Response to reviewer's comments - Reviewer 2

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Title: Field comparison of load-based wind turbine wake tracking with a scanning lidar reference

Color coding: Reviewer comments, authors responses, paper citations

Dear Reviewer,
First and foremost, thank you for taking the time to read through and review our manuscript. Answering your comments increased the quality of the manuscript. In the following we address each of your comments individually.

With kind regards,
The authors

1) While kind of discussed, it would help to state your contributions to this work explicitly in a pointwise list at the end of the introduction.

If you refer to the authors contributions – these are documented at the end of the paper, after the appendix and before the references. The scientific contribution to the research field is indeed documented at the end of the introduction, just before the paper structure is outlined. Here we define the research gap and deduce how this work fills that gap. We have adjusted the part to highlight the sub-aspects of the research gap that are answered in this paper.

"The research gap can be concluded as follows: Existing work for load-based wake tracking lacks either

- a consideration of wake dynamics and time resolution, or
- a field validation, or
- (in case of a field validation) an independent reference to compare with.

The objective of this work is to fill the gap by addressing all three aspects: The works shows direct estimation of the instantaneous wake centre position in a field experiment with two utility-scale wind turbines. The load-based estimate is compared to the wake position probed with a scanning lidar, which serves as an independent reference. To that purpose, the uncertainty of the lidar estimate is quantified using analytic error propagation following the GUM […]."

2) Sect 2.1: You directly start describing the wind farm, while I would expect it would be more interesting to say something first about the scientific contribution you are bringing with your work. Consider changing the order.

We have indeed considered a different order, even when writing the initial draft, but chose to stay with this order for two reasons. Firstly, we see the field testing itself as one of the core scientific contributions of this paper, so no contradiction in starting with description of the field experiment. Secondly, the field setup influences the wake estimation methodologies. A general idea of the setup is important to understand certain follow-up topics, e.g. how the training data for the load-based method is generated, how the lidar-related coordinate transforms are formulated or which sensor uncertainties need to be considered.

3) Fig XX: All figures need a more elaborate caption. Now the figures are not interpretable apart from the main text.

Thank you for pointing this out. We have added additional information to the captions of most figures to make them more self-explanatory.

4) Eq 3 to 7: very standard theory, really needed to include in this paper? Or make it more specific to your case. Also, explain why you assume 0 noise acting on the state and output.

We agree that the formulation of an EKF is well-known for people from a control & estimation background. For people from a wind physics or lidar background it might be new, that is why we introduce it to make sure we document our work steps thoroughly. We see the same for other papers in this field, e.g. (Braunbehrens et al., 2023; Eichstadt et al., 2016; Lio et al., 2021).

Regarding your second point: This must be a misunderstanding, we do not assume zero noise acting on the state and output. The notation of the models *f* and *h* implies to define the noise as an input, as seen e.g. in Eq.8. When using the local linearisations in the EKF, however, the noise term enters via the additive noise covariance matrices **Q** and **R** (see Eq. 4&5). Thus, the second input to the models *f* and *h* is set to zero (to not conflict with the notation while also not implying another source of noise).

The equations are discretized for their implementation in the state transition function $f(x_k, n_{x,k})$. Note that the $n_{x,i}$ represents the *i*th element of the noise vector n_x. The time index *k* is omitted here, because the continuous representation is chosen. Since the noise term enters linearly, they are incorporated in the EKF formulation via the additive noise covariance matrix **Q**.

5) Eqs 8a-8d: Please elaborate more on this model. It seems very simple for the dynamics you want to capture. Is it linear? If yes, why do you need an EKF, and not a normal KF? Also, elaborate more about how a (linear?) combination of the chosen state vector elements leads to the 3 nonrotating blade moments. An elaborate explanation and justification of the dynamic model and chosen measurements are largely missing. ---> Ah, you explain this in the next subsection. Would it make sense to swap the order 2.2.3 and 2.2.2? So first fully define f() and h(), and then incorporate them into the state estimator.

Regarding the state transition model described in Eqs. 8a-8d:
The entire section 2.2.2 motivates and derives the state transition model, leading to the formulation in Eq. 8. As you have noticed, the loads are not touched here, because the state transition model solely considers how the filter states change with time. This is mentioned at the beginning of section 2.2.2:
The dynamic model describes how the system state evolves over time. In this study, the model should capture how the wake centre position changes over time. Depending on the atmospheric conditions and the wind farm control strategy, the wake trajectory is subject to various dynamic

influences. Time scales of wind direction changes, wake-steering control and wake meandering need to be incorporated by the dynamic model of the EKF, while effects corresponding to small-scale turbulence with no expressiveness towards the wake position need to be rejected.

Regarding the linearity of the model:
As you point out correctly, the dynamic model $f(x_k, n_{x,k})$ to describe the random walk behaviour of a meandering wake indeed boils down to a first-order linear formulation. However, the measurement transition model $h(x_k, n_{y,k})$ (described in section 2.2.3) is nonlinear. That is why an EKF is required. Still, $f\left(x_k, n_{x,k}\right)$ does not need to be linearized in every iteration. Instead, the state transition matrix **F** can be formulated directly. We added this information explicitly to the general EKF formulation in section 2.2.1

Note, that the state transition model $f\left(x_k, n_{x,k}\right)$ used in this work can be formulated as a linear operation (see next subsection). Thus, the local linearisation in Eq.4 is not necessary in every iteration, since **F** can be directly pre-computed.

Regarding the order:
Section 2.2.1 describes the EKF formulation and defines the state and measurement vectors. This needs to happen first, otherwise the models f() and h() would not be interpretable.

Section 2.2.2 defines the state transition function f(). It appears first in the EKF algorithm and is also more concise, that is why we describe it first.

Section 2.2.3 defines the measurement transition function h(). It links the wake position to the rotor loads. We see no benefit in swapping order with section 2.2.2.

Section 2.2 describes the aforementioned structure, such that the reader knows in which order the load-based wake tracking is presented. We added more detail to the description of the section sturcuture at the beginning of sect. 2.2 in order to avoid any confusion for the reader.

The interaction between the individual aspects of the load-based wake tracking problem is shown in the overview chart in Fig.2. The EKF and its sub-components are described in the following sections. In section 2.2.1 the EKF formulation and the definition of states and inputs takes place. Section 2.2.2 defines the state transition function *f()*, and section 2.2.3 defines the measurement transition function *h()*.

6) 2.2: Kind of a literature survey. Can it be largely moved to the introduction of the paper?

Section 2.2 is not a literature survey. We assume that you refer to section 2.2.2, which includes a number of literature references. In section 2.2.2, the state transition model is motivated and we provide background information for the formulation of Eq.8. As you argued in your previous comment, such an elaboration is desirable to explain the design choices. We discuss specific aspects of wake and wind direction dynamics and their characteristic time scales. This has a direct relation to the model formulation of this section. In our opinion, it is far too detailed and extended to find room in the general introduction section of this paper.

7) 2.2.3: You use the Coleman transformation to obtain the nonrotating blade moments (tilt/yaw). It is well-known that for larger, more flexible rotors, you need some sort of decoupling strategy -- possibly in the Coleman transformation by an azimuth offset -- to obtain decoupled axes. You do seem to consider this aspect with the variable "d". Because it is a crucial aspect for larger flexible

rotors, I highly recommend that you incorporate it into your research and elaborate more; there have been publications on this topic in the past.

You are perfectly right, the yaw-tilt coupling needs to be considered and this is in fact done via the parameter *d*. It describes the phase delay of an inert blade reaction when fed through the Coleman transform. In the context of this work we do not state absolute values of *d* since it refers to a commercial turbine subject to confidentiality. We further added the references (Lu et al., 2015) and (Mulders et al., 2019) which provides background information on the yaw-tilt-coupling in high detail. Moreover, the parameter *d* is now indicated in the contour plot of the measurement model:

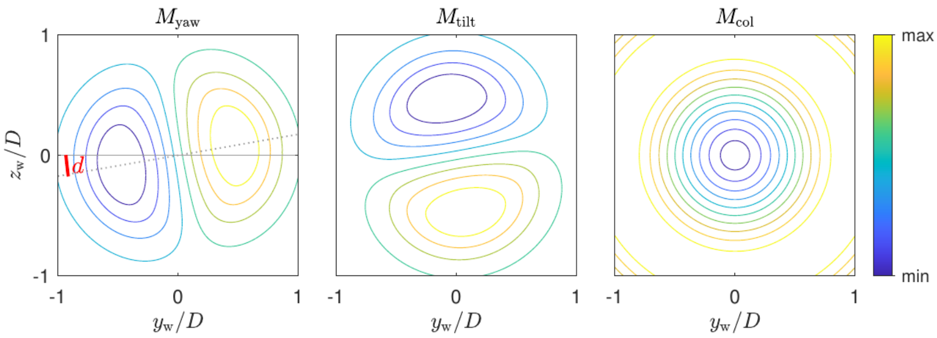

Figure 3. Contour plot of the measurement model outputs in dependency of the wake position. Normalized with their respective maximum and minimum for confidentiality. The fitting parameter d is indicated, describing the phase-offset of the yaw-tilt-coupling.

8) Sect 3.: I got lost in the structure of this section. Please announce what you will be discussing in the first part of the section (directly under 3.), and come up with a clearer structure, so that the storyline makes more sense.

Thank you for pointing this out. Please note that the general paper structure is outlined at the end of the introduction. But we understand the need to give guidance at the beginning of each main section. We thus added the following description in the beginning of section 3.

In this section, the results of the field experiment and the wake estimation are reported. In section 3.1, the wake conditions contained in the data set are described, considering both the wake position variability and the wake deficit shape. In section 3.2, the wake position estimates of the load-based EKF and the lidar are compared.

9) Sect 4.: Also, what is the purpose of this section? What will you discuss? Announce that at the start of the section.

Also thanks for hinting at this. We added the following description in the beginning of section 4.

In this section, the results are interpreted and ranged. First, the influence of the site specifications on the results is discussed, considering the generalizability of the findings. Secondly, the wake tracking performance is discussed. The comparison to existing works in literature considers their individual testing conditions and performance metrics. Finally, the applicability of the presented wake tracking in the context of wind condition awareness and wind farm flow control is discussed.

10) Often, a "?" appears when citing, check

Please excuse the inconvenience of this and thank you for pointing it out. It turned out to be a corrupted bibtex item that slipped our checks for the final compilation of the document. We have of course corrected this in the revised version for all occurrences of this reference. The missing reference was (Kidambi Sekar et al., 2024).

Braunbehrens, R., Tamaro, S., & Bottasso, C. L. (2023). Towards the multi-scale Kalman filtering of dynamic wake models: observing turbulent fluctuations and wake meandering. *Journal of Physics: Conference Series*, *2505*(1), 012044. https://doi.org/10.1088/1742-6596/2505/1/012044

Eichstadt, S., Makarava, N., & Elster, C. (2016). On the evaluation of uncertainties for state estimation with the Kalman filter. *Measurement Science and Technology*, *27*(12), 125009. https://doi.org/10.1088/0957-0233/27/12/125009

Kidambi Sekar, A. P., Hulsman, P., Van Dooren, M. F., & Kühn, M. (2024). Synchronised WindScanner field measurements of the induction zone between two closely spaced wind turbines. *Wind Energy Science*, *9*(7), 1483–1505. https://doi.org/10.5194/wes-9-1483-2024

Lio, W. H., Li, A., & Meng, F. (2021). Real-time rotor effective wind speed estimation using Gaussian process regression and Kalman filtering. *Renewable Energy*, *169*, 670–686. https://doi.org/10.1016/j.renene.2021.01.040

Lu, Q., Bowyer, R., & Jones, B. L. (2015). Analysis and design of Coleman transform-based individual pitch controllers for wind-turbine load reduction. *Wind Energy*, *18*(8), 1451–1468. https://doi.org/10.1002/we.1769

Mulders, S. P., Pamososuryo, A. K., Disario, G. E., & Wingerden, J. van. (2019). Analysis and optimal individual pitch control decoupling by inclusion of an azimuth offset in the multiblade coordinate transformation. *Wind Energy*, *22*(3), 341–359. https://doi.org/10.1002/we.2289