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Optimization of a Semisubmersible Floating Offshore Wind Turbine for the Oregon Coast via OpenFAST

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ABSTRACT

The increasing demand for renewable energy has driven advancements in floating offshore wind turbine (FOWT) technology, particularly for harnessing the vast wind energy potential in deep waters. This study focuses on optimizing the 5MW Semisubmersible FOWT for the Oregon coast, a region identified for its strong and consistent winds and deep-water depths. To accurately model the Oregon coast, three key environmental parameters - mean wind speed, maximum significant wave height, and mean water depth - were calibrated to reflect realistic and representative values. The optimization process targets three key physical parameters of the substructure: cylinder spacing, cylinder and pontoon diameter, and cylinder and pontoon thickness. Using the OpenFAST simulation tool, the study models the environmental conditions of the Oregon coast. Stress factors including nacelle acceleration, anchor tension, tilt angle, and tower base bending moment are analyzed in the findings. The findings show that a 30% increase in cylinder spacing reduces stress factors by 1.23~3.19%. Ultimately, this improves the stability and durability of the design.

Introduction

The increasing demand for renewable energy has led to significant progress in wind power technology. As a result, floating offshore wind turbines (FOWTs) have stood out as a promising option for capturing the vast wind potential in the deep ocean. FOWT has increased in popularity because of its ability to be installed in deep waters where wind speeds are stronger and more reliable. Even minimal variations in wind speed led to exponential increases in energy potential. However, being located in deep waters creates issues of maintenance and durability. In order to maximize the durability of FOWTs off the west coast, analyzing stress factors is important to optimize the design of FOWTs. By understanding and mitigating these stress factors, substructure systems can be designed to withstand the harsh environment. The optimization process helps to elongate turbine lifespans, reduce maintenance costs, and improve energy efficiency.

Although the East Coast of the United States has seen advancements in FOWT development, the West Coast has lagged behind them. In order to maximize offshore wind potential, both the east and west need to be utilized. The Oregon coast has been identified by National Renewable Energy Laboratory (NREL) as a potential suitor for future FOWT development due to its strong and consistent winds making it a high-energy potential area. Additionally, the rapid drop-off of the continental shelf creates deep water conditions close to the shore lowering both maintenance and transportation costs. Other than geographical advantages, the state of Oregon has ambitious renewable energy goals with the potential of FOWT development to reduce carbon emissions and their reliance on fossil fuels.

FOWTs have been developed through various design concepts (semisubmersible, spar, tension-leg, and barge, for example). The semisubmersible design was chosen because of its suitability to the harsh characteristics of the Oregon coast. Compared to other designs, semisubmersible systems provide superior stability in severe wind and wave conditions, making them particularly effective off the Oregon coast. Also, the rapid drop-off of the continental shelf along the Oregon coast results in varying and deep-water depths. The semisubmersible can be deployed across a range of water depths due to its simpler anchor system, making it well-suited for the region.

OpenFAST, an open-source wind turbine simulation tool developed by the NREL was used to simulate test designs for the optimization process. The simulation model integrated several key modules: structural dynamics (namely, *ElastoDyn* module in OpenFAST), blade dynamics (*BeamDyn*), wind conditions (*InflowWind*), aerodynamic forces (*AeroDyn*), hydrodynamics (*HydroDyn*), and mooring line behavior (*MoorDyn*). The semisubmersible substructure was modified within *HydroDyn* to model the interactions between the floating platform and the wave sequence. The design model used the tower design based on the NREL 5MW Reference Wind Turbine for Offshore System Development.

Methodology

The 5MW Semisubmersible floating system for Phase II of Offshore Code Comparison Collaboration Continuation (OC4) was selected as the baseline reference for the experiments. The design was created by NREL for the DeepCwind project to establish offshore wind in Maine and has been widely used as a reference system in the FOWT research community. For the current study, this semisubmersible structure was modified to be optimized for the unique conditions of the Oregon coast.

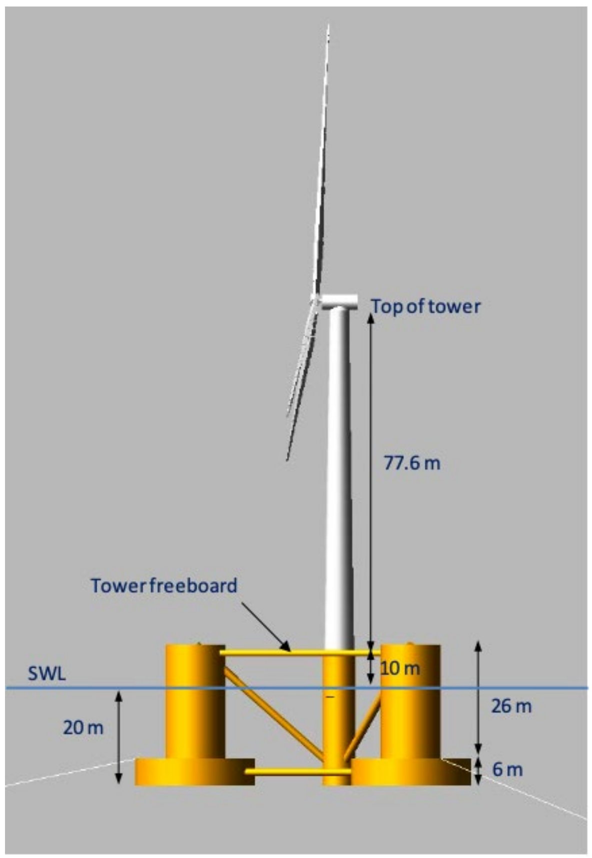

Figure 1. Model of the 5MW Semisubmersible floating system for Phase II of Offshore Code Comparison Collaboration Continuation (OC4)

Figure 1 shows the 5MW OC4 reference system. To modify the substructure, three physical parameters of the substructure were chosen as the design variables. Those being (1) cylinder spacing, (2) cylinder diameter, and (3) cylinder and pontoon thickness. These parameters were chosen because they have a significant impact on the structural performance and stability of the floating system. For the optimization process, only the substructure was considered because the 5MW Baseline turbine tower design was used as a fixed reference. This tower design has been actively explored for onshore and offshore fixed wind turbines; hence it is already largely optimized. By focusing on the substructure, the study aims to enhance the floating system's performance without modifying the tower design.

To determine the geographical and oceanographic variations of the Oregon coast, data from the NREL Oregon Offshore Wind Site Feasibility and Cost Study document was utilized. The three environmental variables for the simulation – (1) wind speed, (2) significant wave height, and (3) water depth are matched according to the document. For wind speed, the mean value (8.03 m/s) was taken to provide a baseline for the typical conditions that an FOWT may face. The maximum significant wave height (3.85 m) was used to represent the most extreme wave conditions. It was used to ensure that the design could withstand worse-case scenario wave impacts. Lastly, the mean water depth of the Oregon site (402 m) was used.

Stress factors were used to compare designs and their feasibility. These factors were the following outputs: nacelle acceleration (namely *NcIMUTAxs, NcIMUTAys, NcIMUTAzs* in OpenFAST terminology), anchor tension (*AnchTen1, AnchTen2, AnchTen3*), tilt angle (*PtfmRDxi, PtfmRDyi*), and the bending moment at tower base (*TwrBsMxt, TwrBsMyt*). These stress factors were chosen because they are indicators of the structure's durability and performance as well as the stability of the substructure. Also, the stress factors of anchor tension and bending moment at tower base are the key drivers of FOWT cost. Outputs correspond to time-series responding to time-varying wave and wind models. The total run-time was set at 60 sec. I converted these time-series into representative scalar values using the following method.

When considering nacelle acceleration as a stress factor, I found the maximum vector magnitude of the pitch, roll, and yaw (x, y, z) acceleration components. The maximum is over all time steps. Similarly, for tilt angle and the bending moment at tower base, the vector magnitude of the pitch and roll components were found. The square root of the sum of squares (hence, vector magnitude) was used to consider all components when comparing the maximum values for each design. For anchor tension, the maximum value over all time steps and over all the anchors was used. By considering the highest tension, the design is tested to handle worst case scenarios. Finding the maximum value works to prevent anchor failure by maintaining tension within a compliant threshold.

Results

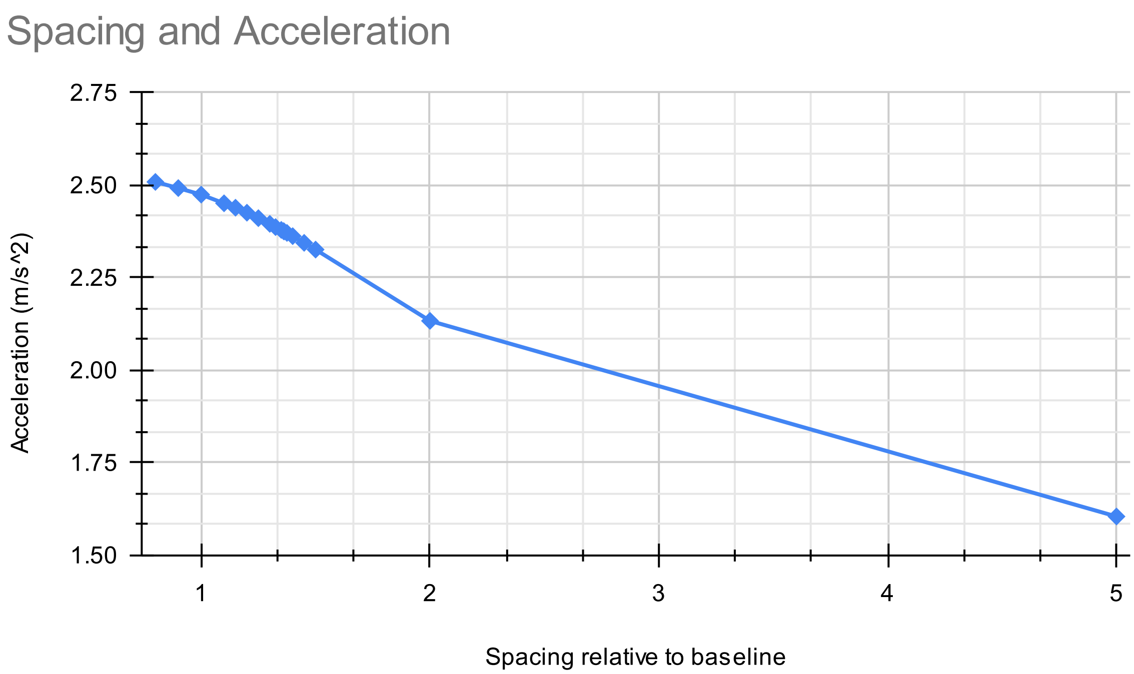

Figure 2. Nacelle Acceleration vs Cylinder Spacing

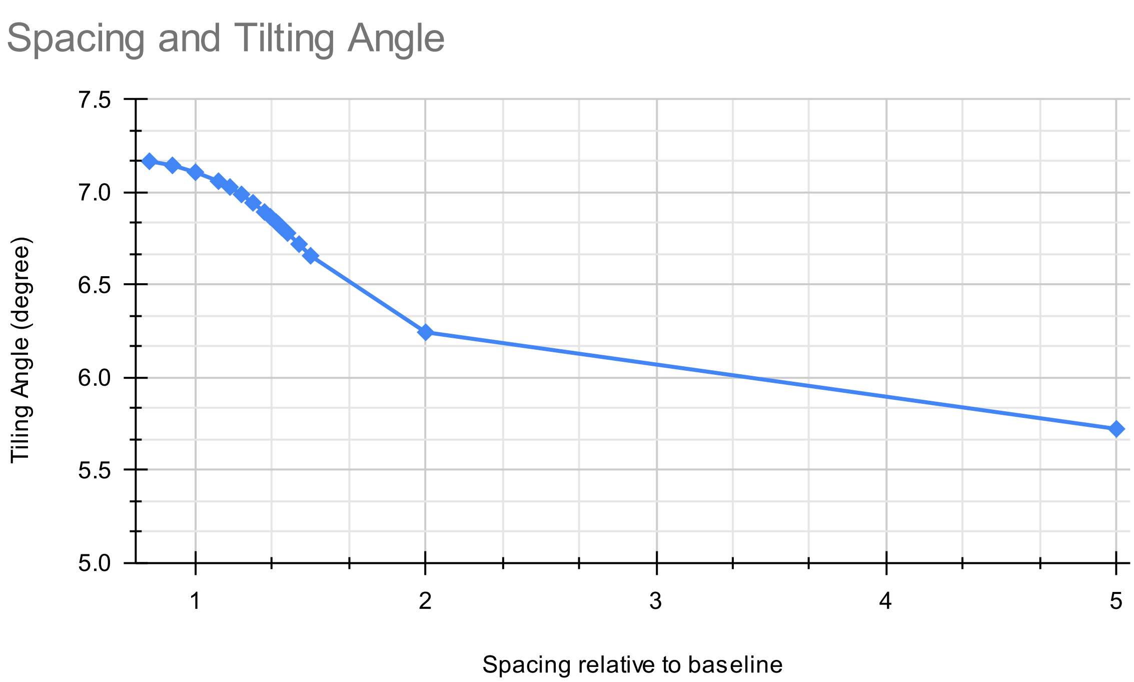

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Figure 3. Tilting Angle vs Cylinder Spacing

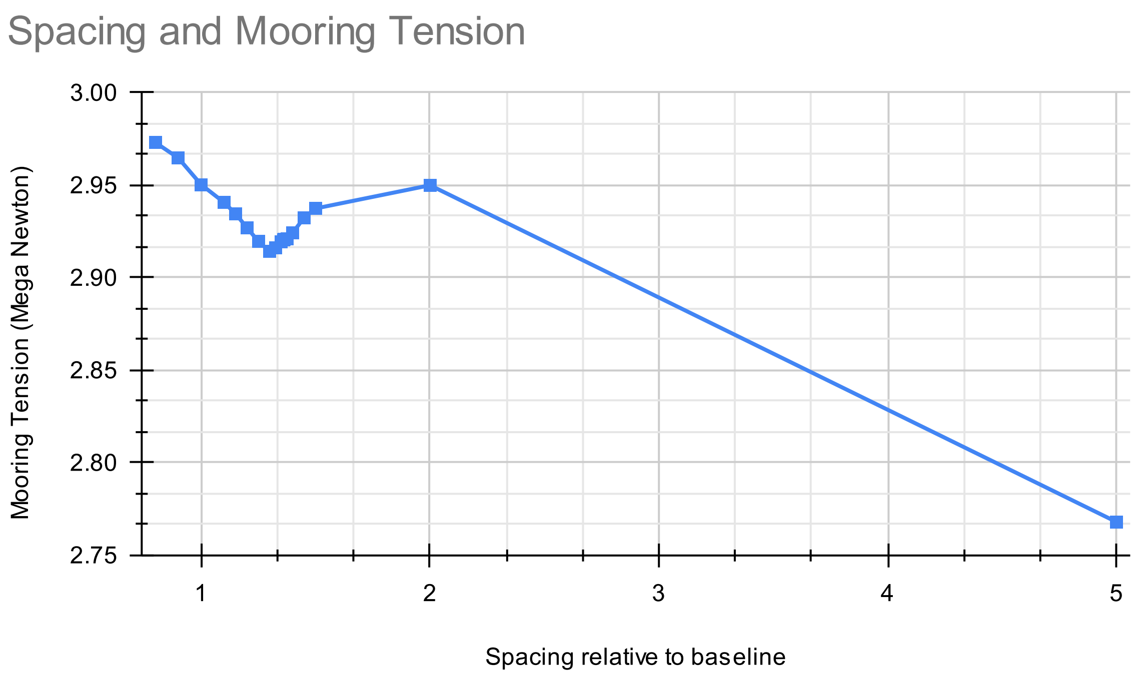

Figure 4. Mooring Tension vs Cylinder Spacing

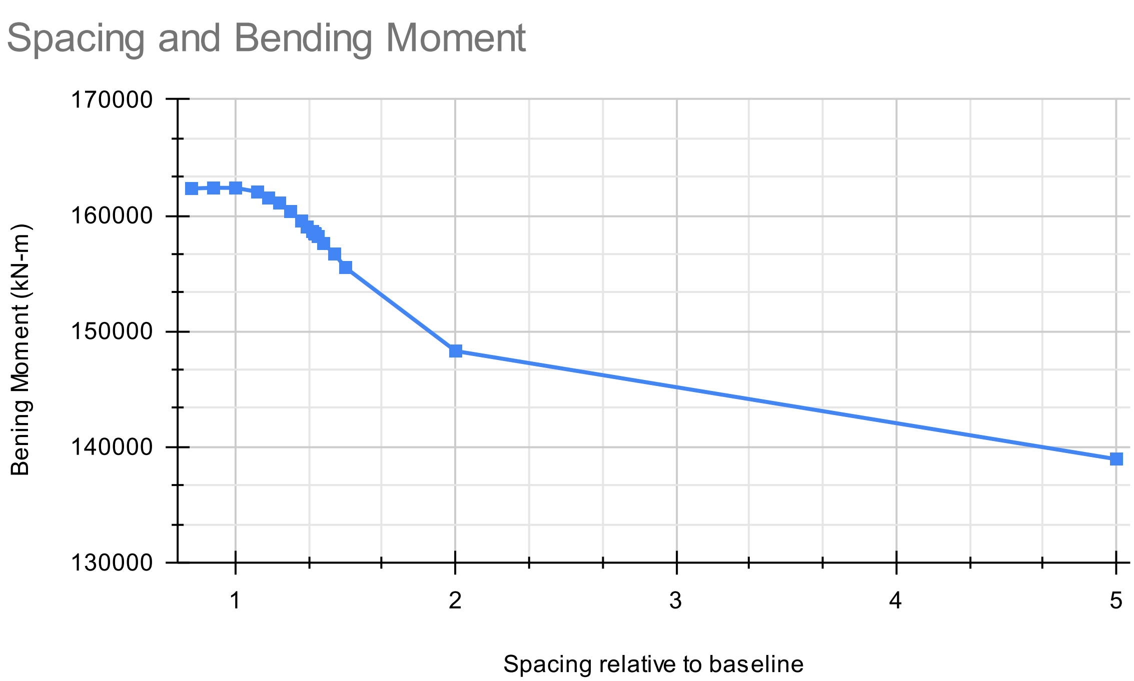

Figure 5. Bending moment at tower base vs Cylinder Spacing

Figure 2~5 show the patterns the physical input parameters (cylinder spacing, cylinder and pontoon diameter, and cylinder and pontoon thickness) had on the stress factors. X-axis in the Figures represents spacing ratio relative to the baseline (for example, 1.0 represents the baseline, and 2.0 represents the doubled spacing relative to the baseline.) Table 1 lists four stress factors with respect to various relative spacing ratio experiments.

In regard to cylinder spacing, it is evident that more spacing led to decreases in stress factors in general as expected. The relationship between the spacing and stress factors were all monotonically decreasing except for maximum mooring tension. A 30% increase in spacing yields optimized mooring tension (~2,914 kN) which is 1.23% lower than the baseline's mooring tension (2,950 kN). Because of the complicated relationship between cylinder spacing and the mooring tension, there's a small dip in mooring tension observed from 0.8x to 2x of relative spacing ratio. 5x of the relative spacing ratio is meant to verify the trend but is not practical to implement as the resulting design would be prohibitive. Hence, 30% increase in spacing is an attractive design choice as it exploits the dip in terms of mooring tension.

Table 1. Cylinder spacing and corresponding changes in stress factors

Relative Spacing Ratio	Acceleration	Tilting Angle	Mooring Tension	Bending Moment
0.8	2.509280565	7.168221934	2973131.5	162321.0499
0.9	2.492640916	7.146038058	2964781	162386.9598
1	2.474970312	7.1090789	2950368.8	162377.9774
1.1	2.451506483	7.06068739	2940758.5	162041.2796
1.15	2.439579941	7.028974141	2934668	161521.3199
1.2	2.4260856	6.989285058	2927128	161056.8117
1.25	2.411357473	6.943925323	2919734.2	160355.9847
1.3	2.395965348	6.894286049	2914215.2	159518.3214
1.35	2.379628409	6.840455507	2919354.8	158601.5083
1.4	2.36273181	6.780685787	2924387.5	157566.5663
1.45	2.344653351	6.720875229	2932503	156667.8461
1.5	2.326421977	6.658182864	2937500	155480.2788
2	2.133801552	6.245320331	2950038.8	148276.3066
5	1.605158883	5.723840099	2768058.8	138934.7152

For the diameter of the cylinders and pontoons (see Table 2), the relationship between changes and stress factors was complicated. Any changes (increase and decrease) in diameter had at least one stress factor deteriorate. Furthermore, from changing diameter, there were no positive overall changes. For these reasons, I did no further investigations into diameter modifications.

Table 2. Cylinder and pontoon diameter and corresponding changes in stress factors

Relative Diameter Ratio	Acceleration	Tilting Angle	Mooring Tension	Bending Moment

0.9	2.44501544	8.682006136	3199640	165475.0745
1	2.474970312	7.1090789	2950368.8	162377.9774
1.1	2.597519857	5.49201989	2946647.5	150494.1279
1.2	2.732374538	4.483319632	3028965	138955.3669

Changes to the thickness of the cylinders and pontoons led to negligible change. Hence it was not continued.

Conclusion

In this research, I optimized a design of the reference 5MW Semisubmersible floating system for Phase II of OC4 for the Oregon coast via OpenFAST simulation. In order to model the Oregon Coast, three environmental parameters were implemented: mean wind speed, maximum significant wave height, and mean water. An operation point with decreased stress factors was identified by adjusting physical design parameters for the semisubmersible substructure cylinders and pontoons. The operation point was a result of a dip in the nonmonotonic curve of mooring tension when adjusting the spacing of the substructure cylinders. The final design exploits that dip to produce a design with reduced stress factors that does not seriously compromise cost limitations.

Acknowledgments

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