Journal of Physics: Conference Series

PAPER • OPEN ACCESS

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To cite this article: Mohammad Youssef Mahfouz *et al* 2022 *J. Phys.: Conf. Ser.* **2265** 042004

A parametric study of the mooring system design parameters to reduce wake losses in a floating wind farm

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Abstract. Wake effects inside a conventional fixed bottom wind farm decrease the power produced by the downwind turbines, hence decreasing the farm's annual energy production (AEP). However, floating offshore wind turbines (FOWTs) have the ability to relocate their positions laterally through surge and sway motions. This flexibility provides a new degree of freedom (DOF) in the floating wind farm layout, which can be used to decrease the aerodynamic interactions inside the floating wind farm and hence decrease the wake losses. The lateral movement of FOWTs can be passively controlled by the mooring system design. The mooring system's restoring characteristics allows the FOWT to only move within a specific area in the x-y plane known as the watch circle. Current state of the art mooring system designs are following oil and gas design basis where the floating platforms are not allowed to have large lateral displacements. In this work, we use full factorial design to analyse the effect of different mooring system design parameters on the ability of the floater to relocate its position. The analysis shows that each design parameter has a different way of affecting the FOWT's response. The mooring lines' headings control which wind directions cause the biggest displacements in the crosswind direction. The smaller the lines' diameters the higher the displacements of the FOWT. Finally, the longer the line length the smaller the mooring system's stiffness and hence the larger the FOWT's displacement. The results of this study can be used as the basis for floating wind farm optimization, in which the wind turbines are allowed to passively relocate their positions according to the wind speed and wind direction.

1. Introduction

The global goal to cut down our energy related carbon emissions and become greenhouse gases neutral pushes us to harness more of the wind energy potential. This is done by clustering wind turbines together into wind farms in attractive sites with high wind resources. However, wind farms suffer from wake losses, where downwind turbines produce less energy than upwind turbines due to aerodynamic interactions inside the wind farm [1]. In addition, wakes increase the turbulence intensity of the wind field, which increases the turbines' fatigue loads [2]. One solution to decrease the wake effects is to separate the wind turbines by long distances, which increases the efficiency of the wind farm but decreases its capacity density. Another solution to decrease the wake effects in the wind farm is optimizing the wind farm layout. These approaches are good for both onshore and bottom fixed offshore wind turbines due to their inability to relocate their positions according to the wind direction. However, for floating wind farms, the ability of floating offshore wind turbines (FOWTs) to move laterally (surge and sway motions) introduces a new degree of freedom for floating wind farms layout. If the downwind FOWTs move in the crosswind direction, they move out of the wake of the upwind turbines. This motion can be used to decrease the wake effects inside floating wind farms hence increasing their AEP, and decreasing the loads on the FOWT.

Early investigations about the effect of moving the FOWT and how to benefit from it were discussed by [3–7]. [3] studied the effect of repositioning of FOWTs on energy production by simulating two turbines in a row facing the wind direction and forcibly moving the downwind turbine in the crosswind direction. [3] used the NREL 5MW reference model, with $126.4m$ rotor diameter (D). The results showed that there is a significant gain in the energy produced by the downwind turbine if it moves crosswind by a distance more than $0.2D$. Moreover, moving the downwind turbine by a distance of $1D$ in the crosswind direction led to an increase of 41% in energy production. In order to make the FOWT move in the crosswind direction, [4–6] used the FOWT's controller to have a component of the aerodynamic thrust force perpendicular to the wind direction by varying the nacelle yaw angle and the induction factor. However, the motion of the FOWT was restricted by the design parameters of the mooring system. [7] presented a wind farm layout optimization technique for FOWTs attached to winch controlled mooring systems. [7] changed the mooring configurations according to the wind direction to have the optimum farm layout. To the best of our knowledge, our study is the first study that discusses the relationship between the mooring system design parameters and the ability of the FOWT to passively move in the crosswind direction.

The mooring system provides the stiffness in surge and sway degrees of freedom (DOFs) for the FOWT. Therefore, changing the mooring system design will change the mooring system stiffness and hence the ability of the FOWT to move in surge and sway DOFs. For example, a symmetric mooring system with uniform stiffness in all directions will lead to a circular watch circle where the FOWT will have equal displacements in all wind directions. This means that all FOWTs in the wind farm will always maintain a constant distance relative to each other for all wind directions. On the other hand, an asymmetric mooring system will have a different stiffness value at each wind direction, and hence the watch circle will not have a circular shape. Therefore, the FOWTs inside the wind farm will have different distances relative to each other for each wind direction depending on the mooring system's design. Currently the common practise for designing mooring systems for FOWTs follows the design basis recommended for offshore oil and gas platforms, where the motions of the platform need to be minimized. However, for FOWTs, allowing the floater to have greater displacements horizontally could be used to decrease wake losses in the wind farm. Therefore, in this paper we try to answer two main questions: Can the mooring system make a FOWT move in the crosswind direction? How do different mooring system design parameters (for example the mooring line's length) influence the motion of the FOWT?

In order to answer these questions we did full factorial design experiments on catenary mooring systems to analyse the effects of each mooring system parameter on the ability of a FOWT to relocate its position at different wind directions. The output of this study can be used to develop a new floating wind farm layout optimization technique. This paper is structured as follows. First we introduce the methodology used in the full factorial design analysis of the mooring system. Then we analyse the results and show the effect of each mooring system parameter on the ability of the FOWT to relocate, and on the overall stiffness of the mooring system. Finally, we summarise our results and present our future plans in the conclusion.

2. Methodology

In order to perform our parametric study we needed to know: Which design parameters to include in our full factorial design experiment? How to calculate the FOWT's mean displacements with the mooring systems in our design matrix? These are the two questions we will answer in this section to explain the methodology we applied in our study.

In our full factorial experiment, the IEA Wind 15 MW reference wind turbine coupled to the Activefloat platform [8, 9] was used as a FOWT. Therefore, before deciding on our design space we looked at the baseline mooring model of the 15MW reference model. It is a symmetric mooring system made of three mooring lines [8], which allows only small lateral motions for the FOWT and does not induce significant crosswind motions. The displacements of the FOWT when attached to the baseline design can be seen in Figure 1. The first plot shows the position of the FOWT in the horizontal plane at each wind direction in 5° increments. In the polar plots the radial distance represents the FOWT's displacements in meters. The angles represent the wind directions, where 0° means the wind is blowing from left to the right, and 90° means the wind is blowing upwards in the image. The black solid lines in the polar plots show the mooring lines headings. We will use this convention to represent our results throughout the paper.

In Figure 1, the steady response of the FOWT at a wind direction of 40° is used to explain what we mean by perpendicular displacement and inline displacement. At a wind direction of 40° the position of the FOWT in the horizontal plane is highlighted with the red circle. We can see that the FOWT's displacement is not only in the wind direction but also a small component of the displacement is perpendicular to the wind direction. The displacements correspond to the slightly triangular shape of the watch circle, which is caused by the nonlinear force-displacement response of the three catenary mooring lines.

The perpendicular displacement in the crosswind direction is what we want to increase in order to enable turbine repositioning, which could be used to decrease the wake losses inside a wind farm. For example, if two turbines behind each other are facing the wind, our goal is to have the mooring systems pulling the first FOWT to the right side in the crosswind direction, and the second one to the left side in the crosswind direction. For the baseline mooring design in Figure 1 the FOWT's total displacements range between 12 m and 15 m. The displacement in the crosswind direction does not exceed 2 m. This crosswind displacement is not nearly enough compared to the rotor diameter. Therefore, our design space should not start from this baseline model.

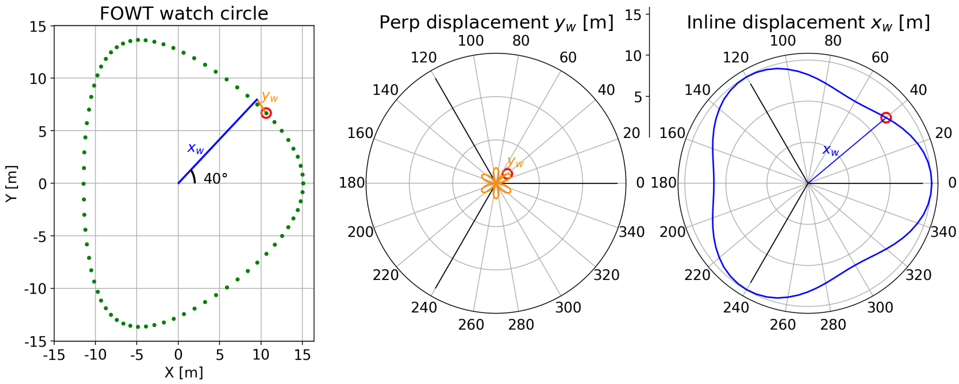

Figure 1. Visualisation of the FOWT's watch circle and displacements at each wind direction for the baseline mooring design of the 15MW Activefloat reference FOWT model. We use wind direction of 40° to explain the response.

2.1. Design parameters
In our factorial design experiment our main goal was to include as many mooring design parameters as possible. However, we had to decide on some parameters to be constant. Therefore, we fixed the number of mooring lines to three mooring lines, we used a constant sea water depth of 200 m, and we assumed the mooring lines are made of studless steel chains. In the following few paragraphs we introduce a list of design parameters included in our matrix and discuss how many levels of each of these parameters were used in our factorial design.

2.1.1. Mooring line diameter (d): Two values for nominal mooring line diameter were used for each line, 0.06 m and 0.12 m. These values were chosen to lay within the range of nominal diameters of commercially available chains, between 0.025 m and 0.18 m [10]. The equivalent diameters, the mass density and the axial stiffness of the lines were calculated following the equations presented in [11] for studless chains. Therefore we have two levels for the diameters of each line and hence 2^3 designs.

2.1.2. Line headings: The goal for the line headings was to use all possible combinations of the three lines' headings, while making sure none of the combinations is a rotated image of another one. Since we have three mooring lines, each line was allowed to be placed within a 120° range; line one can only be between 0° and 120°, line two between 120° and 240°, and line three between 240° and 360°. The step used while changing the headings of each line was 10° and any two lines were not allowed to lie on top of each other. Hence, the minimum accepted angle between two mooring lines was 10°. Applying this method, we ended up with 72 possible combinations for the lines headings.

2.1.3. Anchor radius (R) and line length (L): The anchor radius was chosen as a multiple of the rotor diameter. Three values of anchor radii were used for each line $3D$, $4D$, and $5D$. Following the approach presented in [4], the line length was defined as a function of the anchor radius and the sea water depth (equation 1):

$$L_{min} = \sqrt{depth^2 + R^2} \qquad L_{max} = depth + R \qquad L = L_{min} + \beta(L_{max} - L_{min}) \tag{1}$$

where the minimum accepted value for the line length (L_{min}) is when the line is fully stretched, and the maximum (L_{max}) value is when there is no horizontal tension in the line. Three values for β at 0.5, 0.7,and 0.9 were chosen for the length of each of the three lines. Therefore, for each line we have nine combinations of anchor radius and line length, and the total number of systems is 9^3.

2.2. Full factorial design
Combining the above design parameters for our full factorial design matrix, we have 18 levels (9 due to anchors radii and lines lengths iterations, and 2 due to diameters iterations), 3 factors (3 mooring lines) and 72 combinations for the lines headings. Therefore our full factorial matrix contains $18^3 \times 72 = 419904$ mooring system designs.

2.3. Static simulations
After creating our design matrix, we used MoorPy, a python-based quasi-static mooring analysis tool [12], to compute the FOWT's equilibrium states due to different wind thrust forces. The FOWT was included in MoorPy as a six DOF solid body with its hydrostatic characteristics. The aerodynamic loads were modelled as a constant force vector acting on the FOWT. For simplicity we transposed the aerodynamic force vector acting on the rotor directly to the floater at sea water level and assumed the tower was rigid with zero aerodynamic drag. Whenever the

wind direction changed the aerodynamic force vector acting on the FOWT was updated. In our analysis we neglected the wave and current forces for simplicity, as the mean wave and current forces were small when compared to the aerodynamic forces.

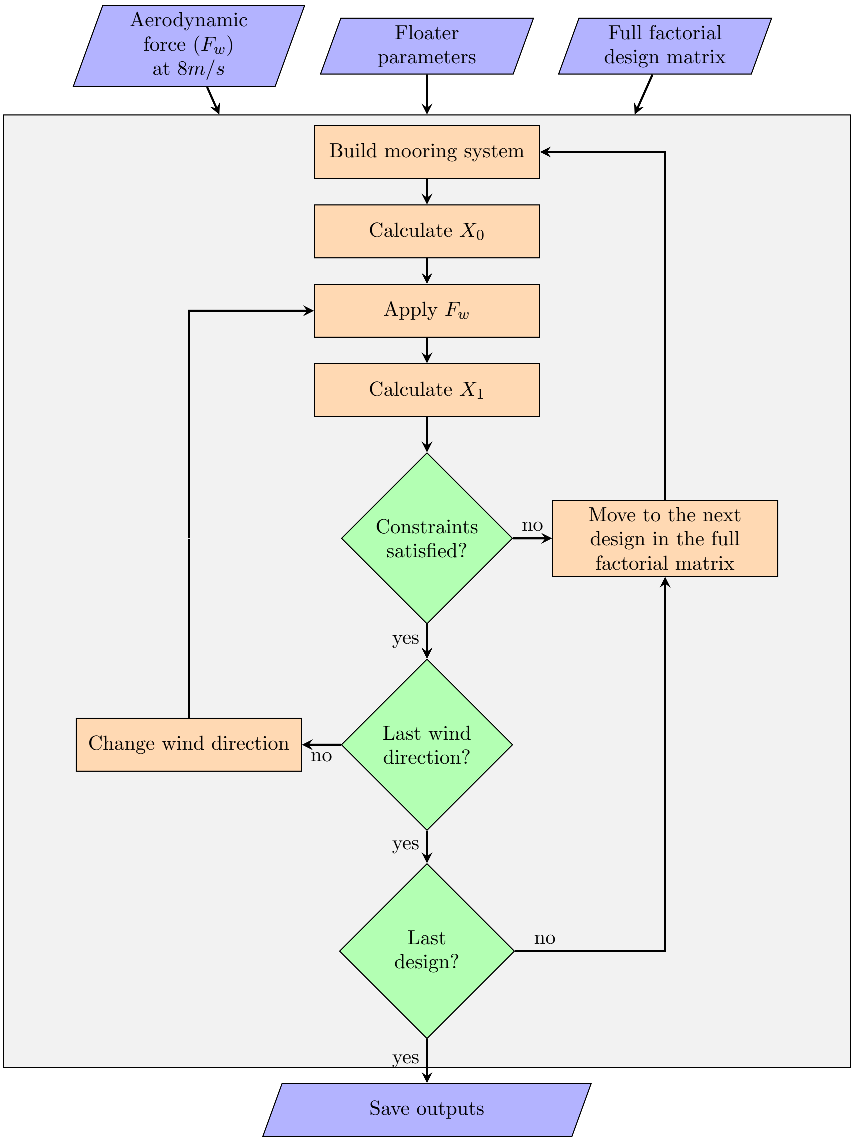

Figure 2. Methodology of the full factorial analysis

We used a quasi-static model and applied the aerodynamic force as a static force because we are most interested in understanding the FOWT's mean displacements when attached to our mooring designs rather than its dynamic response. Moreover, static analysis gave us a chance to check a bigger design space in a short time, which was more valuable for this parametric study. A flow chart of the methodology used in our analysis can be seen in Figure **??**. The floater hydrostatic parameters, the aerodynamic forces at $8m/s$, and the full factorial design matrix were given as input to MoorPy. The rated wind speed of the 15MW FOWT reference model is around $11m/s$, but the aerodynamic force at $8m/s$ was used in the analysis. This is because we want to check if the turbine can relocate in the crosswind direction below rated as this is the operation region where we can gain an increase in AEP through wake mitigation.

Once the inputs were provided to MoorPy, the first mooring system was built and the equilibrium position in the absence of external forces, X_0, was calculated. Afterwards, the aerodynamic forces were applied and the new static equilibrium position X_1 was calculated. We considered all wind directions between 0° and 360° with a step of 5°, thus we checked 72 wind directions. The next step was to check if the current mooring system satisfied the constraints. There were three constraints that we checked for:

- There were no vertical forces on the anchor.
- The maximum allowable yaw motion of the FOWT was 10°.
- The maximum allowable roll motion of the FOWT was 2°.

If the mooring system satisfied these constraints, we changed the wind direction and repeated the process again till we went over all wind directions and all mooring systems in our design matrix. If the system did not satisfy the constraints, we moved to the next system in our design matrix. Finally, we saved all the FOWT DOFs displacements for each wind direction and each mooring design, along with the tension forces in the lines and the overall system stiffness. At the end of our static simulations from the 419904 mooring designs in the input design matrix, 28205 designs satisfied the constraints.

3. Results

In this section we analyse the effect of each design parameter on the FOWT's watch circle, and the displacement of the FOWT perpendicular to the wind direction. We start by analysing the effect of the line headings, then we analyse the effects of line diameter, line length, and anchor radius.

3.1. Effect of line headings

Figures 3, and 4 show the watch circle of the FOWT, the displacements perpendicular to the wind, and aligned with the wind direction at two different lines headings combinations. Those lines headings were randomly chosen from our results. Each figure shows the response of five randomly chosen mooring systems with the same line headings but different line diameters, line lengths, and anchor radii.

In Figures 3, and 4 we can see that at constant lines headings, the wind directions causing the maximum and minimum displacements are the same for all designs. For example in Figure 3, the maximum inline displacement for all mooring systems happened at wind directions between of 30° - 40°. For the perpendicular displacements, the maximum displacements occured at wind directions between 90°, and 310°. The same effects can be seen in Figure 4. Therefore we can conclude that the wind directions causing the maximum and minimum displacements of the FOWT depend only on the lines headings. The magnitude of the displacements can be tuned using the other design parameters. Also, when comparing the watch circle shown in Figures 3 and 4 to that shown in Figure 1 of the baseline design, we can see that the positions of the FOWT at each wind direction are no longer equally separated from each other. However, we see hot spots at the corners of the watch circles in Figures 3 and 4, hence the wind direction changes but the FOWT's position does not change. This indicates that the FOWT moves not only in the wind direction but also in the crosswind direction.

In order to understand the relationship between the line headings and the wind directions causing the maximum and minimum displacement, we looked at the mooring lines' force directions. On the left side of Figure 5 the force vector of the first mooring line is drawn in red F_1, and the force vector of the second line F_2 is drawn in blue. The aerodynamic force F_w, in green, is acting in between the two lines. For simplicity, the force of the third mooring line is neglected as it is downwind so it has a lower tension and plays a smaller role in the platform's motion. Angle a is the angle between the two force vectors F_1 and F_2, while angle b is the angle

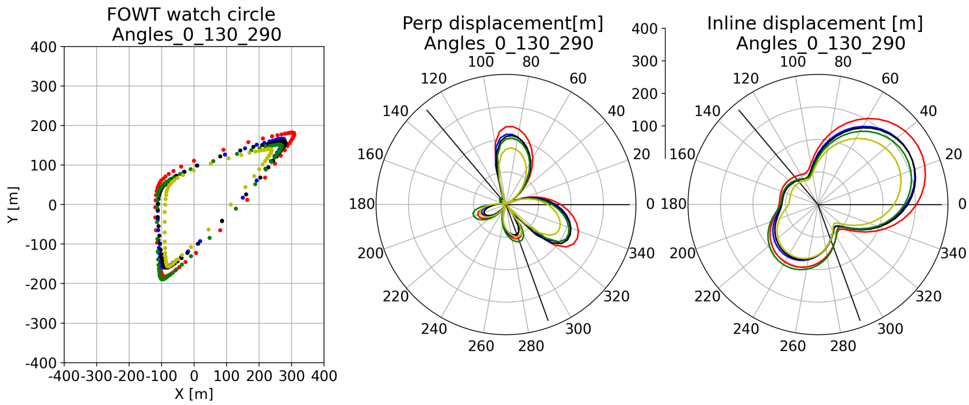

Figure 3. Visualisation of the FOWT's watch circle and displacement at each wind direction for five randomly chosen mooring systems with 0°, 130°, and 290° lines headings

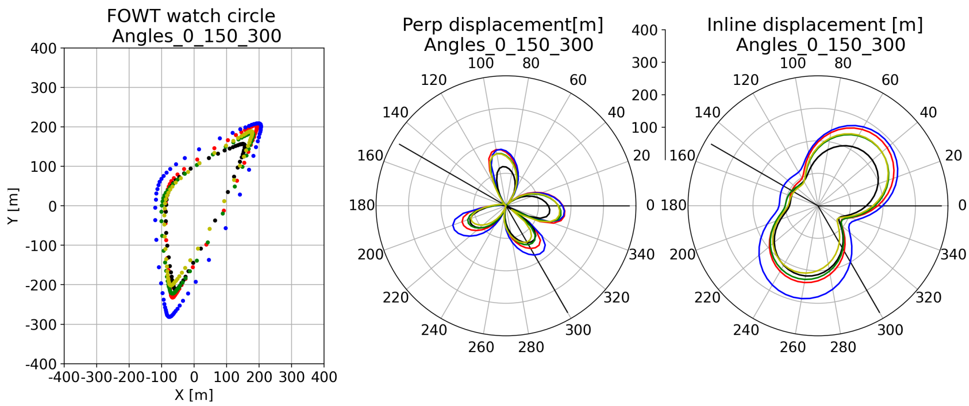

Figure 4. Visualisation of the FOWT's watch circle and displacement at each wind direction for five randomly chosen mooring systems with 0°, 150°, and 300° lines headings

between F_w and F_1. Decomposing the forces in the wind direction is shown in equation 2, while decomposing them perpendicular to the wind direction is shown in equation 3. The right side of Figure 5 is the graphical the representation of equation 2, showing the values of F_1, F_2, and the absolute value of F_w as the angle b changes from zero to a. When F_1 and F_2 are positive, they are counteracting F_w, and vice versa.

$$F_w = \begin{cases} F_1 & b = 0 \\ F_1 cos(b) - F_2 sin(a - b - 90°) & a < b < 0 \\ F_2 & b = a \end{cases} \tag{2}$$

$$0 = \begin{cases} F_2 & b = 0 \\ F_1 sin(b) - F_2 sin(a - b) & a < b < 0 \\ F_1 & b = a \end{cases} \tag{3}$$

After analysing equations 2 and 3, the right side of Figure 5 can be divided in three sections according to the value of the angle b. Region one $0 < b < a - 90°$, where F_1 is counteracting both F_2 and F_w. Region two $a - 90 < b < 90$ where both F_1 and F_2 are counteracting F_w. Finally, region three $90 < b < a$ where F_2 is counteracting both F_1 and F_w. The FOWT is displaced in the crosswind direction only in regions one and three, because for these wind directions one of the lines is compressed by the aerodynamic forces. Therefore, the FOWT needs to move in the

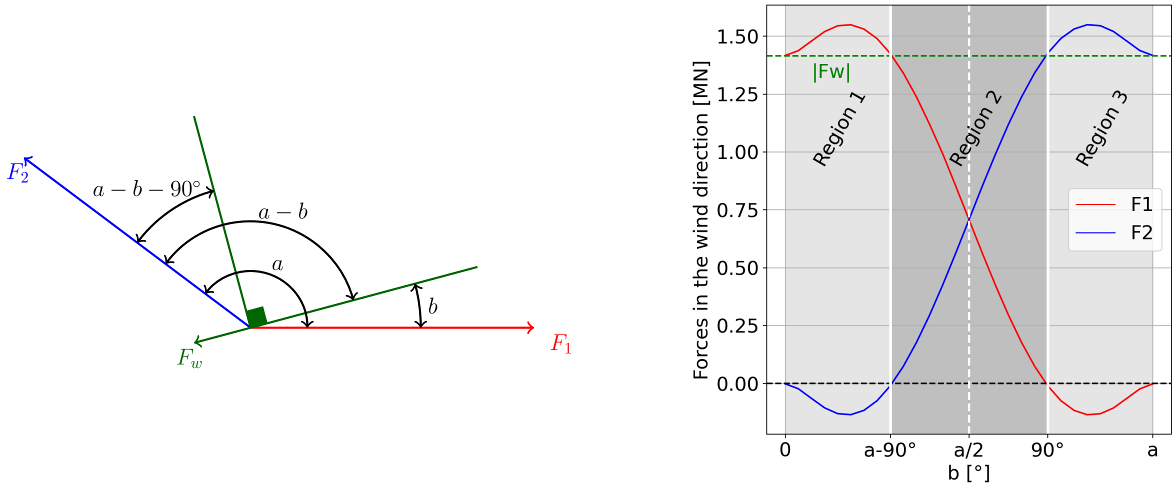

Figure 5. Mooring lines' forces when the wind is blowing between lines one and two

crosswind direction to build enough tension in the compressed line to maintain equilibrium in the crosswind direction. On the other hand, if the difference between two adjacent lines headings is less than 90°, there will be no displacement by the FOWT in the crosswind direction. As regions one and three will not exist and only region two will be there with both lines always counteracting F_w. At $b = a/2$ the maximum displacement in the wind direction happens as F_1 and F_2 can only build enough tension to oppose F_w by moving the FOWT in the same direction of the wind forces. We can look at Figures 3, and 4 to prove that these conclusions are true for the shown headings. In Figure 3, if the wind direction is between 110° and 180° (i.e. between lines one and three) there is no crosswind motion as the two lines are separated by an angle $a = 70°$. Looking at Figure 4, we see that the maximum crosswind displacement occurs when the wind direction is between 180° and 240° which means the wind vector is making an angle $0 < b < a - 90°$ with line one. In Figure 3, the maximum inline displacements happen at wind directions of 30°, and 245°, which are the wind directions where the wind force is blowing exactly in the center between two lines.

3.2. Effect of lines diameters

To check the effect of the diameter on the FOWT's displacement, we kept the diameters of mooring lines two and three fixed at 0.06 m, changing only the diameter of mooring line one between 0.06 m, and 0.12 m. For all other parameters the three mooring lines have the same values. Figure 6 shows the FOWT's position in the unloaded equilibrium state, the loaded equilibrium displacement in the crosswind direction, and the absolute difference between the two positions at both states at each wind direction.

In Figure 6, the unloaded equilibrium states are affected by the diameters. When line one has a larger diameter, it pulls the FOWT toward its anchor. While when all three diameters are $0.06m$, the FOWT's unloaded equilibrium is almost at equal distances from the three anchors. On the other hand, the loaded position is only affected by the diameter of line one, when the wind directions are acting between mooring lines one and two or between mooring lines one and three. There is no effect for the change of the diameter in the loaded position when the wind direction is acting between lines two and three since the two lines are identical. Both the aligned to the wind and the perpendicular to the wind displacements are larger when line one has a smaller diameter. This is expected as a smaller diameter, means a smaller weight, and hence the FOWT needs to displace for a larger distance to build up enough tension force in the mooring lines. On the right side of Figure 6, we see the delta displacement between the loaded

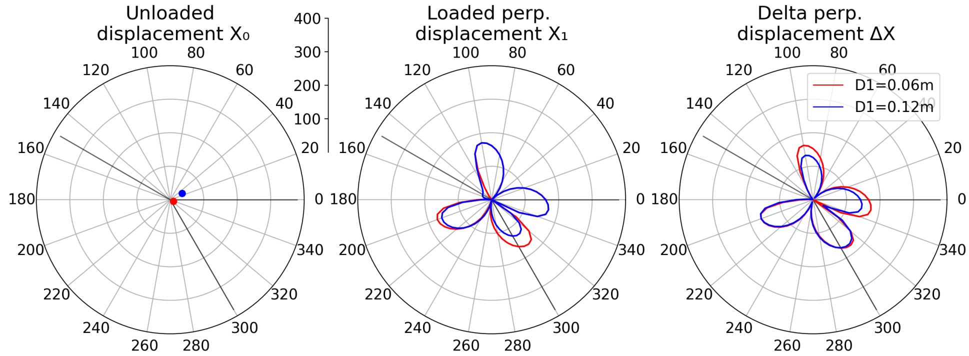

Figure 6. The unloaded and loaded equilibrium positions of the FOWT perpendicular to the wind direction and the difference between them at two diameters values

and unloaded positions. This is more relevant for wind farm optimization for wake mitigation where we only care about the motions of the FOWT relative to their unloaded positions.

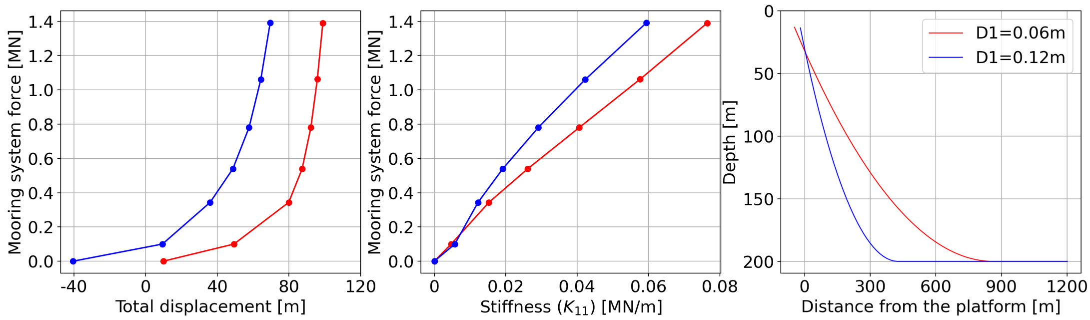

Figure 7. The mooring system forces and the corresponding FOWT's position and stiffness, and the catenary shape of line one at two diameters values. The wind direction is at 180°

In order to check the effect of different diameters on the mooring system's stiffness, we looked at the displacement-force, the stiffness-force curves, and the catenary profile of the mooring line with two different diameters in Figure 7. The forces and the catenary profile are drawn at wind direction of 180°. We chose this wind direction, because it is opposite to the tension force of mooring line one, for which we change the diameter values. A mooring system with a smaller diameter has a higher stiffness at higher loads when compared to a system of a larger diameter. The reason is that the tension force depends on the mass of the suspended length of the mooring lines so the lighter line needs to have a longer suspended length than the heavier line in order to have the same tension force. Therefore, a lighter mooring system needs to make a bigger displacement, compared to a heavier mooring system, in order to increase its tension force by the same value. The catenary profiles of the lines show that as the suspended length increases, the line becomes less slack, and hence a line with a longer suspended length will have a higher stiffness. On the other hand, at the unloaded equilibrium state, the stiffness of the heavier mooring system is slightly higher.

3.3. Effect of lines lengths

The effect of the line length on the FOWT was analysed with the same method presented in the former section to analyse the effect of the diameter. Two mooring lines' design parameters were fixed making these two mooring lines identical, the headings of the three lines were fixed, and the anchors radii were kept constant. The length of line one was changed and the response was analysed in Figure 8. For the unloaded equilibrium state, the shorter the line was the more it pulled the FOWT towards its anchor. When the three mooring lines shared the same length ratio of 0.5, the FOWT stayed at equal distances from the three anchors. However, when the length of the first mooring line increased, the FOWT was pulled closer to the anchors of the shorter lines. When the aerodynamic force was applied, the effect of the first line's length could only be seen for wind directions between 120° and 330°. As expected a FOWT attached to a longer line can displace for a larger distance in the crosswind direction. The difference between the loaded and unloaded states is more affected by the difference due to the unloaded state. Therefore, the line with a longer length has a bigger displacement for wind directions between −30° and 120°, while for the other directions the displacements are approximately equal.

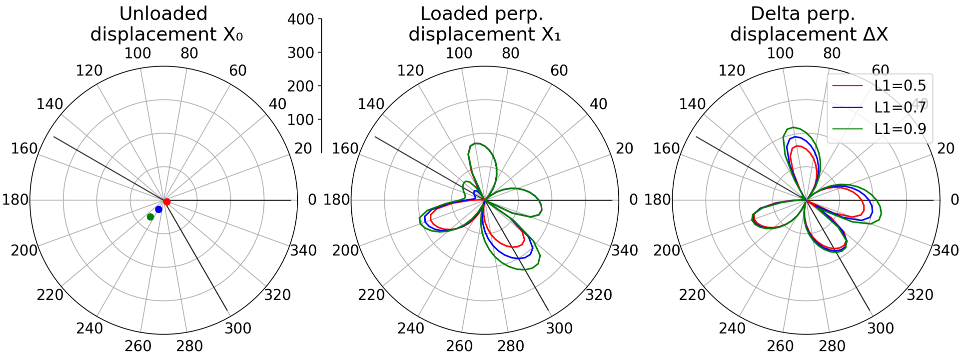

Figure 8. The unloaded and loaded equilibrium positions of the FOWT perpendicular to the wind direction and the difference between them at three line lengths values

Although a system with a longer line has a bigger displacement, the stiffness of the system in Figure 9 is just slightly affected by changing the lines lengths. The mooring system with a longer line has lower stiffness compared to a mooring system with a shorter line. A longer line means a larger section of the line's length is lying on the seabed without adding to the horizontal tension. Hence it can make a bigger displacement to increase its hanging length and hence its tension force before reaching equilibrium state. Looking at the catenary profiles shown in Figure 9 we can see that the slackest line is the longest line, and hence the least stiff.

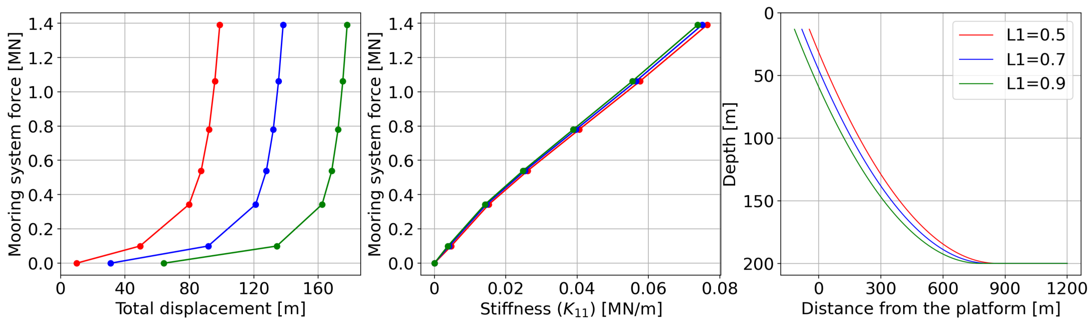

Figure 9. The mooring system forces and the corresponding FOWT's position, and the catenary shape of line one at three line lengths values

The anchor radius had almost no effect on the equilibrium states, the system's stiffness and the catenary shapes. We believe that this will always be the case as long as there are no vertical tensions on the anchors.

4. Conclusion

Through this work we found out that a FOWT can relocate its position up to $1.2D$ in the crosswind direction, depending on the stiffness of the mooring system attached to it. Different mooring designs were capable of relocating the FOWT's position passively, with different displacements for each wind direction. This flexibility of the FOWT to relocate its position can be used to mitigate the wake losses inside a floating wind farm. We explained how the mooring system's design affected the FOWT's lateral motions through analysing the mooring system's design parameters. We used the full factorial design experiment approach to perform our parametric study, iterating over each design parameter and calculating the displacement of the FOWT in each wind direction.

Studying the effect of the mooring system's headings on the FOWT's displacement showed that as long as the headings of the mooring system were kept constant, the maximum and minimum crosswind displacements happened at the same wind directions. Changing other design parameters can tune the magnitude of the displacement, but it will always occur at the same wind direction. Knowing the design headings, we can predict which wind directions will cause the maximum crosswind displacement and use the other design parameters to tune the magnitude of the displacements according to our design goals. Moreover, we showed that if two lines headings were separated by $90°$ or less, there would be no crosswind displacement for all wind directions between these two lines. Therefore, if we want to prevent crosswind motion for some wind directions we can achieve this by bringing two lines' headings closer to each other, or adding an extra mooring line. Finally, the amplitude of the displacement, in both crosswind and in the wind direction, increased if we increase the angle between two adjacent mooring lines in our system.

Investigating the effect of the mooring line diameter, we found that a FOWT attached to a mooring system of a smaller diameter was capable of making larger displacements. However, at loaded conditions the mooring system with the smaller diameter had a higher stiffness than a system with a larger diameter. This is because of the catenary profile of the mooring line, where a mooring line with a smaller diameter is more tensioned than a line with a larger diameter. The effect of the mooring line's length on the FOWT displacements, was that a mooring system with a longer line would have larger displacements. Moreover the stiffness of the longer mooring line was slightly lower than the shorter mooring line. This can be explained through the catenary profile of the lines. The longer the mooring line the more slack it was. The anchor radius had no effect on the FOWT's ability to relocate or on the mooring system's stiffness. This was because all our systems had zero vertical forces on the anchor and none of our mooring lines were taut or semi taut.

Through this work we used the same floater and turbine. We believe the floater's design and the turbine's design will have limited effect on the horizontal displacement of the FOWT, as only the mooring system provides horizontal stiffness in a FOWT. Moreover, we neglected the effect of the waves and hydrodynamic forces, because these forces are small compared to the aerodynamic forces acting on the FOWT. However, we are planning to include these forces in our future work while validating our results using dynamic simulations. Moreover, we added a constraint that no vertical tensions on the anchors were accepted, which meant no taut or semi taut mooring lines were accepted. This is because a taut mooring system made only of steel chains will have a higher stiffness and hence limit the ability of the FOWT to relocate its position. Finally, we fixed the sea water depth to $200m$ and did not check the effect of changing the depth on our system's response.

The mooring system's force-stiffness curves, in Figures 7, and 9, show there was a big change in the mooring system's stiffness whenever the overall forces of the mooring system changed. This could lead to higher fatigue loads on our mooring system when compared to the current state of the art mooring designs. However, since the FOWT is capable of relocating its position the amplitude of the tension forces in the mooring lines are lower than the amplitude of the tension forces in the current state of the art mooring designs. These smaller amplitudes mean the system can survive more fatigue cycles. We are planning to take a closer look at the ultimate and fatigue loads of the mooring system in our future work using dynamic simulations. The effect of each design parameter on the cost of the overall mooring system's cost was not discussed in this work, but will be also assessed in our future studies.

The results of this work will be used in future work to develop a new technique for floating wind farm layout optimization. Knowing that a FOWT can have different displacements for each wind direction allows us to plan the wind farm's layout to be different for each wind direction. In future work, we are planning to find the optimum wind farm layout for each wind direction then find the mooring systems capable of moving the turbines to match the results. In a floating wind farm, we can have different mooring designs attached to each FOWT according to how we want it to relocate in the wind farm layout. For example, we can rotate the mooring designs of two FOWTs such that they move in opposite crosswind directions. The potential of relocating the FOWT was shown in [5]. For one wind direction in a 3x6 wind farm, relocating the FOWTs increased the farm relative efficiency by 53.5%.

Acknowledgments
The research leading to these results has received partial funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 815083 (COREWIND).

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