Analysis of platform motions effect on the fatigue loads and aerodynamic unsteadiness in floating offshore wind turbines

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Floating platform motions introduce an additional level of complexity to the analysis models for floating offshore wind turbines. A series of simulations of the NREL 5MW wind turbine on a semi-submersible platform, in constrained (fixed) and free-to-move configurations, were done in OpenFAST software. Simulated time histories show that the platform motions increase the force and bending moment at the blade root by 3% and 7.4% respectively, while increase the same quantities at the tower base by 61.3% and 59.4%. The rainflow counting method was used to calculate the cyclic load and fatigue at the blade root and the tower base. The results show that the platform motions result in higher fatigue on the tower base in both design load cases, power production and parked. Platform motions show a lesser effect on the fatigue at blades root while the wind turbine is operational and negligible effect while idling. Understanding the relation between platform motions and the differences in loads and consequently the fatigue can provide better tools for wind turbine design.

1. Introduction
Wind energy is a rapidly growing field of research because of the need for clean energy resources. The up-scaling of wind turbine structures and the associated large rotors define the need for optimizing the components to have less weight to ensure cost-effective and efficient energy conversion. This consideration results in lighter and more flexible blades for large-scale horizontal axis wind turbines [1]. The motions of a floating sub-structure for offshore wind turbines, i.e., surge, sway, heave, roll, pitch, and yaw, affect the aerodynamic characteristics such as flow separation, lift coefficient, and separation development. At the same time, a wind turbine applies an external dynamic force that is transmitted through the tower to the platform thus affecting the hydrodynamic responses of the supporting platform. These conditions introduce an additional level of complexity to analysis codes and can result in up to 10% to 20% uncertainty in power prediction and, 30% in dynamic loads [2,3,4]. Understanding the differences in loads and consequently the fatigue in wind turbines components between fixed and floating platform, is a vital design consideration of floating offshore wind turbines.

2. Approach
In this work, the National Renewable Energy Laboratory (NREL) 5 MW wind turbine supported on the OC4 semi-submersible platform [5] is used to calculate the fatigue at the blade root and tower base with fixed platform and free to move platform in all six degrees of freedom. The turbine hub height above sea water level (SWL) was 90 m, the rotor diameter was 126 m, and the rated wind speed was 11.4 m/s, which corresponded to a rated rotor speed of 12.1 rpm [6].
2.1. Wind turbine response simulation
OpenFAST is a coupled aero-hydro-servo-elastic analysis tool that was developed by NREL [7]. The aerodynamic calculations within OpenFAST are done by AeroDyn module [8]. AeroDyn calculates the aerodynamic loads on both the blades and tower. The calculations are based on the principles of actuator lines method, where analysis nodes are distributed along the length of each blade. The two-dimensional forces and moment at each node cross section are computed from tabulated blade data. The flow around the blade, the distributed pressure and shear stress are captured at each node cross section and the three-dimensional behavior is captured through corrections in the model (e.g. tip-loss or skewed-wake corrections). AeroDyn calculates the influence of the wake via induction factors based on the quasi-steady Blade-Element/ Momentum theory, the induction reacts instantaneously to loading changes. The aerodynamic models are also linked to hydrodynamic models of the floating structure as well as dynamic structural and control models. This allows fully coupled non-linear aero-hydro-servo-elastic simulations to be performed within the time domain. The wind and wave conditions in these simulations are described in the design load cases (DLCs) of IEC 61400-3 [9, 10].

2.1.1. DLC 1.2 Power production
In this design situation, the wind turbine is operational and connected to an electric load. The wind speed ranges from cut-in speed of 3 m/s to cut-out speed of 25 m/s with a 2 m/s bin size. The TurbSim module [11] was used to generate recurring 10 min wind profile based on the IEC standard with six different seeds for each wind speed bin. The unsteady model [12] was used in OpenFAST AeroDyn.

JONSWAP model was used to create irregular waves in HydroDyn with significant wave height of 7.1 m and wave period of 12.1 s. The generated wave conditions are 4200 s in length with six different seeds for each simulation and wind speed bin.

2.1.2. DLC 6.4 Parked (idling)
In this design condition, the wind turbine is idling where the rotor is in parked condition and blades are feathered at 90 degrees. Wind speed is ranging from 25 m/s to 34 m/s with a 2 m/s bin size. TurbSim was used to generate recurring 10 min wind profile.

Wave height of 10.5 m and wave period of 14.3 s were used to create the irregular waves in HydroDyn. The generated waves are 4200s in length with six different seeds for each simulation and wind speed bin.

2.2. Fatigue analysis
Fatigue analysis was done in MLife, a post processing MATLAB code designed by NREL and based on the techniques outlined in Annex G of IEC 61400-3 [9,13]. MLife uses rainflow counting method and Miner’s rule to calculate statistical and cumulative fatigue damage [14]. The rainflow counting method separates the fluctuating loads from time series into individual hysteresis cycles by identifying local minimum and maximum loads, which models the material memory effect. MLife uses Weibull distribution to extrapolate the damage-cycle counts to computes the time until failure and damage equivalent load [13, 14].

3. Results and discussion
Six time series for each wind speed bin and design load case result in about six hours of data for each case. The data from all the time series were processed in MLife to get minimum and maximum force and bending moment at blade root in both directions, in-plane and out of plane, and the force and bending moment at the tower base in fore-aft and side-to-side direction.

Figure 1 shows the maximum and minimum shear force and bending moment at the blade root and tower base for all wind speeds. The figure shows that platform motions result in 3% higher force and 7.4% bending moment at blade root than the constrained platform. There is also a 61.3% increase in force and 59.4% increase in bending moment at the tower base. Most of the difference occurs at the operational wind speed range and there is a minimum load difference when wind turbine is idling.
The reason for the load difference is possibly the increase in aerodynamic unsteadiness due to the platform motion, as platform motion has minimum effect on loads while wind turbine is idling. The unsteady aerodynamics cause a rapid change in the lift coefficient which cause a load fluctuating on the turbine blades [1]. On the other hand, the difference in force and bending moment at the tower base is obvious in all of wind speed bins, thus the platform motions have direct effects on the loads at the tower base, contrary to those at the blade root [10].

3.1. Fatigue analysis
This section compares the fatigue life of blade root and tower base of floating offshore wind turbine in the case of moving platform and fixed platform, using the rainflow counting method. Loads on the wind turbines components are divided into individual load cycles. These cycles are characterized by load mean and range as the damage accumulates linearly with each cycle. The relationship between load range and cycles to failure (S-N curve) depends on the ultimate design load of the components. The ultimate design load (LUlt) is the highest load that the components can withstand before failure based on its ultimate strength. The ultimate design load is based on a strength analysis of the components cross section, which are unknown here. In this work, the ultimate design load was calculated by multiplying the maximum loads from OpenFAST load history on the components by scaling factors [15].

3.1.1. Time until failure and lifetime damage
Figure (2, 3) shows the time until failure and lifetime damage for the blade root and tower base due to shear force and bending moment. The difference in the lifetime damage for the moving platform and fixed platform is about 1.3% and 3% respectively, assuming a lifetime of 20 years. On the other hand, the tower base lifetime damage due to shear force and bending moment are 49% and 48% respectively. The lifetime damage difference at the tower base is much higher than the blade root as the platform motion has a direct effect on the loads at the tower base and the blade root is affected by the aerodynamic loads.

The net motion of the floating platform in the upwind direction can result in an increase in the relative wind speed on the blades. This increase can increase the generated lift which in turn can increase the rotor speed and thrust. The same effect happens when one considers the net platform motion in the downwind direction. The wind turbine control system adjusts the blades pitch angle to keep the rotor speed constant. In some conditions, pitching the blades with the aim of reducing the generated lift can reduce the thrust, creating a negative damping effect on the platform. The negative damping of the rotor can affect the tower base loads significantly [1, 16].

Figure (1): maximum and minimum shear force and bending moment at the blade root and tower base.
Figure (2): Blade root and tower base time until failure due to shear and bending moment for different ultimate design load.
Figure (3): Blade root and tower base lifetime damage due to shear and bending moment for different ultimate design load.
3.1.2. Damage equivalent load

Damage equivalent load is the fatigue load with fixed amplitude for a fixed mean load and frequency that can produce a damage equivalent to that from variable spectrum loads. Figure (4) shows the damage equivalent load for the shear force and the bending moment at the blade root and the tower base for different ultimate load design. The damage equivalent load for the moving platform is higher than that of the constrained platform, increasing the ultimate design loads lead to reduce the difference in the damage equivalent load between the moving platform and the fixed platform. As for the tower base, the difference in the damage equivalent load is larger than the blade root and increasing the ultimate design load did not have impact on the difference in the damage equivalent load between the moving platform and the fixed platform.

![Damage equivalent load graphs](image)

Figure (4): Blade root and tower base damage equivalent load due to shear and bending moment for different ultimate design load.

4. Conclusions

In this paper, fatigue loads on blades root and tower base of an offshore floating wind turbine are compared to those of a fixed platform. OpenFAST software was used to produce the load history for design load cases 1.2 and 6.4. Fatigue loads are calculated by the rain flow counting method. The following key findings emerged from this study.

- Motions of floating platform increase the fatigue loads on wind turbines blades and tower.
- Fatigue loads are higher at the tower base than the blades root.
- Platform motions have a direct impact on the load at the tower base.
- Platform motions affect the wind turbine rotor aerodynamics which will create a damping effect.

5. Future work

- Frequency analysis of floating wind turbine response will give an insight on how motions frequency and magnitude affect the fatigue loads.
- Comparing different aerodynamic models to have a better representation of the aerodynamic loads. This may help in designing better control system and better structural design.
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