Wind-tunnel analysis of wake-steering control strategies on a multi-column model wind farm
by
D. Micheletto, J. H. M. Fransson & A. Segalini

Replies to Reviewer #1:

We appreciate the feedback regarding our manuscript. In the following we address the reviewer's suggestions for improvement, and point out the changes compared to the original manuscript. Parts that have been rewritten or added will be highlighted in red in the revised version of the manuscript.

> *In general, the manuscript is well-written, interesting, mostly easy to follow, and well-situated within the existing literature.*

We thank the Reviewer for the support to our work.

1. Representation of an infinite wind farm through wall proximity

> *Lines 194–195: I disagree with the claim that the presented setup resembles an infinite wind farm. The lateral turbine columns are positioned very close to the solid wind tunnel walls. This proximity likely constrains the natural wake expansion of an uncontrolled wake and artificially limits wake deflection under yaw. This raises the following questions and concerns about the validity of several conclusions:*

We agree that the setup is not an infinite wind farm. Consider however the spanwise width of the wind tunnel (1200 mm) and the diameter of our turbines (D =150 mm). Thus, the spanwise width of the test section is only $8D$, which does not allow to perform isolated-farm experiments. Probably just one column of turbines could have been tested in the used wind tunnel (allowing a distance of $4D$ between the column and each wall side). The intra-turbine spacing that we have with three columns is already very tight ($S_y = 2.67D$) compared to real farms so we could not pragmatically choose other arrangements other than just reduce the number of columns to two, or decreasing the size of the turbines, with issues appearing with both choices.

If we consider now a farm where no yawed turbines are present, the wall can be exploited if located in the middle between two columns, so that the mirrored turbines will affect the flow as if the wall was absent. This is also questionable since the mirrored turbines (and their wakes) will rotate in the opposite direction. As the Reviewer points out this approximate analogy of infinite farm/confined farm further weakens when wakes start to have yaw deflections: the axial force in the direction of motion remains the same, but the transversal force (generating wake deflection) is opposite, creating an odd symmetry.

We have recently performed additional measurements in another atmospheric wind tunnel with test section width of 3 m and a separation of $4D$ between the lateral walls and edge columns showing similar trends as observed in the present MTL facility, thus supporting our observations. It is also worth stressing that the "infinite farm" assumption does not affect the data analysis, it is solely related to the reduction of degrees of freedom evaluated in this work. Such reduction was necessary to achieve a meaningful characterization of the control-variable space, which would otherwise have been prohibitively lengthy. Nevertheless, in the revised version of the manuscript we will rename the "infinite farm" assumption, since it is a questionable pragmatic choice and we don't want our measurements to be representative of this condition.

> *1.1 What is the blockage ratio of the setup?*

If the Reviewer refers to blockage ratio as the area of the frontal rotors normalized by the test section area, that is 5.9%, near the edge where blockage corrections starts to be needed (Segalini & Inghels, 2014). Using Glauert theory, this corresponds to an equivalent free-stream velocity of $U'_\infty = 1.026U_\infty$.

> *1.2 If the setup were representative of an infinite wind farm, why do the left and right columns react differently to yawing of the first row turbine (lines 291 ff.)? In an infinite wind farm, all columns should behave equally.*

We agree that the farm does not behave as an "infinite" one and the presence of the side walls certainly contributes to these differences. As mentioned before, the yaw-induced transversal forces of the mirrored turbines are opposite to the real ones. This would lead to a symmetric response between the left and right columns, wherein the behavior of the right-column turbines at $\gamma_1 > 0°$ should be the same as that of the left-column turbines when $\gamma_1 > 0°$. This trend is visible in the first-row turbines, but not in the other rows. There, the asymmetry is likely broken by the turbine rotation (all turbines rotate in the same direction). Another contributing factor to the different responses could be linked to the differences between turbines. The rotors and generators were carefully designed and similarly manufactured and calibrated but their operative set points, identified by the optimization algorithm, differed, creating discrepancies between turbines.

> *1.3 Section 3.1.3 (particularly lines 331–333) contradicts the infinite-farm hypothesis. The authors state that lateral columns benefit from lateral entrainment, yet by definition in an infinite wind farm lateral entrainment does not exist, because each column is neighbored by two other column.*

We agree and have resolved this contradiction by reframing the infinite-farm assumption.

> *1.4 In Fig. 18, why does the relative performance of the columns change so strongly with wind speed (e.g., the center column is the worst at 7 m/s but the best at 8 m/s)? Could this be an artifact of blockage and local acceleration effects from insufficient spacing to the tunnel walls?*

We can speculate that, as the Reviewer suggests, there may be local accelerations caused both by presence of the walls and by characteristics of the wind-tunnel and of the devices used to replicate the ABL. The latter also lead to the flow inhomogeneity shown in Fig. 3. It is possible that such inhomogeneities are modified by the free-stream velocity. This, in combination with the Reynolds-dependence of the turbine performance, results in different variations of the greedy power coefficient between columns (as can be evinced from Fig. 18) and may contribute to the observed sensitivity to U_∞.

> *The conclusions would be significantly strengthened if the influence of the side walls were assessed, for example, by repeating experiments with only a single turbine column placed at left, center, and right positions. This would clarify the wall's impact, especially when wakes are steered toward it.*

The suggested experiment will characterize only the individual column contribution but the farm is not a linear object and the behavior of each column is not providing the farm by linear superposition. The issue of the side walls could be resolved by numerical simulations (at that is why we provide all details about the wall location of the present experimental setup) or by studying a similar farm in a bigger facility where wind-tunnel confinement is less influential, which we have done in a separate experimental campaign.

2. Asymmetry in yaw steering performance

> *The asymmetry in power generation between positive and negative yaw angles (Fig. 7) is surprising and highly relevant for ongoing research and recent efforts in commercial deployment of wake steering. If wake steering benefits only from one yaw direction, the concept itself requires reevaluation. This point needs more careful discussion:*

We agree. We believe that this is a result of the wind profile shear and wake rotation. We exclude the effect of the confinement because we observed a similar asymmetry in the larger wind-tunnel experiment.

> *2.1 Lines 277–282: The authors attribute the asymmetry to lower tip speed ratio compared to real turbines, causing enhanced wake swirl. To what extent do these results translate to utility-scale turbines? Should we expect directional dependence of yaw steering benefits in practice?*

We don't attribute the asymmetry to the lower tip-speed ratio. This asymmetry has been observed both in LES simulations of full-scale turbines (Fleming et al. 2018) and in experimental studies with the turbines operating at high tip-speed ratios (Bartl et al. 2018), albeit not as pronounced. We hypothesize that the reduced tip-speed ratio and consequent high swirl of the present wakes may amplify these asymmetries.

> *2.2 How sensitive is this asymmetry to inflow conditions? Would a differently sheared inflow produce the same result?*

Most likely no. However, we expect no qualitative differences either: a different shear will lead to a different optimal angle of all yaws, but the asymmetry will remain. In the larger-tunnel experiment, the inflow was different (we used different spires) and the tunnel walls were further apart, but the γ_1 asymmetry remained.

> *2.3 Fig. 11c: The proposed explanation of the linear trend due to vertical wake displacement is not convincingly demonstrated. Can this be substantiated with wake measurements or LES?*

The straight line in Fig. 11(c) was added there for visualization aid as it is just the simplest polynomial that fits the trend. The vertical displacement is a possible explanation that is consistent with the results, but we did not perform measurements to demonstrate it. The phenomenon has been observed in previous wake measurements (Bastankhah and Porté-Agel 2016, Bossuyt et al. 2021) but, as far as we are aware, there are no experimental or numerical data on three aligned turbines with the first one being yawed in opposite directions. We have performed wake measurements in the larger wind tunnel but the results were not helpful in this respect.

3. Graphical presentation

> *3.1 Several figures use the label "config Nr" on the x-axis. While interesting trends are presented, this label does not convey the underlying physical parameter being varied, making interpretation difficult. Replacing "config Nr" with a meaningful physical variable would improve clarity.*

We agree that "config Nr." is not a physical parameter, however we believe that, in some cases, presenting the data in chronological order highlights trends that would otherwise be difficult to note, such as the sensitivity of downstream turbines to their own yaw angles when the upstream rotors have a constant yaw. We replaced "config. Nr." with "$\Delta C_{P,\mathrm{farm}}$" in Fig. 12.

> *3.2 Many results are shown as scatter plots with both marker color and shape encoding additional variables. This creates very dense visualizations where trends are difficult to see. Moreover, continuous colormaps for discrete yaw angles are confusing. Alternative formats, such as contour plots with the row-wise yaw angles on x- and y-axes, and performance metrics (Cp, thrust, etc.) as a colormap, may more clearly highlight the trends. Additionally,*

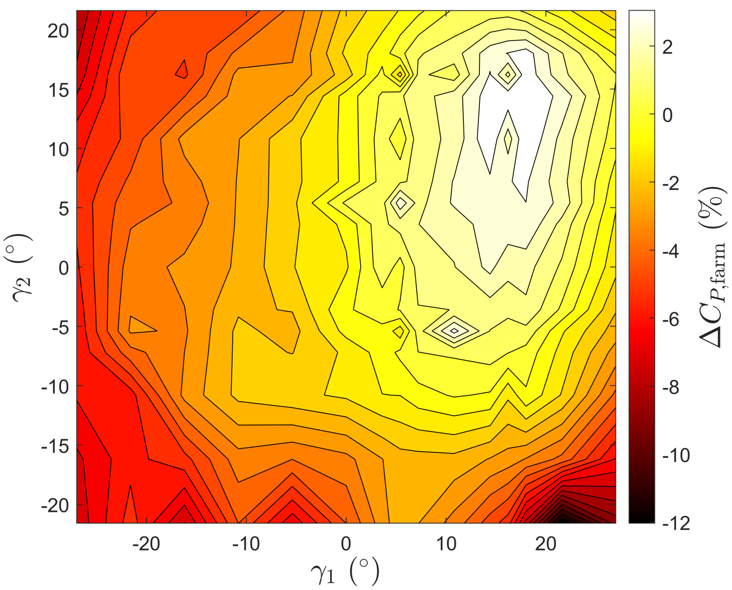

Figure 1: Normalized change of farm power coefficient as a function of the yaw angles of the first (abscissa) and second (ordinate) row turbines, measured in EXP1 and EXP2.

> *varied parameters (e.g., γ_3) could be separated into dedicated subplots.*

We have replaced continuous colourmaps with discrete ones. However, we elected to keep scatter plots as they more accurately represent the experimental data. Contour plots have a smoothing effect that tends to mask certain details. For example, Fig. 1 presents the same information as Fig. 7 in the manuscript, but it does not clearly show that only positive values of γ_1 result in performance gains. In addition, due to the overall small influence of γ_3 on the farm performance, the differences between the three subplots corresponding to the three values of γ_3 would be small. Furthermore, non-zero values of γ_3 were only evaluated on a subset on configurations (see Table 1), so the three subplots would not depict the same ranges of γ_1, γ_2.

Minor comments

> *Line 3: "wide range of wake steering control strategies" is vague; consider "wide range of yaw steering configurations in a wind*

> *farm."*

We modified the manuscript accordingly.

> *Line 40: The abbreviation "LES" should be defined.*

The definition has been included.

> *Fig. 6: Why is $C_{p,opt}$=0.325 so much lower than the Betz limit of 0.593?*

Correct. However, this is a typical power coefficient of small wind-tunnel models with diameter 15 cm or smaller. This is a result of the low Reynolds number of the experiments and of the high solidity of the used blades.

> *Line 147: The use of gradient-based optimization for each yaw setting makes sense scientifically, but how realistic is this for actual wind farm operation? Could comparable methods be applied in practice?*

The operation of the adopted DC motors with no gearbox is different from the operation of a full scale turbine. Our contribution does not aim for a high technical readiness level, but rather in the identification of the power gains achievable by means of yaw actuation.

> *Fig. 14: Appears redundant with Fig. 13, given the correlation between power and thrust.*

Certainly, but we believe the inclusion of the figure serves as a meaningful validation that such correlation persists even for turbines deep within the array.

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Replies to Reviewer #2:

We appreciate the feedback regarding our manuscript. In the following we address the reviewer's suggestions for improvement, and point out the changes compared to the original manuscript. Parts that have been rewritten or added will be highlighted in red in the revised version of the manuscript.

> *Although the present manuscript makes it difficult to draw concrete conclusions for turbine arrays, the yaw-asymmetric findings for turbine columns are interesting and might warrant further investigation. It is difficult however to draw conclusions for turbine arrays, because of the high irregularities between the lateral columns. I think it highly likely that these irregularities are caused by unintended wall-interactions, due to the lateral turbines being placed only 1.33D from the wall. Depending on how the wall-boundary layer evolves, the steered wakes probably heavily interact with this layer. The assumption of neighbouring specular farms on line 137 regarding this is rather questionable. An argument might be made if the neighbouring farm was mirrored perfectly, but this falls apart when the yaw-asymmetry presented here is taken into account, since this makes mirroring impossible. Could you please provide further explanation on how the wall-nearness would not cause measurement problems?*

We agree that the wakes interact with the boundary layers developing along the side walls and that, due to the wake rotation, the symmetry assumption is invalid. However, we argue that this interaction has only a quantitative effect on the farm response, not qualitative. If the wake-wall interactions were a dominant feature, we would expect that the performance of the lateral columns would be maximized either when the wakes of the first-row turbines are deflected away from the walls ($\gamma_1 > 0^\circ$ for the left column and $\gamma_1 < 0^\circ$ for the right one) or when the wakes are deflected towards the walls ($\gamma_1 < 0^\circ$ for the left column and $\gamma_1 > 0^\circ$ for the right one). Instead, both columns are optimized when $\gamma_1 > 0°$, indicating that there must be another primary mechanism determining the asymmetry with respect to the sign of γ_1 and the behaviour of the lateral columns.

In addition, we have recently performed additional measurements in another atmospheric wind tunnel with test section width of 3 m and a separation of $4D$ between the lateral walls and edge columns. Qualitative differences between the columns were not observed in that experiment, further suggesting that the presence of the walls only plays a minor role.

We will modify the manuscript to undertone the statement at line 137 and implement the suggestions from both Reviewers.

> *Furthermore, the authors show many scatter plots that could perhaps be better visualised as heatmaps for easier interpretation.*

We prefer to keep the scatter plots since these show the experimental data more clearly. Even as heatmaps, the figure will look qualitatively similar with the drawback that some details will be lost. For example, Fig. 1 presents the same information as Fig. 7 in the manuscript, but it does not show clearly that only positive values of γ_1 result in performance gains, for example. Furthermore, separate contour plots would be required to distinguish between different values of γ_3.

> *1. The literature review in the introduction might benefit from a table summarizing the previous works. Sec.4 could then refer back to this as well.*

We will include this in the revised version of the manuscript.

> *2. Fig.1: for clarity, perhaps color/shade/texture the different components and add a legend or define them in the caption. For this and all figures, place them closer to where they are referenced.*

We followed the Reviewer's advice and used different colours, as shown in Fig. 2.

> *3. Please refer to Micheletto et al. (2023b) in the caption of Fig. 2 as well and make it clear in the caption that the data presented there is not from this campaign.*

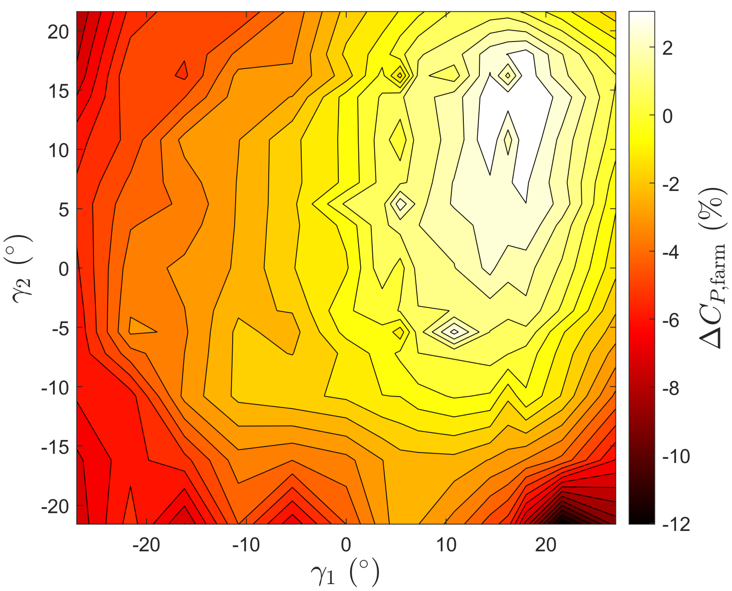

Figure 1: Normalized change of farm power coefficient as a function of the yaw angles of the first (abscissa) and second (ordinate) row turbines, measured in EXP1 and EXP2.

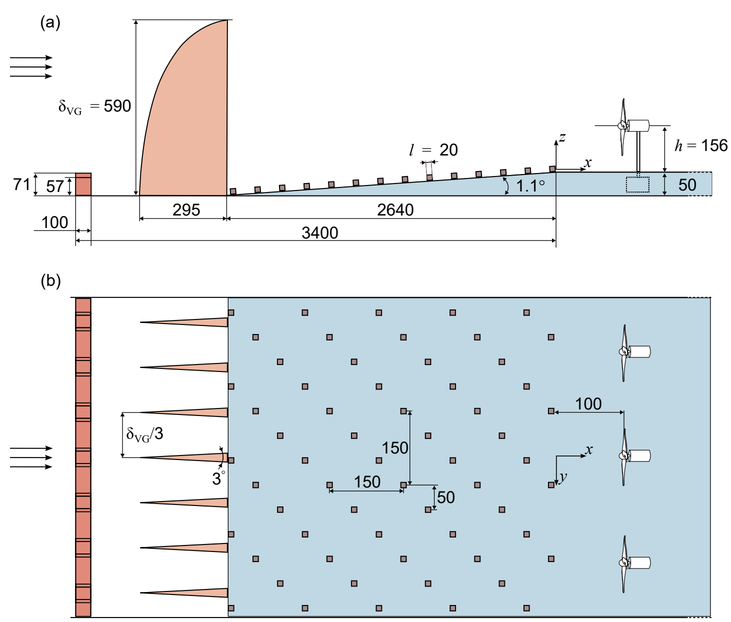

Figure 2: Updated version of Fig. 1, describing the experimental setup.

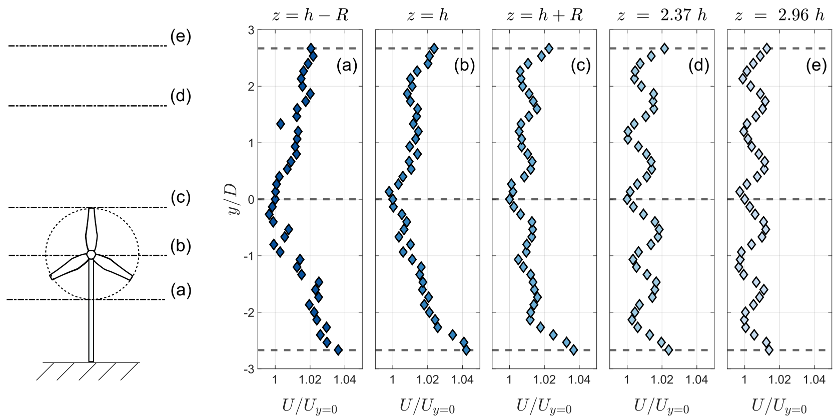

Figure 3: Updated version of Fig. 3

We have added the suggested reference in the revised manuscript.

> *4. Fig. 3: The data points should extend to the lateral rotor tips instead of the hub. Perhaps add another subplot of the same size of a x-z slice with a turbine sketch and horizontal lines labelled a/b/c/d/e*

Unfortunately, the $y-$range of the traversing system used to acquire the data was limited to ± 400 mm, hence it was not possible to acquire data at the lateral rotor tips. We have included the subplot suggested by the Reviewer, as seen in Fig. 3 of the present response.

> *5. How did you calibrate the zero position of the yawing stepper motor? Additionally, how did you ensure that the zero position aligned with a step position of the stepper? In other words, how did you ensure that your target of 0deg resulted in 0deg and not something on the interval [-0.9, 0.9]? You do mention this briefly in Fig. 11.*

During the installation of the farm, each turbine tower was aligned with reference lines drawn on the foam panels. Once this alignment was complete, two stop screws were used to fix the tower to the stepper motor shaft. In addition, the same reference lines were used, before each experiment, to ensure that the starting point of each stepper coincided with the zero-yaw position. Although this approach cannot guarantee a perfect alignment, the error is kept within a single step, and thus does not qualitatively influence the characteristics of the optimal configurations.

> *6. Fig. 5 shows a tower with a very high roughness. Can you comment on how this could show up in your measurements?*

We agree, the tower has a high roughness due to the motor cables and the flat frontal section on the bottom half of the structure. Nevertheless, we assume that the flow field is dominated by the rotor wakes, as typical in other numerical simulations and experiments of wind farms. This is further confirmed by the wake measurements in a vertical plane behind an isolated turbine (presented in Micheletto et al. 2023b), which showed that the influence of the tower wake on the mean flow and velocity fluctuations is negligible for $x/D \geq 2$.

> *7. Lines 240-246: It would have been interesting to replace C2 with a tuft at hub height to see if the local wind direction changed visibly.*

We agree that this would have been very interesting. Unfortunately, we did not plan for that during the current measurement campaign.

> *8. For all scatter plots, please use a higher aspect ratio to space the markers out more: I'd say use up to 80% of the text width. For Fig. 7 I would suggest swapping the axes too.*

We agree with the Reviewer that wider figures will have a better appearance and data appreciation. However, we are not sure whether this is really worth. The scatter plots are here used to indicate a qualitative trend (for instance the asymmetry in γ_1) and we feel that this is achieved with the current setup. The two-column template of WES forces us to keep the majority of the figures within one column unless a larger figure is needed for a quantitative assessment. We will keep this comment in mind when resubmitting the manuscript.

> *9. In Fig. 7, could you include the LLS fit of each column separately too?*

The figure is already quite full as is, so we prefer to keep it in its current format.

> *10. At the end of line 343 you state: "yawed in the opposite direction of the turbines upstream." However, in EXP2 there are Type 2 configurations according to table 1, meaning that C3 is yawed in the same direction as C2?*

In this work, we refer to Type 1 or Type 2 configurations only in relation to the yaw angles of the first- and second-row turbines. EXP2 contains primarily Type1 configurations, but also some Type2 examples, when $\gamma_2 < 0°$. In the line mentioned by the Reviewer, we state that when γ_2 is large and positive, i.e. in Type 1 configurations (since γ_1 is always positive in EXP2), then the optimal γ_3 is negative.

The cases with $\gamma_3 < 0°$ and $\gamma_1, \gamma_2 > 0°$ may be interpreted as another kind of Type2 configuration, with both the first and second turbines acting as the upstream rotors. However, we find that further classifying the configurations in relation to the third row of turbines would unnecessarily complicate the discussion.

> *11. Sec. 3.2: For consistency, it makes more sense to compare C_T values than thrust values. Since you use a constant hub height wind velocity, C_T and T, and C_P and P are just scaled pairs. Therefore, I would advice to either present C_T and C_P results, or T and P results, but not mixed.*

We changed the figures to present the C_T in the revised version of the manuscript.

> *12. Sec. 3.3: Consider defining an EXP3 collection and including a row of Uinf values in table 1.*

Good suggestion. We will extend table 1 accordingly in the revised version of the manuscript.

> *13. Is there a reason you only tested increased free stream velocities, but not decreased?*

We also conducted some tests with $U_\infty = 6$ m/s. In this case, however, the velocity experienced by the donwstream turbines (especially the ones in the second row) in the greedy configuration was lower than the cut-in velocity, so the turbines would stop rotating. For this reason, we considered the comparison with lower velocities not relevant.

14. h and l are defined in the captions of figures, but not in text.

We included the definition in the revised version of the manuscript.

15. Typesetting of h on line 104.

We corrected this in the revised version of the manuscript.

16. Table 1. bottom right cell is formatted differently, I suggest -5.4:5.4:5.4 for consistency.

We corrected this in the revised version of the manuscript.

17. Fig 13d is not labeled

We corrected this in the revised version of the manuscript.