Effects of upstream rotor tilt on a downstream floating wind turbine

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Abstract. This work quantifies the relationship between the design tilt of an upstream rotor and the structural response of a spar floating offshore wind turbine located in its wake. Three wind speed scenarios are considered: below, at, and above rated operation. The inflow is generated with the Mann model and the wake and loads are simulated with FAST.Farm. As the upstream rotor tilt goes from 0° to 6°, we find that the mean wake is displaced upward by more than 0.2 rotor diameters (D) by a downstream distance of 7 D. The vertical velocities increase by up to 35 cm/s in the center of the wake. As a result, the downstream rotor is partially waked and experiences a rotated velocity vector. With a higher upstream rotor tilt, the velocities and moments on the downstream turbine increase their mean axial value and their lateral and vertical standard deviation. These changes affect the blade and tower loading and the floater motion primarily in the out-of-plane direction: the damage-equivalent loads for the tower pitch moment and blade-root moment increase by up to 10% because of higher variability at the first mode for the tower and at one blade passing frequency for the blade root. Lesser effects are observed for the roll moments and for floater sway and heave. When the joint effect of rotor tilt and platform motion is considered, the load response on the downstream system is amplified primarily for tower pitch and blade out-of-plane moment.

1. Introduction
The tilt angle of a wind turbine rotor directly affects its wake and, consequently, the power and loads on downstream turbines. This relationship has been studied primarily in two contexts: wake-steering control and floating offshore design. The potential of using rotor tilt to vertically steer wakes and maximize wind power plant performance has been found promising for land-based downwind rotors when the possibility of tower strike is not an issue [4, 3, 1, 2, 10]. In the context of floating offshore wind, tilt can be seen as a control parameter [7] and dynamic operational parameter that is modulated by the platform pitch motion. This back-and-forth rotation of the floater has been found to push the wake upward and modify the mean and turbulent wake characteristics, especially in low-turbulence settings [9, 8, 6]. While the mean platform pitch angles of a floating system might be small (1°-3° according to a modeling study of spar and semisubmersibles [5]) when compared to those required for power gains through control (10°-30° according to several studies [4, 3, 1, 2]), these floater pitch-induced changes in
tilt need to be considered in the design process along with other similar parameters, such as rotor precone and design tilt [10, 9].

While the effect of rotor tilt on wakes has been extensively analyzed, no studies have considered how these changes in the wake affect the structural response of a downstream, floating wind turbine. To support the design of floating systems, we need to understand how rotor tilt, as a design parameter, affects the wake and downstream turbines even before the effects of platform pitch are considered. Here, we address this unknown by performing simulations of a realistic offshore wind turbine to quantify the effects of upstream rotor tilt on the structural response of a downstream, spar floating wind turbine.

2. Simulations

All simulations consider a pair of 6-MW offshore wind turbines separated by 7 rotor diameters (D) and aligned with the mean wind under three wind speed scenarios: below rated, at rated, and above rated. To isolate the effects of design tilt (i.e., to exclude the effects induced by the platform pitch), the platform motion is turned off for the upstream turbine but maintained for the downstream turbine. The rotor tilt of the upstream rotor is varied between 0°, 3°, and 6°.

All simulations are performed with Mann turbulence inflow and the midfidelity wind plant model FAST.Farm. The FAST.Farm version used in this study does not yet incorporate the curled wake model and does not include wake-added turbulence, which are forthcoming features.

The turbulent inflow to the simulations is prescribed from Mann boxes. One box is generated for each wind speed scenario, using the parameters given in table 1. During the wake simulations, a mean wind speed profile is added to the turbulence field following the reference height wind speed \( U_{\text{ref}} \) and power-law shear exponent \( \gamma \) in table 1, where the reference height \( z_{\text{ref}} = 157.5 \) m is the vertical center of the box. The turbulence intensity values chosen for each scenario represent offshore conditions, ranging between 6.4% and 7%. We did not simulate waves in any of the cases.

| Simulation Scenario | nx [m] | ny [m] | nz [m] | \( \Delta x [m] \) | \( \Delta y [m] \) | \( \Delta z [m] \) | \( \alpha \epsilon^{2/3} [m^{4/3} s^{-2}] \) | \( L [m] \) | \( \Gamma \) | \( U_{\text{ref}} [m/s] \) | \( \gamma \) | \( I [%] \) |
|--------------------|--------|--------|--------|----------------|----------------|----------------|-------------------|--------|--------|----------------|--------|------|
| Below rated        | 4096   | 128    | 64     | 5             | 5             | 5             | 0.011             | 33.6   | 3.9    | 8.4            | 0.10   | 6.4  |
| At rated           | 4096   | 128    | 64     | 5             | 5             | 5             | 0.019             | 33.6   | 3.9    | 10.9           | 0.10   | 6.4  |
| Above rated        | 8192   | 128    | 64     | 5             | 5             | 5             | 0.129             | 33.6   | 3.9    | 26.4           | 0.12   | 7.0  |

Table 1: Parameters used to generate turbulent inflow with the Mann model: number of points along \( x \) (nx), \( y \) (ny), and \( z \) (nz) directions; spatial discretization along \( x \) (\( \Delta x \)), \( y \) (\( \Delta y \)), and \( z \) (\( \Delta z \)) directions; viscous energy dissipation parameter (\( \alpha \epsilon^{2/3} \)); eddy length scale (\( L \)); shear distortion parameter (\( \Gamma \)). The reference height wind speed (\( U_{\text{ref}} \)), power-law shear exponent (\( \gamma \)), and ambient turbulence intensity (\( I \)) used in each scenario is also given.

We simulated the wake and load response with FAST.Farm. The two wind turbines are defined identically, except for two parameters: rotor tilt and platform motion. While the rotor tilt of the upstream turbine varies for each simulation, the downstream rotor is always simulated with a tilt of 6°. Finally, while the downstream turbine platform is allowed six degrees of freedom, the upstream floater is stationary. The temporal and spatial parameters used in FAST.Farm for each wind speed scenario are given in table 2. The spatial discretization of the farm-scale (\( \Delta x_{\text{Low}}, \Delta y_{\text{Low}}, \Delta z_{\text{Low}} \)) and turbine-scale (\( \Delta x_{\text{High}}, \Delta y_{\text{High}}, \Delta z_{\text{High}} \)) domains within FAST.Farm was set to 5 m to match that of the Mann inflow and thereby avoid interpolation.
Simulation Scenario $\Delta t$ $\Delta t_{\text{high}}$ nx$_{\text{low}}$ ny$_{\text{low}}$ nz$_{\text{low}}$ nx$_{\text{high}}$ ny$_{\text{high}}$ nz$_{\text{high}}$ Wake Planes
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Below rated 1.0 0.2 525 128 64 50 50 40 175
At rated 1.5 0.375 600 128 64 50 50 40 140
Above rated 1.125 0.375 600 128 64 50 50 40 100

Table 2: Spatial and temporal parameters used to define the farm-scale (subscript “low”) and turbine-scale (subscript “high”) computation grids within FAST.Farm: time step ($\Delta t$); number of points along $x$ (nx), $y$ (ny), and $z$ (nz) directions; and number of planes used to track the wake as it advects downstream.

Figure 1: Mean vertical wake center at $x/D = 7$ relative to the turbine hub height, for the three wind speed scenarios and upstream rotor tilt values.

Figure 2: Mean vertical velocity at $x/D = 7$ for the rated wind speed scenario. Values are for the 6° rotor tilt simulation relative to the 0° rotor tilt simulation.

Figure 3: Vertical profile of mean vertical velocity at $x/D = 7$, $y/D = 0$ for the three wind speed scenarios and the 0° and 6° rotor tilt cases.

3. Results
3.1. Wake
The wake is analyzed on a $y - z$ plane at a distance of $x/D = 7$ downstream of the first wind turbine. This is the exact distance between the two turbines, so we performed a separate simulation for each case to include only the upstream turbine and sample the wake flow field at the exact location where the downstream turbine sits. Therefore, the wake flow field analyzed here is not affected by the presence of the second wind turbine.

Results show a clear upward shift in the mean wake center for the below and rated cases (figure 1). The wake center moves up by more than 0.2D between the 0° and 6° simulations in the below-rated and at-rated wind speed scenarios. We also see an increase in the mean vertical velocity field spanning the entire footprint of the wake, as exemplified in figure 2. The vertical velocity increase is highest at the wake center and reaches up to 35 cm/s in the rated wind speed scenario. The vertical distribution of vertical velocities sampled at the wind turbine location ($y/D = 0$) is shown for the three wind speed scenarios and two rotor tilt values in figure 3. The analysis reveals that $w$ is enhanced in the three wind speed scenarios but that this enhancement is most prominent at rated wind speed. As the wake moves up with higher rotor tilt angles, the streamwise velocity increases below hub height and decreases above it (not shown...
now, but will be discussed more later). The combination of upward wake displacement and increased vertical velocity causes the downstream rotor to be partially waked and to experience a rotated velocity vector and different velocity magnitudes. The effect of these changes on the aerodynamic footprint of the downstream rotor will be analyzed next.

3.2. Rotor aerodynamics

When the downstream rotor is partially waked, the rotor bottom experiences higher, free stream wind speeds. This has three aerodynamic repercussions: the rotor as a whole experiences higher velocities and therefore higher forces; these forces are spatially uneven across the rotor area and lead to higher moments on the rotor; this uneven aerodynamic footprint leads to more temporal variability in the velocities, forces, and moments.

To quantify the aerodynamic changes experienced by the downstream rotor as the rotor tilt of the upstream rotor changes, we analyze rotor-integrated velocities and moments for the below and rated wind speed scenarios and the three rotor tilt configurations. The distributions (figures 4 and 5) are shown for three loading directions in a hub coordinate system: normal to the rotor \( (x_h) \), laterally parallel to the rotor \( (y_h) \), and vertically parallel to the rotor \( (z_h) \). This coordinate system rotates with the rotor, and the \( z_h \) axis is aligned with one of the blades. These figures reveal that the velocities and forces on the downstream rotor do not change linearly with upstream rotor tilt—the changes are relatively small when comparing \( 0^\circ \) to \( 3^\circ \) and are much more pronounced between \( 3^\circ \) and \( 6^\circ \).

When we compare the \( 0^\circ \) and \( 6^\circ \) cases, we can identify clear trends. The velocities and moments normal to the rotor have a higher mean value at \( 6^\circ \) (figures 4a and 5a). For the below and rated cases, respectively, the velocities are \( \sim 2\% - 3\% \) higher and the moments are \( \sim 4\% - 6\% \) higher. The velocities parallel to the rotor, laterally (figure 4b) and vertically (figure 4c), preserve their zero-mean distributions across the three rotor tilt cases. However, the range and variability of the distributions change substantially: below rated, the standard deviation of the lateral and vertical velocities increases by \( \sim 25\% \); at rated, the increase is \( \sim 18\% \). The higher velocities are not equally distributed across the rotor and lead to higher mean and standard deviation in the moment distributions. The median in-plane moments increase four-fold in magnitude for the rated wind speed scenario (figures 5b and 5c). The standard deviations of the in-plane moments also increase, by \( \sim 9\% \) below rated and \( \sim 18\% \) at rated.

![Figure 4](image-url)

(a) Normal, Out of Plane  (b) Lateral, In Plane  (c) Vertical, In Plane

Figure 4: Distribution of rotor-averaged moments experienced by the downstream wind turbine. Moments are on the hub coordinate system. Values are shown for the below-rated and rated simulations (colors) and for the upstream rotor tilt of \( 0^\circ \), \( 3^\circ \), and \( 6^\circ \) (dashes).
3.3. Structural response

In terms of structural response, we analyze how the upstream wind turbine rotor tilt affects the downstream turbine tower and blade loading and platform motion.

Figure 6 shows time averages and short-term damage equivalent loads (DELs) for the simulations with an upstream rotor tilt of 0° and 3° normalized by the same quantity for the 6° rotor tilt simulation. We see that in terms of mean loads (figure 6a), higher rotor tilt leads to higher tower-top pitch moment and lower the tower-base roll moment. These trends are the same for the rated case (not shown here). In terms of DEL (figure 6b), differences are seen for tower top and base pitch moments and blade root out-of-plane moments (note that we are not comparing the two bars to each other in figure 6, but rather both of them to the reference value of 1.0). These differences reach magnitudes of up to 10%, with the 6° case having the highest DEL values. The tower-base roll moment and blade-root in-plane moment DEL differences stay below 5% and do not show clear trends.

Figure 6 shows power spectra for the downstream wind turbine tower and blade. This analysis reveals that the 6° case has consistently lower power at the low frequency end of the spectrum.
Therefore, the higher DEL shown in figure 6b for the 6° case is coming from mid to high frequencies. Note that the spectral peak seen near $10^{-2}$ Hz for some quantities is likely coming from the turbulent inflow, as it is also seen in the spectra of the hub-height axial velocity at the upstream and downstream wind turbines (not shown). However, the frequencies responsible for the load changes in response to upstream rotor tilt are higher, as will be described below.

![Figure 7: Power spectral density (PSD) for the tower, blade, and platform of the downstream wind turbine when the upstream rotor has a tilt angle of 0° (red, solid line) vs. 6° (black, dashed line). The 3° rotor tilt results are omitted for clarity. The spectra are shown only for the below-rated wind speed scenario, and are derived from a 2000-second time series using a hanning window of 600 s.](image)
In the case of tower-top pitch moment (figure 7b), the spectral peak responsible for these differences in variance is found at the tower eigenmode. For tower base (figure 7a), the variance difference driver is the second spectral peak at mid frequencies. Results from the floater pitch motion are similar (not shown).

The tower-base roll moment (figure 7c) also exhibits a second spectral peak with the same trend: higher power for the 6° case. Its location is further down the spectral range than the tower base pitch signal, and its location corresponds to the floater roll eigenmode. Results for the floater roll are similar, but omitted here. A small sensitivity to rotor tilt was seen in the spectra for sway and heave. No sensitivity to rotor tilt was observed for the floater surge and yaw.

For blade-root out-of-plane moment (figure 7e), we also see that a higher rotor tilt increases the 1P spectral power at 0.1 Hz (the rotor speed is $\sim 6.2$ rpm for the below-rated case shown), confirming the DEL results in figure 6b. No sensitivity to rotor tilt was seen for the blade-root in-plane moments (figure 7f).

### 3.4. Compounded effect of rotor tilt and floater pitch

Up to this point, the analysis considered the effect of upstream rotor tilt on the response of a downstream wind turbine when the upstream platform is fixed. Here, we consider a scenario in which the upstream platform is allowed six degrees of freedom. We investigate the compounded effect of design rotor tilt and platform pitch motion on the downstream turbine. For this analysis, we consider only the below-rated wind speed scenario. We performed three simulations, one for each of the rotor tilt values considered in this study: 0°, 3°, and 6°.

We see a clear effect of the platform motion on the wake at $x/D = 7$ regardless of the upstream rotor tilt angle. This effect is shown for the simulation without rotor tilt in figure 8. With added platform motion, the streamwise wind velocity increases on the lower half of the rotor and decreases on the upper half by up to 0.5 m/s. The platform motion also increases the vertical velocity throughout the wake footprint by up to 15 cm/s.

![Figure 8](image_url)

Figure 8: Difference in streamwise and vertical velocity in the wake of the upstream turbine at $x/D=7$ for the floating minus fixed scenarios. The data refer to the below-rated wind speed case with an upstream rotor tilt of 0°. The black circle outlines the rotor position.

To consider the compounded effects of rotor tilt and platform pitch, we compare the results of the zero-tilt fixed platform simulation to those of the six-tilt floating platform. While the rotor tilt alone had led to an increase of up to $\sim 29$ cm/s for the below-rated case, the platform motion and rotor tilt combined lead to an increase of $\sim 43$ cm/s (figure 9a). The changes in streamwise velocity follow the same trend, but also present higher magnitudes when both effects are combined, surpassing 1 m/s (figure 9b).
Figure 9: Difference in the time-averaged vertical profiles of vertical (a) and streamwise (b) velocities sampled in the wake of the upstream wind turbine (at $x/D = 7$) for the below-rated wind speed scenario. The velocities are sampled at the lateral position of the wind turbine ($y/D = 0$). The black line shows the effect of upstream rotor tilt on the wake velocities (i.e. the differences shown are for the cases in which the upstream wind turbine is “fixed” but the upstream rotor tilt is either 6° or 0°). The red line shows the combined effect of upstream rotor tilt and platform motion on the wake velocities (i.e. the differences shown are for the case with a floating, 6°-tilt upstream wind turbine vs. a “fixed”, 0°-tilt upstream wind turbine).

The amplified effect of rotor tilt and platform motion on the wake amplifies the load response of some components on the downstream wind turbine. Of all quantities considered in this work, the ones that responded most significantly to the added degrees of freedom to the upstream turbine were tower pitch moment and blade-root out-of-plane moment (figure 10). To a lesser extent, an effect was also detected on the floater heave and sway (not shown).

Figure 10: Same as in figure 7 but showing a limited set of quantities and comparing the simulations in which the upstream wind turbine was fixed with a 0° rotor tilt, fixed with a 6° rotor tilt, and floating with a 6° rotor tilt.
4. Discussion
This study revealed that rotor tilt, as a design parameter, has a direct effect on the structural loading of a floating offshore wind turbine. These effects are related to the upward displacement of the wake as a whole and the added vertical velocity in response to increased rotor tilt. These wake changes lead to higher mean axial velocities and moments on a downstream, partially waked rotor, and higher standard deviation of lateral and vertical velocities and moments. These aerodynamic changes, in turn, can lead to higher fatigue loads on the tower because of increased pitch moments and on the blade because of increased out-of-plane moments. The added variance of these moments is due to specific frequencies, which were identified with spectral analysis. For the tower top, it coincides with the first mode of the structure. For the blade root, it coincides with the 1P blade-passing frequency. These fore-aft effects are also observed on the platform motion, although the spectral analysis was not explicitly shown here. Lesser but noticeable changes were also seen in the spectra for the tower base and platform roll.

A brief analysis considered the joint effect of design tilt and platform motion. The results revealed that changes in the wake at a distance of 7D downstream can surpass 1 m/s in the streamwise velocity component and 40 cm/s in the vertical velocity component. These changes primarily affect the tower pitch moment and blade-root out-of-plane moment.

The analysis presented here considered three wind speed scenarios: below, at, and above rated. The trends and magnitudes were similar for the below and at-rated cases. Above rated, the wake was extremely weak at the considered distance of 7D and the effects on the downstream rotor were not substantial.

The results of this study reveal that rotor tilt alone, even on a stationary platform, can directly affect the structural response of a spar floating wind turbine. These effects can be even more pronounced when platform motion is also considered. The study conducted here utilized a midfidelity wake model, which has a simplified physical description of the wake with several assumptions and parameterizations. Follow-up research should consider high-fidelity simulations and more turbulence scenarios to better understand how tilt, as a design and control parameter, can potentially be leveraged in the future of floating offshore wind technology.

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