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Your reference n/a
Contact person Zekai Chen
Telephone/fax +1 (236) 883 8298 / n/a
E-mail chenzk0429@gmail.com
Subject Response to Reviewers

Delft University of Technology

Delft Center for Systems and Control

Address
Mekelweg 2 (3ME building)
2628 CD Delft
The Netherlands

www.dcsc.tudelft.nl

Anonymous Reviewer #2
Reviewers, Wind Energy Science

Dear Reviewer(s),

We sincerely thank you for the constructive and thoughtful feedback on our manuscript *LiDAR-enhanced Closed-Loop Active Helix Approach* (Ms. Ref. No.: wes-2025-161). We have revised the paper thoroughly. Below, we respond point by point, quoting each comment and indicating the changes made. A clean manuscript with highlighted changes is provided in the resubmission.

Yours sincerely,

Zekai Chen
Aemilius A.W. van Vondelen
Jan-Willem van Wingerden

Enclosure(s): Response to comments of Anonymous Reviewer #2

Response to comments of Anonymous Reviewer #2

Reviewer: *Overall, this revision is a much stronger paper, accepting most of the suggestions presented in my previous review. The results and discussion sections of the paper contextualize the findings in a much more practical way. Additionally, the flow of the paper works well as it stands.*

Authors: We thank the reviewer for the positive comments and appreciate the time and effort to review our work. As authors, we are nothing but pleased to adopt the valuable advice we got to improve the quality of our work with the goal of pushing the boundary of wind energy research. Therefore, a sincere gratitude to the reviewer(s).

Reviewer: *The length is quite long, however, so the authors could consider moving parts of the analysis to the Appendix. For example, only a high-level overview of the LiDAR processing chain is necessary for the reader to understand the results, and the same applies to the system identification process. This would allow the reader to focus better on analyzing the more relevant information, such as the helix identification and transformation, as well as the* $\mathcal{H}_\infty$ *controller synthesis. A few additional suggestions are presented below.*

Authors: We appreciate the reviewer for this valuable piece of advice. In the latest version of the manuscript, some details about LiDAR modeling, the Helix frame transform, and the internal model system identification are put in the appendix section so that the main body of the paper offers a high-level introduction of the proposed framework rather than delving into details for every single component. Several supporting sentences are added correspondingly in Section 3, 3.2.1, 3.2.3, and 3.3.1 to enhance the flow of the paper.
Inserted text: Please note that some details of the design can be found in the Appendix section. The goal of this section is to provide a high-level overview.

Lastly, a detailed explanation of the LiDAR model and the corresponding assumptions made can be found in Appendix A.

A detailed explanation of the Helix frame transform can be found in Appendix B. As a result, this transform maps the rotating input and output signals, $(\beta_{\text{tilt}}, \beta_{\text{yaw}})$ and (z, y), to a more static signal representation, $(\beta^e_{\text{tilt}}, \beta^e_{\text{yaw}})$ and (z^e, y^e), simplifying the subsequent controller design.

The detailed introduction of the system identification process can be found in Appendix C. Consequently, the frequency domain response of the identified model is illustrated in Fig. 9, indicating several observations...

Reviewer: *Perspective of wind stakeholders: Line 378+ addresses why the closed loop helical wake generation is beneficial to stakeholders. However, the argument that they"value the consistency in wind farm performance to ensure predictability of power production and reduce operational risk" is vague. The results demonstrate that the vortex placement is more consistent in shear conditions, but not in turbulent conditions due to the variance from the nominal trajectory due to high frequency turbulence components. If such an argument with wind farm stakeholders is not able to be adequately justified, then it may be better to stick with the reasoning that closed loop helix generation has not been attempted before, and that additional work can discern whether this method results in the consistency that stakeholders value. Looking at the current results from the single run case, it is difficult to see where this consistency would manifest itself.*

Authors: We appreciate the reviewer for the advice. Indeed, we found it hard to adequantely justified the statement. Therefore, in the latest version of the manuscript, we have changed the narrative from "maintaining a more consistent matches the stakeholders' value" to "this simple goal is chosen to show as a proof of concept" to keep a more neutral stand.

Inserted text: This simple target was selected to demonstrate the feasibility of the closed-loop Helix approach as a proof of concept......Therefore, the reference signal should be selected flexibly depending on the operator, and future studies should explore whether a consistent helical wake matches the stakeholders' interest and explore more condition-based reference choices.

Reviewer: *Single run results: Although mentioned in the discussion, it should be made abundantly clear in the Simulation Setup section (4.1) that only one simulation is run per wind condition. A natural place would be around line 375, where the rest of the simulation parameters are defined. This would yield clearer interpretation of Figure 14, which could be interpreted as a multi-run statistical analysis rather than a single run analysis.*

Authors: We thank the reviewer for pointing this out. In the latest version of manuscript, we added the text below in section 4.1 to make it clear to the audience that the results presented in this paper are from a single run.

Inserted text: Each scenario was evaluated via a single simulation run, serving as a proof of concept to demonstrate the efficacy of the proposed control framework.

Reviewer: *Figure 13 S&T (Shear and Turbulent) analysis: The paper clearly states why the CL helix controller cannot eliminate fluctuations in the vortex trajectory due to its low cutoff frequency. However, it seems as if the trajectory is experiencing a higher variance from the nominal uniform trajectory in CL3 vs OL3 (i.e., comparing the rightmost graphs in Figs 11 and 13). Since the paper states a single wind seed was used, it is surprising that this behavior exists, and the paper does not mention that it increases - rather it states that the extra oscillations are not able to be mitigated as expected. It could be worth quantifying the extent of these oscillations with respect to the uniform case. Perhaps an additional part of the figure could enumerate the variance of the turbulent helix trajectory from the non-turbulent trajectory, which would free the viewer from having to make their own conclusions visually.*

Authors: We thank the reviewer for this insightful observation. In the latest version of the manuscript, we have expanded our discussion regarding this increased oscillation in the result analysis part of section 4.4.3.

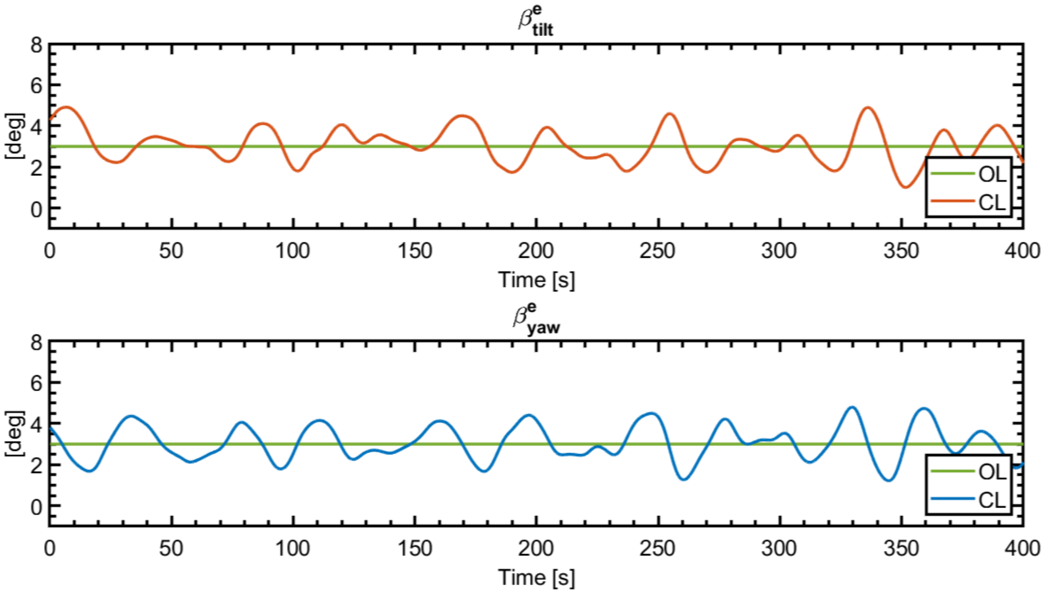

Figure 1: Control input in the case where both turbulence and shear are present.

In general, the increased oscillation could stem from both the actuation of the wind turbine and the aerodynamic performance of the modified wake. The above figure illustrates the control input in the Helix frame for the combined turbulence and shear case. The input shown in this figure can be seen as a combination of two components: a main periodic component with the frequency of f_e, which is used to correct the steady-state bias induced by the shear, and an additional dynamic oscillating component, which is used to stabilize the turbulence. The time-averaged values of both inputs are 3.06 ($\bar{\beta}^e_{\text{tilt}}$) and 3.03 ($\bar{\beta}^e_{\text{yaw}}$), which are higher than the open-loop counterparts. These increased pitch actuations might stem from the need to both correct the bias and stabilize the oscillation. As a result, this increased value contributes to the increased hub jet oscillation.

Another reason to explain the increased oscillation might be the aerodynamic feature of the wake. To the best of the author's knowledge, the increased oscillation could be explained by the close relationship between enhanced wake recovery and earlier near-wake breakdown of vortices, a phenomenon consistent with the findings of [2] and [1]. Specifically, by correcting the shear-induced bias in the CL_3 case, the proposed system facilitates more rapid wake recovery compared to the OL_3 case. This accelerated recovery is reflected in the increased oscillations of the hub jet, which stem from the earlier breakdown of the vortex structure. While the current data demonstrate this trend, a comprehensive fluid-dynamic characterization of the underlying mechanisms remains outside the scope of this work and needs to be addressed to facilitate a better understanding of wake recovery induced by dynamic wake mixing control. Consequently, we have noted in the revised text that further fundamental studies are warranted to explore this phenomenon from a fluid dynamics perspective.

Inserted text: As mentioned in the preceding analysis, correcting the shear-induced bias facilitates enhanced wake recovery, thereby increasing the total power production of the wind farm. However, this correction comes at the cost of higher fatigue and power loss in the upstream turbine. Compared to the open-loop case (OL_3), the hub jet in the closed-loop case (CL_3) exhibits larger oscillations. This behavior can be attributed to both the increased time-averaged pitch actuation of 3.06 ($\bar{\beta}^e_{\text{tilt}}$) and 3.03 ($\bar{\beta}^e_{\text{yaw}}$) that are used to both correct the shear induced bias and stabilize the turbulent induced oscillations, and the close relationship between enhanced wake recovery and earlier vortex breakdown, a phenomenon supported by the findings of [2] and [1] have shown. Consequently, the increased oscillation of the hub jet in CL_3 could be explained by the premature vortex breakdown. Further studies should be conducted to understand this phenomenon from a fluid dynamics perspective.

Reviewer: *Figure 16: The y-axis limits should be shrunk. It is difficult to discern the two lines. In addition, the analysis for this figure is a bit misleading. For one, it is visually difficult to discern the difference in time-averaged magnitude between the OL and CL pitch signals, so a quantitative result should be given. Additionally, the primary concern for pitch actuation is changes in pitch actuation, rather than magnitude, since changing blade pitch results in actuator degradation. Perhaps this is a nuance of the MBC transform that I am not grasping, but regardless, some additional clarification could be beneficial.*

Authors: We thank the reviewer for noticing it. To make it clearer for the audience, we have rescaled the y-axis to only between 2 and 4 and quantified the change of time-averaged magnitude in the closed-loop case compared to the open-loop counterpart in the revised manuscript.

Our calculation shows that the time-average magnitude of β^e_{tilt} and β^e_{yaw} are 2.95 and 2.93 compared to the constant 3 of their open-loop counterparts. Since the magnitude of the blade pitch signal β_i is directly proportional to β^e, as the Helix frame transform shows, a reduction in the time-averaged magnitude of β^e_{tilt} and β^e_{yaw} corresponds to a lower time-averaged magnitude of $\beta_{1,2,3}$ for the upstream wind turbine. As shown in Figure 5 of [3], this reduction contributes to higher power production for the upstream turbine.

We fully agree with the reviewer's concern that increasing pitch actuation frequency can lead to actuator degradation. This is evident in the definition of Pitch Bearing Damage (PBD):

$$\mathrm{PBD}(\phi) = \sum_{k=1}^{N} \delta\beta(k) \cdot \left[\max((\cos\phi \cdot M_{\text{flap}}(k) + \sin\phi \cdot M_{\text{edge}}(k)), 0)\right]^m . \qquad (1)$$

where ϕ is the radial position of the bearing, $\delta\beta$ is the pitch difference, M_{flap} and M_{edge} denote the flap-wise and edge-wise blade bending moment, and m is the inverse Wöhler slope. Consequently, changes in pitch actuation ($\delta\beta$) are directly linked to PBD.

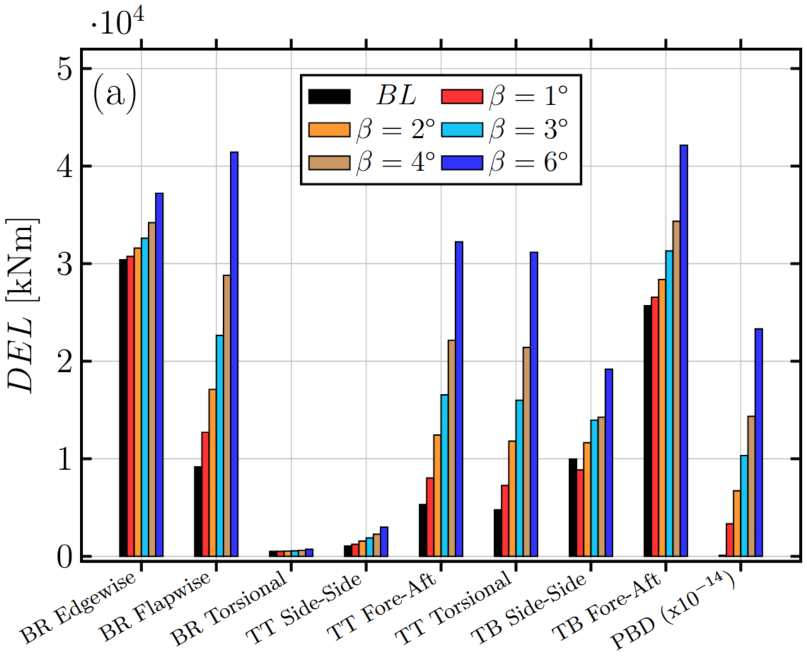

Figure 2: The relationship between the blade pitch signal magnitude β and the fatigue loads of a wind turbine when generating a helical wake. Figure adopted from [3].

Nevertheless, a decrease in the time-averaged magnitude of blade pitch signals also plays a critical role in reducing fatigue load. Figure 2 shows the relationship between the magnitude of blade pitch signals and the fatigue load of a wind turbine, where the Helix approach is actuated. The figure demonstrates that a lower signal magnitude (β_i) contributes to reduced fatigue, thereby benefiting turbine operation.

Consequently, the net decrease in fatigue loads observed in our work results from two competing effects: the penalty of increased pitch variation ($\delta\beta$) and the benefit of a lower time-averaged magnitude ($\bar{\beta}$). Our results indicate that the benefit of the lower mean magnitude dominates, outweighing the minimal penalty incurred by the pitch oscillation.

Inserted text: More specifically, the time-averaged magnitude of β^e_{tilt} and β^e_{yaw} are 2.95 and 2.93 compared to the constant 3 of their open-loop counterparts. This explains the power increment in the upstream wind turbine, as proved by the work of [3], whereas the downstream power remains largely unchanged due to dominant natural turbulent mixing.

References

[1] Stefano Gambuzza and Bharathram Ganapathisubramani. The influence of free stream turbulence on the development of a wind turbine wake. *Journal of Fluid Mechanics*, 963:A19, 2023. doi: 10.1017/jfm.2023.302.

[2] Emily L Hodgson, Mads H Aa Madsen, and Søren J Andersen. Effects of turbulent inflow time scales on wind turbine wake behavior and recovery. *Physics of Fluids*, 35(9), 2023. doi: 10.1063/5.0162311.

[3] Emanuel Taschner, Aemilius A W van Vondelen, Remco Verzijlbergh, and Jan Willem van Wingerden. On the performance of the helix wind farm control approach in the conventionally neutral atmospheric boundary layer. In *Journal of Physics: Conference Series*, volume 2505, page 012006. IOP Publishing, 2023. doi: 10.1088/1742-6596/2505/1/012006.