Design optimization of the mooring system for a floating offshore wind turbine foundation

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Abstract

This report presents a study about the modeling and optimization of different mooring systems for Floating Offshore wind Turbines (FOWT) for different water depth level. This study was proposed by Principle Power Inc. (PPI), designing the mooring system for its patented WindFloat foundation. Extended analysis on the anchor types, mooring lines and mooring configurations are presented in this report in order to select the best and most economical option for the WindFloat technology. The mooring system proposed consists on a catenary configuration with a drag embedment anchor and combination of two types of mooring lines, synthetic rope and chain.

With this configuration, a total of nine mooring systems for different water depths are designed and optimized according to the rules and guidelines of the two certification bodies, Bureau Veritas (BV) and American Bureau of Shipping (ABS). The software OrcaFlex v9.8e is used to satisfy the certification body requirement of using a time-domain simulation tool. The same metocean conditions, soil type, FOWT foundation, wind turbine and line pretension are considered for all the designs.

As a result of this study, shallow mooring designs presented heavier chains than deep waters, driving their mooring costs. On the other hand, deep waters designs have longer mooring lines, making this parameter their cost driving. These facts lead to a minimum range between shallow and deep waters. This minimum range is between 60 m and 80m water depth.

Keywords: Offshore wind; FOWT; WindFloat; Principle Power; Mooring system; Anchor; Mooring configurations; Water Depth.

1. Introduction

The offshore wind industry plays a key role across the renewable energy and maritime industry [1]. Offshore wind turbines are becoming larger and more powerful, and being deployed in deeper waters. They can be mounted on a fixed bottom base such as monopiles, jackets or tripods (see Figure 1). However, the economic feasibility of these technologies suffer some disadvantage for water depths larger than 60m [2]. At sites with high water depths, the concept of floating offshore wind turbines (FOWT) seems to be an appropriate economic solution. FOWTs are mainly composed by a turbine, floating foundation and mooring system.

Floating foundations concept can be divided in three main different technologies, tension leg platforms (TLP), semi-submersible platforms and spars. WindFloat is a semi-submersible foundation designed and proven by Principle Power Inc. (PPI). PPI works as a technology service provider for the offshore deep water wind energy market.

The mooring system hardware and installation incurs a significant cost for floating structure projects. The mooring systems for FOWTS have been benefited from the offshore oil and gas experience, as described in [3], [4], [5]. However, there are still several unknowns regarding the FOWT technology and site parameters, such as wave excitations and water depths. Highlighting a report from EWEA in 2013 [1], “it is recommended that more research must be done on mooring and anchoring systems for wind turbines”. This report presents the most common anchor technologies, mooring lines and mooring configurations in order to select the best and most economical combination for the WindFloat technology .

Furthermore, water depth has long been recognised by the offshore wind industry as a key parameter in mooring system design [6]. However, there is no project research for FOWTS about the driving hardware costs parameters depending on water depths. In this report, mooring system are designed for different water depths satisfying the statements from the certification bodies, Bureau Veritas (BV) [7] and American Bureau of Shipping (ABS) [8].

1.1 Objectives

The purpose of the project is to identify which parameters drive the mooring system design depending on the water depth for a WindFloat foundation, optimizing the mooring system according to the statements of the certification bodies, BV and ABS. Different anchor types, anchor installation procedures, mooring lines and mooring configurations are analysed to select the best option for the WindFloat technology. The hardware costs are considered to identify the cheapest water depth mooring design.

1.2 Scope

This study focuses in the design and optimization of different mooring systems for nine different water depths: 50m,60m,70m,80m,100m,120m,200m, 250m and 400m.

In order to be accurate in de design, the mooring systems have to follow some of the statements imposed by the certification bodies, BV and ABS. They present three different main studies. Intact conditions case, damaged case and fatigue analysis. The purpose of the project is not to define nine designs to satisfy all the certification bodies' requirements, therefore, only the intact case study will be considered as a guideline to design the mooring system.

The mooring system design is strongly dependent on a large number of variables. Therefore, some parameters must be fixed to be able to compare the mooring designs. The metocean data, type of soil, floating foundation, wind turbine, anchor size, line pretension and some mooring line sizes and materials must be fixed for all water depths. This is more detailed explained in Assumptions subchapter from section 5, Methodology.

FOWTs have a very innovative and recent market, being very competitive and sensitive. This fact compromises the necessity of publishing some values in an extra document named: "Design optimization of the mooring system for a floating offshore wind turbine foundation. Confidential Parameters". In addition, some results are presented as a function of a reference case. The aim of this project is to identify the trends on the design depending on the water depth.

The costs analysis of the study is only focused on the hardware costs of the main parts of the mooring system, the anchors and the mooring lines.

2. Platform and Wind Turbine

2.1 WindFloat

The semi-submersible floating platform is considered a WindFloat. The WindFloat is a floating foundation for offshore wind turbines with a simple, economic and patented design made by Principle Power Inc.

The WindFloat is made of steel. The geometry consists in three columns forming a triangle, where the turbine is set on the centre of one of the columns. This design enables the structure to be fully assembled onshore and then moved offshore to its final location. This fact reduces significantly the installation cost of the platform when is compared to fixed foundations as monopile or jacket type. These fix bottom foundations require offshore installations and heavy lift operations that involves significant vessel capabilities and high installation costs.

The static and dynamic stability of the WindFloat foundation provides sufficiently low pitch, roll and heave motions performance enabling to be used for offshore wind turbines. The heave stability is achieved because the patented water entrapment plates at the base of each column. This plates entrain water resulting in large added-mass component. The sharp edges of the plates increase the viscous damping.

For the performance of the pitch and roll motions, the WindFloat has a patented hull-trim system, also known as active ballast, which distributes water ballast between the three columns of the WindFloat. The purpose is to change the centre of gravity and compensate the variable turbine thrust force due to the low frequency changes in wind speed and direction. This system is closed-loop, so no water moves out or in of the system, Figure 1 presents a scheme of the WindFloat showing the ballast system and heave plates.

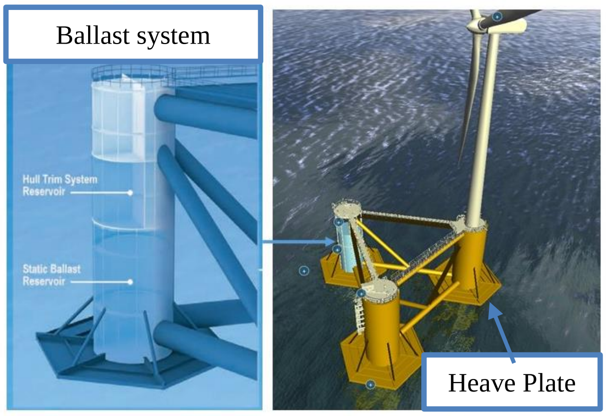


Figure 1 WindFloat Platform and ballast system [9]

2.2 Wind Turbine

The Wind turbine used for this study is from General Electric (GE). The turbine has been designed following class I-B IEC-61400-1/IEC-61400-3 [10]. The turbine characteristics in upwind are summarised in Table 1.

Table 1 Turbine Characteristics [10]

Class I-B IEC-61400-1/IEC-61400-3	
Rated Power	6 MW
Rotor Diameter	150 m
Hub Height	100 m
Rated wind speed	11 m/s
Cut in wind speed	3 m/s
Cut off wind speed	25 m/s

The power control system of the turbine includes a variable speed blade pitch control. The turbine also has a nacelle yaw control to avoid misalignments with the wind and a drivetrain control to maintain a constant power output. This turbine, according to GE, is developed for all offshore conditions.

3. Mooring System

3.1 Anchors

Nowadays, different types of anchors are presented in the offshore industry. In this chapter, the most common anchors are presented explaining its design and installation procedure.

The anchors are divided as: deadweight anchor, drag embedment anchor (DEA), anchor piles and vertical load anchor (VLA).

3.1.1 Deadweight Anchors

The deadweight is the simplest anchor. It consists of a heavy object placed on the seafloor to resist vertical and/or horizontal loads. The holding capacity comes mainly from the weight of the anchor and partially from the friction between the anchor and the soil.

3.1.2 Drag Embedment Anchors (DEA)

The drag embedment anchor (DEA) is the most common type of anchoring system available nowadays.

This anchors are designed to penetrate in the seabed, where the holding capacity is mainly generated by the resistance of the soil in front of the anchor. It is very well suited for resisting large horizontal loads, but it does not perform well for large vertical loads.

3.1.3 Anchor Piles

These anchors consist in a cylindrical pile made of steel. They are used for taut mooring systems and TLP since they can hold omnidirectional loads. The installation costs are usually expensive. Depending on the design and embedment mode, the main anchor piles can be divided in: driven, suction and torpedo piles.

Driven piles are relatively long, slender and open-ended steel columns. These anchors are usually installed by impact hammering, vibrating or pushing into the seabed. The installing operation difficulties increase for deep water depths.

Suction pile anchors are caisson foundations. They are penetrated into the seabed to a target depth by pumping out the water, creating under-pressure inside the pile and forcing the anchor into the seabed.

Torpedo piles consist of a pile with stabilizing fins, conical tip, ballast and a chain attachment on the pile top. They are dynamically penetrated to the soil by the free-fall velocity caused by gravity.

3.1.4 Vertical Load Anchors (VLA)

The VLAs, are installed in a similar way than drag embedment anchors, penetrating the anchor into the seabed with a horizontal load, however, VLAs need deeper penetration. Once the anchor is at the desired penetration a change on the fluke angle enables them to hold vertical and horizontal loads. The VLA gets its high holding capacity when the fluke is oriented nearly perpendicular to the applied load [11].

3.1.5 Anchors Summary

Figure 2 [12] shows a scheme of the studied anchors. Table 2 summarises the main characteristics of the different anchor types presented over this chapter. The table is divided into colours, depending on the characteristics, where green means a good performance or cheap cost and red means poor performance or expensive.

The site investigation shows the level of importance of each item, listed as low, high or not applicable (NAN). Low rating means a low impact or not necessary investigation in order to design the anchor, making the site investigation cheaper and corresponding to green box.

Table 2 Anchor summary

		DeadWeight	**DEA**	**Piles**	**VLA**
Soil Type	**Soft Clay**	Good	Good	Good	Good
	Medium Clay	Good	Good	Good	Good
	Hard Clay	Good	Good	Bad	Bad
	Sand	Good	Good	Good for Driven	Bad
	Hard Rock	Good	Bad	Bad	Bad
Site Investigation	**In-Situ Strength**	Low	Low	High	Low
	Laboratory Strength	High	High	High	High
	Dynamic Response	NAN	Low	High	High
Load Direction	**Omnidirectional**	Performs well	Inadmitible	Performs well	Performs well
	Horizontal	Performs well	Performs well	Performs well	Performs well
UHC/Weight Ratio		Highest	Lowest	High	Low
Installation Costs		Expensive for high UHC	Cheapest	Expensive	Expensive

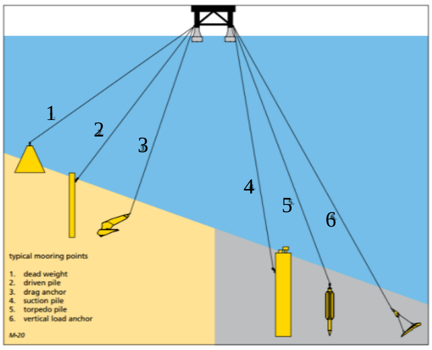


Figure 2 Anchor types

1. Deadweight Anchor
2. Driven Pile
3. DEA
4. Suction pile
5. Torpedo Pile
6. VLA

3.2 Mooring Lines

The materials commonly used in the mooring market are: steel chain, steel wires and synthetic ropes. Table 3 summarises the main properties from the different materials.

Table 3 Mooring line summary

Properties	Steel		Synthetic Rope	
	Chain	Wire Rope	Low Modulus	High Modulus
Density	High	Low-Intermidiate	Low	Buoyant
Abrasion Resistance	High	High	Low-Intermediate	Intermediate
Fatigue Resistance	Intermediate	High	Low	Very high
Elasticity	Low	Intermediate	High	Low
Installation	Easy	Intermediate	Harder due to creep	Hard due to creep
Reparation	Easy	Change all line	Change all line	Change all line
Costs	Cheap	Intermediate	Cheap	Expensive

The table above cannot be clasified by colours as Table 2. Because the characteristics of the line would have different levels of significance depending on the mooring configuration.

3.3 Mooring Configurations

3.3.1 *Catenary system*

In this configuration, the mooring lines form a catenary shape. The lines can be divided in two segments. The suspended line, connected to the floating structure and freely hanging in the water. And the lying on the seabed segment that finishes applying horizontal loads on the anchor.

The stiffness produced by a catenary configuration is due to its geometric change. It strongly depends on the weight of the line, as it can be observed in Equation (1).

$$C_{11} = \frac{\partial T_H}{\partial X} = W\left[\frac{-2}{\sqrt{\left(1+2\frac{T_H}{Wh}\right)}} + \cosh^{-1}\left(1+\frac{Wh}{T_H}\right)\right]^{-1} \qquad (1)$$

The most economic option is to increase the weight only in the seabed touchpoint. Usually using chains lying on the seabed and synthetic ropes as a suspended line.

3.3.2 *Taut system*

The Taut leg system has the mooring lines pre-tensioned until they are taut. The mooring lines terminates with an angle at the seabed, usually at 45 degrees. This means that the anchor is loaded by omnidirectional loads.

The stiffness produced by a taut configuration is due to the line elasticity. As it can be observed in Equation (2).

$$C_{11} = \frac{\partial T_H}{\partial X} \approx \frac{AE}{L_0} \qquad (2)$$

The restoring force of a taut mooring system is proportional to the Youngh modulus. However, too high modulus material would suffer too high tension. Therefore, the best line options for taut systems would be low young modulus synthetic ropes or wire ropes.

3.3.3 *Mooring Configuration Summary*

Concluding and analysing the different anchors, mooring lines and mooring configurations presented over this chapter, the most feasible option for the WindFloat technology for a water depth range between 50m and 400 m is the catenary configuration with a drag embedment anchor and mooring line combination of synthetic rope and chain.

For shallower water depths than 50 m, the most feasible option would be a catenary configuration with DEA and only chain line, since increase the line weight would decrease the mooring costs. On the other hand, for deeper water depths than 400 m, the most feasible option would be a taut configuration with VLA or suction piles and low modulus synthetic rope. This configuration should be analysed since decreasing the length of the line would decrease the mooring hardware costs, but installing VLA or suction piles would increase the anchor installation costs.

4. Certification Requirements

Requirements, rules and guidelines are published by classification societies in order to design a safety mooring system. This study uses the guidelines from Bureau Veritas (BV) and American Bureau of Shipping (ABS) classification societies. BV guidelines can be found in the Rule note NR 493 [13] for the classification of mooring systems for permanent and mobile offshore units. For the specific rules for FOWT, the guidelines are layout in rule note NI 572 [7]. The ABS guidelines are found in the guide Floating Offshore Wind Turbine Installation (FOWTI) [8].

5. Methodology

5.1 Modelling Tools

OrcaFlex is a commercial time-domain simulation tool developed by Orcina [14] that performs hydrodynamic analysis of offshore structures. The software has been developed to be very applicable to model FOWTs. OrcaFlex 9.8e is used for the computations presented in this study. The hydrodynamic coefficients of the platform are obtained from the commercial software WAMIT [15].

5.2 Design Basis and Conventions

Following the reasons presented in **¡Error! No se encuentra el origen de la referencia.**, the station keeping selected is a mooring catenary system with a drag embedment anchor. The mooring lines are a combination of different materials; a suspended line made of synthetic rope and steel chains lying on the seabed. A heavier chain is chosen for the line sections close to the touch down area in order to enhance the effect of the catenary system.

The mooring system is composed by three identical lines, one per each column, and equally spaced around the FOWT. This fact is based on the symmetry of the platform and the omnidirectionality of the metocean data, justified in metocean section of this document.

Mooring line 1, ML1, is attached at the wind turbine column. ML2 is at the following column in anti-clock wise direction and ML3 is connected to the remaining column. The mooring system distribution is presented in Figure 3.

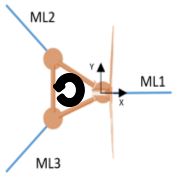


Figure 3 Mooring lines distribution

The general axis are set in the turbine column as also shown in Figure 3. The angle conventions are in degrees and anti-clockwise from the global X-axis. The metric system used is the SI, with forces in tonnes (t).

5.3 Load Cases

Load cases are defined by the certification societies. Nevertheless, as it is explained in the scope, only three load cases are considered. Two cases are imposed by the certification body; the maximum operating load case (MOSS) and the extreme load case (ESS). The third load case is required to check the design for excessively frequent turbine shutdowns due to platform horizontal motions induced by turbulent wind (HMTW).

5.3.1 Maximum operating Sea State Load Case (MOSS)

This load case covers a turbine operating during 1-year return period storm, shown in metocean data chapter. The thrust force is maximum at the rated wind speed, which makes it a design case.

The thrust value associated with the rated wind speed is shown in the confidential parameters document. This thrust force, applied at the hub height, generates a moment and a platform heel angle. To balance this moment and keep the average platform heel at +/- 1º a compensating moment is applied on the platform, corresponding to the active ballast mass.

5.3.2 Extreme Sea State Load Case (ESS)

The ESS load case is considered when the FOWT has to face a 50- years return period sea state, defined in the metocean data chapter. In this case, the wind speed is over the cut off speed, hence the turbine is parked. The pitch angle of the blades is kept at 90º. The turbine has a nacelle control in order to avoid the misalignment with the wind. When the turbine is parked, the rotor is locked to avoid rotations.

Nevertheless, the wind is still producing a force due to the drag on the blades and tower. The ballast effect must be considered to make sure that the average pitch and roll angles are null to minimize structural stresses. The active ballast is simulated by a compensating momentum, applied on the platform.

5.3.3 Horizontal Motions induced by Turbulent Wind Load Case (HMTW)

The turbine has a safety system switching off the turbine in case of excessive accelerations levels at the hub or excessive misalignment between the wind and the nacelle. A turbulent wind could lead to high standard deviations in the horizontal platform motions, inducing high nacelle acceleration and misalignments. Therefore, the mooring system stiffness should reduce the horizontal platform motions, induced by the turbulent wind.

The wind considered for this load case is turbulent. The average speed of the inflow is 14 m/s at the hub height. The turbulence intensity (TI) is set to 15%. The wind profile is computed using TurbSim. The wind direction is at 90º from the X-axis, as it is the most critical direction in terms of the largest horizontal motions. The nacelle is oriented to face the wind, providing a zero average nacelle yaw error.

The considered motion parameter in order to design the mooring system for the HMTW load case is the yaw motion standard deviation. The simulation time is set to 30 minutes to track enough data to compute the horizontal motion standard deviation. The build-up period is set to 200 seconds.

The aerodynamic loads were simulated by using an equivalent blade drag coefficient, calibrated by PPI. Similar to the other two load cases, an active ballast is simulated in order to compensate the momentum created by the thrust force.

In this load case, no waves nor currents excitations are considered.

5.4 Metocean Data

The metocean data are site and water depth dependent. However, the same metocean parameters are considered in the analysis and comparison of the mooring designs for different water depths. In order to study the influence of the water depth on the FOWT mooring designs, simplified metocean data sets are defined. They are arbitrary defined in the attempt of reflecting the three main load cases: the MOSS, the ESS and the HMTW. Their corresponding metocean data are presented in Table 4.

Table 4 Metocean data for different load cases

Load Case	Hs [m]	Tp [s]	Wave type [16]	Wind Speed [m/s]	Current Speed [m/s]
	3h average			z=100 m	z=0 m
MOSS	5	10	JONSWAP	11	0,25
ESS	8	12	JONSWAP	35	0,50
HMTW	0	0	-	14 TI=15%	0

Those conditions are omnidirectional, hence a directional analysis is performed to determine the combination of wave, current and wind directions, giving the highest loads on each mooring line. Analysing the results, the highest load is found in ML1 with a wave and wind propagation direction collinear at 180º.

In addition, the analysis at 0º propagation are also computed since the maximum offsets are found when the environment conditions are collinear between the two lines.

5.5 Mooring Design

A large number of variables are considered in order to design a mooring system; pretensions, top angle, anchor tensions, maximum tensions, line lengths, line weights, metocean conditions, seabed type or floating platform restoring coefficients are some examples. As it has been explained in the previous chapters, the floating platform, wind turbine, metocean conditions, seabed type and basic design would be considered the same for all cases. Therefore, the mooring system design would only depend on the length, weight and pretension of the lines.

The anchor size is also considered to be the same for all water depths. As a consequence, all the cases will have the same maximum anchor tension. In addition, the anchor uplift must be lower than 0,1º as imposed by certification societies.

The principal goal of the mooring system is to restrain platform motions to acceptable limits. The maximum motion allowance is imposed in order to avoid damages on the platform and surroundings, such as cables or other FOWTs. Floating platforms have 6 degrees of freedom; heave, surge, sway, pitch, yaw and roll. The mooring system is mainly designed to control the surge, sway and yaw motions. The ballast system and platform structure are mainly restraining heave, pitch and roll motions. The combination of both, surge and sway motions, is commonly known as offset, following Equation (3):

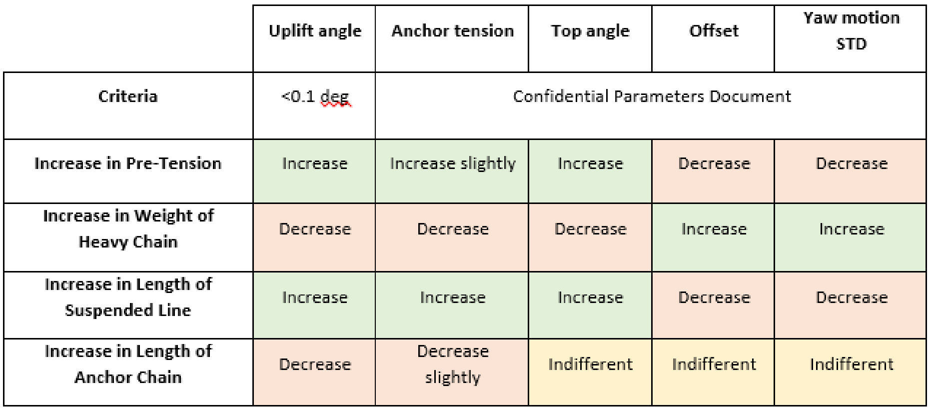
$$Offset = \sqrt{Surge^2 + Sway^2}. \qquad (3)$$

The top angle is the declination angle between the mooring line at equilibrium conditions and the vertical. The platform response in surge, sway and yaw depends on this parameter. For a larger top angle, the horizontal restoring force would be higher and reducing motions. However, it would reduce the catenary effect, thus the mooring system would have less damping and the anchor would issue higher tensions peaks. The nine water depth cases will have similar top angles.

Finally, as previously explained, the yaw motion standard deviation criteria is set in order to avoid switching off the turbine during operating conditions due to nacelle accelerations or misalignment for the HMTW load case.

The mooring line tensions and platform motions depend on the mooring design parameters. Table 5 shows the interaction of the outputs and the main design parameters such as pretension, heavy chain weight, suspended line and anchor chain length. The output response is presented when the design parameter increases. In addition, Figure 4 shows a sketch of the variables considered for a catenary mooring system.

Table 5 Moring design variable interaction



	Uplift angle	Anchor tension	Top angle	Offset	Yaw motion STD
Criteria	<0.1 deg	Confidential Parameters Document			
Increase in Pre-Tension	Increase	Increase slightly	Increase	Decrease	Decrease
Increase in Weight of Heavy Chain	Decrease	Decrease	Decrease	Increase	Increase
Increase in Length of Suspended Line	Increase	Increase	Increase	Decrease	Decrease
Increase in Length of Anchor Chain	Decrease	Decrease slightly	Indifferent	Indifferent	Indifferent

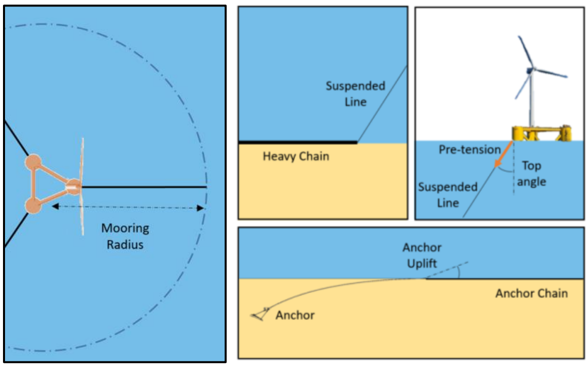


Figure 4 Design variables of a catenary mooring system

The pretension is assumed to be fixed at 40t for all water depths. The pretension value is chosen as a trade-off between platform offsets and anchor tensions.

The mooring line can be divided into five sections. Some sections are assumed to be the same for all water depths in order to simplify the analysis by decreasing the number of variables. Others, like synthetic rope, is water depth dependent to ensure enough clearance between the synthetic rope and seabed. In this way, the synthetic rope would not touch the seabed in any case. The synthetic rope length follows the equation shown in the confidential parameters document.

With all the assumptions considered, the design and optimization of the water depth specific mooring system is reduced to variations of:

- The length of the suspended chain.
- The weight of the heavy chain.
- The length of the anchor chain.

6. Mooring Optimization Results and Discussion

This chapter reports the mooring designs that would meet the designs criteria for the studied range of water depths. The results identify some trends of hardware cost when adapting the mooring design to different water depths defined as follows:

- Shallow waters of 50m, 60m, 70m, 80m, 100m
- Intermediate waters of 120m, 200m, 250m
- Deep water of 400m.

As it is explained in the Scope, the purpose of the project is to identify trends of the mooring designs depending on the different water depths. For that reason, all the results discussed are represented as non-dimensional values. The non-dimensionalization of this work is computed dividing the absolute values by a reference one. The selected reference case is the 100m water depth in the ESS load case.

6.1 Mooring Design

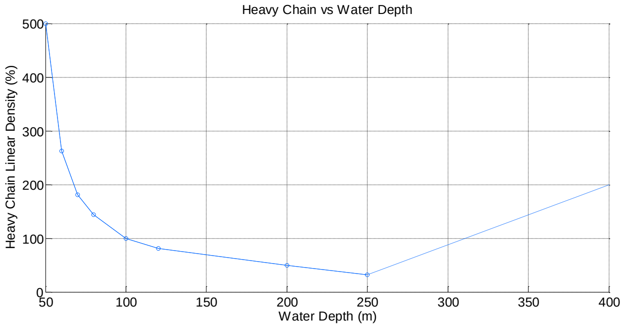


Figure 5 Heavy chain for different water depths

Figure 5 presents the heavy chain weight for the different studied water depths. The restoring capacity of a catenary system depends on the catenary shape, requiring higher gravity forces in shallow waters than deep. This fact is presented on the figure above, where shallow waters required a heavier chain to satisfy the requirements. Shallow waters' heavy chain weight increases exponentially when the water depth decreases. The shallowest case of 50m water depth has the heaviest chain. This fact makes the heavy chain the driving parameter to design the mooring line for shallow waters, since small decrease on the water depth requires heavier chains.

On the other hand, intermediate waters' heavy chain weight decreases linearly for deeper water depths. This tendency is identified until 250 m case, where it reaches the lightest point.

The deep water case of 400m required heavier chains than 250m. For light heavy chains, the suspended line is too steep (low top angles) resulting in higher motions and overpassing the requirements. Therefore, the heavy chain was increased in order to concentrate again the weight at the touch down point. This method enhances the catenary shape of the system increasing the top angle and the restoring force, being able to satisfy the platform horizontal motions criteria.

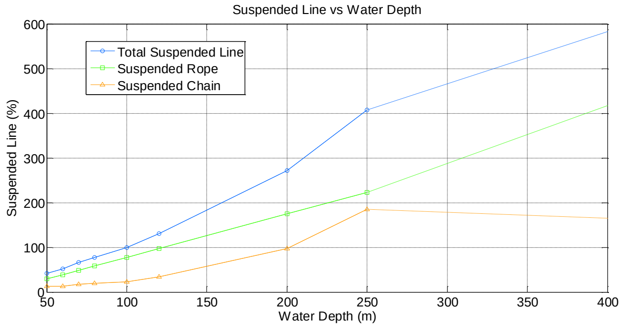


Figure 6 Suspended line for different water depths

Figure 6 presents the design results of the suspended line length. This line is composed by synthetic rope and suspended chain. The objective of varying the suspended line is to adjust the top angle to increase the restoring force on the mooring line.

Contrary to the trend of the heavy chain weight, in shallow waters the suspended line length increases linearly with the water depth. On the other hand, intermediate water design's trend seems to increase exponentially.

When the heavy chain weight is increased, the top angle decreases. Therefore, in order to avoid too steep top angles and a decrease in the restoring force generated by the catenary shape of the system, the length of the suspended line has to increase. Table 5 shows the relation between those parameters.

In order to satisfy all criteria, the mooring design of the deep water case of 400m could not follow the equation found in the confidential parameters document for the synthetic rope length. As a consequence, the designed value was increased. Consequently, the suspended chain and the total suspended line were reduced compared to the intermediate waters trend.

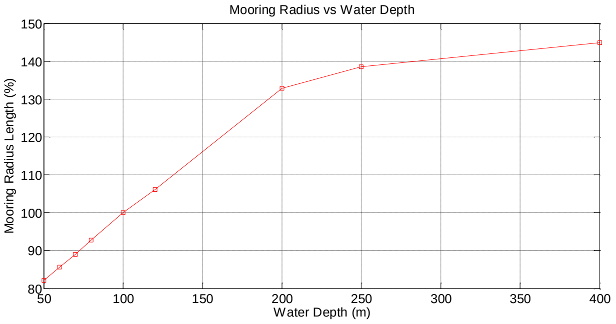


Figure 7 Mooring radius for different water depths

Figure 7 shows how the mooring radius increase when water depth increases. The mooring radius is an important parameter to be optimized, since the site areas where the FOWT can be installed are usually limited. For shorter mooring radius, higher density of turbines can be achieved resulting in a larger energy production for a given site area.

6.2 Mooring Responses

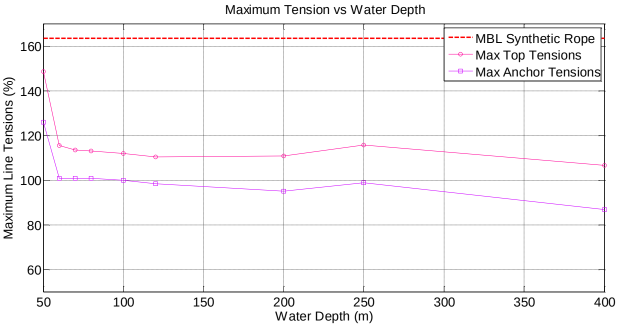


Figure 8 Maximum tensions for different water depths

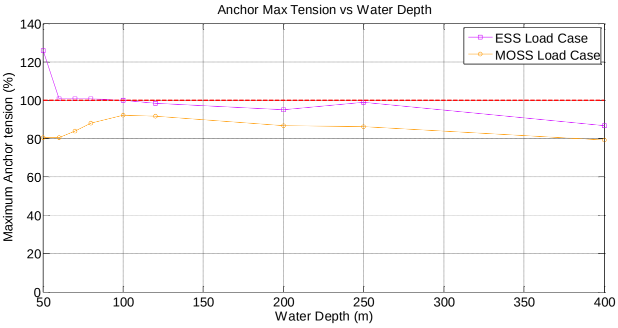


Figure 9 Anchor tensions for different water depths

Figure 8 presents the maximum line tensions for each water depth. The maximum tensions occur at the platform mooring connector (PMC). At this point the line is composed of a synthetic rope. The MBL limit, taken into account the safety factor, is shown in the figure as a red line. As it can be observed, all the maximum tensions are below this limit, therefore, the rope meets the safety requirements imposed by the standard society in terms of maximum tensions.

Maximum anchor tensions for each water depth are plotted in Figure 9. This graph has also the limit represented by a red line. The limit is the maximum anchor tension criteria used to design the mooring line. The results show how all water depth cases satisfy the criteria except the shallowest, for the ESS load case. This case faces 25% more anchor tension than the criteria imposed for the other cases. For the 50m water case and the assumptions considered, it was impossible to satisfy both criteria, offset and anchor tensions. Hence a compromise was found by applying a larger limit, the impact of this decision leads to have more expensive hardware and installation anchor costs.

The results obtained in Figure 9 shows that the anchor has to support higher tensions for ESS load case than MOSS. This fact satisfies the hypothesis of using ESS as the design load case.

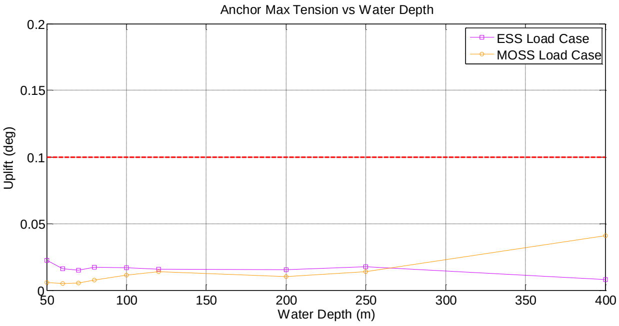


Figure 10 Anchor uplift for different water depths

The anchor uplifts are presented in Figure 10 for both load cases. As it can be observed, no water depth in any load case overpass the limit of 0,1°. Therefore, the DEA only holds horizontal loads.

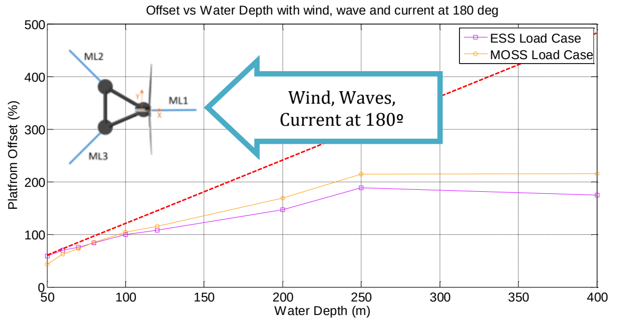


Figure 11 Offset for different water depths with wind, waves and current at 180º

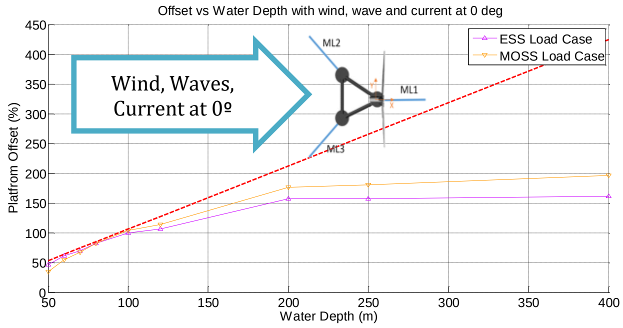


Figure 12 Offset for different water depths with wind, waves and current at 0º

The platform offset motions were computed for both, ESS and MOSS and directions of 180º and 0º, in Figure 11 and Figure 12, respectively. The offset criteria depends on the direction and water depth. It is represented as a red line. All the offset responses are below the red line, hence all the directions and load cases satisfy the offset criteria. As it can be observed in the figures above, 180º provenance sea state direction is collinear with ML1 and 0º provenance sea state direction is between ML2 and ML3.

For shallow water depth cases the motion offset values are closer to the limit than for deep water cases. Therefore, the offset motions (surge and sway) were driving the mooring design for those cases. Although intermediate and deep waters have higher motions, the criteria is less restricted and do not affect the design. The platform motions for those water depths were more constrained by the yaw motion standard deviation for HMTW load case.

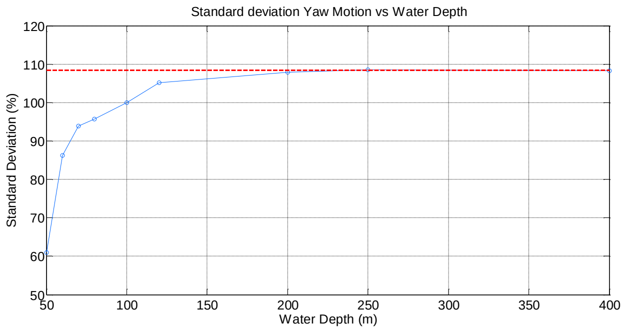


Figure 13 Standard deviation yaw motion for different water depths

Figure 13 shows the standard deviation for the platform yaw for the HMTW load case. As a main difference from the platform offset, the standard yaw deviation criteria is constant for all water depths. This limit is represented with a red line.

The platform surge, sway and yaw motions are larger for deep water cases than shallow. However, contrary to the offset criteria, the yaw standard deviation criteria is constant, making the intermediate and deep water cases closer to their limit than shallow waters. This fact makes the standard yaw motion deviation the design motion parameter for intermediate and deep waters.

Comparing Figure 13 with Figure 5, it can be observed how both graphs follow a contrary exponential trend. For high heavy chain weights, the standard yaw deviation is low. The reason is that for high values of heavy chain and same top angle, the motion damping coefficient is higher, the stiffness of the mooring system increases and the platform motions decreases.

6.2 Mooring Hardware Costs

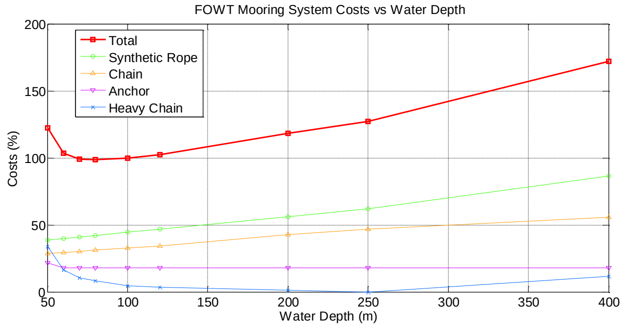


Figure 14 Hardware mooring costs for the different water depths

The mooring system costs per FOWT, for each water depth are presented in Figure 14. This graph is divided into different parts of the mooring system: synthetic rope, chains, heavy chain and anchor costs.

As it can be observed in the cost analysis, the chain and synthetic rope increases linearly with the depth. The heavy chain costs are proportional to the heavy chain weight, being more expensive for shallow waters than deeper. The anchor costs, on the other hand, are constant for all water depths since all the cases have similar anchor tensions, except the shallowest case of 50 m, where the anchor tension has a higher limit.

At the end, the total cost presented in the figure above, is the sum of the costs from the different mooring system parts. As it can be observed, the trend of the total costs have a minimum range from 60 m to 80 m water depth.

This minimum is originated by two factors, the weight of the heavy chain driving the shallow water costs and the length of the lines driving the intermediate and deep water costs.

7. Conclusions

Nine FOWT mooring system designs have been presented and discussed in this work. These nine designs were divided into three categories; shallow, intermediate and deep waters. The main objective is to identify which parameters are driving the mooring hardware costs.

The FOWT is composed of a turbine, floating foundation and mooring system. The foundation is based on the WindFloat technology designed by Principle Power Inc. The wind turbine is a Haliade 150-6MW turbine design by General Electric. For the mooring system, different anchor types, line materials and mooring configurations have been analysed in this report. The most economic and reliable option for the WindFloat technology and studied depths is a catenary system with a drag embedment anchor and a combination of different line materials, synthetic rope and chain.

The design basis presented for the different cases was composed by three identical lines equally spaced. The mooring lines are composed by a synthetic rope suspended in water and chains lying on the seabed. The chains have different sizes, being lighter near the anchor. At the touch down area, the chain weigh is increased in order to enhance the effect of the catenary system and increase the restoring force of the mooring.

In order to optimize and satisfy the standards of the certification bodies, the nine designs had to satisfy specific criteria for three different load cases, maximum operating sea-state (MOSS), extreme sea-state (ESS) and horizontal motion induced by turbulent wind (HMTW) load cases. For practical reasons, all designs have the same platform, turbine, seabed type, metocean conditions, and line pretension. Only three variables were water depth dependent; the length of suspended line, the weight of heavy chain and the total length of the mooring line. The tool OrcaFlex v9.7 was used to simulate and design the mooring systems.

Considering mild metocean conditions for all the study, the shallow mooring designs present heavier chains on the seabed touching point than intermediate and deep water cases. Hence heavy chain weight drives the design costs for shallow waters. On the other hand, intermediate and deep water designs have longer synthetic ropes and chains, making these parameters the cost driving ones. This leads to a minimum between shallow and deep waters. The minimum range for the considered metocean data is found from 60 m to 80 m water depth.

FOWT mooring system designs are very site dependent. However, this study can improve the understanding of the mooring systems, making offshore floating wind technology more cost competitive. A further study and improvement of this report would be to analyse the trends of the mooring design for more severe sea states. The procedure could be the same as presented in this report changing another variable, the wave excitation (Hs and Tp).

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