Effects of yaw misalignment on platform motions and fairlead tensions of the OO-Star Wind Floater Semi 10MW floating wind turbine

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Abstract. Floating offshore wind farms (FOWFs) are subject to wake effects similar to onshore and fixed-bottom offshore wind farms. Due to the smaller surface roughness, wake recovery is slower in offshore compared to onshore wind farms. Therefore, wake mitigation methods will become relevant for FOWFs as it is for onshore and fixed-bottom offshore wind farms. A common method is to apply yaw misalignment to steer the wake out of the rotor of the downwind turbine. However, it is necessary to investigate possible effects of yaw misalignment on a single turbine before farm-level investigations. This study focuses on the motion response of the platform and damage equivalent loads (DELs) of the mooring line tensions of the OO-Star Wind Floater Semi 10MW floating wind turbine. In order to satisfy environmental variability, the effect of yaw misalignment is investigated at different wind directions and wind/wave misalignments. DELs of three mooring line tensions at the fairleads were calculated using the rainflow algorithm and were reported as relative, normalized with respect to the aligned nacelle operation. Floater motions were analyzed to understand effects of misaligned operation. The results indicate that yawed inflow leads to a complex coupled response of floating offshore wind turbines (FOWTs). At slightly above rated wind speed, the yaw misalignment generally increases DELs due to the thrust increase. Conversely, yaw misalignment operation at below rated wind speeds leads to different responses on lines depending on environmental conditions. The steady state floater position has a large impact on DELs which may lead to a yet unknown response behavior of FOWFs. DEL trends in the presence of wind/wave misalignment are similar to those of aligned wind and wave.

1. Introduction
The past two decades have seen the rapid increase in offshore wind technology research due to the superior wind resource potential in offshore compared to onshore areas [1]. Consequently, offshore wind has become a rapidly growing renewable energy technology. The offshore wind energy industry is currently dominated by fixed-bottom wind turbines, which are constrained by shallow water depths. However, it is possible to take advantage of further wind potential by venturing out into open seas with FOWTs. In recent years, different FOWT demonstrators were erected around the globe [2]. In 2017, the first FOWF, Hywind Scotland, was commissioned with 30 MW capacity [3]. There are several FOWF projects planned to be constructed in Europe in the upcoming years [3], which will increase the necessity of power optimization and load reduction of FOWTs.
Recent developments in the field of wake mitigation mostly focus on pitch control and wake steering on onshore and fixed-bottom offshore wind turbines [4]. These methods mainly help to improve the overall power generation of the farm [5] and in some cases to decrease structural loads [6]. The findings of these studies further support the idea of applying the wake deflection control strategy to FOWFs. However, it is important to investigate effects of yaw misalignment on an individual turbine before application to the whole farm. In extreme weather conditions, it is shown that yaw misalignment can cause a significant increase in anchor tensions of a FOWT [7]. This indicates that yaw misalignment could have a similar effect on fairlead tensions during normal operation and should therefore be investigated.

The main difference between floating and fixed-bottom turbines is that the sub-structure is not fixed but free to translate and rotate. Therefore, the presence of yaw misalignment is expected to result in an unconventional motion response of the floater, and the FOWT is likely to experience a tension transmission between the mooring lines. Asymmetric loading on the mooring lines will consequently affect the fatigue. It is necessary to investigate its consequences before adapting this control strategy for floating offshore wind farms. The present study will focus on effects of yaw misalignment on the platform motion response and DEL of mooring line tensions at the fairleads of a FOWT.

The following section describes the floating wind turbine, simulation tools and combinations, environmental conditions, and the post-processing methodology. The results are divided into subsections according to environmental conditions; namely wind speed, wind direction, and wind/wave misalignment. To avoid excess plotting, a single case is chosen from variable combinations where investigated effects are most apparent. DELs and frequency analysis of mooring line tensions at fairleads are discussed along with platform motions. Conclusions as well as possible areas of future research are given in the final section.

### 2. Methodology

The simulations were carried out with the aero-servo-hydro-elastic tool OpenFAST v2.2.0 [8] developed by the National Renewable Energy Lab (NREL). Each parameter combination was simulated with six wind field realizations of 1-hour simulations. The DTU 10 MW reference turbine [9] adapted with the Olav Olsen-Star Wind Floater [10] from the LIFES50+ project was used in this research. The DTU 10 MW reference turbine tower mass was almost doubled to increase the tower eigen-frequencies above the blade-passing frequency (3P) range as reported in LIFES50+ [11]. In LIFES50+, the basic DTU Wind Energy controller replaced the baseline controller to solve the negative damping problem using the pole-placement method [10].

| Parameter               | Value                                      |
|-------------------------|--------------------------------------------|
| Wind Speed              | [5.0, 7.1, 10.3, 13.9] m/s                 |
| Wind Direction          | [0, 30, 60] deg                            |
| Nacelle Misalignment    | [−30, −20, −10, 0, 10, 20, 30] deg         |
| Wave Misalignment       | [0, 15, 90] deg                            |
| Current                 | 0 m/s                                      |

The simulation variations, which were covered in this study, are given in table 1. It is noted that the mooring line tension varies depending on the wind direction. Therefore, wind direction of
0, 30 and 60 degrees were simulated to cover many possible loading scenarios making use of the 120-degree symmetry of the floater. Three cases of wave misalignment were introduced: aligned, slight (15 degrees) and substantial (90 degrees) misalignment to account for the variability of waves. The yaw misalignment was simulated from negative to positive 30 degrees with 10-degree increments.

The geometry of the system was defined in the FAST coordinate system and is given in figure 1. Surge and sway motions correspond to x- and y-directions in the fixed-frame, respectively. Wind propagation direction was defined from the 0 degree line and clockwise rotation corresponds to a positive wind angle. Yaw and wave misalignments were described relative to the wind direction. In this case, clockwise rotation corresponds to a negative misalignment and vice-versa. The floater was free to translate and rotate. Thus, it is essential to recognize that the angle between the wind direction and the rotor varies slightly as the platform yaws.

![Figure 1. Description of the OO-Star Wind Floater Semi 10MW floating wind turbine coordinate system and propagation direction of wind, wave, and yaw misalignment.](image)

The turbulent wind and the corresponding significant wave heights and peak periods were set based on the LIFES50+ report for Design Load Case (DLC) 1.2 [12] for the Gulf of Maine area and is shown in table 2. The simulations were carried out as close as possible to the IEC standard 61400-3 [13] for normal power production under turbulent wind conditions. Six realizations of periodic 1-hour turbulent wind fields were created with TurbSim [14] using the Kaimal normal turbulence model. The first 1200 seconds of each 4800 seconds simulation were removed to account for the transient effects caused by the initial conditions. Since wake steering is of interest at below rated operation, most of the selected speeds lie below the rated wind speed, 11.4 m/s. As reported in LIFES50+, the wind turbulence was set to Class C [11].

| Wind Speed [m/s] | Wave Height [m] | Wave Period [s] |
|-----------------|----------------|-----------------|
| 5.0             | 1.38           | 7.0             |
| 7.1             | 1.67           | 8.0             |
| 10.3            | 2.20           | 8.0             |
| 13.9            | 3.04           | 9.5             |
The mooring lines were simulated as lumped-masses using MoorDyn [15] with 100 segments per line and irregular waves were created using the JONSWAP spectrum. Hydrodynamic loads were calculated based on potential flow theory and the 2nd-order floating platform forces are computed with Newman’s approximation with the help of AQWA [16]. Only one realization of stochastic waves per wind field was considered for the simulations, since the focus of this work is to analyze effects of yaw misalignment rather than waves. Currents were not taken into consideration.

Skewed wake effects appear when inflow yaw misalignment is introduced. Thus, Pitt/Peters [17] skewed wake correction model was used in AeroDyn [18] to capture the skewed wake effects as much as possible. In future works, it is important to carry out a sensitivity analysis on the wake models and their effect on the fatigue loading of mooring lines.

Platform displacements and rotations as well as three fairlead tensions are the main interests for each of the wind speeds, wind directions, wave misalignment, and yaw misalignment angles. Mean of floater displacements and rotations were averaged for six realizations to acquire a representative steady state value. Standard deviations of the realizations were combined using the pooled standard variance method [19], given as:

\[
s_{\text{pooled}}^2 = \frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2 + \ldots + (n_k - 1)s_k^2}{n_1 + n_2 + \ldots + n_k - k}
\]

where \(n_k\) is the sample size and \(s_k^2\) is the sample variance of the simulation \(k\).

DELs of three mooring line tensions at the fairleads were calculated from time series using the rainflow algorithm for 1 Hz. They are reported with an averaged value per combination and a standard deviation of six simulations. Moreover, DELs were normalized with respect to the base case, which is the aligned orientation for each wind speed and fairlead.

3. Results

The results are divided with respect to environmental conditions to understand some of the underlying causes of mooring line loading behavior under yaw misaligned operation. The first three subsections cover the aligned wind/wave combinations. Results of the 0 and 60 degree wind propagation are considered initially, because these directions lead to symmetry between two of the fairleads. It is followed by the investigation of platform motions and DELs at 30 degree wind direction. Lastly, the presence of wind/wave misalignment is evaluated. DELs are reported in percentages. The marks in the plots represent mean value of six turbulent wind simulations and the transparent areas represent standard deviations.

3.1. Wind propagation direction of 0 degrees

It is essential to clarify the influence of yaw misalignment at different wind speeds on the results of interest. Figure 2 shows the DELs of the mooring line tensions at the fairleads where each plot represents one fairlead for the wind speeds of interest. In the following discussion, the names of fairleads are shortened to F1, F2, and F3 according to figure 1.

The DELs of F1 present a similar trend below the rated wind speed, 11.4 m/s. Yaw misalignment introduces a reduction in DELs under rated wind speed simulations. Both the positive and negative 30 degree yaw misalignment result in 25 to 30% reduction in DELs. However, an inverse trend is observed for the above rated speed turbulent simulations. An increase of approximately 55% is found at negative and positive 30 degree misalignment. Trend of F1 DELs at above rated speed is mostly a consequence of the controller’s reaction to yaw misalignment. In region 3, the pitch actuator becomes operational and the thrust is reduced as wind speed increases. When the nacelle yaws, the wind speed component that is perpendicular to the rotor decreases. This results in lesser pitch angles at rated power and finally, no pitching in region 2. As a result, the thrust and F1 DELs increase. In 13.9 m/s turbulent wind simulations,
platform surge and pitch motions are not largely affected by the yaw misalignment. Sway, roll and yaw motions are similar to those of below rated wind speeds, but at a higher amplitude.

The DELs at F2 and F3 are influenced by platform motions, but the effect of the pitch controller is no longer as visible as it is for DELs at F1. DELs can increase more than 60% depending on the yaw misalignment direction. At above rated wind speed, the direction change of the thrust force provokes sway and surge motions of the platform which in turn induce higher loading on the mooring lines. However, deriving a concrete conclusion for DELs at F2 and F3 is more complex than that of F1.

The frequency analysis of the mooring line tension at F2 for one of the wind realizations is given in figure 3. It is clear that the main excitation comes from the surge-sway natural frequency region, which was reported as 0.0055 Hz in the LIFES50+ project [10]. At 5 m/s wind speed, positive yaw misalignment induces higher loads compared to negative 30 degree and aligned operation. It is observed that the loading at 30 degree yaw misalignment is only slightly higher than the aligned, which corresponds to the frequency domain analysis results.

As the wind speed increases, loading at negative 30 degree yaw misalignment is much higher than aligned operation and surpasses the loading at 30 degree yaw misalignment at 10.3 m/s wind speed. It was expected that the negative mean sway motion would cause higher loads at F2 and lesser increase in the loads at F3. However, mean sway motion at wind speeds 5 m/s
and 7.1 m/s is not the driving factor for this excitation. This aspect is better investigated at lower wind speeds where the positive misalignment results in higher DELs at F2. Before moving to lower wind speeds and diving deeper into platform motions, it is crucial to recognize that due to symmetry of the platform, F2 and F3 experience similar loading trends with opposite yaw misalignment. Furthermore, a 10% difference is observed when DELs of F3 at positive yaw misalignment and of F2 at negative misalignment are compared. The gyroscopic effect of the rotor’s rotation is expected to be the driving factor of the difference.

Aiming to identify the causes and establish relationships between steady state platform motions and fairlead DELs, one of the below rated wind speeds is investigated. It should be noted that platform motions below rated wind speeds have similar trends with changing amplitudes. Platform motions and DELs at 7.1 m/s wind speed are taken as the exemplary case and is shown in figure 4.

![Figure 4. Platform motions and relative fairlead DELs at $\theta_{\text{wind}} = 0^\circ$, $\theta_{\text{wave}} = 0^\circ$ for 7.1 m/s wind speed.](image)

It is relatively easy to derive a conclusion for the DELs at F1 similar to the above rated wind speed results. At below rated wind speeds, mooring line tension at F1 follows the trend of mean surge motion. The mean pitch motion is affected similarly to the surge motion. Another study on directionality effects of aligned wind/wave [20] reports that without wave effects, sway-surge motions are determined by the thrust and restoring forces from mooring lines. The decrease of thrust in surge direction with yaw misalignment prompts less surge motion and consequently, lower DELs at F1. The heave motion is not affected by the yaw misalignment and does not contribute to any change of DELs.

Despite the notable mean sway motion change due to negative yaw misalignments, the increase in the DELs of F2 is lower than that of F3. One possible explanation is that the platform yaw rotation is as important as the mean surge and sway motions. The platform performs a counter rotation to the nacelle rotation direction. The higher the wind speed, the higher the platform yaw motion. However, this motion is limited by mooring lines, because they provide restoring forces in the yaw degree of freedom. Nevertheless, the yaw rotation changes the position of fairleads in the global coordinate system, and in turn changes the loading of the mooring lines. It could indicate that at higher wind speeds, mean sway motion is dominating the increase in DELs of fairleads while the mean yaw rotation is dominating at lower speeds. It is possible to observe up to 10 meters displacement in sway degree of freedom at 10.3 m/s wind
speed, where F2 DELs are boosted much more than DELs at F3. This loading situation presents an interesting phenomenon which requires further investigation of the fairleads’ global positions in time domain. Another interesting observation is that DEL standard deviations of F2 and F3 are much larger at higher yaw misalignments. Standard deviations of the sway motion display the same trend, which is even clearer at 10.3 m/s wind speed.

It should be noted that at 7.1 m/s and 0 degree wind propagation direction, 30% decrease on the F1 DELs corresponds to much higher absolute loads than the combined 35% increase of F2 and F3. This is due to very high thrust in the surge direction.

### 3.2. Wind propagation direction of 60 degrees

The wind direction is essential to the loading behavior of mooring lines. Depending on the wind direction change, mooring lines transfer loading to each other. The transition of the wind direction from 0 to 60 degrees leads to a load transfer from F1 to F2 until they were approximately equal due to new symmetry. Platform motions and fairlead DELs are shown in figure 5 for 60 degree wind direction. In misaligned operation, DELs at F1 and F2 have symmetric behavior. Investigation of platform motions present an expected correlation of surge motion with F1 DELs and sway motion with F2 DELs. DELs at F3, on the other hand, change with the combined motion of the two. At negative 30 degree misaligned operation, it is possible to reduce the DEL of F1 by 37% and of F3 by 11% while boosting the DEL of F2 by approximately 4%. Overall, misaligned operation can induce additional mean loading up to 6.3% at F1; however, the loading of other lines are reduced as can be seen in the figure below.

![Figure 5](image.png)

**Figure 5.** Platform motions and relative fairlead DELs at $\theta_{\text{wind}} = 60^\circ$, $\theta_{\text{wave}} = 0^\circ$ for 7.1 m/s wind speed.

A brief mention of above rated wind speed, 13.9 m/s, is necessary, because the yaw misalignment induces negative overall outcome on the DELs at the fairleads. A positive 30 degree misalignment can lead to 75% increase in the DEL of F1, 20% in that of F2 and 9% in that of F3. Negative misalignments result in 69% increase in DEL at F1, 17% at F2 and 10% at F3.

### 3.3. Wind propagation direction of 30 degrees

Unlike the other two wind directions, 30 degree misalignment does not cover any mooring line symmetry. It is difficult to make conclusions for this case due to effects caused by complex
Figure 6. Platform motions and relative fairlead DELs at $\theta_{\text{wind}} = 30^\circ$, $\theta_{\text{wave}} = 0^\circ$ for 7.1 m/s wind speed.

interactions of platform motions on fairlead DELs. The mean platform sway motion decreases with positive misalignment since the rotor becomes perpendicular to the 0 wind direction at 30 degree misalignment. Naturally, nacelle rotation to negative misalignment causes a decrease in surge direction which affects F1 the most. The yaw motion is identical to those of other wind directions. An interesting outcome of positive yaw misaligned operation is that all three fairlead DELs can be decreased. Negative 30 degree yaw misalignment leads to a reduction only for DELs of F1, up to 41%. The maximum mean DEL increase of F1, F2 and F3 in the investigated range of misaligned operations are 3.2%, 10.6% and 3.4%, respectively.

Once again a brief mention of above rated wind speed, 13.9 m/s, is necessary. In this case, a positive 30 degree misalignment can lead to 11% reduction in the DELs of F2, 3% in that of F3 and a boost of 84% to the DEL at F1 which is the main load bearing line out of the three. Negative 30 degree misalignment results in increase of all DELs, particularly 106% at F2.

3.4. Wave misalignment
Here, the comparison is solely between the DELs at yawed operation and aligned operation. The effect of wave misalignment to aligned wind/wave is not investigated. The observation focuses on the influence of yaw misalignment in the presence of wave misalignment.

When the wave misaligned simulations were examined, it was found that the presence of wave misalignment did not change the increase or decrease trends of DELs with respect to yaw misalignment. The most affected configuration is given in figure 7 at 7.1 m/s wind speed and 30 degree wind propagation direction. Similar to the previously reported DELs, they are normalized and relative to their environmental conditions at 0 degree yaw misalignment.

It is clear that the presence of high wave misalignment induce larger increase at negative yaw misalignments and lower reduction at positive misalignments for F2 and F3. DELs of F2 at 0 and 15 degree misalignments correspond to a 3% increase in loading at negative 30 yaw misalignment, whereas 90 degree wave misalignment corresponds to an approximate 8% increase. Approximately 36% of F2 DEL reduction is observed for aligned wind/wave and 15 degree misalignment. On the other hand, 90 degree wave misaligned simulations result in 31% reduction. This is the most extreme below rated wind speed case in which having wave misalignment causes the most negative outcome in terms of DELs. The effect of wave
misalignment presence on DEL trend with respect to yaw misalignment is minimal. However, in this study, the change in absolute loading with wave misalignment is not considered as everything is normalized and relative to their own aligned operation. Therefore, the presence of wave misalignment should be taken into account during yaw misaligned operations.

4. Conclusion
In this study, effects of yaw misalignment on platform motions and DELs at fairleads of a FOWT are investigated. In order to account for environmental variability simulations with various wind speeds, wind directions, and wind/wave misalignments were carried out. Each combination of environmental conditions were simulated for six 1-hour realizations of turbulent wind fields. Platform motions of six realizations were averaged and pooled standard deviations were calculated. DELs at fairleads were calculated using the rainflow algorithm and the average DELs of 6 realizations along with the standard deviations were presented.

It is shown that the relative changes of DELs at fairleads with yaw misalignment are dissimilar for different wind speeds. At slightly above rated wind speeds, the introduction of yaw misalignment can induce up to 70% increase of DELs at a fairlead. This was mainly traced back to the controller’s transition from region 2 to 3. At below rated wind speeds, the coupled effect of platform displacements and rotations introduce the different trends of the relative change of DELs. For a wind speed of 10.3 m/s, the mean platform motion on surge and sway directions dominate the relative change of DELs whereas for a wind speed of 5 m/s, yaw motion of the platform is considered to be more effective than sway-surge motions.

This study explores the influence of yaw misalignment on a FOWT for three wind direction cases which would cover many possible directions due to symmetry of the platform. Yaw misalignment results in distinct relative changes of DELs at different wind directions. Also, platform motions do not resemble those at another wind propagation direction except for the yaw rotation and heave. However, for wind directions of 30 and 60 degrees and a wind speed of 7.1 m/s, yaw misalignment does not promote more than 10.6% increase in DELs at a fairlead. Moreover, it is shown that yaw misalignment could reduce DELs at all fairleads in specific environmental conditions. Presence of wind/wave misalignment does not create differences in loading trends during yaw misalignment. The relative change of DELs with yaw misalignment
is almost identical between aligned wind/wave and misaligned wind/wave cases.

It is clear that the steady state floater position has a large impact on DELs and is largely affected by yaw misalignment. Future work will cover a more in-depth research on the dynamic motion of the fairleads during yaw misaligned operation to interpret the effects of platform rotation along with the mean surge and sway motions.

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