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Effect of floating wind turbine wakes on the thrust dynamics of a downstream turbine

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Abstract. Floating offshore wind turbines (FOWTs) experience platform-induced motions that modulate power and rotor thrust and can imprint coherent disturbances on the wake, with potential implications for both wind farm yields and fatigue of downstream turbines. Control strategies such as dynamic yawing can also improve wind farm performance at the expense of increased fatigue. This work presents wind tunnel experiments investigating how imposed surge, pitch, and yaw motions of an upstream model turbine affect the thrust response of a downstream turbine operating in the wake under low-turbulence inflow conditions ($TI \simeq 2\%$). Two identical performance-scaled models of the DTU 10MW turbine are arranged in tandem at spacings of 2–5D. The upstream turbine is subjected to prescribed harmonic motions characterized by the Strouhal number and normalized motion velocity (surge/pitch) or yaw amplitude (yaw). Results show that low-frequency surge and pitch motions produce a clear periodic response in downstream thrust, whereas higher-frequency surge/pitch cases do not yield discernible peaks at the imposed motion frequency. For prescribed yawing motions, an increase in mean downstream thrust is observed with increasing Strouhal number and yaw amplitude, while spectral signatures appear primarily as sidebands around the rotor frequency. These findings help clarify which motion-induced disturbances persist through the wake in low-TI conditions and provide a baseline for future studies at higher ambient turbulence and with additional floating degrees of freedom.

1. Introduction

Floating offshore wind turbines (FOWTs) differ from fixed-bottom turbines since their platform motion creates dynamic loading on the rotor. These changes in thrust induce velocity perturbations that propagate downstream, thereby affecting the characteristics of the wake. This is of primary interest since wake interactions within wind farms lead to power production losses on downstream turbines due to velocity deficits and also increase fatigue loading from wake-added turbulence. Different types of dynamic loading arise due to platform motions, primarily in the form of surge, pitch, sway, and yaw.

Messmer et al. [1] demonstrated that for low turbulence intensity ($TI \leq 2\%$), surge accelerates wake recovery at moderate reduced motion frequencies ($St \simeq 0.3 - 0.9$), synchronizing wake pulsations with motion frequency. St represents the Strouhal number and is defined by $St = fD/V_\infty$, where f is the motion frequency, D the diameter of the rotor, and V_∞ the inflow



velocity. Pulsing is pronounced for $St \simeq 0.2 - 0.55$, while only meandering and mild pulsing occur at higher frequencies ($St \simeq 0.6 - 0.9$), validating previous large-eddy simulations. Fontanella et al. [2] observed thrust fluctuations and coherent velocity perturbations downstream even at $St = 1.2$ in tandem turbine experiments, and Taruffi et al. [3] reported that high-frequency surge ($St = 1.5$) can amplify upstream thrust oscillations by up to 150%, though its wake impact remains unexplored. Schliffke et al. [4] highlighted that harmonic motions yield sharp peaks in the power spectral density (PSD) of wake velocities at the excitation frequency, while broadband or random sea loads do not. This suggests that controlled harmonic motions may create coherent spectral features in the wake, which could either enhance mixing or increase fatigue loads on downstream turbines, depending on the frequency and amplitude of the motions.

Full-scale measurements from the Hywind Scotland wind farm analysed by Angelou et al. [5] confirmed this trend, showing no discernible wake spreading from natural surge motions ($St \leq 0.1$), when the floater is subjected to a random sea state. The authors also highlighted that this could be due to dominant ambient turbulence ($TI \simeq 5\%$), underscoring the disparity between controlled low- TI laboratory conditions and realistic offshore environments. Platform-induced effects become negligible, as ambient turbulence dominates wake recovery. This has been confirmed by Pagamonci et al. [6] using LES simulations. Under turbulent inflow, tip vortex breakdown occurs closer to the rotor, significantly altering wake development compared to laminar conditions. Testing under low- TI environments nevertheless enables the isolation of floating-motion effects on wake characteristics.

Besides platform-induced motions, dynamic loading of downstream turbines can also arise from control strategies designed to improve wake mixing and farm-level efficiency. Among these, yaw-based strategies have gained particular attention, alongside induction control and helix-based methods [7]. Dynamic yawing refers to a time-varying motion in which a wind turbine intentionally oscillates about its yaw axis. Such dynamic yaw motions can modify wake deflection, wake recovery, and unsteady loading, and are therefore relevant for both wake-steering control strategies and floating wind turbine applications where platform motions induce yaw oscillations, although the latter are less important in amplitude. The study by Mühle et al. [8] investigates dynamic yaw through wind tunnel experiments using small-scale wind turbines and numerical simulations. They found that dynamic yawing, especially at low levels of inflow turbulence, significantly improves power capture for downstream turbines. The effectiveness is, however, diminishing in high turbulence conditions. Another study by Gutknecht et al. [9] investigated the benefits of combining dynamic yawing with a helix active wake mixing strategy to enhance wind farm efficiency, using porous disks. Specifically focusing on the dynamic yawing technique, the authors found that this method significantly increased the effective wind speed at downstream turbines, thereby improving wake recovery and overall power output. The optimal Strouhal number for dynamic yawing was identified to be around 0.15, which resulted in thrust gains of up to 48%. Duan and Porté-Agel [10] performed wind-tunnel experiments on cyclic yaw control with wind turbine models, operated at optimal tip speed ratio (TSR). They showed that periodic yaw oscillations enhance wake mixing, can increase downstream turbine power, introduce coherent wake perturbations that propagate downstream, and modulate the loading and performance of waked turbines. Their results also indicate that the effectiveness of cyclic yaw depends strongly on the yaw frequency and amplitude, suggesting the existence of an optimal forcing Strouhal number for wake recovery. More recently, they have extended their experimental studies of cyclic yaw control with different inflows and wind farm configurations [11]. The largest gains were obtained within a specific range of yaw Strouhal number in the range of $St = [0.10, 0.25]$ and yaw amplitudes $A = 20 - 30^\circ$. These results are also observed for higher turbulent intensity, but the dynamic yawing has a less important impact than in low

turbulent conditions.

The above literature highlights consistent wake perturbations induced by FOWT motions and control strategies in low-turbulence laboratory conditions. Yet, few studies have investigated the influence of upstream motion of an FOWT on downstream turbine loads. This motivates further investigation of the wake-rotor interactions in low-TI environments. This study builds on previous literature by examining a wider range of amplitudes and frequencies across different motions and by comparing the results with existing studies. The resulting experimental dataset is made openly available to the scientific community in an online repository [12]. This study aims to answer the following questions:

- What is the effect of large dynamic motions of upstream floating wind turbines on the thrust of downstream turbines in low-turbulence conditions?
- What frequencies are transported through the wake and can be expected on downstream turbines for surge, pitch, and yaw motions of an upstream turbine?

2. Methodology

2.1. Experimental setup

To experimentally investigate the wake effects of floating wind turbines, a hybrid wind-tunnel testing approach was employed. The wake aerodynamics are fully reproduced within the wind-tunnel facility, while floating-platform dynamics are prescribed using a hexapod through harmonic oscillations of single degrees of freedom as done in previous work [3]. The upstream wind turbine (WTM1) is mounted on a hexapod, whereas the downstream turbine (WTM2), identical to the first one, is located in the wake and operated under fixed conditions.

The wind turbine model used for both turbines is a three-bladed, fixed-pitch scale representation of the DTU 10MW reference turbine, scaled at a ratio of 1:148. The model operates with a velocity scale of 3 and is designed according to a performance-scaling approach aimed at accurately replicating the thrust force, which is crucial for FOWT studies. A representation of the turbine is laid out in Figure 1b, which is instrumented as follows: a six-component load cell (ATI mini45 SI-290-10) is installed between the tower top and the nacelle to measure rotor integral loads and obtain forces and moments. Since the downstream turbine is assumed to be rigid and no structural deformation is considered, the axial load measured by the load cell is assumed to be equivalent to the aerodynamic thrust acting on the turbine. The rotor is driven by a motor controlled at a constant speed by a servo drive. The aerodynamic performance of the model, under both static and dynamic conditions, was comprehensively assessed in a previous study by Taruffi et al. [3].

The experiments were conducted in the Open Jet Facility (OJF) at Delft University of Technology, which has a closed-loop open jet test section with a nozzle exit dimension of $2.85\text{m} \times 2.85\text{m}$. Although this value is lower than turbulence intensities typically reported for offshore wind conditions ($TI \simeq 10\%$, depending on atmospheric conditions [13]), low-turbulence environments are highly relevant for fundamental investigations. Low-turbulence inflow conditions allow the isolation of intrinsic rotor and wake dynamics with minimal interference from background turbulent fluctuations, which would increase the uncertainty of the measurements. In higher-TI conditions, the fundamental wake mechanisms are often masked by broadband turbulence, making interpretation more difficult. Furthermore, low-TI environments are easier to reproduce in other facilities and in numerical simulations. In the present wind-tunnel experiments, the turbulence intensity at hub height at the upstream wind turbine position was about 2%. Although this is not a laminar condition, the flow is close to a smooth flow. It

was then assumed that inflow turbulence-induced effects on the downstream turbine are minor. Furthermore, to enhance reproducibility, the wind field is taken as uniform and free of shear.

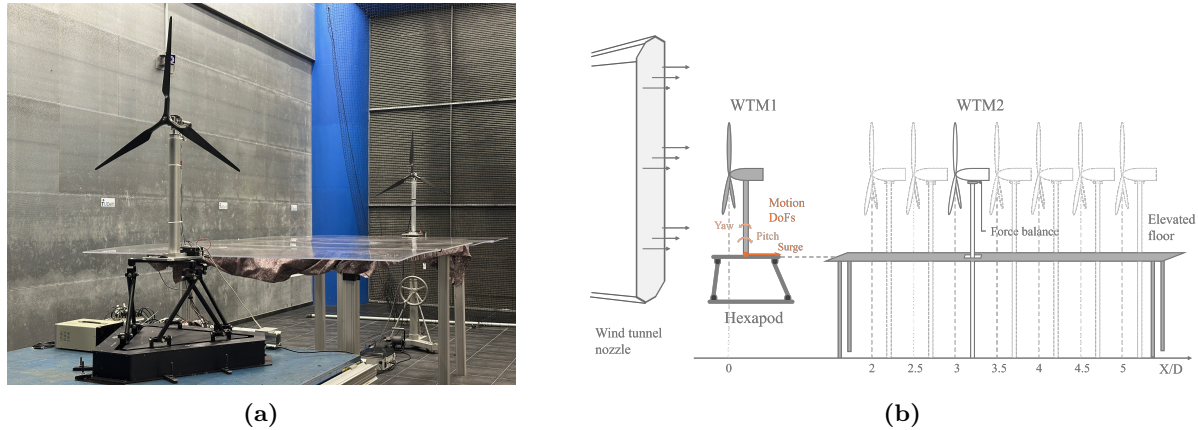


Figure 1. Picture of the tandem turbine setup in the Open Jet Facility (a) and sketch of the experimental setup for different locations of WTM2 (b)

As shown in Figure 1a, the two turbines were separated by a straight floor adjusted to the bottom of the upstream turbine (WTM1). This configuration minimizes vertical flow deflection and prevents downwash of the incoming flow toward the downstream turbine (WTM2). In these experiments, only the upstream turbine was subjected to platform motions representative of a floating wind turbine, while the downstream turbine remained fixed at the tower base. This choice was made to decouple wake-induced aerodynamic loading from additional unsteady effects associated with floating platform dynamics. By eliminating platform motion, the measured load fluctuations of the downstream turbine can be attributed primarily to wake characteristics and rotor–wake interactions, enabling a clearer interpretation of the underlying aerodynamic mechanisms. This fixed configuration thus provides a well-defined reference case for future investigations, including floating degrees of freedom, and has been done in previous studies [2].

2.2. Test cases

The motions are characterised by the Strouhal number St , the normalized motion velocity, denoted as $\Delta V^* = \Delta V/V_\infty$ for the surge and pitch motions, and the yaw amplitudes for the yaw motions. These are the most relevant parameters influencing thrust variation and wake structures, as ΔV describes the variation in inflow velocity, while V_∞ represents the velocity at the nozzle of the wind tunnel. The Strouhal numbers for the surge and pitch cases were selected to match the scaled excitation frequencies associated with the surge natural frequency of the TripleSpar floating platform supporting the DTU 10MW reference turbine. In the present experimental scaling, this corresponds to an excitation frequency of 2Hz. An additional case at 5Hz was considered, representing wave-induced excitation within the typical offshore wave frequency range. This high-frequency case has not been tested in such an experimental setup. The relative inflow velocity levels were selected to represent both standard conditions ($\Delta V^* = 0.05$) and cases that exceed standard operating ranges ($\Delta V^* = 0.1$) based on [3]. For the yaw motion cases, both the oscillation amplitudes and Strouhal numbers were selected to be consistent with the parameters reported by Gutknecht et al. [9]. The chosen Strouhal number range corresponds to the regime in which maximum power gains were observed. Additionally, the yaw amplitudes were selected to match those examined experimentally by Mühle et al. [8].

Each measurement presented in this work includes 100 cycles of the imposed motion and was repeated once to assess the repeatability of the results.

The upstream turbine was operated at rated conditions (wind speed $V_\infty = 4\text{m/s}$ and rotational frequency $\Omega = 480\text{rpm}$). The downstream turbine was operated at its optimal tip-speed ratio (TSR = 7.5) at constant rotational speed when the upstream turbine was static. In the absence of wind turbine torque control, identifying the operating state requires knowing the inflow velocity at the position of the downstream turbine. However, the latter cannot be directly measured when the turbine is present. The downstream turbine was therefore operated based on an estimate of the mean inflow velocity obtained from a previous particle tracking velocimetry campaign conducted with an otherwise identical setup, but without the downstream turbine installed. Velocity fields were available at all downstream distances, with the measurement volumes covering the upper part of the wake, extending approximately one and a half rotor radii above hub height. Assuming an axisymmetric velocity distribution over the rotor plane, the velocity profile is averaged over the circular rotor area. Using this estimated inflow velocity and the known optimal tip-speed ratio, the corresponding rotational speed of the downstream turbine was then determined. For each upstream motion, at constant downstream position, the turbine is operated at the same rotational speed, at the optimal TSR for static conditions. If one had increased the rotational speed of the wind turbine to accommodate for optimal TSR, an increase in thrust could also have been attributed to the increase in rotational speed. Since $\partial T/\partial U$ with fixed blade pitch and rotational speed is positive for these operational conditions, it can be said that an increase in thrust can be attributed to the increase in incoming velocity. The test conditions are summarized in Table 1.

Parameter	Test Cases
Motions frequencies	Surge: $St \in \{0.6, 1.5\}$ Pitch: $St \in \{0.6, 1.5\}$ Yaw: $St \in \{0, 0.1, 0.15, 0.2, 0.225, 0.25, 0.3\}$
Downstream distances	$x/D \in \{2, 2.5, 3, 3.5, 4, 4.5, 5\}$
Amplitudes	$\Delta V^* \in \{0.05, 0.1\}$ for surge and pitch; $A \in \{5\text{deg}, 10\text{deg}, 15\text{deg}\}$ for yaw
Rotational speed (WTM2, rpm)	Optimal TSR = 7.5 {2D : 189; 2.5D : 202; 3D : 252; 3.5D : 274.59; 4D : 299; 4.5D : 320; 5D : 317}

Table 1. Test cases presented in this work.

3. Results and discussion

3.1. Influence of surge and pitch motions on downstream turbine

First, the cases in which WTM1 undergoes low-frequency surge and pitch motions are analyzed. A phase-averaged analysis is performed on the thrust of the downstream wind turbine over 100 motion cycles. A second phase-averaged analysis is done with the repetition of the measurement. Both results of the two measurements are then averaged out. For visualisation purposes, the signals are processed using a fourth-order low-pass Butterworth filter with a cut-off frequency of 10Hz, prior to phase averaging. This filtering choice is justified, as no relevant physical frequencies are expected above the selected cut-off.

A high amplitude, low-frequency surge case is compared for each distance downstream in Figure 2 for two different amplitudes. The phase-averaged results presented in Figure 2a show that the phase-averaged thrust follows a sinusoidal variation with an offset and a certain phase

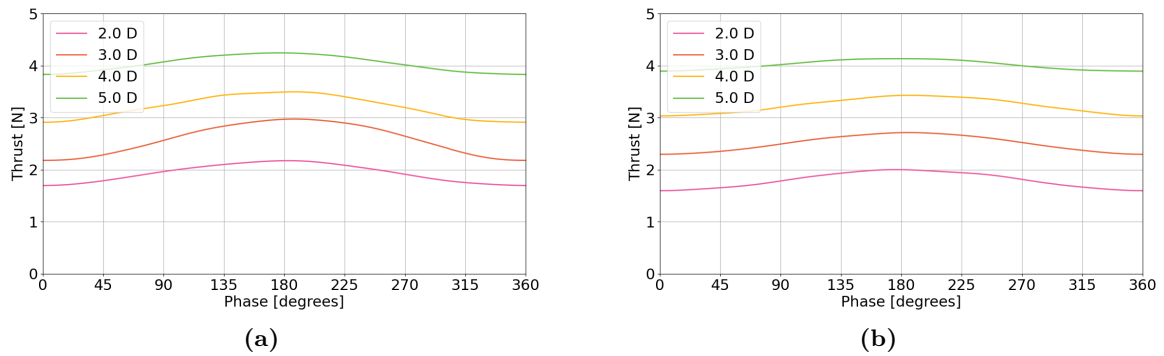


Figure 2. Phase-averaged thrust of the downstream turbine for low frequency surge case ($St = 0.6$, for both high amplitudes ($\Delta V^* = 0.1$) (a) and low amplitudes ($\Delta V^* = 0.05$) (b).

amplitude. The offset corresponds to the mean thrust measured by WTM2, while the phase amplitude of the sinusoid is correlated to the energy present at the upstream motion frequency. Qualitatively, the sinusoidal behaviour of the phase-averaged data correlates well with the imposed upstream motion. Additionally, an increase in the mean thrust over the distances covered is seen. This is expected behaviour since the wake recovers with downstream distance and the turbine is operated at optimal TSR for a static turbine at the same position, based on the knowledge of the wake recovery. From a more quantitative analysis, the results show that the phase amplitude peaks at 3.5D before decreasing towards 5D. Similar patterns are observed for all surge and pitch cases for low frequency, regardless of the WTM1 amplitudes tested, as shown in Figure 3. This suggests that the maximum energy at the motion frequency peaks at a certain distance and is decreasing with distance, showing a progressive dissipation of the energy content of the incoming flow with downstream distance. By comparing with a low amplitude $\Delta V^* = 0.05$, as shown in Figure 2b, the same trends can be seen. However, the amplitude of the phase-averaged oscillation is almost halved, compared to the high-amplitude motion. This shows that the amplitude of the motion has an impact on the downstream turbine, but only until 3 – 4D. The same analysis can be applied to the low-frequency cases in pitch, with very similar results. In the results presented in Figure 3, there is no clear trend on whether surge or pitch cases show higher amplitudes in thrust variation.

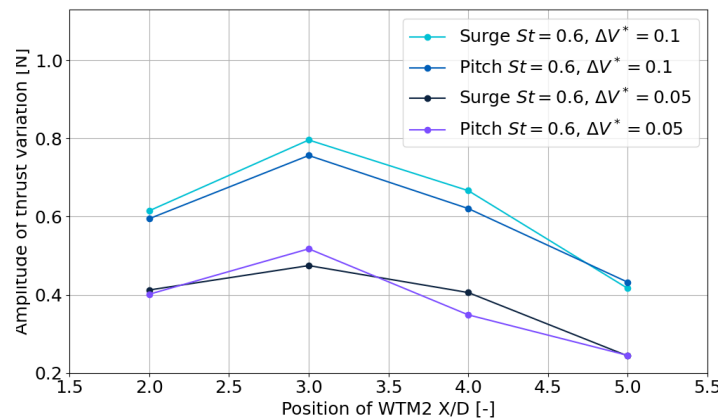


Figure 3. Amplitude of thrust variation for different test cases, over the tested distances

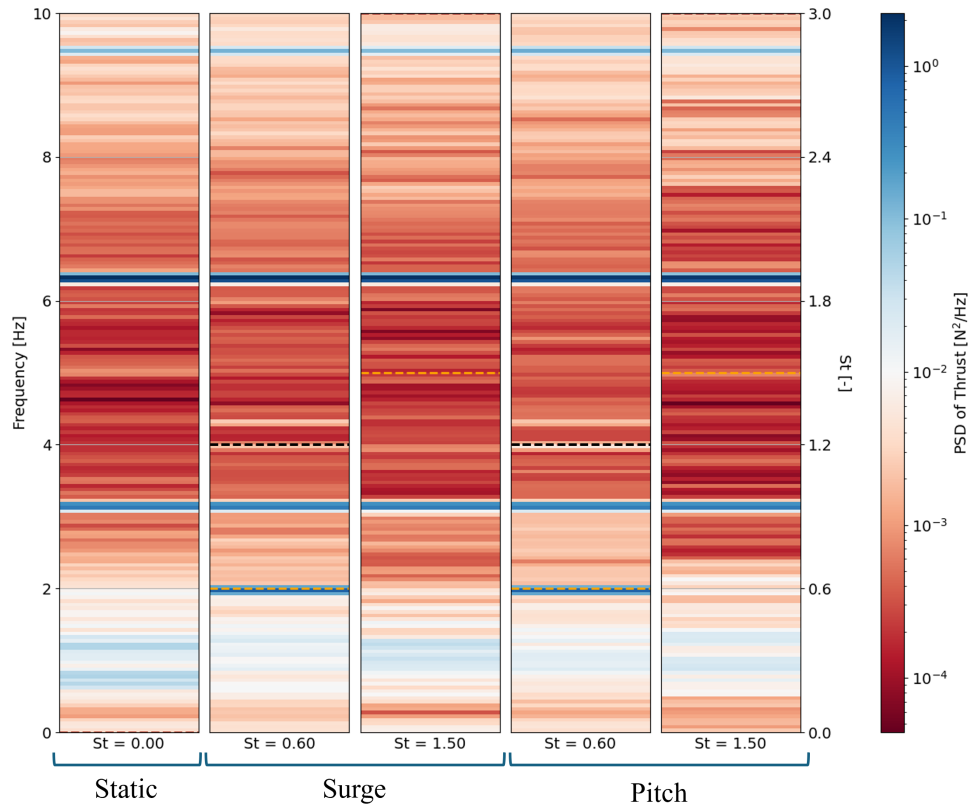


Figure 4. Comparison of downstream rotor thrust PSD placed at 2D, $\Delta V^* = 0.1$. The yellow dotted lines represent f while the black dotted lines represent $2 \times f$.

For high-frequency cases, however, the amplitude of the thrust variation is very low when doing a phase-average analysis, compared to low-frequency cases. Thus, the power spectral densities of the thrust signals are computed using Welch's method. The signals were divided into overlapping segments using a Hamming window, with a 50% overlap between consecutive segments. The segment length was selected to ensure adequate frequency resolution at the frequencies of interest, corresponding to at least ten periods of the dominant excitation frequency. Figure 4 shows the power spectral density of the thrust of the downstream turbine, placed at 2 diameters downstream, in the wake of an upstream turbine moving at high amplitude for all frequencies. As revealed by the two-dimensional PSD heatmaps, no increase in the spectral intensity was observed for high-frequency motions, for surge or pitch. Peaks can, however, be seen for the low-frequency cases, whereas a peak at around 3Hz is representative of the rotational speed of WTM2 at that location. These results show that even for a high relative inflow velocity (i.e. WTM1 motion amplitude) and short distance to the upstream wind turbine, the motion frequency of an equivalent wave frequency is not seen by the downstream rotor at two diameters downstream. This may suggest that wave frequencies are not carried in the wake, or only to a small extent. This trend is the same for all distances downstream. This result further expands the literature [1, 2], where lower St have been tested.

Furthermore, broad large peaks in thrust force can be seen for the low frequency range

$St = [0.1, 0.4]$, for the static and all dynamic cases. These broad peaks can be identified as characteristic of wake meandering, as it has been identified by previous studies, especially when inflow turbulence is low ($TI \leq 2\%$) [1]. If the observed behaviour is related to wake meandering, it could originate from intrinsic shear-layer instabilities within the wake. This would indicate that wake meandering may persist even at high St numbers, although additional analysis is needed to verify that the observed fluctuations are not caused by another phenomenon.

3.2. Influence of yawing motions on downstream turbine

Dynamic loading can also occur in the context of artificially yawing the upstream turbine to increase the wake recovery. Figure 5 provides a comparison of the relative thrust difference experienced by a downstream wind turbine as a function of the Strouhal number, under conditions of dynamic yawing at three distinct amplitudes: 5deg, 10deg, and 15deg. The reference case is a two-turbine setup where both turbines are static and rotating at the optimal TSR. Then the first turbine is dynamically yawed sinusoidally.

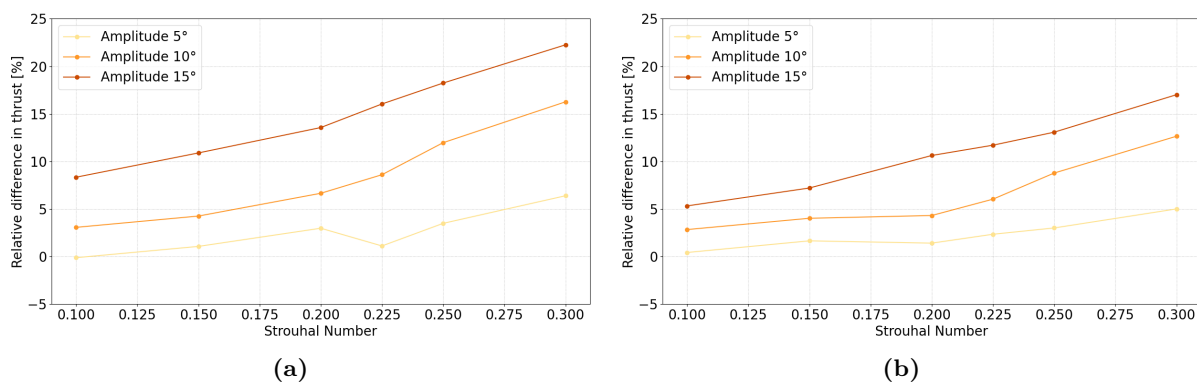


Figure 5. Thrust increase of the downstream wind turbine due to dynamic yawing of the WTM1 at a distance of 4D (a) and 5D (b) downstream

Results for distances of 4D and 5D are shown; the measurements reveal a clear upward trend, indicating that the relative thrust difference increases with increasing Strouhal numbers for both yaw amplitudes. This trend is consistent across both distances, suggesting that the downstream turbine is recovering faster as the yawing frequency increases. In all cases, a smaller yaw amplitude shows a lower relative difference in thrust amplitude compared to a higher yaw amplitude for the same Strouhal number. This indicates that larger yaw amplitudes result in more significant variations in thrust amplitude, a pattern that holds true at both 4D and 5D distances. These trends are comparable with results obtained by Mühle et al. [8] in low-TI conditions. When comparing the two distances, it is evident that the relative difference in thrust is generally higher at 4D than at 5D for the same Strouhal number. This indicates that the influence of dynamic yawing on thrust amplitude becomes less pronounced as the distance from the upstream turbine increases. Additionally, the gap between the relative differences for the 10deg and 15deg yaw amplitudes tends to shrink at 5D, particularly at higher Strouhal numbers. With increasing yaw amplitude, the thrust amplitude increases, but this increase is less significant with increasing distance, which means that the effect of the dynamic yawing dampens out at higher distances.

Similar to the analysis performed for surge and pitch motions, a PSD analysis is carried out for different yawing Strouhal numbers at a downstream distance of 4D. As revealed in Figure 6, the upstream yawing frequency cannot be clearly seen in the thrust of the downstream

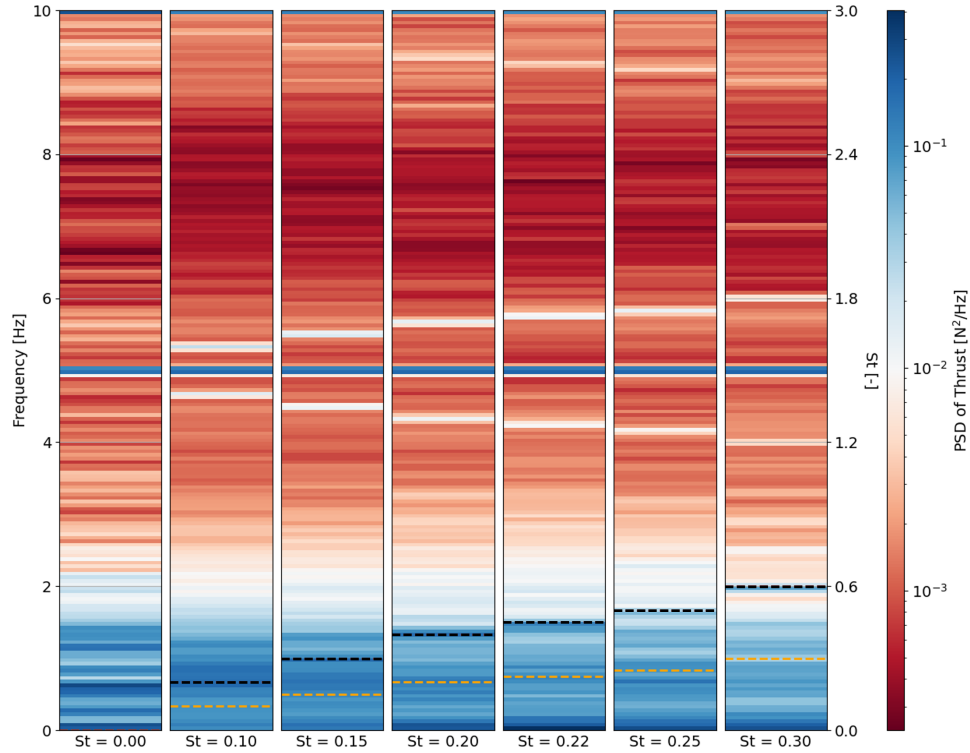


Figure 6. PSD of the downstream turbine thrust, placed at four diameters downstream of a yawing turbine, for an amplitude of 15deg. The yellow dotted lines represent f_{yaw} while the black dotted lines represent $2 \times f_{yaw}$

turbine. This may be because the peak is obscured by low-frequency fluctuations in the wake, or it may suggest that the yawing frequency is not preserved as it propagates downstream. This interpretation could explain differences with recent findings by Duan et al. [11] who showed through power spectral analysis that cyclic yaw and the power fluctuation level depend strongly on the yaw Strouhal number. At low Strouhal numbers, the periodic power fluctuations of downstream turbines remain well sustained, while increasing the Strouhal number leads to a progressive decay of this periodic behaviour. However, smaller peaks can be seen at the frequencies $\Omega \pm f_{yaw}$. These can be interpreted as sidebands, indicative of amplitude modulation of the rotor-induced thrust by the yaw-driven wake dynamics. This shows that the yawing frequency is still present to some extent in the wake. For some cases, at twice the yawing frequency, a more pronounced spectral peak can be seen, as for cases from $St = 0.2$ onwards. While the origin of the $2 \times f_{yaw}$ frequency component remains uncertain, it is consistent with findings from other experimental studies, which have observed it for lower frequency surge, pitch motions ($St = 0.3$)[2] and yaw motions [11]. A plausible interpretation is geometric: as the wake is periodically deflected laterally, the downstream rotor can move into and out of the wake twice per yawing period, which would naturally introduce a response at the second harmonic. For lower yaw amplitudes (5deg), the second-order peaks are no longer discernible, and the associated

sidebands become barely noticeable. At a larger turbine spacing (5D), a similar trend is observed for both the first- and second-order yaw-induced effects on the downstream turbine, although the corresponding spectral peaks are weaker.

4. Conclusion

This experimental study examined how imposed platform-relevant motions of an upstream floating wind turbine - surge, pitch, and yaw (mainly for dynamic yawing purposes) - affect the thrust loading of a downstream turbine operating in its wake under low-turbulence inflow conditions. By keeping the downstream turbine fixed, the measured thrust fluctuations could be attributed primarily to wake-rotor interaction mechanisms, enabling a clearer interpretation of frequency transport and load modulation.

For surge and pitch, the downstream thrust response depends strongly on motion frequency. Low-frequency cases (representative of the scaled surge natural frequency) exhibit a clear periodic modulation in the phase-averaged downstream thrust, consistent with the upstream harmonic excitation. The modulation amplitude increases up to an intermediate spacing (approximately 3 – 4D) and then decreases toward larger spacings, suggesting an optimal range where coherent wake disturbances most strongly couple with the downstream rotor before dissipating downstream. In contrast, for the high-frequency surge/pitch cases considered (representative of wave-frequency excitation), no clear amplification at the imposed motion frequency is observed in the downstream thrust spectra across the tested spacings, indicating limited persistence of these higher-frequency disturbances through the wake under the present conditions.

For dynamic yawing, the experiments show a systematic increase in mean downstream thrust with increasing yaw Strouhal number and yaw amplitude, consistent with enhanced wake recovery. However, the imposed yawing frequency is not clearly identifiable as a distinct peak in the downstream thrust spectra, which may be because of the strong broadband signals in the same frequency range, as other experiments have shown that clear peaks can be detected [11]. Instead, weaker spectral signatures emerge as sidebands around the downstream rotor rotational frequency $\Omega \pm f_{yaw}$, indicating amplitude modulation of the rotor loading by yaw-driven wake dynamics. Additionally, in several cases, a component at twice the yaw frequency is observed, which is consistent with a second-harmonic response arising from the downstream turbine entering the wake twice per motion period. As yaw amplitude decreases and/or spacing increases, both first- and second-order spectral signatures become progressively weaker and may no longer be discernible.

Overall, the results demonstrate that (i) low-frequency platform-relevant motions can mark coherent disturbances that measurably affect downstream thrust, whereas (ii) higher-frequency surge/pitch excitations may not persist to the downstream rotor in a detectable way under the tested conditions, and (iii) dynamic yawing primarily manifests in the downstream thrust through mean-load changes, modulation sidebands and second harmonic, rather than a dominant peak at the yaw frequency. These findings provide a basis for future campaigns to quantify how increasing ambient turbulence and introducing downstream platform degrees of freedom modify wake transport and fatigue-relevant loading patterns. Higher turbulence inflows are expected to dampen these effects, such that only low-frequency motions remain relevant for wake-rotor interactions and therefore for floating wind farm design optimization. Future work could use the wake-induced loading results to compare damage-equivalent loads on the downstream turbine under different inflow conditions to assess how platform motions and ambient turbulence influence downstream fatigue loading.

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