"Experimental analysis of the dynamic inflow effect due to coherent gusts"
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Authors response to reviewer comments

We would like to thank Georg Raimund Pirrung and one anonymous reviewer for their thorough review, time and constructive and very meaningful comments. Their input helped to improve the original manuscript.

We addressed the few remaining minor comments of reviewer 1 and reply to these point by point. First the marked text from the PDF and the underlying comment (in italics) is repeated, followed by an answer of the authors and if applicable the excerpt from the LaTeX-Diff file (framed), highlighting the changes. Line numbers in the reviewer comments refer to the first revised document and to the second revised document for the response.

<u>Anonymous, Reviewer #1</u>

R1C1. ***[Reviewer #1]*** line 39: *"*They found relevant lower fatigue loading for the out-of-plane blade root bending moments and tower bottom fore-aft bending moment for the higher fidelity FVWM type simulations" - *what to compare with?*

[Authors] Thank you for this comment. We added ', compared to BEM type simulations' at the end of the sentence to clarify (see also excerpt R1C2 l41).

R1C2. ***[Reviewer #1]*** lines 40-41: *"*The implementations of non-uniform inflow in BEM was identified as one relevant contribution to this behaviour, however they also suspected the dynamic inflow effect to be responsible for some of the differences between BEM and FVWM in turbulent inflow." - *unclear*

[Authors] This point can be made clearer. Thank you for the comment.
As BEM assumes uniform inflow, handling of for instance sheared flow needs some extra assumptions. Here different approaches can (and are) taken. Just to mention two approaches. A simple approach is to just take a rotor averaged wind velocity to obtain the induction factors in BEM for ring segments of different radii and then use these with the local wind velocity at the different blade position to get the local velocity triangles at the blade airfoils. A much more sophisticated approach is for example the polar grid approach used in HAWC2 and described by Madsen et al. 2020.
We refined and extended the statement in the paper:

> shear on the loading of wind turbines. They found relevant lower fatigue loading for the out-of-plane blade root bending moments and tower bottom fore-aft bending moment for the higher fidelity FVWM type simulations~~. The implementations of~~ , compared to BEM type simulations. The implementation of how non-uniform inflow influences the induced velocities over one rotation in BEM was identified as one relevant contribution to this behaviour, however they also suspected the dynamic inflow effect to be responsible for some of the differences between BEM and FVWM in turbulent inflow.

R1C3. ***[Reviewer #1]*** *line 234: "*Errorbars indicate the quadratically added up uncertainty of inflow wind velocity and the 95% CI of the load measurement for the 20s long considered measurement length per wind velocity step." - *it needs explanation for the first appearance in the paper*

[Authors] The term already was introduced in line 128 (Rev 1) /129 (Rev 2)

R1C4. ***[Reviewer #1]*** *lines 263-264:* The quasi-steady turbine loads and inductions, shy of dynamic inflow effects, are obtained for the dynamic wind field by interpolation from this characterisation. - marked

[Authors] We made this part clearer and used 'lacking the' instead of 'shy of':

> The quasi-steady turbine loads and inductions, ~~shy of~~ lacking the dynamic inflow effects, are obtained for the dynamic wind field by interpolation from this characterisation. The reference wind speed of the gust at the rotor plane position is used for

R1C5. ***[Reviewer #1]*** *lines 295-302:* "Schepers (2007) describes the dynamic inflow for a fast change in thrust alongside the reproduced Fig. 6 a as: "The trailed vorticity is formed at the blade and convected downstream with the local total velocity, partly wake induced [..]. Then a change in bound vorticity (e.g. through a change in pitch angle) modifies the vorticity which is trailed into the wake. Due to the fact that the vorticity is convected with a finite velocity, the resulting wake becomes a mixture of 'old' and 'new' vorticity. Consequently the velocity induced by such wake includes a contribution from the 'old' and the 'new' situation" - *Maybe shortly summarize it in your own words?*

[Authors] You are right. With some distance to the paper we think rephrasing it to avoid the direct quotation is better style. See below for the changes:

> The Øye model is developed for the assumption of constant wind velocity and filters the induced velocity through two first-order differential equations. ~~Schepers (2007) describes~~ In Schepers (2007) the dynamic inflow effect is described for a fast change in thrust alongside the reproduced Fig. 6 a~~as: "~~. The trailed vorticity is formed at the blade and convected ~~downstream with the local total velocity, partly wake induced . .. Then a~~ with the total local velocity, which is in parts induced by the wake. A change in bound vorticity ~~(e.g. through a change in pitch angle) modifies the vorticitywhich is~~ through a pitch step modifies that vorticity, trailed into the wake. Due to the ~~fact that the vorticity is convected~~ convection with a finite velocity, ~~the resulting wake becomes a mixture of 'old' and 'new' vorticity. Consequently the velocity induced by such wake includes a contribution from the 'old' and the 'new' situation"~~ a mixed wake forms that consists of 'old' and 'new' vorticity. This mixed wake influences then the induced velocities.

R1C6. ***[Reviewer #1]*** *lines 303-304:* "Schepers (2007) estimates that the effect of this mixed wake is 'felt' by the rotor until it has travelled 2D to 4D, before the induced velocity has reached a new equilibrium. - *The sentence is misleading. The rotor will shortly feels the change, just the effect will establish or it will reach a new equilibrium till 2-4D.*

[Authors] We made this part clearer, by referencing to the rotor flow.

> Schepers (2007) estimates that the effect of this mixed wake ~~is 'felt' by the rotor~~ influences the rotor flow until it has travelled $2D$ to $4D$, before the induced velocity has reached a new equilibrium. In Berger et al. (2021a) a relevant distance of $2D$ is

R1C7. ***[Reviewer #1]*** *lines 560-562:* "Widely applied engineering models that filter the induced velocities, like Øye model (Snel and Schepers, 1994) in GH Bladed and OpenFAST, the new DTU model (Madsen et al., 2020) in HAWC2 and ECN model (Snel and Schepers, 1994) in Phatas, cannot adequately catch the dynamic inflow phenomenon due to gusts. - *Have you test them? if not, you are not sure. please remove it then.*

[Authors] We have shown in the paper that a sole time derivative filter on the induced velocity cannot capture the effect seen due to a gust. Therefore, all dynamic inflow models that use this approach cannot catch the effect adequately. For both the ECN and new DTU model the described 'working mechanism' in the given references is to filter the induced velocities. Therefore, we decided to not show further comparisons with these models in the paper (which was planned at an early stage of the research before we have analysed the experiment), as the qualitative outcome is already clear. However, we have tested (early in the research) the ECN and new DTU models for the sine gust with similar behaviour as seen for the Øye model. So we refined our statement while maintaining the important conclusion of a methodological shortcoming of such widely applied engineering models.

> leads to an amplification of the induced velocities. The effect is also seen in FVWM simulations for the loads and induced velocity~~.~~, however with slightly lower amplitudes for the induced velocity than in the experiment. Widely applied engineering models ~~that~~ filter the induced velocities, ~~like~~ e. g., the Øye model (Snel and Schepers, 1994) in GH Bladed and OpenFAST, the new DTU model (Madsen et al., 2020) in HAWC2 and the ECN model (Snel and Schepers, 1994) in Phatas~~,~~. Exemplified at the Øye model and by analytical considerations it was shown that such approach cannot adequately catch the dynamic inflow phenomenon due to gusts. ~~They damp~~ The filtering damps the induced velocity~~due to the filtering~~, thus leading to higher fatigue loads. As an initial ~~model~~ attempt to tackle the dynamic inflow effect due to gusts we proposed an improvement in the implementation of the Øye model, adding an additional term with a time derivative filter on the wind velocity.
>
> Now, that the effect is known further, pinpointed wind tunnel experiments are needed for the development, tuning and validation of dynamic inflow models for gusts. One focus should be to further reduce uncertainties, especially in the inflow. Furthermore, the typical operation of variable speed controlled wind turbine in the free field is more complex than the presented

R1C8. ***[Reviewer #1]*** *Fig A1 & A2: This is my main comment. In Figure A1 and figure A2, the modified Oye model improves the phase prediction, but the prediction in amplitudes are much higher especially when the induced velocity is increasing. Could you explain this? And, could you make it more moderate in the abstract and the conclusion, at least mention this shortcoming or where it needs further improvement.*

[Authors] Thank you for this comment. In parts this difference is connected to the also higher steady amplitudes in the BEM model compared to the FVWM model. We did not further investigate these small steady differences here. The dynamic differences further might have a similar origin as we saw for a pitch step comparison between that FVWM and experiment in Berger et al. 2020. The change to the discussion is seen in the excerpt in R1C7 l 561. See below the excerpts for the abstract and the more detailed discussion of possible reasons for the differences in the appendix.

> amplification of the induced velocity. The commonly used Øye engineering model predicts increased gust load amplitudes and thus higher fatigue loads. With an extra filter term on the quasi-steady wind velocity, the qualitative behaviour observed experimentally and numerically can be caught. In conclusion, these new experimental findings on dynamic inflow due to gusts and improvements to the Øye model enable improvements in wind turbine design by less conservative fatigue loads.

For the BEM case the original Øye dynamic inflow model gives a reduction in amplitude through the filtering approach, as is expected. The improved Øye model as well as the dynamic FVWM lead to higher amplitudes, compared to the respective (quasi-)steady cases. In general the behaviour in relation to the respective (quasi-)steady case of the improved Øye model and the FVWM are similar. However, amplitudes for the dynamic FVWM are lower than estimated by the improved Øye model, especially when the induced velocity increases. In parts these differences also reflect the difference in the respective steady signal, which shows higher amplitudes for the BEM model than for the FVWM. Also in the comparison of a pitch step experiment in Berger et al. (2020) with this FVWM simulation setup an offset for the fitted slow time constant, mainly for the pitch step to high load, was seen. There it was reckoned that this is related to the wake convection in the simulation model. For a further dynamic inflow gust model development based on this FVWM setup these differences should be further investigated.