studied the structural vibration characteristics of a 2.5-MW offshore wind turbine prototype with a composite bucket under different operational conditions and extreme typhoon status by analyzing the observed vibration response data. They concluded that the structural vibration showed a positive correlation with the wind speed in standstill conditions, wherein the wind turbine was affected only by the environmental excitations, and as the wind speed increased, the offshore wind turbine structure vibrated more severely with the first frequency of 0.33 Hz and the dominant frequencies varied between 0.317 Hz and 0.344 Hz.

Noren-Cosgriff and Kaynia [4] studied the first natural frequencies and damping ratios of a 3.6-MW-monopile-supported offshore wind turbine in the North Sea that was affected by environmental loads from wave and wind and nonlinear soil behavior. Their results showed that during a storm event, the first natural frequency decreased as load increased until the peak of the storm and then increased after the storm. Hu et al. [5] monitored a 5-MW offshore wind turbine for 2 years and studied the environmental and operational effects on the dynamic properties of the turbine. They showed that the observed frequency decreased and increased frequently, which was mainly caused by the operation of the rotor blades, and the frequency varied with the nacelle position because of two closely spaced modes with the same mode shapes but in perpendicular directions.

The Campbell diagram is a classical way to show the relationship between forcing mechanisms in rotary machinery, as a function of the rotation rate of the system, relative to important system resonances over the system's operating range [6]. Peterson et al. assumed a constant value for the first two support structure's lateral modes for all rotor speeds in the Campbell diagram for a representative offshore wind turbine design [6]. Jonkman studied the Campbell diagram for a National Renewable Energy Laboratory (NREL) 5-MW reference offshore wind turbine spinning in a vacuum condition; in the absence of aerodynamics. By the numerical study of the OpenFAST model, he showed that in the vacuum condition, tower fore-aft (FA) and side-to-side (SS) bending modes had natural frequencies that were quite independent of rotor speed [7]. OpenFAST is a multiphysics, multifidelity tool for simulating the coupled dynamic response of wind turbines. The tool enables the analysis of a range of wind turbine configurations, including two- or three-bladed horizontal-axis rotors, pitch or stall regulation, rigid or teetering hubs, upwind or downwind rotors, and lattice or tubular towers. The wind turbine can be modeled on land or offshore on fixed-bottom or floating substructures. OpenFAST is written as a modular framework, wherein different modules work together as a simulation of a wind turbine [8].

Due to the fact that first and second natural frequencies of offshore wind turbines identified from data measurements vary in the standstill, normal, and shutdown/startup operational conditions as well as different environmental conditions, e.g., storms, this study focuses on the effect of these conditions on the modal parameters of the wind turbines using a multiphysics model, especially for the larger offshore wind turbines being used today. In this paper, a multiphysics model of a 6-MW fixed-bottom jacket-supported offshore wind turbine with three blades is studied through the OpenFAST simulation tool. The modules used in this paper in OpenFAST are ElastoDyn, SubDyn, AeroDyn, and InflowWind. Throughout the simulation conducted in OpenFAST, modal parameters, representative of dynamic properties of the offshore wind turbine, were obtained. The first fore-aft and side-to-side natural frequencies and damping ratios of a 6-MW turbine as well as the blade modes are investigated under various operational and environmental conditions, e.g., rotor speed and wind speed. The 6-MW turbine is supported by a jacket structure connecting to piles in the soil. The wind turbine model is confidential and most of the properties used for the 6-MW turbine are the scaled values from the NREL 5-MW reference wind turbine [9].

WIND TURBINE MODELING IN OPENFAST

OpenFAST uses a coordinate system, shown in Figure 1, where x follows the nominal wind direction (positive downwind), and the z-axis is vertical. The FA and SS directions are assumed in directions x_n and y_n, respectively, and are perpendicular to each other.

The rotor nacelle assembly (RNA) is modeled in the ElastoDyn module with detailed information about the blades, hub, nacelle, and drivetrain. SubDyn is used to model the jacket, transition piece, and tower. The jacket and tower are modeled as steel structures in SubDyn. All of the structural members are modeled using beam elements. SubDyn uses the Craig-Bampton reduction method with fewer degrees of freedom (DOF) compared to the full finite element method (FEM) DOFs [10]. In this study, eight Craig-Bampton modes are currently used. Rayleigh damping is used to model structural damping in SubDyn. For the boundary conditions, the wind turbine is assumed fixed at the seabed. The AeroDyn module [11] is used to simulate aerodynamic loads on the blades. The InflowWind module is used to introduce the wind environmental conditions; we consider the steady wind speed defined by the mean wind speed shown in Table 1.

To consider operational and environmental conditions, several wind speeds and rotor speeds are investigated, as shown in Table 1. The rated wind speed for this turbine is 11.51 m/s and all the values in this table are for the wind turbine operating below the rated wind speed. When operating wind turbines, pitch control is used to keep the power constant when the wind speeds are higher than the rated wind speed [12]. Considering pitch angle in addition to other environmental and operational conditions adds more complexity to the system in order to determine the effects on the modal parameters. Therefore, for the operational conditions below the rated wind speed, shown in Table 1, we consider blade pitch to be zero in the simulations.

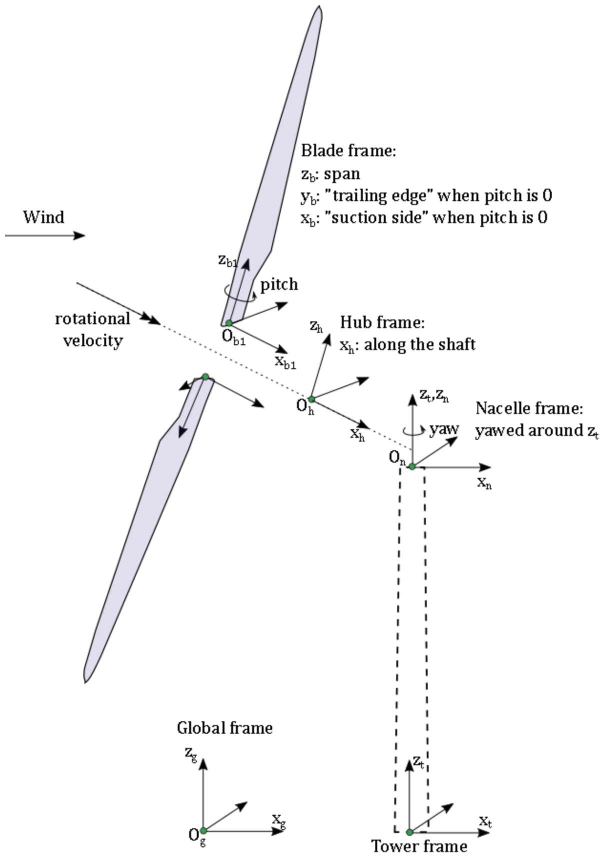

Figure 1: OpenFAST main coordinate system [13]

For studying the effects of blade flexibility on the modal parameters of the system, two cases are investigated: one with rigid blades and the other with flexible blades. In both cases, the modes of blades considered in the analysis are first flapwise, first edgewise, and second flapwise, and the mode shapes of the blades are shown in Figure 2. The mode shapes are the same as the NREL 5-MW reference wind turbine [9]. In the analysis of the blades, three rotor modes are investigated: regressive, progressive, and collective. In the first two modes, regressive and progressive, the motion of each of the blades leads or lags by a phase difference. The progressive mode is sometimes called the high-frequency cyclic mode and the regressive mode is called the low-frequency cyclic mode [14]. In the rotor collective mode, all the blades oscillate in phase and with an identical amplitude.

Table 1- Operating points for OpenFAST simulations of the 6-MW wind turbine

Wind Speed (m/s)	Rotor Speed (rpm)	Blade Pitch (°)
0.0	0.0	0
3.0	3.9	0
7.0	8.9	0
11.0	11.5	0

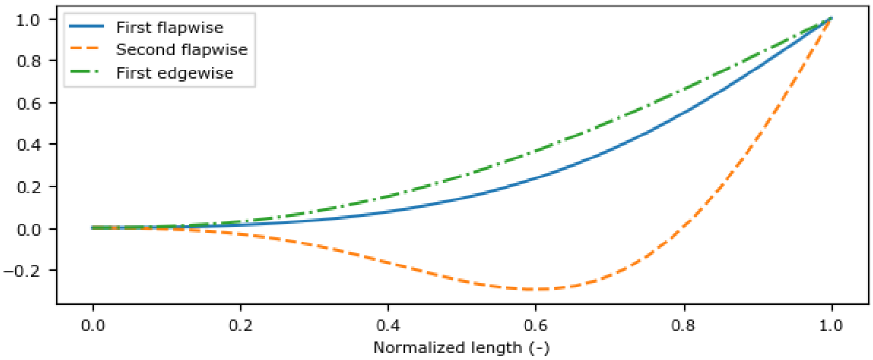

Figure 2: Blade flapwise and edgewise mode shapes used in OpenFAST.

ANALYSIS

The modal parameters investigated in this report are the first natural frequencies, damping ratios, and mode shapes of the full wind turbine, including the RNA, tower, and substructure. The modal parameters are determined through linearization in OpenFAST. The tight coupling functionality of the OpenFAST modularization framework supports operating-point (OP) determination and linearization of the coupled system. For full-system modal analysis and determining natural frequencies, damping ratios, and mode shapes, OpenFAST uses linearization of the underlying nonlinear system equations [7, 8].

First, the wind turbine model is analyzed without aerodynamics and in parked condition, considering both cases when blades are set to rigid or flexible. In the parked condition, the first blade points up with zero azimuth angle. Results are shown in Table 2. The first tower SS frequency decreased by about 0.002 Hz (about 0.7% decrease) and its damping ratio does not change with blade flexibility. The first tower FA decreased by 0.007 Hz, which is a 2.7% decline, as it is affected by the blade's flapwise mode. Considering blade flexibility in the model, the system flexibility increases in the FA direction; therefore, the first tower FA frequency decreases.

Table 2 - Tower first FA and SS natural frequencies when blades are set to rigid or flexible in the parked condition

	Rigid Blades		Flexible Blades	
Mode	Natural frequency (Hz)	Damping ratio (%)	Natural frequency (Hz)	Damping ratio (%)
First tower SS	0.277	1	0.275	1
First tower FA	0.279	1	0.272	1

Second, the first natural frequency of the wind turbine tower was considered in the operational condition and presented in the Campbell diagram shown in Figure 3. The solid lines show the first natural frequency and damping ratios, in which the blades are considered rigid. The first natural frequencies, FA and SS, of the wind turbine tower with rigid blades do not change by changing rotor speed. In this case, the damping ratio of the first tower FA increases linearly from 1% to 8.5% for the rotor speed of 0 and 11.5 rpm, respectively. The other case we studied is the wind turbine with flexible blades. The dashed lines show the modal parameters for this case. The first tower FA frequency increases from 0.272 Hz to 0.291 Hz; equivalent to a 7% change in frequency. The change in the first FA frequency can be due to different reasons and the possible combination of all of them. In this study, centrifugal stiffening of blades might affect the natural frequency of the tower and increase the tower frequency. Inertia properties of the rotor change with the location of the center of mass and any changes in the rotor inertia affect the system frequency. The inertial properties reduce modal mass, consequently, increase the tower frequency. Aerodynamic loads also add stiffness to the system and play a role in increasing the tower frequency.

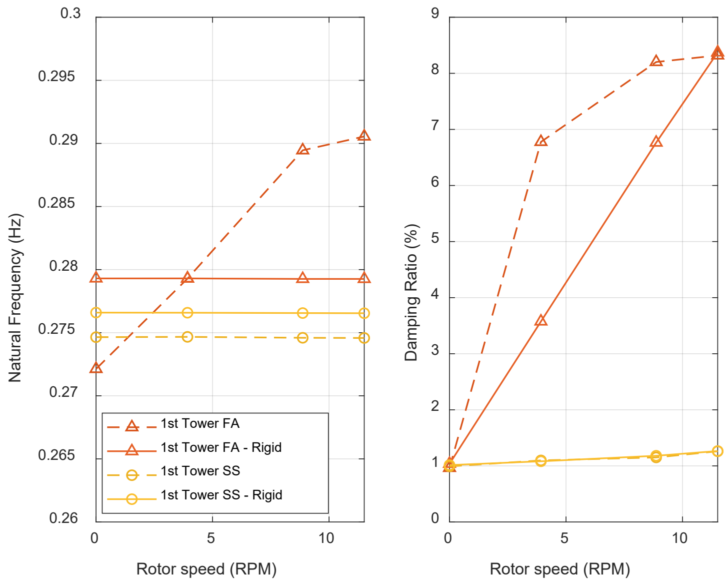

Figure 3: Campbell diagram of the wind turbine for the first FA and SS tower modes.

The change in tower SS and FA frequencies are typically not visible in the Campbell diagram presented in the literature because these values are often presented together with the blade frequencies. The change in natural frequency of the tower is indeed negligible in comparison with the change in blade frequency. The change in tower damping ratios observed in Figure 3 is due to aerodynamic damping. The aerodynamic damping has a remarkable effect on the structural response of operating wind turbines and plays a key role in restraining vibrations of the tower. Therefore, it should be considered to achieve an optimum design [15]. The damping ratio of the first FA mode increases from 1% to 8.5%, which is similar to the case of rigid blades; although, in the flexible blade case, the increase is not linear.

Finally, a Campbell diagram for the same operating points, presented in Table 1, is created for the different blade modes and shown in Figure 4. As expected, the natural frequency of the progressive modes—first flapwise, first edgewise, and second flapwise— increases as the rotor speed grows. In comparison, the regressive modes' frequencies decrease with increasing rotor speed. For the collective modes, the first blade edgewise frequency does not change significantly, but the first and second flapwise modes increase as a result of a rise in the wind speed or rotor speed due to centrifugal stiffening. The centrifugal force increases the flapwise stiffness, as it will contribute to the restoring forces on the blade if it bends [16] and is clearly shown in Figure 4. The effect of centrifugal stiffening on the edgewise mode is typically lower. The wind turbine blades in normal operation are subject to aerodynamic, centrifugal, and gravity forces [17]. The loads affect the stiffness of the blades and, in turn, affect the tower.

Flapwise modes are highly damped by the aerodynamic forces and this damping is expected to increase with wind speed. This is observed in Figure 4, where at the rotor speed of 11.5 rpm (corresponding to a wind speed of 11 m/s) the first flapwise regressive damping ratio reaches 90%. Damping of the edgewise mode is typically low, and for the current range of wind speeds studied, no significant change is observed.

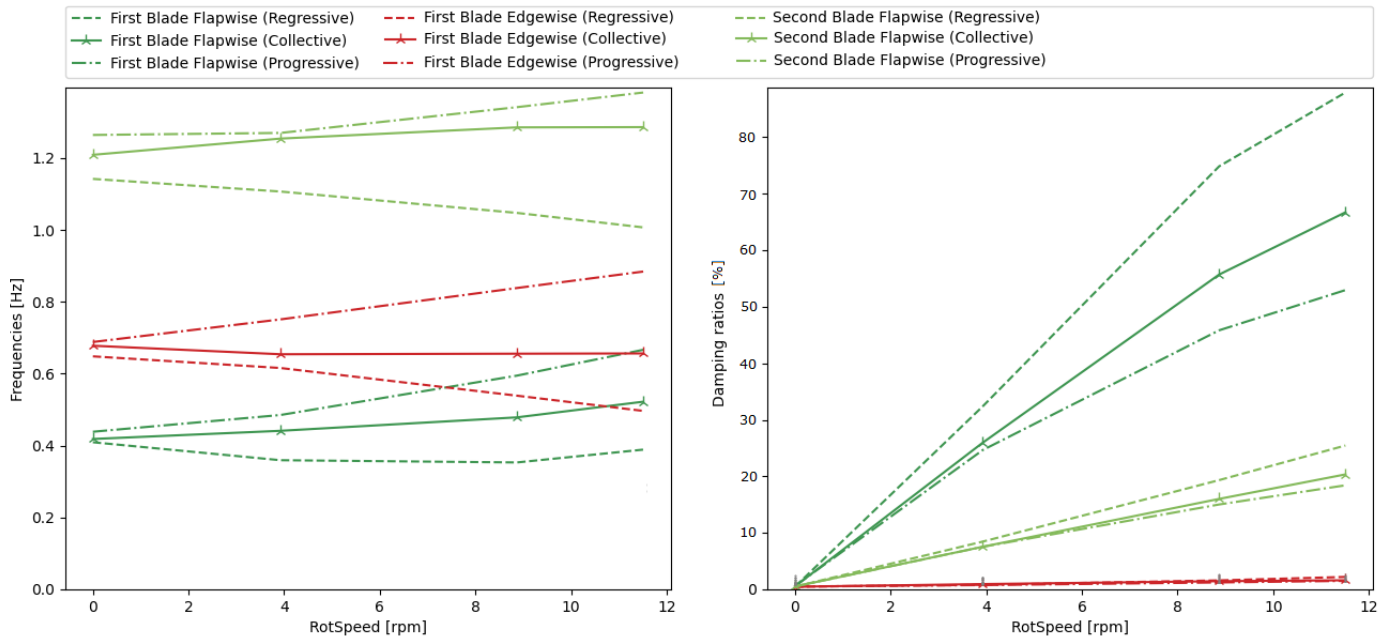

Figure 4: Campbell diagram of the turbine for the various blade modes.

CONCLUSION

In this study, we conducted a sensitivity analysis of a realistic model of a 6-MW jacket-supported offshore wind turbine. Our goal was to investigate how changes in wind speed and rotor speed affect the turbine's dynamics and performance. In this regard, a numerical model of the wind turbine for the operational condition below the rated wind speed was studied in the OpenFAST open-source aero-hydro-servo-elastic wind turbine tool. The natural frequencies and damping ratios of the first FA and SS tower and blades modes are obtained from OpenFAST using linearization. Further, we studied the effect of blade flexibility on the tower frequencies. Results show that:

1. Blade flexibility affects the tower modes. The first tower FA and SS frequency drops by 2.7% and 0.7%, respectively, when blades are flexible than when blades are rigid in the parked condition of the turbine. As the rotor speed and wind speed grow, the first tower FA frequency increases by 7% in the case of flexible blades and does not change when the blades are rigid. The reasons for increasing the frequency are the centrifugal stiffening of blades due to rotor speed, change in the inertia properties of the rotor, and the aerodynamic loads.
2. The first tower SS frequency and damping ratio are not altered due to change in wind speed or rotor speed in both cases of rigid and flexible blades.
3. The damping ratio of first tower FA increases from 1% to 8.5% when wind speed changes from 0 to 11 m/s. This is due to aerodynamic damping.

This study confirms the following results for the blade frequencies and damping ratios. These results are similarly concluded by other researchers where they studied the Campbell diagram of the wind turbines [7, 18]. Based on our study on the effects of wind and rotor speed on the natural frequencies and damping ratios of the first and second blade edgewise and flapwise modes as well as the second blade flapwise mode, we concluded that:

1. Blade frequencies and damping ratios are affected by the wind speed and rotor speed. The natural frequency of the first and second flapwise progressive modes as well as the first progressive edgewise mode increases as wind and rotor speed rise. On the contrary, the natural frequency of the regressive mode decreases. For the collective mode, the edgewise frequency does not change, but both the first and second flapwise frequencies increase as the wind or rotor speed increase.

2. Aerodynamic damping affects the damping ratio of the flapwise blade modes to a remarkable degree. The extreme case is the first flapwise regressive damping, which rises to 90% in a wind speed of 11 m/s.

For future work, other offshore wind turbines will be studied to see if their modal parameters match the trend concluded in this paper. Considering soil conditions at seabed will be also informative about the effects on tower frequency. Furthermore, investigating the identified modal parameters from data measurements of an offshore wind turbine and comparing them to the ones obtained in this study can be helpful.

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