Assessment of mooring configurations for the IEA 15MW floating offshore wind turbine

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Abstract. To achieve cost-effective deployment of floating offshore wind farms, it is necessary to reduce mooring costs of Floating Offshore Wind Turbines (FOWTs). Beyond the cost, in terms of environmental impact, the seabed disrupted area due to mooring lines should be mitigated with care. The objective of this paper is to shed light on design parameters for cost-effective and low-footprint mooring configurations for FOWTs using coupled dynamic analyses. A design space is explored for mooring configurations with different pretension ratios, laid down length ratios and clump weight sizes. Ultimate and fatigue load cases are simulated in OpenFast to compute the floater motions, mooring line tensions and fatigue damage. With constant pretension ratio of 0.15 and adding clump weights of 40t, mooring line length, mooring footprint and peak tension can be reduced by 14%, 15% and 9% respectively, while maximum surge and fatigue damage increase by 25% and 12% respectively. This paper will serve as a basis for further work on mooring design in the EU H2020 funded project COREWIND and provide a practical reference for the mooring system design for FOWTs.

1. Introduction
Large-scale offshore wind farms have been under constructions all over the world and the deployment in deep waters is promising. One of the big challenges for development of floating offshore wind farms in deep waters is how to achieve cost-effective deployment. It is found that for different concepts of Floating Offshore Wind Turbines (FOWTs), the weight of mooring system costs in the Levelized Cost Of Energy (LCOE) varies but plays a significant role [1]. Reduction in mooring costs is essential for commercial deployment of floating offshore wind farms.

Beyond the cost, the environmental impact of mooring systems for FOWTs on ecological systems at seabed should be taken into account, as more and more floating offshore wind farms are under planning. For a catenary mooring system, part of the mooring lines lay on the seabed, where the existence and the movement of mooring lines form a disrupted area. For example, a circle is illustrated with radius of mooring footprint for a catenary mooring configuration [2]. The existence and movement of mooring lines would disrupt the seabed and affect the marine habitat. The disturbance due to swing moorings on marine habitats is mentioned in[3]. Therefore a feasible mooring design with smaller mooring footprint is preferred in order to reduce the disrupted area at seabed.

Mooring footprint is defined as the horizontal distance between floater center line at static equilibrium and anchor positions. It is an indicator of a reliable mooring configuration in both economic and environmental aspects, as it is directly linked to mooring line length and...
determines the disrupted area at seabed. The material cost of mooring lines is proportional to mooring line length. Thus it is important to optimise the mooring footprint of FOWTs.

Currently, there is no information available concerning the footprint allowances from guidelines. It is mentioned in [4] that sufficient length of mooring line is required to avoid lift-up for certain anchors, but no specific requirement is provided. In addition, the current studies of FOWT mooring systems focus on the analyses of mooring layout to maintain stability of the floater [5] [6] [7] and the investigations of mooring line properties on the floater motion [8] [9], but few studies cover dynamic analysis of FOWTs to evaluate mooring footprint and consider the economic and environmental impact.

Clump weights are commonly utilized in offshore engineering. The applications of clump weights for FOWTs have been studied in [10] [11] [12]. Computed by finite element program, it is shown the clump weight mooring system of chains and wire ropes can reduce maximum line tension compared to mooring system of chains for a Hywind pilot spar concept FOWT [10]. In contrast, it is proved that adding clump weights can reduce surge motion but increase fairlead tension for a spar concept FOWT through quasi-static analysis [12]. As for fatigue analysis, it is found that different clump weights lead to different fatigue damage [11].

However, none of these studies mention the change of the mooring pretension and mooring configuration after adding clump weights. In this paper, the impact of adding clump weights are investigated by assuming constant pretension ratio and adjusting mooring line length for different mooring configurations. In addition, dynamic analysis is performed in OpenFast to determine the dynamic responses of the FOWT. The difference of applying quasi-static and dynamic approaches for FOWTs indicates that quasi-static analysis may underestimate peak values as mooring line dynamic strongly affect tensions [13] [14] [15].

The main objectives of this paper are to propose cost-effective and low-footprint mooring configurations by adding clump weights and to assess dynamic performances, mooring cost and seabed disrupted area of the IEA 15MW FOWT for different mooring configurations. Section 2 introduces a preliminary design model of the IEA 15MW FOWT. In Section 3, a design space is explored with different pretension ratios, laid down length ratios and clump weight sizes. Section 4 presents numerical simulation results. Design Load Case (DLC) 6.1 for extreme conditions and 1.2 for fatigue analysis are addressed. Section 5 compares the mooring cost and the seabed disrupted area for different mooring configurations. Section 6 summarizes all results and outlines the future work.

2. FOWT model and environmental conditions

A preliminary design model of the IEA 15MW FOWT from EU H2020 Project COREWIND is studied in this paper. Key parameters of the IEA Wind 15MW turbine can be found in [16]. The turbine has three blades and turbine class is IEC 1B. Rotor diameter is 240m and rated speed is 10.59m/s. The supporting floater is a semi-submersible structure named ‘ActiveFloat’, of which the principle dimensions and hydrostatic properties can be found in [17].

The mooring layout and configuration are shown in Figure 1, where right-handed Cartesian coordinate systems are applied and the origin locates at centerline of the floater. The mooring system consists of three catenary lines, which are equally spaced with 120° angle between adjacent lines. Line1 is parallel to negative X-axis, line2 and line3 are symmetric about positive X-axis. The coordinates of fairlead point1 are (-42.5m,0m,-15m). The properties of mooring lines are referred to mooring designs in [18] with Minimum Breaking Load (MBL) of 20156kN.

The site is Gran Canaria Island with water depth of 200m. TurbSim is applied to generate turbulent wind fields. No wind-wave directional misalignment is considered in this paper. The environmental force points to positive X-axis. DLC1.2 is accounted for fatigue load cases and DLC 6.1 for ultimate load cases. The environmental conditions are taken from design basis[19] and summarised below.
Figure 1. Mooring layout and configuration.

(i) No wind, wave or current are included in static equilibrium tests.

(ii) For DLC6.1, Extreme Wind speed Model with 50-years return period (EWM50) is considered and the maximum 10-minutes average speed is 28.35 m/s at reference height of 135 m. JONSWAP wave spectrum with $H_s = 5.11 m$ and $T_p = 9 s$ is used and current speed is 0.57 m/s for 50-years return period condition induced by wind speed at sea surface.

(iii) For DLC1.2, Normal Turbulence Model (NTM) is used and wind speed ranges from 2 to 12 m/s with interval of 2 m/s. A wave-wind scatter diagram is reproduced with modifications on probability distribution. PM wave spectrum with two significant heights $H_s = 1 m$ and $H_s = 2 m$ are considered. The pair of $H_s$ and $T_p = 7 s$ comes from the most probable occurrence in the wave scatter diagram for site Gran Canaria Island.

3. Design space of mooring configurations

The design space consists of three pretension ratios $t_{pre}$, three laid down length ratios $l_{lay}$ and four sizes of clump weights $W$. Each combination of these variables ($t_{pre}$, $l_{lay}$, $W$) generates a different mooring configuration, shown in Table 1. Static equations of a catenary mooring line with a clump weight given in [20] are solved analytically to determine the lengths and the footprints of mooring lines.

$t_{pre}$ is defined as ratio of mooring pretension over MBL. Mooring pretension is the initial tension to hold the floater at static equilibrium positions without wind, wave nor current [2]. Three $t_{pre}$ values are considered for a rough range of 10% to 20% MBL, which is commonly used in the oil and gas design practises [2].

$l_{lay}$ is described as ratio of laid down length ($L_{lay}$) over hanging length ($L_{hang}$). Laid down length is the distance laying at seabed from touch down point to anchor, while hanging length can be derived from catenary equations given mooring line properties and pretension. The restoring force provided by mooring system of chains comes from mooring line weights. To avoid lift-up forces, it is required to lay enough mooring lines at seabed. The test $l_{lay}$ values of 0.3 and 0.5 are respectively referred to [18] and [21]. The total mooring line length ($L_{total}$) is the sum of hanging and laid down length.

The clump weight sizes $W$ and locations are according to [12]. The clump weight of 40 t...
Table 1. Design space of mooring configurations.

| Group | Number | $t_{pre}$ | $l_{lay}$ | $W$[t] | $L_{hang}$[m] | $L_{lay}$[m] | $L_{total}$[m] | Footprint [m] |
|-------|--------|-----------|-----------|--------|---------------|-------------|---------------|---------------|
| 1     | 1      | 0.10      | 0.50      | 0      | 394           | 197         | 591           | 573           |
| 1     | 2      | 0.15      | 0.50      | 0      | 500           | 250         | 750           | 746           |
| 1     | 3      | 0.20      | 0.50      | 0      | 587           | 294         | 881           | 884           |
| 2     | 4      | 0.15      | 0.30      | 0      | 500           | 150         | 650           | 646           |
| 2     | 2      | 0.15      | 0.50      | 0      | 500           | 250         | 750           | 746           |
| 2     | 5      | 0.15      | 0.70      | 0      | 500           | 350         | 850           | 846           |
| 3     | 4      | 0.15      | 0.30      | 0      | 500           | 150         | 650           | 646           |
| 3     | 6      | 0.15      | 0.34      | 10     | 483           | 167         | 650           | 644           |
| 3     | 7      | 0.15      | 0.39      | 20     | 466           | 184         | 650           | 642           |
| 3     | 8      | 0.15      | 0.51      | 40     | 430           | 220         | 650           | 638           |
| 4     | 4      | 0.15      | 0.30      | 0      | 500           | 150         | 650           | 646           |
| 4     | 9      | 0.15      | 0.30      | 10     | 483           | 145         | 628           | 622           |
| 4     | 10     | 0.15      | 0.30      | 20     | 466           | 140         | 606           | 598           |
| 4     | 11     | 0.15      | 0.30      | 40     | 430           | 129         | 559           | 547           |

equals to 15% of mooring line mass ($L_{total} = 650m$). The distance from the fairlead to the clump weight along the mooring line is 325m and the distance from the clump weight to the anchor position ranges from 230m to 325m for different mooring configurations.

The design space are divided into four groups. Group1 studies the pretension ratio effect and group2 for the mooring length ratio impact. Both group3 and group4 focus on the impact of adding clump weights. The comparisons of group3 and group4 can reflect the variances of mooring lengths and mooring footprints after adding clump weights. With a constant pretension ratio of 0.15, by adding clump weights of 40t, the total length and the footprint of mooring line 1 can be decreased from 650m to 559m and from 646m to 547m respectively.

4. Numerical simulations of different mooring configurations

4.1. Static equilibrium tests
The comparisons of analytical solutions and OpenFast results show good agreement as shown in Figure 2. For all configurations, the deviation is within 1% for most of the line tensions. Exception is the mooring configuration 3 ($t_{pre} = 0.20$), the analytical solution is 3.6% larger than the simulated line tension in OpenFast. This is due to uncertainty in mooring line elongation as elasticity is neglected in analytical solutions. For the mooring configuration 1 ($t_{pre} = 0.10$) the deviation is 0.1%. The good agreement of static mooring line tensions verify the set-up of different mooring configurations.

4.2. DLC6.1 extreme load calculations
The idling wind turbine under 50-year extreme wind, wave and current conditions is analyzed to determine the extreme responses. Six one-hour simulations with a yaw misalignment of ±8° have been performed in DLC6.1 with different mooring configurations. Sensitivity tests of mooring line pretension ratio indicate that within three values of $t_{pre}$, $t_{pre} = 0.15$ gives most reasonable horizontal offset. Therefore, configurations in group2, group3 and group4 with a
constant pretension ratio of 0.15 are simulated in DLC6.1. The maximum, mean and minimum values of dynamic performances on motions and line tensions are shown in Figure 3 to Figure 5.

Figure 2. Comparisons of pretension and line tension in static tests.

Figure 3. Extreme load test:motions for group2.
Figure 3 shows the variations of laid down length on motions under extreme conditions and the difference is insignificant. Figure 4 and Figure 5 illustrate the effect of added clump weights on floater motions and mooring line tensions. It is observed that by adding clump weights, surge and sway excursions increase while pitch and line tensions decrease. Adding clump weights of 40t, peak value of surge rises from 15.8m to 19.8m while peak value of pitch declines from 2.65° to 2.36° and maximum line tension drops from 6.881MN to 6.285MN.

The observation of reduction in mooring line tension by adding clump weights is consistent with the findings of [10] but inconsistent with conclusions of [12]. The observation of surge promotion by adding clump weights is in contrast to the statements of [12]. In this analysis, the mooring pretension ratio is fixed for mooring configurations with clump weights, so the mooring line tension at static equilibrium is constant. The clump weights does not add extra weight to the mooring system, instead it contributes to the constant mooring line tension. As presented in Table 1, the mooring line length is adjusted for different clump weights to reflect the trade-off between clump weight size and mooring line length. In this sense, the mooring configurations with clump weights behave more slack as the clump weights help to bear part of the tensions.

4.3. DLC1.2 fatigue damage calculations
DLC1.2 accounts for normal power production of wind turbines. 99% of fatigue load for wind turbine components comes from DLC1.2 for the semi-submersible FOWT [14]. At early design phase of the 15MW FOWT, no available information is provided on the importance of all fatigue load cases [22], it is assumed that fatigue life of mooring lines is determined by DLC1.2. The purpose of this fatigue analysis is not to check the fatigue limit but to quantify the influence of
Figure 5. Extreme load test: forces for group3 and group4.

added clump weights to the mooring fatigue life.

As shown in Figure 4, the difference of mooring line length for group3 and group4 is slight and group4 gives a bit smaller surge motion than group3, so group4 (\(t_{\text{pre}} = 0.15, t_{\text{lay}} = 0.3\)) are considered in DLC1.2. The yaw misalignment is 10°. No corrosion or marine growth is included in fatigue damage computation. For studless mooring chains with grade R4, the intercept parameter of S-N curve is 6E10 and the slope of S-N curve is 3 [4]. Miner’s law is applied for linear damage accumulation. Six wind and wave seeds are applied and total fatigue damage is sum of the partial damage of each tested environmental condition multiplied by the occurrence probability. The fatigue results are list in Table 2. It can be seen that with a constant mooring pretension ratio, adding clump weights increases the fatigue damage.

| Clump weights | \(W = 0t\) | \(W = 10t\) | \(W = 20t\) | \(W = 40t\) |
|---------------|-------------|-------------|-------------|-------------|
| Fatigue Damage ratio% | 7.39E-06 | 7.72E-06 | 7.83E-06 | 8.25E-06 |
| Fatigue life [hour] ratio% | 1.35E05 | 1.29E05 | 1.28E05 | 1.21E05 |
5. Mooring cost and seabed disrupted area

Table 3 shows the mooring cost and seabed disrupted area for group4. With constant water depth and anchor number, the mooring cost depends on mooring line lengths [1]. To consider the service life of mooring lines, the normalised mooring cost is defined as mooring material cost over the fatigue life and describes the mooring cost per year. No scientific models are available to precisely assess the mooring system influence on seabed ecology and marine habitats. As an indicator of the environmental impact, seabed disrupted area is roughly evaluated by a geometric shape of circle with radius of mooring footprints.

Given $t_{pre} = 0.15$ and $l_{lay} = 0.3$, adding clump weights can reduce mooring material cost, normalised mooring cost and seabed disrupted area. The effect to reduce seabed disrupted area is more visible with increasing clump weights. For normalised mooring cost, as max deviation is 4%, the effect on clump weights is less pronounced. By adding 40t clump weights, the configuration lowers the mooring material cost by 14% and seabed disrupted area by 28%.

| Clump weights | $W = 0t$ | $W = 10t$ | $W = 20t$ | $W = 40t$ |
|---------------|----------|----------|----------|----------|
| Mooring line length[m] | 650 | 628 | 606 | 559 |
| Mooring material cost ratio % | 100 | 97 | 93 | 86 |
| Normalised cost | 4.80E-03 | 4.85E-03 | 4.74E-03 | 4.61E-03 |
| Normalised cost ratio % | 100 | 101 | 99 | 96 |
| Seabed disrupted area[m²] | 1.31E06 | 1.22E06 | 1.12E06 | 9.39E05 |
| ratio % | 100 | 93 | 86 | 72 |

6. Summary and future work

This paper proposes cost-effective and low-footprint mooring configurations for the IEA 15MW FOWT using coupled dynamic analyses. It investigates the influence of adding clump weights with constant mooring pretension ratio for various mooring configurations. Extreme and fatigue load cases are simulated in OpenFast and the results are compared to assess different mooring configurations and their impact on dynamic performances, mooring cost and seabed disrupted area.

For constant pretension ratio of 0.15, adding clump weights promotes maximum surge excursion and decreases peak line tensions. With 40t clump weights, the maximum surge experiences 25% growth from 15.8m to 19.8m while the peak line tension drops by 9% from 6881kN to 6285kN. Meanwhile, by neglecting marine growth, corrosion and stress concentration, adding clump weights can cause more fatigue damage (up to 12%) of mooring lines. The fatigue life of mooring line calculated in DLC1.2 is regarded as service life, excluding the weighted importance of other fatigue load cases. Adding 40t clump weights, mooring line shows a 10% lower fatigue life. For simulations of DLC6.1 and DLC1.2, only $t_{pre} = 0.15$ is considered, it is suggested to explore the mooring pretension variance in ultimate and fatigue load analysis of mooring designs for future studies.

As no precise models are available to quantify the environmental impact, the seabed disrupted area is used as a rough indicator. Mooring line material cost is function of mooring line length, without considering the cost of clump weights. By adding clump weights of 40t, the mooring footprint can be reduced by 15%, the seabed disrupted area can be decreased by 28% and
the material cost of mooring lines can be declined by 14%. To consider the service life of mooring lines, mooring cost is normalised by dividing the material cost over the fatigue life and it shows negligible variances with different clump weights. For future studies on mooring cost and environmental impact, it is suggest to include the cost of added clump weights in the cost function and to develop more precise models to assess the disturbance at seabed.

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