Authors' response to Referee 3

General

The authors present an experimental study in a wind tunnel for a control strategy for wind turbines. The control system, named Helix, increases the rotational component of the wake by pitch control for sinusoidally varying yaw and tilt moments. Experiments are performed under low turbulence conditions using a single or two scaled turbines, studying in different steps, the wake averaged statistics and phase-locking techniques. Also, several sensors provide turbine level observations. The authors then discuss and quantify wake recovery and vortex meandering. It is found that operating the scaled turbine with the Helix control results in faster wake recovery when compared with the baseline cases.
The manuscript is well written and the experiments and results of interest for the wind energy community. Nevertheless, before recommending publications I ask the authors to address the following comments and remarks:

We thank the referee for reviewing this manuscript, the valuable feedback, and the constructive comments. At this stage of the review process, we respond to referee #3's comments and propose improvements for the journal manuscript. The referee's original comments are printed in bold followed by the corresponding answers. A screenshot of the different versions of the updated passages from the manuscript is provided below the answer.

Specific comments

1) **The study concerns low turbulence conditions only. Nevertheless, background turbulence significantly affects the development of the wake and the structures within it. This therefore raises the question, discussed by the authors in the introduction, about the relevance of present results in realistic conditions. While the present study presents a fundamental interest, I consider that the authors should discuss in better detail, using the several works available in the literature, how their results will be modified when background turbulence is present.**

Thank you for raising this point. The same topic was also brought up by referee #2. We agree that it is important to address this point better. We added a small discussion about this in the literature review in the introduction chapter. We added a source of a study where the authors investigate the effect of inflow turbulence on the efficiency of dynamic wake mixing and show that inflow turbulence has a significant inflow on the effectiveness of wake mixing for power optimization. Furthermore, we updated the future works slightly to say that further investigations on inflow turbulence are needed.

> approach experimentally in a wind tunnel (W/T) and should give a detailed insight in the wake aerodynamics. To provide such a detailed insight, the flow in the wind tunnel has to be a clean lab flow, which is uniform and is characterized by a very small turbulence intensity. Such clean inflow will not only highlight the effects of the control technique in the wake but also influence their effectiveness. Wake mixing techniques like Helix add turbulence to the wake. Consequently, if the turbine inflow is already characterized by higher ambient turbulence the effect of wake mixing will be mitigated. In a recent study Mühle et al. (2024) compare power gains for wake mixing by dynamic yaw for different inflow turbulence. They found a strong reduction of the effect on the power of a two-turbine setup in case of high inflow turbulence and thus confirm the findings of Munters and Meyers (2018a). Nevertheless, they suggest that wake mixing has the potential to improve the power output of a wind farm in case the wakes are strong and persistent.

Nevertheless, the Helix technique and its real-world realization ~~is~~ are just at the beginning of its development. Consequently, this study can only provide a first insight ~~on~~ into the potential and wake mixing mechanisms. ~~An~~ Additional wake analysis with different Stroual numbers is required to prove that the wake meandering is the main driver for increased mixing. Moreover, an investigation of the influence of inflow turbulence on ~~the wake mixing potential could be the next step~~wake mixing is needed to understand its potential in more realistic inflow conditions characterized by higher levels of ambient turbulence. Further, testing the Helix technique in wind farm control studies could be promising.

2) **Also, the setup presents a large blockage. This is also briefly discussed by the authors, and they use a very simple model to cater for this issue. Nevertheless, blockage not only affects the hub velocity but it also severely modifies the wake development, the air it entrains and the evolution of structures. Several works discuss the relevance of blockage and propose different corrections (see for instance Saghi et al 2016, Steiros et al 2022, among several others). Blockage is one of the main limitations of the experimental setup and should be addressed carefully.**

Thank you for this important comment. The same concern was also raised by Reviewer #1 and Reviewer #2. We agree that the blockage is very high and was not discussed appropriately. We added information about the blockage effect in section 3.2. We included a paragraph in which we use several studies investigating the blockage effect to discuss the effect that blockage is expected to have on wake development.

however accelerated, resulting in a higher velocity experienced by the turbines. ~~An estimation of the~~ To account for such an effect on the turbine performance, it can be corrected by applying analytical models, a recent review is presented in the study by Steiros et al. (2022). More information is presented by Ross and Polagye (2020) who conducted an experimental assessment of such models and their application to different wind turbine concepts. In the present study, the performance was corrected by a calculation of the Rotor Effective Wind Speed (REWS) for the upstream G1, done as described in Campagnolo et al. (2022)~~, .~~ This revealed a blockage-corrected free-stream velocity $U_{\infty,corr} \approx 5.9\ m/s$, which correlates to the rated wind speed of the model wind turbine. Consequently, the turbine is operated at a tip-speed ratio of approx. $\lambda = 8.2$. ~~In the~~ Based on the authors' knowledge, there are no analytical blockage correction models that would allow us to quickly assess the influence of the wind tunnel walls on the wake. One possible way to investigate this is to use computational fluid dynamics (CFD). Zaghi et al. (2016) studied the effect of blockage on a model wind turbine with a Reynolds Averaged Navier-Stokes (RANS) simulation. They analyzed the streamwise wake velocity and found increased velocities in the area behind the rotor but also in the outer region of the wake in case a wind tunnel wall was present. In a more detailed analysis Sarlak et al. (2016) used Large Eddy Simulation (LES) combined with the actuator line technique to investigate wake velocity and Reynolds stresses for different blockage ratios up to $\alpha = 0.2$. They found a significant impact on the mean wake velocity in the case of the highest blockage ratio. Especially in the region outside of the rotor, the velocity is found to increase; this augmentation is mitigated in the rotor area but is still present. Furthermore, they concluded that blockage has no considerable effect on the wake mixing rate as maximum and minimum velocities do not differ significantly. In a combined experimental and numerical study McTavish et al. (2014) investigated the influence of wind tunnel blockage on the wake width and found that the wake compresses when blockage increases. Consequently, the wake results of the presented study are expected to be characterized by slightly higher streamwise velocities and a narrower wake compared to a full-scale test. As a result, in the analysis of the

3) **The time-resolved five-hole probe has a large head surface (around 8 squared millimeters) and therefore, for a turbulent wake in a wind tunnel, lies within the inertial range of turbulence. It is then important to check the effective temporal resolution, taking into account both background noise in the wind tunnel and spatial filtering effects. I therefore suggest that the authors show some typical spectra obtained with the probe. Also, the description of the calibration process is quite long, has it been performed by the authors or by the manufacturer? If it is the latter case, I suggest that the discussion is taken out of the manuscript.**

Thank you for your comment on the probe. Since Reviewer 1 also asked for changes related to the FRAP, we changed the text. We removed the detailed section on the FRAP, despite the probe being developed and calibrated by the author in collaboration with the manufacturer (see Dissertation of F.M. Heckmeier). To answer your question on the spatial and temporal resolution of the probe, we would like to refer to a study we performed targeting this question. In this study, we addressed this topic and compared the probe to hot-wire probes using grid-generated turbulence ([(2) (PDF) Spatial and temporal resolution of a fast-response aerodynamic pressure probe in grid-generated turbulence (researchgate.net)]).
We ensured the appropriate FRAP usage and showed the probe's spatial and temporal limitations. We added this reference to the text (see also response to Reviewer 1, Question 5).

The spatial and temporal characteristics and the underlying calibration process of the FRAP can be found in the literature (see Heckmeier et al. (2019); Heckmeier and Breitsamter (2020); Heckmeier et al. (2021); Heckmeier (2022)): A high spatial accuracy below 0.2° in both flow angles and 0.1 m/s in the reconstructed velocity can be achieved. The spatial and temporal

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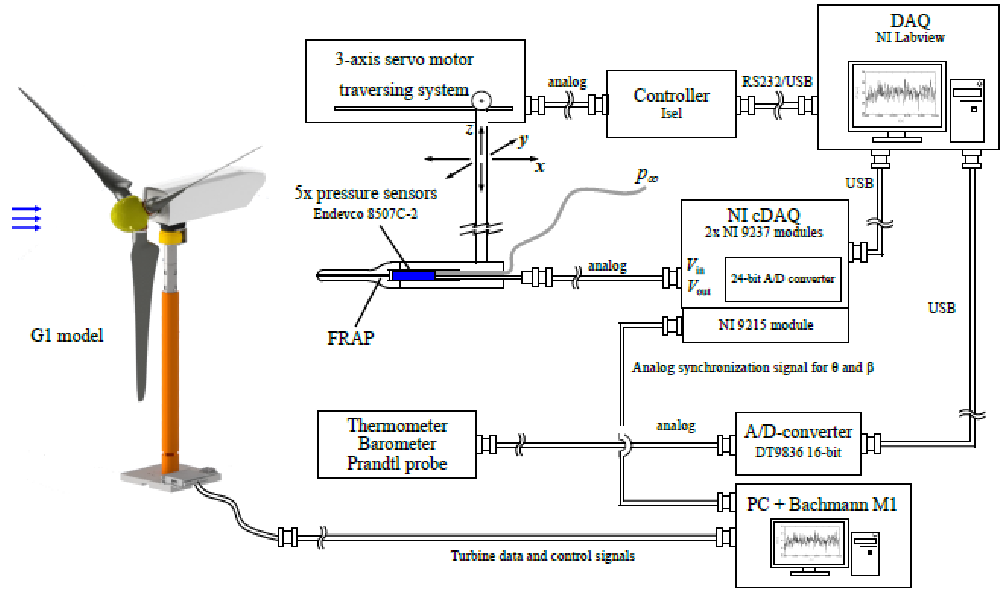
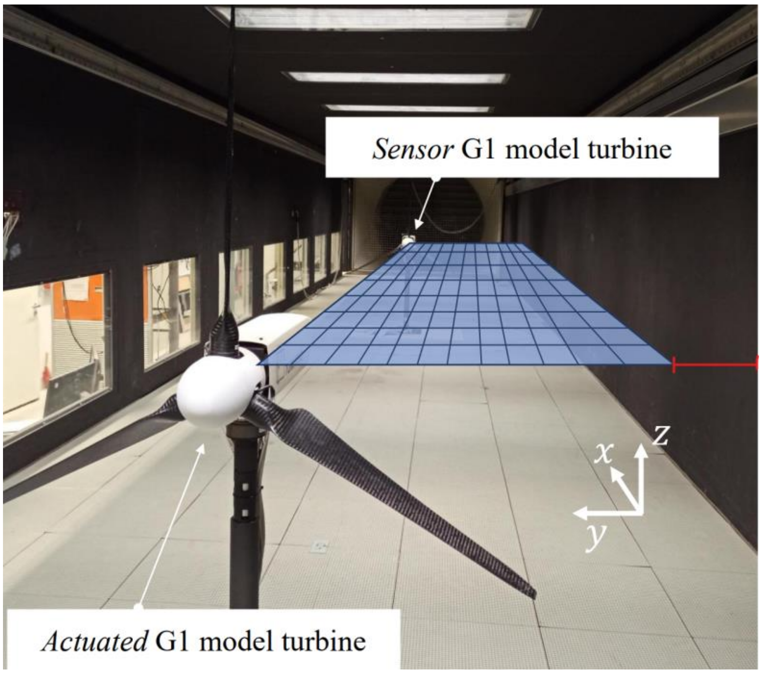


Figure 4. Schematic fast-response five-hole probe and G1 wind turbine model measurement setup for TUM-AER W/T-C

resolution of the applied FRAP has been investigated and hence, shows the suitability of the usage of the FRAP for this experiment.

4) Figure 10 suggests, despite the presence of an adjustable ceiling, a significant pressure gradient in the tunnel. Is that the case or an effect of the y-axis limit?

Thank you for this question. I think this is a misunderstanding and due to the figure limits of the horizontal/y-axis. The wind tunnel has a width of 2.7m. The y-axis is limited by 0.85D=0.935m. Hence, there is an additional ca. 40cm distance from the measurement location to the wind tunnel wall (see the red line in the figure below). We hope this clarifies your question.



5) **In its current form, the manuscript is very long and, given the large number of results presented, some sections are hard to follow. The authors should consider putting some results and discussions in an appendix.**

Thank you for the hint. The manuscript is indeed quite long; unfortunately, the effects of the Helix are complex and, so far, not deeply investigated. We think all the results, figures, and discussions reported in the paper are needed, to provide a complete picture of the method and its impacts.

Technical comments

The manuscript is overall very well written, but it still presents several typos.

Thank you for pointing this out. Yes, also reviewers #1 and #2 have pointed out several typos. We covered all of these, so the manuscript should be in a good state now.