Mooring System Design for the 10MW Triple Spar Floating Wind Turbine at a 180 m Sea Depth Location

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Abstract. This work presents a methodology for the design of a mooring system for the Triple Spar floating platform that supports the INNWIND 10MW wind turbine. The mooring system keeps the platform at the desired location and avoids the drift caused by wind, currents and nonlinear hydrodynamics. A semi-taut mooring system configuration, combining steel chain and polyester, is chosen to reduce the cost. The basic configuration is defined using static equations and provides a smooth relationship between the restoring force and the displacement, to prevent snap loads. A dynamic analysis for the environmental conditions of the Gulf of Maine is performed to verify the performance of the design. The tensions on the lines are well below the maximum breaking limit for the different materials. Nevertheless, the chain weight cannot be decreased as it provides the required mooring system stiffness. It has been verified that the polyester segment does not contact the seabed that could potentially damage it. The dynamic analysis also shows that the anchors do not experience vertical forces and the lines do not impact the platform heave plates. A complete load analysis must be performed to fully validate the proposed design.

1. Introduction
This work presents the design of a mooring system for the Triple Spar floating platform that supports the 10MW INNWIND reference wind turbine. The mooring system keeps the platform at the desired location avoiding the drift caused by the wind, the currents and the nonlinear hydrodynamics. The design of the mooring system is critical, because it has an impact on the resulting loads of the turbine components and on the whole system motions including the global damping of the platform.

The design methodology is described. It is based on a first static analysis for the definition of the main parameters and a subsequent dynamic analysis for the verification of the design. The paper also discusses the restrictions and the parameters that have to be taken into account for the design of mooring systems of floating wind turbines.

2. Floating wind turbine model
The mooring system designed in this work is specific for the Triple Spar floating platform that was developed in the INNWIND.EU project. The Triple Spar floating platform supports...
the 10MW INNWIND reference wind turbine [2]. The main characteristics of this wind turbine are collected in Table 1.

| Rotor orientation       | Upwind                                      |
|-------------------------|---------------------------------------------|
| Control                 | Variable speed / collective pitch           |
| Rotor diameter          | 178.3 m                                     |
| Hub Height              | 119 m                                       |
| Minimum Rotor speed     | 6 rpm                                       |
| Maximum Rotor speed     | 9.6 rpm                                     |
| Gear box ratio          | 50                                           |
| Hub Overhang            | 7.1 m                                       |
| Shaft tilt angle        | 5 deg                                       |
| Blade Pre-cone          | 2.5 deg                                     |
| Nacelle Mass            | 446 Tons                                    |

When the INNWIND 10MW reference wind turbine is supported by the Triple Spar floating platform, the tower has to be shortened 25 m, which is the foreboard height of the platform above SWL (still water level), to keep the hub height of 119 m. This modified tower has a base diameter of 7.7 m and a length of 90.63 m. The resulting mass of the shortened tower is 433 Tons and the center of gravity is located at 38.56 m from the base. The Triple Spar platform, shown in Figure 1, is a hybrid design with characteristics of the semisubmersible and the spar concepts. It is composed by three concrete cylinders with a draft of 54.464 m. The heave plates, also in concrete, are added at the cylinder's base to increase the damping in heave. A steel transition piece connects the platform with the wind turbine.

The general platform properties are summarized in Table 2.

**Figure 1.** Triple Spar platform geometry [1]
Table 2. Summary of the platform properties

| Platform      | Draft         | 54.464 m |
|---------------|---------------|----------|
|               | Elevation of tower base above SWL | 25.0 m   |
|               | Water displacement | 29205.09 m² |
|               | Center of mass below SWL | 36.02 m |
|               | Center of buoyancy below SWL | 27.54 m |
|               | Platform mass   | 28228.63 Tons |
|               | Ballast mass    | 17264.0 Tons  |
| Columns       | Length         | 65.0 m   |
|               | Distance to the center | 26.0 m |
|               | Diameter        | 15 m     |
|               | Elevation above SWL | 10.5 m |
| Heave plates  | Thickness      | 0.5 m    |
|               | Diameter        | 22.5 m   |
|               | Mass            | 678.7 Tons |
| Tripod        | Total height   | 15.0 m   |
|               | Height outer cylinder | 11.0 m |
|               | Diameter outer cylinder | 5.64 m |
|               | Bar cross-section width | 5.64 m |
|               | Mass            | 971.3 Tons |

3. Environmental conditions
The project LIFES50+ reports environmental conditions for three different locations considered moderate, medium and severe conditions [7]. The location of the Gulf of Maine (moderate), in the United States of America, was selected for the dynamic verification of the mooring system, because it is considered representative of the target design location for the Triple Spar concept. Table 3 presents the main environmental parameters.

Table 3. Environmental conditions

| Parameter                  | Value      |
|----------------------------|------------|
| 50-year wind at hub height | 44 m/s     |
| 50-year significant wave height | 10.9 m   |
| 50-year current           | 1.13 m/s   |
| Extreme water level range | 4.3 m      |
| Water depth                | 180 m      |

4. Mooring design methodology
Certain restrictions must be considered in the design of mooring systems. First, the resulting natural frequencies of the moored system should be outside of the dominant frequencies range...
of the wave spectrum to avoid significant dynamic excitations. Second, the anchor should not experience vertical loads to prevent lift up from the seabed and the lines tension must not exceed the Minimum Breaking Load (MBL) of the materials. In addition, the impact of the lines with any elements of the platform, such as heave plates, has to be avoided. In mooring lines combining chain with synthetic materials, it must be ensured that the synthetic part does not contact the seabed to avoid damage by friction. It is also important to obtain a smooth relationship between the platform displacement and the mooring system restoring force. Otherwise, snap loads causing critical increases in the tension of the lines could arise. Finally, the mooring system has to be able to counteract the forces causing the drift of the system such as currents, second order hydrodynamic forces and aerodynamic forces.

For the design of the Triple Spar mooring system, a semi-taut concept was selected to obtain a cost efficient design. The semi-taut configuration combines different materials in the same line. In this case, polyester was used in the upper part of the line and a steel chain was selected for the lower part, in contact with the seabed. This configuration combining synthetic lines with chain reduces the amount of steel needed and is more cost efficient than a standard catenary mooring line using chain.

The first dimensioning of the mooring system was performed using static calculations. This allowed estimating the restoring forces provided by the system, the mean tension of the lines and the allowable excursion of the platform. Once the configuration was set up, a dynamic verification considering the environmental conditions of the location was required to verify the performance.

4.1. Static design

On the first design step, the static catenary equations were used to iteratively reach the adequate mooring configuration. The elastic catenary equation was applied for the chain segment coupled with the elastic taut equations for the polyester line. A plane seabed was assumed and the stretching of the line follows the Hookes law. More details on these equations can be found in [8] and [9].

During this design process, the mooring restoring force as a function of the platform excursion was computed to verify that a smooth curve is obtained and thus, snap loads will be avoided during the operation of the wind turbine. These snap load can cause very high extreme tensions on the mooring lines, provoking a failure of the system.

Figure 2 shows, for the final configuration, the resulting horizontal force of the mooring system as function of the surge excursion of the platform. The curve is smooth and approximately linear. The curve also shows that the semi-taut system is able to counteract the rotor design thrust force of 1500 kN at rated wind speed and the design extreme wind load of 2050 kN [2]. The maximum allowable excursion is 31.5 m. Beyond this excursion the line aligned with the direction of the excursion would totally lift up and the anchor would experience vertical force.
In this configuration, the angle between the water plane and the mooring line is 55.8 deg, based on this steady calculation. This angle should not reach 86.7 deg to avoid the contact between the line and the heave plate at the base of the platform columns. The maximum value of this angle will be verified afterwards, based on dynamic simulations. Figure 3 shows the semi-taut shape of one mooring line at zero platform excursion.

Figure 3 shows that the chain segment lays on the seabed connected to the anchor meanwhile the polyester segment at the upper part connects the platform fairlead to the chain. The lower
part of the polyester segment is not in contact with the seabed. Nevertheless in the dynamic analysis of the system, it will be verified that the polyester is not in contact with the seabed in any case, to avoid the damage of the material. Table 4 presents the resulting configuration of the mooring system.

### Table 4. Mooring system parameters

| Parameter                        | Value                           |
|----------------------------------|---------------------------------|
| Number of lines                  | 3                               |
| Pretension at fairlead           | 1700 kN                         |
| Fairleads above MSL              | 10.5 m                          |
| Fairlead radial position         | 33.5 m                          |
| Anchor radial position           | 572.9 m                         |
| Chain length                     | 344 m                           |
| Chain weight /length in air      | 6350.0 N/m                      |
| Chain weight/length in water     | 5526.9 N/m                      |
| Chain nominal diameter           | 0.180 m                         |
| Chain equivalent diameter        | 0.324 m                         |
| Chain axial stiffness            | 2.8 E6 kN                       |
| Polyester length                 | 239.0 m                         |
| Polyester weight /length in air  | 240.0 N/m                       |
| Polyester weight /length in water| 60.0 N/m                        |
| Polyester nominal diameter       | 0.200 m                         |
| Polyester equivalent diameter    | 0.151 m                         |
| Polyester axial stiffness        | 4.32 E4 kN                      |

### 4.2. Resulting natural frequencies

Table 5 shows the resulting natural periods of the platform that were obtained by free decay’s tests using FASTv8 [10]. The resulting natural periods of the moored platform are located out of the dominant frequencies of the wave spectrum (4 s - 25 s), with the exception of the platform heave motion. The contribution of the mooring system to the heave stiffness is low and thus, can not modify the heave natural frequency of the unmoored platform. Nevertheless, the heave plates installed at the bottom of the columns are conceived to damp the heave motion.

### Table 5. Damped natural periods of the moored platform

| Degree of freedom | Period (s) | Frequency (Hz) |
|-------------------|------------|----------------|
| Surge             | 166.0      | 0.006          |
| Sway              | 166.0      | 0.006          |
| Heave             | 16.8       | 0.059          |
| Roll              | 25.5       | 0.039          |
| Pitch             | 25.5       | 0.039          |
| Yaw               | 99.65      | 0.010          |
4.3. Dynamic verification of the design

The dynamic performance of the mooring system under the loads of wind, wave and currents is verified in this Section. A set of 16 load cases, considered the most critical, were selected based on the recommendations by [3] and [11]. These cases are defined based on the standard IEC 61400-3 [12]. Table 6 shows the load cases selected to verify the mooring lines design.

Table 6. Reduced design load cases

| Cases | DLC | Description            | Wind speed [m/s] | Waves Hs [m] | Tp [s] | Sea current [m/s] | Wind - Wave misalignment (deg) |
|-------|-----|------------------------|------------------|-------------|--------|------------------|-------------------------------|
| 1     | 1.6 | Production             | 9.4              | 10.9       | 14.8   | 0.154            | 0                             |
| 2     |     |                        | 11.4             | 11.4       | 20     |                  |                               |
| 3     |     |                        | 13.4             | 20         | 25     |                  |                               |
| 4     |     |                        |                  |            |        |                  |                               |
| 5     |     |                        |                  |            |        |                  |                               |
| 6     | 2.2 | Production + Fault     | 11.4             | 4.45       | 7.47   | 0.154            | 0                             |
| 7     |     |                        | 20               | 10.3       | 11.37  |                  |                               |
| 8     | 6.1a| Parked/Idling          |                  | 10.9 x 1.09 | 14.8   | 1.13            | -30                           |
| 9     |     |                        |                  |            |        |                  | 0                             |
| 10    |     |                        | 44 m/s x 0.95 [k1] | 7.7 x 1.09 | 12.4   | 1.13            | 30                            |
| 11    | 7.1 | Parked + Fault         | 36.7 m/s x 0.95 [k1] | 7.7 x 1.09 | 12.4   | 1.13            | -30                           |
| 12    |     |                        |                  |            |        |                  | 0                             |
| 13    |     |                        |                  |            |        |                  | 30                            |
| 14    |     |                        |                  |            |        |                  | -30                           |
| 15    |     |                        |                  |            |        |                  | 0                             |
| 16    |     |                        |                  |            |        |                  | 30                            |

As this is a reduced set of load cases, the variation of mean sea level and rotor misalignment were not considered. The simulations were done using FASTv8. The mean drift effect was calculated based on the Newman approximation [13]. The sea current was modelled with a logarithmic velocity profile that reaches zero speed at 60 m of water depth. Viscous forces were added on the platform columns using a Morison approach with a drag coefficient $C_d = 0.61$. Mooring lines were simulated with the MoorDyn dynamic model [14] based on lumped mass method that takes into account tangential and also along the line drag and inertial forces. The drag coefficients used in the numerical model were obtained from [15] and are shown in Table 7.

Table 7. Normal and tangential drag equivalent coefficients

| Section     | $C_{dn}$ | $C_{dt}$ |
|-------------|----------|----------|
| Steel chain | 1.333    | 0.633    |
| Polyester   | 2.12     | 0.0      |

Figure 4 represents the numbering of the three lines that compose the mooring system. Line 2 is aligned with the wind. The $\beta$ angle represents the wind-wave misalignment.
The results of these simulations were processed to obtain the extreme mooring line tensions, to check that the connection point does not reach the seabed and the anchor does not experiment vertical loads in any case.

Table 8 presents the largest (max) and the smallest (min) tension obtained from the simulations. These maximum and minimum values can be found on the diagonal of the table. The other values, out of the diagonal, correspond to the tension on the other lines when the extreme value is produced. The maximum tension of 4139 kN appears on line 1 caused by the case 6.1 that combines the extreme wind model with the severe sea state. This maximum tension is below the minimum breaking load (MBL) of the polyester line (13172 kN) and the steel chain (30689 kN). Although the breaking limits of the materials are significantly below the maximum tensions, we did not reduce the diameter of the steel and polyester sections. The reason is that the selected chain is needed to provide the required weight and that a reduction in the polyester section would result in a material with too low axial stiffness. In addition, polyester is a cheap material and a reduction of the diameter would have a low impact on the final cost.

In addition, it has been verified that none of the anchors experience vertical forces in any of the load cases computed, and also that the maximum angle between the water plane and the mooring lines is below 86.7 deg to avoid contact between the line and the heave plates. The depth of the links between the polyester and the steel chain for the three mooring lines has
been checked to ensure that there is no contact between polyester and the seabed. This contact would damage the polyester line due to friction. The lowest value, as can be seen in Table 9, was 165.6 m below still water level for line 2, confirming that there is no contact between polyester and the seabed.

Table 9. Connection node depth position

| DLC | Case | Connection Depth L1 [m] | Connection Depth L2 [m] | Connection Depth L3 [m] |
|-----|------|------------------------|------------------------|------------------------|
| Min | 6.1  | -142.2                 | -141.3                 | -118.2                 |
| Min | 7.1  | -110.2                 | -165.6                 | -112.3                 |
| Min | 6.1  | -117.0                 | -135.7                 | -142.9                 |

5. Conclusions

A semi-taut mooring system has been designed for seakeeping the 10MW turbine on the Triple Spar floating platform. The configuration of the mooring system has been set up based on static calculations. A smooth relationship between the restoring force and the platform excursion was achieved to prevent snap loads. Afterwards a dynamic verification was carried out based on a limited number of loadcases considered the most critical. The resulting maximum tensions are very far from the MBL of the materials. Although the maximum tensions are not dimensioning the line diameter, the chain weight can not be decreased as it provides the required mooring system stiffness. The resulting natural frequencies of the platform are located out of the dominant frequencies of the wave spectrum (4 s - 25 s). Finally, it has been verified that the line is not hitting the heave plates, the polyester segment is not contacting the seabed, that could potentially damage it, and the anchors does not present vertical loads, in any of the cases considered.

The proposed design is economically more efficient than a standard catenary chain mooring line because the use of polyester reduces the cost of materials. The design is also safe, as the maximum tensions are significantly below MBL and are not design drivers. Nevertheless, a complete load case analysis must be performed to fully validate and optimize the design.

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References

[1] Azcona J, Vittori F, Paulsen U S, Savenije F, Kapogiannis G, Karvelas X, Manolas D, Voutsinas S, Amann F, Faerron-Guzman R and Lemmer F 2017 Design Solutions for 10MW Floating Offshore Wind Turbines. Deliverable 4.37. INNWIND.EU.
[2] Bak C, Zahle F, Bitsche R, Kim T, Yde A, Henriksen L C, Natarajan A and Hansen M 2013 Reference wind turbine report. Deliverable 1.21. INNWIND.EU.
[3] Azcona J, Palacio D, Munduate X, González L and Nygaard T A 2016 Impact of mooring lines dynamics on the fatigue and ultimate loads of three offshore floating wind turbines computed with IEC 61400-3 guideline. Wind Energy Journal
[4] Kallesoe B and Hansen A 2011 Dynamic mooring line modeling in hydro-aero-elastic wind turbine simulations. Proceedings of the 21st International Offshore and Polar Engineering Conference, ISOPE.

[5] Koo B Goupee A L K and H L 2014 Model test data correlations with fully coupled hull/mooring analysis for a floating wind turbine on a semi-submersible platform. Proceedings of the 33rd International Conference on Ocean, Offshore and Arctic Engineering, OMAE.

[6] Hall M, Buckham B and Crawford C 2014 Evaluating the importance of mooring line model fidelity in floating offshore wind turbine simulations. Wind Energy Journal. 18351853

[7] Gómez P, Sánchez G, Llana A and González G 2015 D1.1 Oceanographic and meteorological conditions for the design. LIFES50+ Qualification of innovative floating substructures for 10MW wind turbines and water depths greater than 50m.

[8] Barltrop N D P 1998 Floating Structures: A Guide for Design and Analysis (Marine Technology Directorate Ltd (MTD))

[9] Journée J and Massie W 2001 Offshore Hydromechanics (Delft University of Technology)

[10] National Renewable Energy Laboratory NWTC Information Portal (FAST v8) 2016 retrieved from https://nwtc.nrel.gov/FAST8

[11] Chaviaropoulos P K, Karga I, Harkness C and Hendriks B 2014 PI-based assessment of innovative concepts (methodology). Deliverable 1.2.3. INNWIND.EU.

[12] International Electrotechnical Commission 2009 IEC 61400-3 Ed. 1.0. Wind turbines - Design Requirements for Offshore Wind Turbines

[13] Faltinsen O M 1990 Sea Loads on Ship and Offshore Structures. (Cambridge University Press)

[14] Hall M 2017 MoorDyn User’s Guide

[15] DNV GL AS 2015 Position mooring DNV GL-OS-E301. Offshore standard.