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On the wake re-energization of the X-Rotor
vertical-axis wind turbine via the vortex-generator strategy

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The authors thank the reviewers for their time and valuable insight. Their feedback has been helpful in improving the quality of this manuscript. The following document contains the point-by-point rebuttal to the comments of Reviewer 1 and Reviewer 2. The reviewers' comments are listed below in BLACK, with subsequent responses to each in RED.

Reviewer 1

This paper presents an experimental investigation regarding vortex generator (i.e. blade pitch based) wake recovery strategies for an X-Rotor type Vertical Axis Wind Turbine (VAWT). Stereoscopic PIV measurements are conducted in an open jet wind tunnel up to 6D downstream of the X-rotor on cross-stream planes within the wake. Data are obtained for three different blade pitch configurations (for the upper blades of the X rotor only) and the impact on wake characteristics, wake recovery and wake vortex dynamics are discussed. The paper is well written in general. Few points that might be considered for improving the paper are listed below:

1. Please provide a trade-off analysis quantifying the power loss from the upstream turbine when it's operated at different pitched cases versus the potential energy gains obtained within the wake.

   Thank you for this comment. Indeed, as discussed in Section 5, a trade-off analysis was not performed in this investigation as the power performance of the rotor was not measured. This is mainly due to the challenges associated with performance measurements of VAWTs at low Reynolds numbers, which are motor-driven, as discussed in Araya and Dabiri (2015). Nonetheless, prior numerical simulations of the primary rotor of the X-Rotor have been performed when using passive pitch adjustments ranging from $\beta = -10°$ to $10°$ by Giri Ajay et al. (2023), as discussed in Section 1. In this work, the C_p decreases on the order of 15% at a tip-speed ratio of $\lambda = 5$ for both the pitch cases $\beta = -10°$ and $10°$. When considering the analysis of the available power in the wake in Section 4.2, such penalties are notably lower than the gains of 55% and 108% for $\beta = -10°$ and $10°$, respectively, at as close as three diameters downstream. A discussion of these magnitudes in available power gain in the wake with the numerically calculated power deficits of the rotor is added in the revised manuscript in Section 4.2.

   Nevertheless, ongoing work is underway to perform numerical validations of these experimental results. This ongoing work is similar to the recent numerical validation of the experimental results by Giri Ajay et al. (2025), which concerns the study discussed in Section 1 (Bensason et al. (2024)).

2. In addition to thrust coefficients, please provide a table showing the power coefficient levels at different pitch angles as well.

   Thank you for this comment. In relation to your previous comment, the power coefficient of the rotor was not measured in this study.

3. Please discuss scaling issues. This turbine operates at a very low Reynolds number when compared to its full scale counterpart. How would this affect the wake vortex dynamics, which is discussed in detail for the scaled turbine.

   Thank you for this comment. Indeed, a common limitation in lab-scale wind turbine wake studies (of both HAWTs and VAWTs) is the satisfaction of the Reynolds number similarity. The wake of a full-scale (outdoor) H-type VAWT was measured by Wei et al. (2021) at a diameter-based Reynolds number of $1.2 \times 10^6 \leq Re_D \leq 1.8 \times 10^6$. The wake shape was compared with the results of previous water-channel measurements performed at $Re_D = 8 \times 10^4$, confirming a high degree of similarity. These results confirm the observations of Parker and Leftwich (2016) who measured the wake behind a lab-scaled VAWT in a wind tunnel at Reynolds numbers ranging from $Re_D = 6 \times 10^4$ to $Re_D = 1.8 \times 10^5$. The authors report that whilst the maximum flow deficit behind the rotor increases with the Reynolds number (by 17% between the extremes), the overall wake structure is unchanged. I discussion regarding literature of VAWT wake measurements at low Reynolds numbers has been added to Section 3.3 of the revised manuscript.

   For the case of the X-Rotor, no field measurements have been recorded as of yet. However, the numerical study of Ajay and Ferreira (2024) simulated the wake of the full-scale X-Rotor at a Reynolds number of 1.5×10^7 with passive pitch adjustments of $\beta = \pm 10°$. A qualitative comparison of the trailing vortex system and subsequent wake topology shows a very good agreement with the present experimental results.

4. How would this control strategy be implemented on a real full size turbine? What would the authors recommend regarding the necessity of dynamic pitch actuation since a static pitch control would be impractical? Would a dynamic pitch actuation result in similar wake vortex dynamics and recovery?

   Thank you for this comment and intriguing thought. The X-Rotor design includes upper blades that are pitchable in order to regulate the amount of mechanical energy extracted from the wind and hence the performance of the rotor. This has been clarified in Section 1 of the revised manuscript. Hence, the "vortex generator" control strategy could be realized by applying passive pitch adjustments using the existing hardware. A comprehensive overview of the pitch controller design for the X-Rotor is provided by Recalde-Camacho et al. (2024). Whilst the aforementioned control technique highlights the proof-of-concept of using the rotor as a "vortex generator" for wake recovery, a dynamic pitching scheme would likely be required in practice to balance the tradeoffs in rotor performance, structural stability, and wake recovery, as discussed in Section 5. Previous studies, such as that by Le Fouest and Mulleners (2024), optimized the pitching scheme of a VAWT for maximum performance. A similar technique could be applied to include objective functions for wake recovery whilst reducing unsteady flow phenomena such as dynamic stall and large fluctuations in rotor torque. Maximizing rotor performance and wake recovery would be contradictory objectives as the former aims to distribute the load evenly between the upwind and downwind of the actuator cylinder (Figure 1), whilst the latter aims to shift the load unevenly about the quadrants.

   The work of LeBlanc (2024) simulated the wake of VAWT with a cyclic pitching scheme using a lifting line vortex model, expressed as $\beta = A\sin(\theta + \phi) + \beta_0$, where A, ϕ, and β_0 are the pitching amplitude, phase offset, and static pitch, respectively. As with the "vortex generator" technique, cyclic pitch schemes could also result in the shift of load either upwind $(10\sin(\theta + 90))$ or downwind $(10\sin(\theta - 90))$, resulting in similar wake recovery modes as those reported here (i.e, with wake ejection either upward vertically or outward latterly). However, this work did not quantify the power penalty on the rotor. Hence, combining active pitching schemes for the optimization of performance and wake recovery is still an active research topic.

5. Also please comment on the expected effects of freestream turbulence and wind shear on the observed

vortex dynamics within the wake. Current experiments are performed at a very low freestream turbulence level and uniform inflow conditions, which is not realistic in actual wind farms.

Thank you for this comment. Indeed, the current experiments are performed at idealized conditions to focus on the vortex system and wake topology of the X-Rotor, but do not emulate realistic conditions, for example, in an atmospheric boundary layer. As with HAWTs, the inclusion of turbulence would reduce the efficacy of the steering strategy as the flow wake would intrinsically recover faster, and the dominant counter-rotating vortex pair would diffuse faster. Given the limitations of the wind tunnel facility, a scaled atmospheric boundary layer and turbulence could not be tested. However, numerical simulations (RANS) have been carried out by Huang et al. (2023a) for an isolated H-type VAWT with inflow turbulence of 8% with passive pitch adjustments of $\beta = \pm 10°$. The results highlight the efficacy of the streamwise vorticity system in enhancing the momentum flux in the wake, with a reported available power gain as high as 120% five diameters downstream. However, the study of the wake topology of the X-Rotor with conditions that emulate realistic conditions is an interesting future research direction to build on these baseline results. This has been added in Section 5 of the revised manuscript.

6. Adding some wake turbulence related information would be nice. I understand the authors have used only 300 vector maps for averaging, which is not enough to obtain converged statistics, but it would still provide a good supporting information for the arguments presented in the paper, since turbulence has a major effect in wake recovery and the wake dynamics.

Thank you for this comment. The discussion in Section 3.4 evaluates the uncertainty of the mean velocity and vorticity by using the standard deviations of the components. As these are time-averaged measurements, the standard deviations contain fluctuations that are due to both turbulence and periodic flow phenomena. The standard uncertainty is reported as 0.07m/s, which is 2.5% of the freestream flow. The standard uncertainty of the turbulent kinetic energy U_k can be expressed as Sciacchitano and Wieneke (2016):

$$U_k = \sqrt{\overline{u'u'}^2 + \overline{v'v'}^2 + \overline{w'w'}^2} \times \sqrt{\frac{1}{2N}} \tag{1}$$

where $N = 300$ is the number of vector maps. The spatial distribution of U_k is shown in Figure 1 for the three pitch cases at $x/D = 1$.

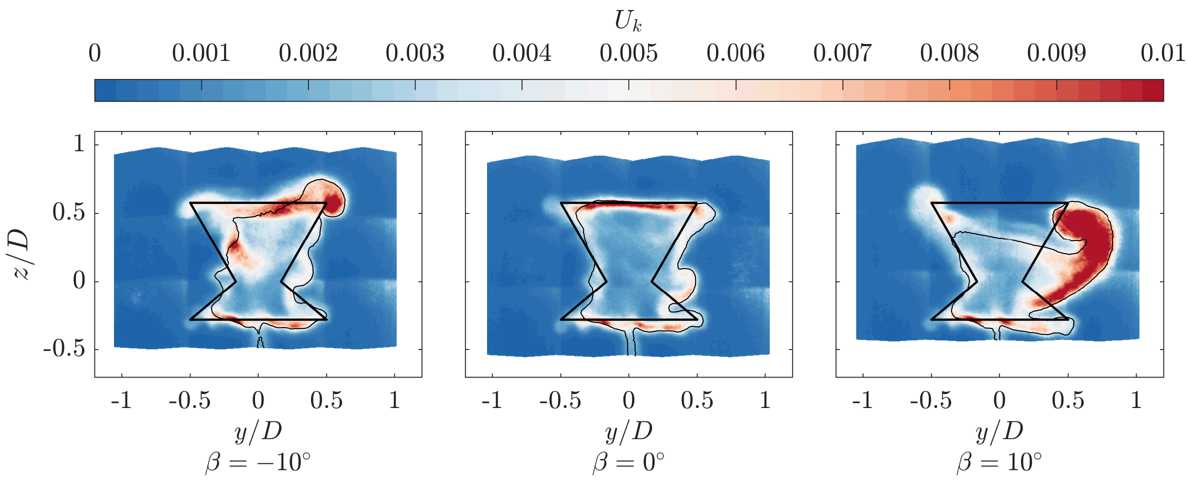

Figure 1: Spatial distribution of the TKE uncertainty at $x/D = 1$ for the three pitch cases.

Consistent with the discussion in Section 4.5 and Figure 16, the turbulent kinetic energy is concentrated about the perimeter of the wake as most of the turbulent mixing occurs in the shear layer. Outside the shear layer, $U_k = 0.001$m/s, whilst in the shear layer it reaches magnitudes of $U_k = 0.017$m/s.

7. Please place the coordinate axes exactly at the origin in Figure 4 to clearly show where the origin is. Also, y-axis is defined as a lateral coordinate and z-axis is referred to as an "axial" coordinate. In reality z-axis is not an axial coordinate. The x-axis, which shows the main streamwise direction, is an axial coordinate so I would recommend not referring to z-axis as an axial coordinate.

   Thank you for this comment. The coordinate axes have been moved to the center of the rotor in the schematic for the revised manuscript. With regard to the naming of the coordinate system, as this is a vertical-axis wind turbine, the axis of rotation (vertical z-axis) is referred to as the axial coordinate in this work. This is different from horizontal-axis wind turbines, where the streamwise x-axis is considered the axial coordinate.

8. Regarding presentation of results, the beta=0 baseline case is always presented as a middle figure but in the text it's always discussed first since that is the baseline reference case. I understand the current layouts showing beta=-10 deg first followed by beta=0 deg and beta=10 deg, but this layout makes it difficult for the reader to follow the figures when reading the text.

   The presentation style of the results aligns with that adopted in previous studies examining the effects of blade pitch on the wake (e.g., Huang et al. (2023b), Bensason et al. (2024)) as well as yaw and tilt in HAWTs (e.g., Bossuyt et al. (2021)). To maintain consistency with established literature and ensure comparability, we have retained this format in the revised manuscript.

9. Freestream wind speed of 2.7 m/s is quite low, and therefore difficult to measure with low uncertainty. What is the estimated uncertainty level for this parameter?

   Thank you for this comment. Indeed, a low wind speed is used in the wind tunnel due to the limitation concerning the dimensionless parameter of the tip-speed ratio $\lambda = \omega R/U_\infty$. The rotational frequency of the rotor cannot be too high due to the limitations of the structural components of the rotor, such as the adapter pieces, blades, and vibration modes. A freestream inflow speed of $U_\infty = 2.7$m/s is within the range of tested wind speeds in the Open-Jet Facility of TU Delft. See works of Taruffi et al. (2024) and who tested as low as $U_\infty = 2.5$m/s and $U_\infty = 3.1$m/s, respectively.

   With regard to the uncertainty level, the same technique used in Section 3.4 can be applied to the area of freestream flow for the $\beta = 0°$ case at $x/D = 1$. The standard deviation of the streamwise velocity component is approximately $\sigma_{U_x} = 0.004$ m/s, which is 0.15% of the freestream flow, and has an expanded uncertainty of $U_{\overline{U_x}} = 4.5 \times 10^{-4}$ m/s.

Reviewer 2

In the paper On the wake re-energization of the X-Rotor vertical-axis wind turbine via the vortex-generator strategy" the authors present results from PIV measurements at different distances to the turbine model investigated. The results show very good agreement with theoretical expectations. The paper is well written and the authors do a good job to explain the complex aerodynamic situations. Nevertheless, one important point is missing, which the authors mention but do not give an answer to: what is the power loss of the turbine when operated with these pitch angels? One finding is the increase in available power for a second in.lien turbine, but that could also be increased by just shutting the first turbine down (extreme measure). I totally agree that it is important to understand the underlying phenomena resulting from the pitched blades and the impact on the wake recovery, but that has to be set in context with the performance of the turbine itself. I highly recommend that the authors measure the power output of the turbine for these three blade pitch angles. If the first turbine suffers too much, what would be the consequence — would a smaller pitch angle also have the same impact on the wake or would that effect be negligible for smaller pitch angles?

Thank you for the comments. As you explained, the objective of the paper was to understand the underlying phenomena of the wake when using the "vortex generator" control strategy for the X-Rotor. Nonetheless, the power penalty of the turbine that is being pitched is a very relevant piece of information when judging the efficacy and viability of the "vortex generator" strategy. Whilst the power of the rotor was not measured in this study, previous studies have quantified the tradeoff when applying passive pitch adjustments to the X-Rotor. Please refer to the response to Comment 1 of Reviewer 1 above, which references the work of Giri Ajay et al. (2023) who numerically predicted a power penalty of 15% for a pitched X-Rotor.

1. In line 50 the authors write that the Xrotor concept has been further advanced to the XROTOR concept. In the following they explain that in that XROTOR design there are HAWT at the tips of the X-rotors. Unfortunately, at this point it is not clear which design they used for the investigations in the paper. In line 51 they write the X-Rotor is an innovative VAWT design . . . ", but isn't that innovative design called XROTOR? They describe primary and secondary blades, but never use XROTOR again in the text. In figure 3, where the model is explained, there are also no HAWT at the blade tips — I was very confused and to not really the point in mentioning the XROTOR concept and explaining it especially since it is not clear when that concept is not of interest any more.

   Thank you for this comment. Indeed, the text creates confusion regarding the difference between the X-Rotor (which is the name of the rotor design) and XROTOR (which is the name of the EU Horizon 2020 project consortium). The X-Rotor design includes blade-tip mounted HAWTs (secondary rotors), which are responsible for power take-off, which is described in Section 1. However, these were not included in this investigation, as it was mainly to study the role of blade pitch on the primary rotor wake. This has been clarified in Section 1 of the revised manuscript.

2. Figure 4 is hard to understand, but I think the authors already did a very good job to explain it. Nevertheless, it is not explained: a) why the blades on the lower side are shorter? and b) why are they not pitched in this investigation. The authors should explain briefly why this is the case instead of just stating that it is like that. Why did the authors chose +-10° for the pitch angles ?

   Thank you for this comment. Figure 4 shows a top-view schematic of the experimental measurement cases. The rotor is moved between three positions, whilst the wake is measured at two cross-stream planes.

   With regard to point (a). The geometry of the X-Rotor, as explained by Leithead et al. (2019), is scaled down geometrically by 1:250. As the cone angles of the upper and lower blades are different, the lengths of the bottom blades are shorter to ensure the same tip diameter as the upper blades. An in-depth discussion about the choice of cone angles for the X-Rotor design is provided by Morgan et al. (2025), which highlights the balance between the gains in power with higher swept volumes and varying tip-speed ratios along the blades.

   With regard to (b). The bottom blades are not pitched for the baseline X-Rotor design as they are responsible for housing the secondary rotors (mounted on the blade tips, but not present in this investigation). Only the upper blades are pitched to moderate the amount of mechanical energy extracted from the wind whilst maintaining the optimal operating conditions. This has been clarified in the revised manuscript of Section 1 and Section 3.1.

   The choice of $\beta = \pm 10°$ was made to keep consistent with previous studies which have investigated the wake of VAWTs with passive pitch adjustments, such as Huang et al. (2023b) for H-type VAWTs and Bensason et al. (2024) for the X-Rotor. This is clarified in line 71 (Section 1).

3. In figure 3 it looks like the sketches of the pitched blades are int he wrong oder — it looks like the the upper right one belongs to the inward blade pitch (10°) and lower right one to the outward blade pitch (-10°)

Thank you for this comment. Indeed, the CAD renders of the pitch settings for $-10°$ and $10°$ were flipped. In the revised manuscript, the order has been corrected, with $-10°$ (pitched-out), $0°$ (no pitch), and $10°$ (pitched-in), from top to bottom.

4. I think figure 5 is not needed since the differences in the planes are not that significant and they have no real consequence for the following analysis. Just mentioning that the planes have been slightly shifted upwards to capture the more interesting areas is enough.

   Thank you for this comment. Indeed, showing the measurement planes for all three cases is redundant. The revised manuscript shows that for the baseline case, whilst describing the differences for the pitched case in the text.

5. The results presented in figure 6 show nicely the effect of the different blade pitch on the wake development. This also raises the question, why the lower blades are not pitched to increase that effect. At the same time, it would be interesting to see how the c_p of the turbines behaves with the pitched blades. I assume that it will go down, but by how much is the question, which is important for optimising the total output of a potential wind farm. Can the authors comment on that ?

   Thank you for this comment. The X-Rotor concept includes pitchable upper blades to regulate the performance of the primary rotor under different wind conditions, similar to traditional HAWTs. The bottom blades do not pitch as they house the secondary rotors (blade-tip mounted HAWTs). Hence, only the upper blades moderate the amount of mechanical power extracted from the wind. Whilst the secondary rotors were excluded from this study, the working principle of the X-Rotor (pitchable upper blades) is reproduced in this investigation. This description has been added to Section 1 of the revised manuscript.

   With regard to the C_p for the pitched blades: the discussion of the penalty for the case where only the upper blades are pitched is presented in reference to the first comment above. For the hypothetical case where the bottom blades also pitched, the work of Giri Ajay and Simao Ferreira (2024) numerically studied the wake behind the X-Rotor where both the upper and lower blades pitched. A comparison of the power penalty compared to the design case was not given; however, it sheds light on the drastic change in the wake topology.

6. In figure 8 the authors should remove (or at least clearly mark) the points for which the area and perimeter could not be calculated since the wake was not completely covered by the PIV data. The points are not representative and are misleading. The text should be adapted accordingly.

   Thank you for this comment. Indeed, distinguishing between data points where the complete wake was not captured within the measurement plane would be helpful to the reader. In the revised manuscript, hollow markers have been used to indicate such planes. The text has also been adapted accordingly.

7. This also applies to all other data in which part of the information is missing, e.g. trajectory of CVP cores — but this only the authors can decide.

   The absence of the complete wake perimeter within the measurement planes does not impact the vortex core trajectories and circulations shown in Figure 13, as the complete vortex cores are captured in the measurements.

8. The discussion in 4.2 (available power) is a little misleading since it only concentrates on the available power in the wake purely based on the u_x component of the wind. Like mentioned before, the X-Rotor will have a decreased power coefficient with the pitched blades, which is totally neglected here. Also, the inflow conditions for the second X-Rotor are totally different since cross flow must be increased dramatically, which in turn must have an impact on the performance of the second turbine. This should be discussed in more detail since the overall producible power should increase and not only the theoretically available power.

   Thank you for this comment. As described with regard to your first comment and with regard to Comment 1 of Reviewer 1, the power of the pitched rotor was not measured in this study. Hence, the analysis in Section 4.2 focuses purely on the available power of a potential downstream rotor, either in-line (Figure 9) or with a lateral offset (Figure 10). Similar analysis has been performed for VAWTs Huang et al. (2023b), and HAWTs Bossuyt et al. (2021); van der Hoek et al. (2024).

Indeed, the inflow of the potential second rotor will be significantly different from that of the first due to the presence of significant cross-flow and turbulence. Nonetheless, the available power metric, as calculated using Equation 8, gives valuable insight into the relative increases in the streamwise momentum of the wake for the different pitch cases. This is, of course, not the actual power performance of a hypothetical downstream rotor, as the impacts of turbulent and skewed inflow on the X-Rotor have not yet been investigated (and fall outside the scope of this study). A discussion of the limitations (exemption of power balance with loss of the pitching rotor) is added to the revised manuscript in Section 4.2.

9. It is really impressive how well the measured data follows the theoretical behaviour sketched in figure 1 (or vice-versa). I can only imagine the experimental effort put in these experiments.

   Thank you.

10. The translucent lines are really hard to see, the authors should increase the contrast a bit.

    Thank you for this suggestion. We have made the translucent lines indicating the projected frontal areas of the rotor in Figures 6, 11, 12, and 16 more visible in the revised manuscript.

11. It could help to label the figures with a), b) and so on, it makes the referencing easier.

    This is a great suggestion. Letter labels have been added to the subplots in Figures 7, 8, 13, and 14. In in-text references to these figures have been adjusted in the revised manuscript.

12. In figure 17 please also use the nomenclature A, A_x, A_y,. . . , etc. to be consistent with figure 16.

    Thank you for this suggestion. The legend of Figure 17 has been adjusted to follow the same nomenclature described in Equation 12.

13. line 24 : HWAT is not explained (even though it should be clear, it would be good just to have all abbreviations explained)

    Thank you for this comment. The definition of HAWT (Horizontal-axis wind turbine) has been added to the revised manuscript.

14. line 109: What is "AC" ?

    Thank you for this comment. The term AC stands for Actuator Cylinder. This acronym has been added to the revised manuscript in line 81 when the method is first introduced.

15. line: 148. After Figure 2 a space is missing.

    Thank you for pointing out. It has been corrected in the revised manuscript.

16. line 319: I believe it should be "the projected frontal area" and not the "the protected".

    Thank you for pointing out this error. It has been corrected in the revised manuscript.

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