Comparison of multiline anchors for offshore wind turbines with spar and with semisubmersible

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Abstract.

Offshore wind energy has become a promising source of renewable energy in recent years with many installed farms around the world successfully producing energy. As preliminary wind resource studies reveal, in the US much of the potential could be tapped in deeper water where floating solutions become favorable. The efficiency of floating offshore platforms is being studied and demonstrated in pilot projects such as Hywind in Scotland. In order to reduce the substructure cost in offshore wind projects, which is usually 25-30%, a novel shared anchor concept has been studied with spar supported turbines. Simulations are carried out with National Renewable Energy Laboratory’s (NREL) OC3 Hywind floating system and 5MW wind turbine. A similar study has been carried out with semisubmersible platforms earlier. Comparing the statistics of the net anchor forces from both the types of platforms reveals decreased anchor forces in case of spar due to large force cancellation and decreased response to wave action. Given the shared anchor concept in-principle reduces the material cost with reduced number of anchors than the conventional anchor types; further reduction in anchor forces in case of spar supported platform would be more cost-beneficial with more material savings.

1. Introduction

Depletion of fossil fuels and global warming from greenhouse gas emissions is driving the search for renewable energy technologies such as Solar, Wind, Tide, Wave etc. [1]. As onshore wind faces its own constraints such as appropriate siting, noise impacts and visual intrusion, offshore wind has started gaining momentum with promising potential zones in US waters. In an offshore wind project, support structures contribute 25-30% of total cost [2]. Though there are various fixed and floating substructure concepts, floating concepts have become a possible game changer in recent years, allowing industry to explore the deep-water wind potential [3]. An offshore wind potential map along with bathymetry shown in figure 1 affirms that there is enormous potential available in deeper water greater than 60 m water depth [3]. Moving to deeper water can also help in overcoming local objections based on visual impacts. With only a few projects completed such as Hywind [4] and WindFloat Atlantic, further
development of floating offshore wind turbines (FOWT) necessitates investigations into various research areas ranging from its reliability to cost efficiency.

![Offshore wind potential map with bathymetry](image)

Figure 1 Offshore wind potential map with bathymetry [5]

The major available floating support structure concepts are the spar, semisubmersible and tension leg platform. These are stabilized primarily using catenary mooring systems and anchors of various types. Fontana et al. [6,7,8] studied a novel anchor concept in which semisubmersibles are moored with multiline anchors. It was found in this study that fewer anchors are required and also the anchor forces are smaller [6] than the conventional single line concept thus making the wind farm potentially more cost effective [7].

The goal of this work is to study the applicability of this novel concept to spar substructures. This paper illustrates the definition of multiline anchor concept, mooring model, time history of anchor forces for various simulations and comparison of these forces with those found in the previous study on multiline anchor with semisubmersibles.

2. Multiline anchor concept

In practice, a floating substructure is stabilized with three to six anchors. In the case of a multiline anchor system, a single anchor is shared and used to stabilize many turbines. Fontana et al. [8] studied the system efficiency, which is the ratio of the number of anchors needed for single line anchoring to the number of anchors needed for multiline line anchoring for a 100-turbine farm. The configuration of turbines and anchors used by Fontana et al. [8] are chosen for this study.

2.1. Configuration

A turbine stabilized with three single line anchors forms a FOWT system. In this study three such FOWT systems are considered as shown in figure 2a. These systems are interconnected by replacing the three single anchors in the middle with one anchor called a multiline anchor as shown in figure 2b. The turbine layout for this study is aligned with the wind/wave/current direction and the turbines are spaced at 1475 m apart which is greater than ten times the rotor diameter (126m), thus mitigating wake effects [9]. The model chosen is the OC3 Hywind with the 5-MW NREL offshore turbine in 200 m water depth. A similar study was conducted by Fontana et al. [6,7,8] with the NREL OC4-DeepCWind platform in 200 m water depth. The anchors in the perimeter of the layout are out of scope of study, hence the study focuses on the three-line anchor at the center of the configuration. This configuration has a turbine moored with three anchors and an anchor supporting three turbines which has an efficiency of three as defined in a previous study done by Fontana et al. [6]. The platform is supported by three catenary mooring lines which are placed at 120° apart. The multiline anchor is studied for its effectiveness in terms of anchor tension forces and direction of anchor force.
Figure 2a Conventional configuration  Figure 2b Multiline configuration

2.2. Multiline anchor net force

The focus of this work is on understanding the dynamics of the multiline anchor net force for a spar supported FOWT. Multiline anchors will be subjected to dynamic environmental conditions such as wind, wave and currents which is termed as WWC. Hence these anchors must provide resistance to the multidirectional loads, in the case of a catenary system without generating uplift on the anchor. In this section an attempt has been made to explain multiline anchor net forces for better understanding of the following simulation results. The multiline anchor system shown in figure 3 has an anchor connecting three turbines. The tension force from the turbine which is in line with the wind wave and current direction is denoted as T1 and tensions from the other two turbines are T2 and T3. The multiline anchor net force $T_{multi}(t)$ is the resultant vector containing components in the x, y and z directions. The z component forces are ignored as in case of catenary mooring lines there is no uplift provided the lay length is not reduced to zero by platform dynamics.

![Multiline anchor net force](image)

The net multiline anchor force has components in x and y directions represented as $T_X(t)$ and $T_Y(t)$ in the equation

$$T_{multi(t)} = \sqrt{T_X(t)^2 + T_Y(t)^2}$$

As the lines connecting the multiline anchor are $120^\circ$ apart
\[ T_X(t) = T_1 - T_2 \cos 60^\circ \cdot T_3 \cos 60^\circ \]
\[ T_Y(t) = T_3 \sin 60^\circ - T_2 \sin 60^\circ \]

The net anchor force from the resultant vector method has shown good correlation with the load resistance of multiline anchors studied by physical modelling of suction caissons loaded in orthogonal directions [10]. The net anchor force time history is the primary subject of study in the remainder of this paper.

3. Modelling and Analysis

In this section, the structural model, mooring model and simulation tool chosen for analysis are described. The National Renewable Energy Laboratory (NREL) Offshore Code Comparison Collaboration (OC3) model is considered for this study.

3.1. OC3 Hywind Model

The OC3 Hywind model uses the NREL 5-MW baseline offshore wind turbine, which is a representative utility-scale, multi-megawatt turbine that has also been widely adopted by the offshore wind research community worldwide. The substructure adopted in this model is a spar-buoy based on the concept developed for the “Hywind” project by Statoil (now called Equinor) [11]. In this work the spar-buoy, mooring and anchor system was designed to support the NREL 5-MW offshore turbine preserving the ideology of Hywind substructure system based on public information data provided by Statoil [11]. The OC3-Hywind model is shown in figure 4 and figure 5.

3.2. Environmental condition

Any substructure system comprising the platform, mooring and anchors is susceptible to a wide range of environmental condition ranging from normal operational to severe survival condition, also known as load cases. The load cases chosen for this study are shown in table 1 in which DLC stands for Design Load Case and SLC stands for Survival Load Case. The three load cases serve the purpose of capturing various conditions such as extreme operational in DLC 1.6, extreme non-operational in DLC 1.2 and survival in SLC. In DLC 1.6 both wind and wave are dominant, in DLC 1.2 wind is dominant and in SLC wave is dominant. This environmental condition also matches with reliable 10-year buoy data from full-scale VolturnUS [13] project off the coast of Maine. As the lines are spaced at 120°, the WWC conditions are studied at 0°, 30°, 60° by changing the propagation (WWC) directions accordingly in FAST simulations to analyze directionality effects on the anchor forces. Farm scale effects such as spatial
coherence and wind wake effects which are due to the connectivity between the FOWTS are not considered in this study. A spatial coherence study with linear waves done by Fontana et al. [14] revealed that the mean anchor force differed less than by 1% between spatially independent wave fields and coherent wave fields. In addition, it was also found that the wave elevation time history studied at points spaced by the turbine spacing are found to be uncorrelated with each other. Based on the study done by Renkema et al. [15] wind wake effects have less significance when the turbines are spaced greater than ten times the rotor diameter. Hence wind and wave conditions are considered as independent at each FOWT location chosen for this study.

| Load case          | DLC 1.6 | DLC 1.2 | SLC |
|--------------------|---------|---------|-----|
| Wind (m/s)         | 11.4    | 10.2    | 45  |
| Turbulence intensity (%) | 10      | 9       | 10  |
| Significant wave height, \( H_s \) (m) | 8       | 2.7     | 12  |
| Peak spectral wave period, \( T_p \) (sec) | 12.7    | 7       | 15.3|
| Jonswap gamma factor | 2       | 2.5     | 2.5 |
| Current speed (m/s) | 0.3     | 0.23    | 0.55|

Table 1 Environmental conditions for simulation

3.3. FAST simulation
Multiline anchor force dynamics are simulated with NREL’s FAST v8 (Fatigue, Aerodynamics, Structures and Turbulence) [16] open source code. Time domain analysis with fully coupled aero-hydro-servo-elastic simulations are carried out. Six one-hour simulations are carried out with different wind and wave seeds for better capturing of the effects of sea state dynamics on multiline anchors. FAST HydroDyn and MoorDyn modules are used in this study.

3.3.1. Hydrodynamic model
HydroDyn can calculate hydrodynamic loads on a structure using various approaches such as strip theory, potential flow theory or a combination of both. Among this, the potential flow theory is suitable for floating structures which are large relative to the typical wavelength. Potential-flow theory includes loads from linear hydrostatic restoring forces, the added mass and damping contributions from linear wave radiation and the incident-wave excitation from first- and second-order diffraction. The hydrodynamic coefficients required for the potential-flow solution are frequency dependent and are obtained separately from a three-dimensional frequency-domain panel code (e.g., WAMIT). In addition to the linear radiation damping from the potential-flow theory and the nonlinear viscous-drag from the relative form of Morison’s formulation additional linear damping was added in the OC3-Hywind module [11].

3.3.2. Mooring model
The MoorDyn module which was adopted in this study uses a lumped mass approach to discretize the cable into parts and studying its dynamics along the line length. The mooring line is fixed at the anchor location and the motions from the structure are transferred through the fairlead. MoorDyn uses internal axial stiffness and damping forces, weight and buoyancy forces, hydrodynamic forces from Morison's equation and couples the results with other modules.

3.4. Mooring design

As the MoorDyn module has the mooring designed for 320m of water depth, the mooring design, including nominal chain diameter, mass density and line lengths, has been developed by satisfying American Bureau of Shipping (2014) [17] criteria such as

1. Average maximum line tension does not exceed the factored minimum breaking strength of the line.
2. Maximum platform offset does not exceed 20% of the water depth of FOWT location
3. No vertical uplift force at the anchor

| Name                        | NREL OC3Simulation of Hywind | Proposed Hywind project [4] | Multiline (Used in this study) |
|-----------------------------|------------------------------|-----------------------------|--------------------------------|
| Water depth                 | 320m                         | 120m                        | 200m                           |
| Mooring system              | 3-line Catenary              | 3-line Catenary             | 3-line Catenary                |
| Mooring line type           | Studless chain               | Studless chain              | Studless chain                 |
| Chain nominal diameter      | 0.09m                        | 0.160                       | 0.124m                        |
| Unstretched mooring line length | 902m                        | 850m                        | 902m                           |

Table 2 OC3-Hywind mooring module default properties

As the mooring module assumes a cylindrical model of the line, volume equivalent diameter and effective elastic modulus of the line has been used in calculating the properties required for the analysis.

![Figure 6: Surge response for various mooring line diameter](image-url)
The hydrodynamic coefficients required for the cylindrical model are obtained by multiplying a correction factor which is a ratio of nominal diameter to volume equivalent diameter to the corresponding coefficients for studless chain. [18]. The line properties obtained after detailed analysis for 200 m water depth are shown in the Table 2. In order to ensure the efficiency of the mooring line properties a study was carried with four mooring line diameters ranging from 90mm-152mm. The surge response for this study is shown in the Figure 6. It was ensured that a mean lay length is 200 m throughout the period of simulation and that the lay length never reaches zero.

4. Results and discussion
The net anchor forces obtained using the aforementioned methodology are studied in detail with various statistical parameters such as mean, maximum and standard deviation for various load conditions.

4.1. Anchor force dynamics
The time history of the anchor force for DLC 1.6 and zero-degree WWC is shown in figure 6a. It is observed that the mean anchor tension from T1 is 751 kN which is in line with WWC is significantly larger than the mean anchor tensions from T2 (321 kN) and T3 (273 kN). A similar trend is observed in the case of DLC 1.2 and SLC, because the line from T1 which is in line with WWC direction is subjected to more significant loads from the wind, wave and current forces compared to T2 and T3 which are oblique to the WWC direction and hence x and y vector components of anchor tension from T2 and T3 cancel out from T1.

![Figure 7a](image-url) Time history of mean anchor force for DLC 1.6 in 0° WWC
Whereas in 30° 60° WWC direction the dominant line tension shifts to the one closest to the WWC direction (figures 6b and 6c). Anchor forces with different WWC direction are shown in figure 7a through figure 7c. In case of 30° WWC it is found that the anchor tensions from T1 and T3 are larger and closer in magnitude compared to T2, at 60° WWC the maximum amplitude is from T3 whereas the contribution from T1 and T2 are smaller and closer in magnitude. The \( T_{\text{multi}} \) anchor force reflects primarily the tension T1 and the x and y components from T2 and T3 are usually equal and in opposite direction leading to the reason for force cancellation.
4.2. Spar and Semisubmersible comparison
The mean and maximum anchor forces for DLC 1.6 at 0° WWC with the OC3-Hywind floating system is compared with similar kind of simulation results studied by Fontana et al. [6] for the OC4-DeepCWind floating system. It is found that the mean multiline anchor force for the spar platform is 498 kN which is 60% of the mean anchor force with semisubmersible. A similar pattern of significant anchor force reduction is observed in case of DLC 1.2 and SLC load conditions. The maximum anchor force in OC3-Hywind system is 635 kN which is 29% of the maximum anchor force from OC4-DeepCWind floating system. The standard deviation of the anchor force in DLC 1.6 is 76.2 kN which is 27% of the standard deviation with the OC4-DeepCWind semisubmersible. In the case of SLC conditions the mean anchor force in the OC3-Hywind system is found to be 263 kN which is 26% of the mean anchor force with semisubmersible. Similarly, the maximum anchor tension in SLC condition at 0° WWC is found to be 437 kN which is just 13% of that with semisubmersible. Detailed numeric results could be found from figure 10 through 12. Comparison of the time history of anchor force is shown in figure 8. The primary reason for the superior performance of the spar for multiline loading is related to the smaller surge and heave motions developed in the spar due to wave loading [19].
Smaller wave excitation can be inferred from the large amplitude anchor tension reduction in case of SLC, which is wave dominated, than in DLC 1.6 for any given WWC direction. In case of SLC (wave dominated case) in 0° WWC maximum anchor tension in spar is just 13% of that with semisubmersible whereas in DLC 1.6 (both wind and wave dominated) maximum anchor tension is 29% of that with semisubmersible. Thus, the lesser anchor tension in turn ends up in smaller anchors in case of multiline configuration.

**Figure 9** Anchor force comparison between Spar and semisubmersible platform

**Figure 10** Maximum anchor tension force in 0°, 30°, 60° WWC for all the load cases
Figure 11 Mean anchor tension force in $0^\circ, 30^\circ, 60^\circ$ WWC for all the load cases

Figure 12 Standard deviation of anchor tension force in $0^\circ, 30^\circ, 60^\circ$ WWC for all the load cases

A similar trend is also observed in $30^\circ$ and $60^\circ$ WWC load cases. Bagbanci et al. [18] studied long-term probability distribution of platform responses in spar and semisubmersible and found that heave, roll, pitch and tower base moment have a much larger amplitude for the semisubmersible compared to spar.
The anchor force rose is the distribution of the resultant force angle, i.e., the orientation of $T_{\text{multi\_angle}}$. Unlike in the case of the single line anchor, in multiline anchor case the net anchor forces are distributed because of the connectivity between the adjacent FOWT systems. As the multiline anchors are the point of resistance to the forces generated due to platform motions from multiple directions, it is necessary to study its distribution carefully because such directional variation may have important implications for anchor selection and design. The mean of $T_{\text{multi\_angle}}$ in case of $0^\circ$ WWC is $0.43^\circ$ and in case $60^\circ$ WWC is $61.3^\circ$ as shown in figure 13a and 13b. The standard deviation of $T_{\text{multi\_angle}}$ is about $3^\circ$ in both the cases whereas in case of semisubmersible is $17^\circ$ which is larger. Since the spar is simple structure, axis symmetric and has less surface area interacting with waves unlike in case of semisubmersible which is a complex structure. Hence less fluctuations are observed in anchor forces which is evident from the mean and standard deviation of $T_{\text{multi\_angle}}$.

5. Conclusion
In this study, comparison of multiline anchor forces between spar and semisubmersible are done and the conclusions are summarized as below

- Mooring system for spar at 200m water depth is designed and one FOWT system (A multiline anchor and three turbines) with spar and semisubmersible is studied at 200m water depth. It is found that the FOWT system with spar has lesser anchor forces compared to that with semisubmersible. This is because spars have less surface area interacting with waves compared to that of semisubmersibles. Hence spars are less excited by waves than semisubmersibles.

- It is found from previous study[6] that the multiline anchor concept with semisubmersible requires fewer anchors, hence fewer geotechnical investigations and lesser seabed footprints; From this study of multiline anchors with spar it is found lesser anchor tension forces than semisubmersibles which provides additional cost savings in terms of anchor size. This is because anchor sizes are directly dependent on the maximum anchor forces which are significantly less in spar.

- Further study of multiline anchors in a farm scale, water depth variation, spatial parameters study, detailed cost analysis with a simulated OC3-Hywind system are in the future scope of work.
With more offshore wind potential found in deeper waters both in east coast as well as in west coast of US, a major constraint in moving to deeper water is the high support structure cost. Hence, this study helps to obtain a trade-off in choosing between various deep-water floating substructures concepts for floating offshore wind turbines.

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References
[1] Schwartz M, Heimiller D, Haymes S and Musial W 2010 Assessment of Offshore Wind Energy Resources for United States NREL Technical report NREL/TP-500-45889 National Renewable Energy Laboratory Golden Colorado United States
[2] Kaldellis JK, Kapsali M 2013 Shifting towards offshore wind energy - Recent activity and future development Energy policy 53 136-148
[3] U.S. Department of Energy 2016 National Offshore wind strategy
[4] Statoil 2015 Hywind Scotland pilot park environmental statement
[5] Musial W, Heimiller D, Beiter P, Scott G and Draxl C 2016 Offshore Wind Energy Resource Assessment for the United States NREL Technical report NREL/TP-5000-66599 National Renewable Energy Laboratory Golden Colorado United States
[6] Fontana C M, Hallowell S T, Arwade S R, DeGroot D J, Landon M E, Aubeny C P, Diaz B, Myers A T and Ozmutlu S 2017 Multiline anchor force dynamics in floating offshore wind turbines Wind Energy 21 1-14
[7] Fontana C M, Arwade S R, DeGroot D J, Hallowell S T, Aubeny C P, Diaz B, Landon M E, Ozmutlu and Myers A T 2019 Force dynamics and stationkeeping costs for multiline anchor systems for floating offshore wind farms with different spatial parameters 38th International conference on ocean, offshore and arctic engineering
[8] Fontana C M, Arwade S R, DeGroot D J, Myers A T, Landon M E, Aubeny C P and Hajjar J F 2016 Efficient multiline anchors for floating offshore wind turbines 35th International conference on ocean, offshore and arctic engineering
[9] Butterfield W, Jonkman J, Musial W, and Scott G 2009 Definition of a 5-MW Reference Wind Turbine for Offshore System Development NREL Technical Report NREL/TP-500-38060 National Renewable Laboratory Golden Colorado United States
[10] Chung J 2012 Physical modelling of suction caissons loaded in two orthogonal directions for efficient mooring of offshore wind platforms Masters Thesis, University of Maine
[11] Jonkman J 2010 Definition of the Floating System for Phase IV of OC3 NREL Technical Report NREL/TP-500-47535 National Renewable Laboratory Golden Colorado United States
[12] Xu X, Srinil N 2015 Dynamic response analysis of apr-type floating wind turbines and mooring lines with uncoupled vs coupled model 34th International conference on ocean, offshore and arctic engineering
[13] Pettigrew NR, Xue H, Irish JD Perrie W, Roesler CS, Thomas AC, Townsend DW 2008, The Gulf of Maine Ocean Observing system: generic lessons learned in the first seven years of operation (2001-2008), MTS Journal 42 91-102
[14] Fontana C M, Hallowell S T, Arwade S R, DeGroot D J, Landon M E, Aubeny C P, Diaz B and Myers A T 2019 Spatial coherence of ocean waves in multiline anchor systems for floating offshore wind turbines Ocean Engineering 149 59-73
[15] Renkema D J 2007 Validation of Wind Turbine wake models Master Thesis, Delft University of Technology
[16] Jonkman J M and Buhl M L 2005 FAST User’s Guide NREL Technical Report NREL/TP-500-
38230 National Renewable Laboratory Golden Colorado United States

[17] American Bureau of Shipping 2014 *Guide for building and classing floating offshore wind turbine installations*

[18] Hall M, Goupee A 2015 Validation of lumped mass mooring line model with DeepCWind semisubmerisble model test data *Ocean engineering* **104** 590-603

[19] Bagbanci H, Karmakar D and Soares CG 2015 Comparison of spar and semisubmerisble floater concepts of offshore wind turbines using long term analysis *Journal of Offshore Mechanics and Arctic Engineering* **137** 061601-1