Mooring Analysis of SPAR Type Floating Offshore Wind Turbine in Operation Condition due to Heave, Roll, and Pitch Motions

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Abstract. In Indonesia, one of the regions that have good potential for Floating Offshore Wind Turbine (FOWT) installations is the Natuna Sea which has a fairly good average wind speed in the range of 10.0 - 15.0 m/s. In addition, the Natuna Sea has a water depth of around 50-250 m with relatively mild wave height. This condition is a suitable environment for the installation of the FOWT. Therefore, it is necessary to investigate the appropriate mooring system configuration due to the motion of the structure. This paper examined the analysis of mooring system of the SPAR type FOWT structure due to its global motion through numerical modelling by using open source software FAST. The analysis was carried out for operation condition, by varying three configurations of the mooring system for the direction of environmental loads (waves and winds), namely 0 degrees (perpendicular in front of the turbine), 45 degrees, and 90 degrees (the turbine side direction) and wind speed. With the scope of such analysis, it could be properly examined the mooring system due to the global motion of heave, roll and pitch of the Spar.

1. Introduction

The need for high-quality wind energy encourages industries and research institutions to develop technologies that can be utilized for improving Offshore Wind Turbine (OWT) with a support structure that is made fixed and floating. The selection of this support structure depends on the design of the desired environmental conditions. The OWT support structure has different depth criteria than oil and gas support structures, although these structures have the same shape and configuration [1]. The OWT structure is economically valuable if installed at a depth between 10-50 meters which includes shallow depth to transition seas while Floating OWT or hereinafter referred to as Floating Offshore Wind Turbine (FOWT) has economic value if this concept is applied at a depth of 50 - 120 meters [1].

One of the institutions that develops this OWT technology is the National Renewable Energy Laboratory (NREL). NREL has been collaborated with U.S. Department of Energy (DoE) for more than 8 years to develop either fixed or floating OWT. Although NREL has several types of floating substructure namely MIT/NREL TLP, ITI Energy Barge, DeepCWind Semi-Submersible, and OC3-Hywind SPAR [2]. But, This research will focus on OC3-Hywind mooring analysis with modification from Mini-SPAR Deep Oil Technology, Inc.
The problem to be analyzed in this paper is the effect of variations in the mooring line, namely 30°, 40°, and 50° at fixed fairlead altitude and certain horizontal anchor distances from SPAR hull centreline to the SPAR type dynamic FOWT response. Only heave, roll, and pitch response will be evaluated in this paper because these three responses significantly affect the FOWT.

2. Research Method
In this section, we will explain how researchers conduct data retrieval, modelling and validation, configure the mooring system and FAST v8, conduct analysis with FAST v8, post-processing, analysis, and comparison of results.

2.1. Data Collecting
Deep Oil Technology, Inc et al. conduct a joint industry test for 3 SPAR models [3]. Drilling & Production SPAR (Consortium SPAR), Mini-SPAR, and The Oryx SPAR. From the three models listed above, Mini-SPAR is the most suitable and reasonable model that could be modified as a Floating Offshore Wind Turbine (FOWT). Here are the main dimension data from Mini-SPAR as shown in Table 1.

| Properties         | Value | Units |
|--------------------|-------|-------|
| Hull Diameter      | 16    | m     |
| Platform Draught   | 135   | m     |
| Platform Length    | 154.23| m     |
| Fairlead Depth     | 13.46 | m     |
| Mooring Lines      | 6     |       |

Environmental data used in this paper are wind, wave, and current data Omni-directional from PT.XYZ in 2014 with 1-year and 100-year return period for operational and extreme condition. The structure is placed in the Natuna Sea at 210 m depth shown in the Table 2.

| Data                  | 1-year | 100-year |
|-----------------------|--------|----------|
| Wave Mean Wind Speed  | 14.2   | 18       |
| Wave Height (m)       | 4      | 5.7      |
| Peak Wave Period (s)  | 9.6    | 10.6     |
| Near Surface Speed (m/s) | 0.68 | 0.96     |
| Current Mid-Depth Speed (m/s) | 0.43 | 0.63     |
| Current Near-Bed Speed (m/s) | 0.31 | 0.39     |

2.2. Modelling and Validation
Modelling Mini-SPAR structure uses MOSES software to gain hydrodynamic properties is the first step. These hydrodynamic data will be processed as input at HydroDyn module. Before the data can be used, MOSES will verify the model, so it can be used for other software. The mooring system is
modelled in Mooring Analysis Program (MAP v0.87.06a) module and these two modules can be coupled together in FAST v8 software.

The validation of the results of the SPAR modelling will be compared with the characteristics published by Deep Oil Technology, Inc. Validated data are Displacement, Pitch Gyraadius, Roll Gyraadius, and Keel to Center of Gravity (KG). The results of structural modelling on MOSES are compared with available data.

2.3. **Mooring Line Configuration**

To keep mini-SPAR stable at predetermined boundaries a well-structured mooring system is needed. From a variety of mooring system configurations, mooring links are considered suitable for mini-SPAR equipped with towers and NREL wind turbines. This journal uses two types of mooring lines. First, the fairlead depth remains at 62.03 m below the water surface while the anchor distance is towards the centerline of the Spar structure, hereinafter referred to as Mooring Configuration 2 (MC2) with three-angle variation (30°, 40°, and 50°). The variations called MC2A, MC2C, and MC2E.

2.4. **FAST v8 Configuration and Simulation**

At this stage, the data and settings performed in various FAST modules are combined into executable files for simulation. Adjustment of simulation settings between modules is also needed so that module configurations can be read and simulations can run in pairs. The time-domain analysis was carried out with a time step of 0.02 s. Analysis has a simulation time of three hours (10,800 seconds) [4]. The simulation is carried out in 2 conditions, namely 1-year condition and 100-year condition for 3 directions of environmental loads, namely 0°, 45°, and 90°. Simulation is carried out for each variation of the MC2 mooring systems.

2.5. **Post Processing, Analysis, and Comparison of Results**

Global response for 6 Degree of Freedom (DOF) from each simulation variation is analyzed. These results are graphed and processed to obtain the root mean square (RMS) parameters of each motion mode (surge, sway, heave, roll, pitch, yaw). From the RMS if it is associated with Natuna sea wave spectra, it can look for the stochastic price-value of the floater motion [5] (Djatmiko, 2012). In addition to RMS, the results of the time domain motion response were carried out by Fast Fourier Transform (FFT) to see the dominant response of motion mode on the frequency domain.

The maximum tensile strength that occurs at fairlead for each variation of MC2 configurations were analyzed using DNV OS-E301 (2010) to determine the mooring line safety criteria [7]. The safety criteria using MBL details and the size of the mooring line are needed.

3. **Results and Discussion**

There are 3 subsections in this results and discussion section.

3.1. **Modelling and Validation**

The modelling of the support structure for an offshore wind turbine in this paper was carried out with MOSES software. The mooring system for each variation of MC2 is modelled in the MAP v0.87.06a module at FAST. The Mini-SPAR FOWT model will be shown in Figure 1 below.
Figure 1. AutoCAD visualization of SPAR-Type Floating Offshore Wind Turbine

Here are the details for mooring line specification and configuration, shown in Table 3 and 4 below.

Table 3. SPAR-Type Floating Offshore Wind Turbine Mooring Line Specification

| Description                                      | Value   | Unit    |
|--------------------------------------------------|---------|---------|
| Spiral Stand Wire Rope                           | -       | -       |
| Spiral Stand Wire Rope Diameter                  | 0.114   | m       |
| Spiral Stand Wire Rope MBL                       | 11,757.54 | kN     |
| Spiral Stand Wire Rope Axial Stiffness           | 1170    | MN      |
| Spiral Stand Wire Rope Sheathed Weight (in air)  | 70      | Kg/m    |
| Spiral Stand Wire Rope Submerged Weight          | 55      | Kg/m    |
| Anchor Bruce FFTS                                | 15      | MT      |

After choosing the best option for mooring line specification, now we decide the mooring line configuration 2 with its mooring line angle variation. The angle chosen for this research is 30°, 40°, and 50°. The mooring line configuration can be seen in the Table below.
Table 4. SPAR-Type Floating Offshore Wind Turbine Mooring Line Configuration

| Description                              | MC2A     | MC2C     | MC2E     |
|-----------------------------------------|----------|----------|----------|
| Mooring line angle to structure         | 30°      | 40°      | 50°      |
| Mooring Line Length                     | 170.86 m | 193.16 m | 230.20 m |
| Fairlead Depth                          | 62.03 m  | 62.03 m  | 62.03 m  |
| Fairlead position due to hull centerline| 8 m      | 8 m      | 8 m      |
| Horizontal distance centerline          | 93.43 m  | 132.16 m | 184.34 m |
| Anchor Depth                            | 210 m    | 210 m    | 210 m    |

The structure model is then compared with the structure data available for validation. In this study, the limit of error of results received was 5%.

Table 5. Mini-SPAR Dimensional Data Validation

| Characteristic       | Mini-SPAR    | MOSES Modelling | Error         |
|----------------------|--------------|-----------------|---------------|
| Diameter             | 16 m         | 16 m            | 0.0000%       |
| Platform Draught     | 135,026 m    | 135 m           | 0.0002%       |
| Length               | 154,229 m    | 154,229 kg      | 0.0000%       |
| Displacement         | 26,531,524.91 kg | 27,550,100 kg | -0.03697%     |
| KG                   | 62.027 m     | 62.027          | 0.0000%       |
| Pitch Gyradius       | 61.286 m     | 61.5 m          | -0.00348%     |
| Roll Gyradius        | 59.792 m     | 61.5 m          | -0.0278%      |
| Center of Buoyancy   | -            | 67 m            | -             |
| Waterplane Area      | -            | 201,025 m²      | -             |
| KM Transversal       | -            | 67.12 m         | -             |
| KM Longitudinal      | -            | 67.12 m         | -             |

3.2. Global Motion Response
The result of the global structure response with time-history data which is the output of FAST v8 is the basic material for calculating root mean square (RMS). Calculations are performed for each loading direction and load conditions for each mooring configuration variation. The tables below show the results of the root mean square global response structure for each condition and direction of loading.
Table 6. RMS value for Heave, Roll, and Pitch MC2 with 1-year return period load from all direction

|       | Heave (m) | Roll (Degree) | Pitch (Degree) |
|-------|-----------|---------------|----------------|
|       | 0°        | 45°           | 90°            | 0°      | 45° | 90° |
| MC2A  | 0.1566    | 0.1567        | 0.1584         | 0.0727  | 0.2366 | 0.5212 |
| MC2C  | 0.3080    | 0.3091        | 0.7287         | 0.0689  | 0.2340 | 0.5457 |
| MC2E  | 0.5473    | 0.5475        | 0.5482         | 0.0718  | 0.2213 | 0.5564 |

From the table above, it is known that the highest RMS value for heave motion (0.7287 m) came from variation MC2C when struck by 1-year return period load from direction 90°, highest RMS value for roll motion (0.5564°) came from variation MC2E when struck by 1-year return period load from direction 90°, highest RMS value for pitch motion (1.4484°) came from variation MC2E when struck by 1-year return period load from direction 90°.

Table 7. RMS value for Heave, Roll, and Pitch MC2 with 100-year return period load from all direction

|       | Heave (m) | Roll (Degree) | Pitch (Degree) |
|-------|-----------|---------------|----------------|
|       | 0°        | 45°           | 90°            | 0°      | 45° | 90° |
| MC2A  | 0.8216    | 0.8214        | 0.8261         | 0.1030  | 0.3088 | 0.6062 |
| MC2C  | 1.0959    | 1.1014        | 1.1126         | 0.1066  | 0.3107 | 0.6264 |
| MC2E  | 1.4421    | 1.4406        | 1.4459         | 0.1086  | 0.3187 | 0.6534 |

From the table above, it is known that the highest RMS value for heave motion (1.4459 m) came from variation MC2E when struck by 1-year return period load from direction 90°, highest RMS value for roll motion 0.6534° came from variation MC2E when struck by 1-year return period load from direction 90°, highest RMS value for pitch motion 1.3139° came from variation MC2E when struck by 1-year return period load from direction 90°.

After gaining the highest RMS value for every motion with 1-year (operation condition) and 100-year (extreme condition) return period, then calculate the spectral density function and plot it into a graph. The graph from the highest RMS value for spectral density can be seen in the figure below.
For heave motion, MC2E have highest spectral density peak with 0.7020 m/(rad/s) at frequency 1.0076 rad/s, followed by MC2C with 0.2265 m/(rad/s) at frequency 1.2380 rad/s. MC2A has the lowest spectral density peak with 0.0550 m/(rad/s) at frequency 1.4440 rad/s.

For roll motion, MC2E have highest spectral density peak with 0.3643 deg/(rad/s) at frequency 0.6469 rad/s, followed by MC2C with 0.2668 deg/(rad/s) at frequency 0.6283 rad/s. MC2A has the lowest spectral density peak with 0.2554 deg/(rad/s) at frequency 0.8913 rad/s.

For pitch motion, MC2E have highest spectral density peak with 2.7568 deg/(rad/s) at frequency 0.6469 rad/s, followed by MC2C with 2.4238 deg/(rad/s) at frequency 0.6225 rad/s. MC2A has the lowest spectral density peak with 0.2554 deg/(rad/s) at frequency 0.8913 rad/s.
lowest spectral density peak with 1.0957 deg/(rad/s) at frequency 0.5608 rad/s. We can see on three-figure above, it can say that MC2E always have the highest peak spectral density at various frequencies. Followed by MC2C and the last MC2A. It happens because of the MC2E has the longest mooring line and the largest angle configuration.

For heave motion, MC2E have highest spectral density peak with 5.0536 m/(rad/s) at frequency 0.6749 rad/s, followed with MC2C with 2.9173 m/(rad/s) at frequency 0.7889 rad/s. MC2A has the lowest spectral density peak with 1.5724 m/(rad/s) at frequency 0.8913 rad/s.

For roll motion, MC2E have highest spectral density peak with 0.4862 deg/(rad/s) at frequency 0.7866 rad/s, followed with MC2C with 0.4467 m/(rad/s) at frequency 0.8005 rad/s. MC2A has the lowest spectral density peak with 0.4337 deg/(rad/s) at frequency 0.8040 rad/s.
For pitch motion, MC2E have highest spectral density peak with 1.1456 deg/(rad/s) at frequency 0.6481 rad/s, followed by MC2C with 0.9212 deg/(rad/s) at frequency 0.6469 rad/s. MC2A has the lowest spectral density peak with 0.7870 deg/(rad/s) at frequency 0.7714 rad/s. We can see on three-figure above, it can say that MC2E always have the highest peak spectral density at various frequencies. Followed by MC2C and the last MC2A. It happens because of the MC2E has the longest mooring line and the largest angle configuration.

3.3. Mooring Line Tension Analysis
The tension force of the time-historical rope is obtained from the results of the FAST simulation and the maximum value of the rope pull force is determined. The Maximum tension strength is used to determine the Minimum Breaking Load (MBL) required by considering the safety factor of 1.43 SF [7]. The following tables show the maximum tension force at in-line and between-line variation for each mooring configuration.

**Table 8. MC2 Maximum Line Tension [kN] for 1-Year Load Environment**

| Line  | Direction 0° | Direction 45° | Direction 90° |
|-------|--------------|---------------|---------------|
| MC2A  | Line 1 7480  | Line 2 5830   | Line 3 5620   |
| MC2C  | Line 1 8300  | Line 2 6280   | Line 3 6470   |
| MC2E  | Line 1 8890  | Line 2 7210   | Line 3 7360   |

From Table 6 it is known that when exposed to a 1-year return period load, MC2A variation has a maximum tension value of 7480 kN on mooring line 1 from load direction 0° and 90°. The MC2C variation has a maximum tension value of 8390 kN on mooring line 1 from load direction 45°. The MC2E variation has a maximum tension of 9060 kN on mooring line 1 from load direction 45°. MC2E has the highest maximum tension because of the horizontal force affected the mooring line at the maximum point.

**Table 9. MC2 Maximum Line Tension [kN] for 1-Year Load Environment**

| Line  | Direction 0° | Direction 45° | Direction 90° |
|-------|--------------|---------------|---------------|
| MC2A  | Line 1 15680 | Line 2 7670   | Line 3 7780   |
| MC2C  | Line 1 18370 | Line 2 8860   | Line 3 9040   |
| MC2E  | Line 1 17810 | Line 2 10440  | Line 3 10510  |

From Table 7 it is known that when exposed to a 100-year return period load, MC2A variation has a maximum tension value of 16340 kN on mooring line 1 from load direction 90°. The MC2C variation has a maximum tension value of 18620 kN on mooring line 1 from load direction 45°. The MC2E variation has a maximum tension of 18170 kN on mooring line 1 from load direction 45°.
MC2E has the highest maximum tension because of the horizontal force affected the mooring line at the maximum point.

According to DNV OS-E301 [7], the calculation of maximum tension of a mooring line should be in the range 0-70% of MBL (Minimum Breaking Load) or Safety Factor (SF) value 0-1.43. The SF value is obtained from the MBL of mooring line divided by maximum tension. Here is the table for safety criteria check.

| Mooring Configuration | Maximum Tension (kN) | Maximum Tension with Safety Factor (kN) | Category |
|-----------------------|----------------------|----------------------------------------|----------|
| MC2A 1year            | 7480                 | 8230.278                               | SAFE!    |
| MC2C 1year            | 8390                 | 8230.278                               | DANGER!  |
| MC2E 1year            | 9060                 | 8230.278                               | DANGER!  |
| MC2A 100year          | 16340                | 8230.278                               | DANGER!  |
| MC2C 100year          | 18620                | 8230.278                               | DANGER!  |
| MC2E 100year          | 18170                | 8230.278                               | DANGER!  |

From the table above, it can be seen that only MC2A when exposed with 1-year return period load condition that categorized safe by DNV criteria. So, it can say that MC2C and MC2E not suitable for the researcher load condition in terms of maximum tension allowed.

4. Conclusion

From the analysis of the dynamic response and tension strength of the steel wire rope produced by modified Mini-SPAR with NREL 5MW Turbine. The conclusion that can be taken are:

- MC2E has all the maximum spectral density peak for heave, roll, and pitch motions either at 1-year return period or 100-year return period, followed by MC2C then MC2A. MC2E variation high response can be seen from the RMS of it, so it could conclude that RMS can be a reference to determine that the response of a structure is good or not and choose which configuration has a better spectral response.
- The maximum tensile strength of 1-year return period load occurs to the entire mooring line 1 at Mooring Configuration 2 (MC2) with the greatest value of 9060 kN in variation MC2E. Followed by MC2C and MC2A variation with 8390 kN and 7480 kN, respectively.
- The maximum tensile strength of 100-year return period load occurs to the entire mooring line 1 at Mooring Configuration 2 (MC2) with the greatest value 18620 kN while MC2C exposed by a load from, next is MC2E with tension 18170 kN. These two variations had the same 45° load direction when getting the maximum tension. Lowest maximum tension owned by MC2A with 16340 kN with load direction 90°.
- Based on DNV OS-E301 (2010), the mooring line has a maximum Safety Factor (SF) value of 70% MBL. For two load case 1-year return period (operation condition) and 100-year return period (extreme condition) only MC2A when exposed by 1-year return period that meet the DNV OS E-301 safety criteria.
- It is highly recommended for next researcher to use bigger and longer mooring line specification to accommodate the maximum tension.
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