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Validation of the near-wake of a scaled X-Rotor vertical-axis wind turbine predicted by a free-wake vortex model

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The authors would like to thank all three reviewers for their time, and valuable comments. Their inputs further improved the quality of the paper, especially with the additional comments from Reviewer #3. The comments of each reviewer are addressed separately. The explanation for each question/comment is marked in blue while the actual changes in the manuscript are marked in red with the updated line numbers.

Reviewer 2

1.Polar data: In the absence of reliable experimental measurements, the presented sensitivity analysis represents a significant improvement in addressing uncertainties in the input polar data. Could you please confirm whether the results shown in the manuscript have been updated to reflect this revised input?

Thank you for the complement. We can indeed confirm that all the results have been updated to reflect this revised input. The differences between the updated results were extremely minor, as mentioned in the last Author Comments. This was due to the blade forces being roughly similar to the first version of the manuscript. We can demonstrate it below by showing a couple of velocity slices below from the first draft of the manuscript and the current version with the polars at an Ncrit of 4 and a Reynolds number 80K. Below, you can find the minor differences pointed out in streamwise velocity slices along the height for Y/D = -0.125 for $\beta = 0°$ which can be most easily seen with the CACTUS results where the red arrow is pointing to at $X/D = 0.27$. The CACTUS results with the updated polars predict marginally higher velocities in the flowfield than before.

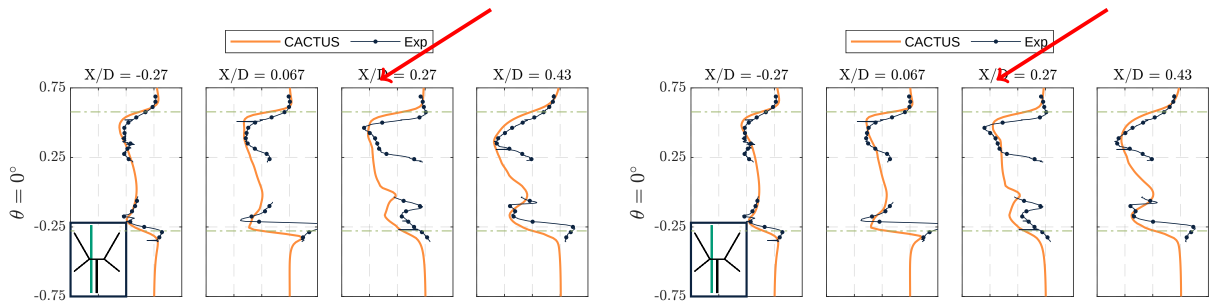

Figure 1: Streamwise velocity u/U_∞ slices along the height of the X-Rotor at lateral position $Y/D = -0.125$ at $\theta = 0°$ and $\beta = 0°$. The X-axis is the streamwise velocity (it is cropped from the figures on the manuscript) On the left is the results from the first draft and on the right is the current version of the manuscript. The red arrow points to some discrepancies to easily notice them.

2.Core radius setup: While the sensitivity analysis on the load predictions provides valuable insight, it does not fully justify the chosen value of the core radius—particularly given the study's focus on wake dynamics.

To strengthen this aspect, please also report the influence of the core radius on the mean wind speed and turbulence intensity in the near-wake velocity field.
This is a very fair request. We have shown the influence on the core radius on the mean wind speed. With the free-wake vortex model, we are not resolving the turbulence in the flow - as there are no closure models used for it. Therefore, we have only provide the streamwise velocity contours in the appendix section. As you can see, there is very little difference in the flowfield between the chosen vortex core size as well as the 10% core size. Therefore, as there is no appreciable difference in the streamwise velocity profiles, we believe our choice of vortex core size does not affect the wake characteristics observed in the study.

Comparing the velocity fields with 10% vortex core size and the default at $\theta = 0°$ (Figure 2) shows minor impact in the flowfield that we consider the solver to be relatively independent of the vortex core size.

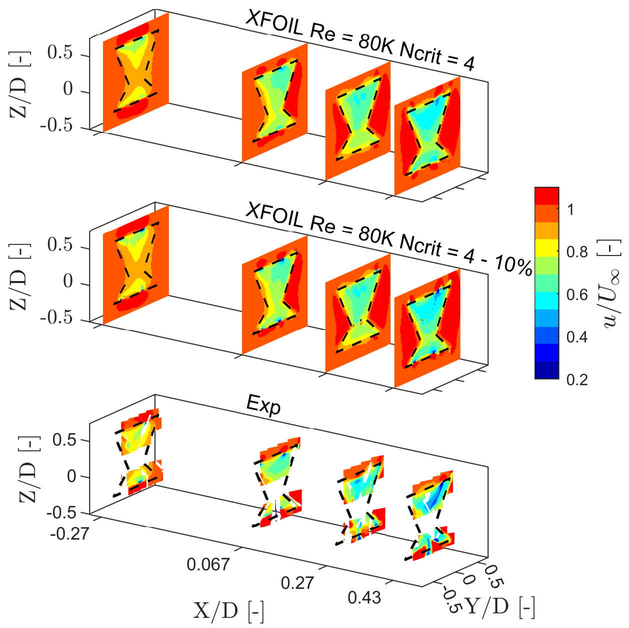

Figure 2: Normalised streamwise velocity (u/U_∞) contours of the X-Rotor at azimuth $\theta = 0°$ at downstream locations X/D = -0.27, 0.067, 0.27, 0.43 where D is the rotor diameter for different input conditions. The first tile is the default case, the second tile shows the case with 10% vortex core size, and the last tile shows the experimental results. The black dash lines indicate the projected frontal area of the rotor on the corresponding plane. All spatial coordinates are normalised the diameters D. The x-axis is magnified to enhance visibility.

3.Flow curvature: This is indeed a complex issue and likely beyond the scope of resolution within the current study. However, I recommend further revising the manuscript to acknowledge and discuss the limitations that this aspect introduces to your approach.
Thank you. We agree that it is quite complex to be tackled within the current study. We have further elaborated the limitation of this model in the methodology section. We recommend reading the tracked changes to fully understand how this elaboration is done in conjunction with comment 1 of Reviewer #3.
We believe flow curvature model is essential for this geometry, but would bring uncertainty to the results when the behaviour of the rotor with and without flow-curvature has not been tested for this geometry. This is indeed a limitation in our approach as the lack of flow curvature would introduce differences in the blade forces and affect the near-wake due to the change in vortex field. As highlighted by Goude (2012), the flow curvature model would introduce a net positive angle of attack to the blade in the upwind half, which would redistribute the loads further upwind (Huang et al., 2023) and directly influence the wake.

Reviewer 3

1. Choosing not to include the flow-curvature (virtual camber) effect to "avoid complicating error attribution" is questionable—excluding a known aerodynamic influence makes it harder, not easier, to understand discrepancies. A practical alternative would be to preprocess the airfoil polars by incorporating the effective camber caused by flow curvature under typical VAWT conditions. These adjusted polars could be used as CACTUS input, offering insight into the impact of virtual camber without modifying the code itself.

Firstly, thank you for your critical feedback on the manuscript. We agree that not using the flowcurvature is a limitation in our work. We considered the possibility of preprocessing the airfoil polars using two methods: (1) using the equation from Goude (2012) where the polars are a function of the relative velocity V_{rel}, and (2) using the geometrical virtual camber algorithms or conformal mapping algorithms.
For method (1), if we preprocess the polars with a prescribed V_{rel} distribution, we would encounter further errors as the wake is simulated by the free-wake vortex model. We pointed this out in our previous response to the referee comments, and in the Methodology section.
As for method (2), it is indeed possible to do this. But, as pointed out by van der Horst et al. (2016) (Figure 3), for high chord-to-radius ratios ($c/R > 0.2$), the existing virtual camber and conformal transformation models provide very different results. As most of the X-Rotor blades operate mostly at very high c/R values, we believe it would induce more errors that have not been investigated before, and therefore leads to further uncertainty on the choice of models. Furthermore, as the angles of attack would be very high near the root sections, the errors would likely compound with the uncertainty of the polars at these high angles of attack. That is why we highlighted that these flow curvature models should be tested for the X-Rotor geometry before using them in high-quality scientific work. Once tested, the blade force profiles can be mapped to high-fidelity CFD results to gain insight into which approaches fit best. However, as agreed by Reviewer #2, this is currently out of the scope of the present study. Therefore, we have elaborated more on our justification of not using the flow curvature model for this study in the manuscript.

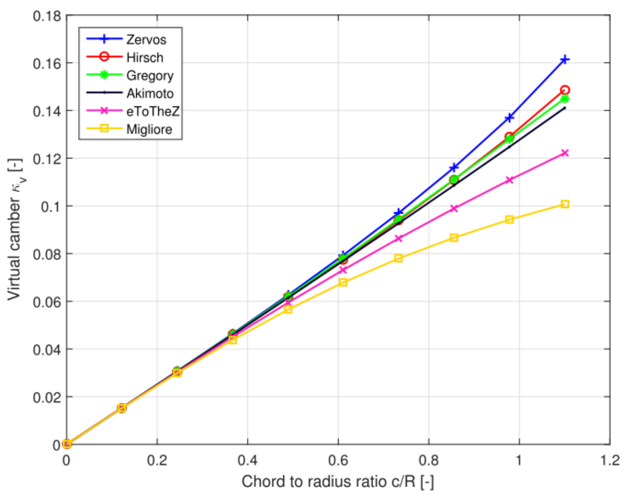

Figure 3: Virtual camber as a function of chord to radius ratio c/R reproduced from van der Horst et al. (2016).

While this provides a more accurate depiction of airfoil motion in VAWTs, we opt not to include it here for two critical reasons. Primarily, implementing the flow-curvature model (such as Goude (2012)) to a rotor geometry with a large spanwise relative velocity distribution would make it exceedingly difficult to isolate the differences observed between CACTUS and experimental results to other factors. Moreover, geometrical virtual airfoil transformations (such as Hirsch and Mandal (1984)) show large inaccuracies at high chord-to-radius ratios ($c/R > 0.2$), which is the regime that most of the X-Rotor blade operates in. Secondly, as CACTUS does not come inherently with a flow curvature correction model, implementing it ourself in the source code would be outside the scope of this study. Furthermore, attempting to pre-emptively correct the airfoil polars without calculating the relative velocities would result in unwarranted errors in CACTUS.

2. The authors attribute wake discrepancies—particularly at $X/D = 0.43$—to the vortex core size, supported by a reference to an actuator line method (ALM) study. While there is a conceptual similarity between force smearing in ALM and vortex core effects in lifting line theory, the two methods are fundamentally different, and this comparison is not directly applicable. Concluding that the discrepancies stem from vortex convection assumes the aerodynamic loads are accurate—something not demonstrated in the paper. The brief mention of uncertainties due to airfoil polars is more relevant and deserves further exploration before focusing solely on the vortex core.

The reviewer is indeed correct. In the original of this manuscript, we attributed the cause to the vortex core size as we ran into stability issues. Given that, in the second and the current version, we have demonstrated that the results are mostly independent to the vortex core size (refer sensitivity study in the Appendix), we should have updated our reasoning for these discrepancies. As the reviewer pointed out, most of them are mostly due to the large uncertainty in the airfoil polars. We have now updated all instances of the reasoning behind the discrepancies with further details on how they are affected by the airfoil polars. You can find the updated text directly referenced by this comment below. Furthermore, we have now elaborated more in Section 3.2 with plots to showcase the uncertainty in our choice of polars as well as the polars documented in Melani et al. (2019) at Re = 80K. Please refer to the marked-up document to fully track all the changes made.

At $X/D = 0.43$, CACTUS slightly under-predicts the velocity deficit across all azimuths. This difference is likely due to the challenge of uncertainty with the polars, as previously discussed in Section 3.2. If the polars were closer to the true experimental airfoil behaviour, the difference could be minimised. This holds true for the rest of the results discussed in this study.

3. In the pitched case, where discrepancies grow more significant, the authors again attribute the issue to the vortex model while overlooking the potential role of load misrepresentation, such as inaccurate polars. This is a missed opportunity for a more balanced analysis.
We agree with the reviewer. This has been addressed together with the previous comment throughout the manuscript.
These discrepancies are primarily attributed to differences in vortex strength predicted by CACTUS, which depend on the airfoil polars selected for the simulation. CACTUS struggles to accurately capture the increase in circulation induced by pitch offsets, as its predictions rely heavily on the input polars. Given that the static stall angle for these polars is $\alpha_{ss} = 9.1°$, pitching the airfoils by $\beta = 10°$ effectively shifts the C_l vs α profile such that the blade would mostly operate in deep-stall conditions throughout its azimuth. As the accuracy of XFOIL becomes questionable at deep-stall conditions (Section 3.2), the errors are compounded.

4. Finally, the sentence in the abstract—"Results indicate that CACTUS effectively replicates the flowfield within the rotor volume and the very near wake when no pitch offsets are applied"—overstates the level of agreement. While results align with experiments in some areas, noticeable discrepancies remain. A more measured phrasing would better reflect the findings.
Thank you for pointing this out. We do agree with the reviewer that the sentence overstates the level of agreement. Therefore, we have now modified the sentence to be measured.
Results indicate that CACTUS is able to predict the flowfield to a reasonable extent within the rotor volume and in the very near wake when no pitch offsets are applied, with discrepancies attributed to the uncertainty of the polars at the low Reynolds numbers.

References

Goude, A.: Fluid Mechanics of Vertical Axis Turbines - Simulations and Model Development, ISBN 9789155485399, 2012.

Hirsch, C. and Mandal, A.: Flow Curvature Effect on Vertical Axis Darrieus Wind Turbine Having High Chord-Radius Ratio, in: European Wind Energy Conference, pp. 405–410, European Wind Energy Conference, 1984.

Huang, M., Sciacchitano, A., and Ferreira, C.: On the wake deflection of vertical axis wind turbines by pitched blades, Wind Energy, 2023.

Melani, P. F., Balduzzi, F., Ferrara, G., and Bianchini, A.: An annotated database of low Reynolds aerodynamic coefficients for the NACA0021 airfoil, in: AIP Conference Proceedings, vol. 2191, p. 20111, ISBN 9780735419384, ISSN 15517616, https://doi.org/10.1063/1.5138844, 2019.

van der Horst, S., van de Wiel, J. E., Ferreira, C. S., and García, N. R.: Flow Curvature Effects for VAWT: a Review of Virtual Airfoil Transformations and Implementation in XFOIL, in: 34th Wind Energy Symposium, American Institute of Aeronautics and Astronautics, ISBN 978-1-62410-395-7, https://doi.org/10.2514/6.2016-1734, 2016.