

# Response to Reviewers: Wake steering under inflow wind direction uncertainty: an LES study

## **Reviewer 1:**

**General Comments:** *I commend the authors for a very well-written manuscript and well-crafted narrative, including the literature review to introduce the problem and recent advances. I agree with much of the authors' methods, results, and conclusions presented and I recommend the manuscript for publication with a few minor revisions that I'll note here, but I do have a couple questions for the authors to consider and maybe add clarifying notes.*

We thank the reviewer for the positive assessment of our manuscript and for the constructive suggestions. We have addressed all comments as detailed below and believe the revisions have improved the clarity and quality of the manuscript.

## **Suggested Revisions:**

- *Line 73: What does it mean that Simley et al. "used a similar approach in reverse" to Rott et al.? Based on the brief descriptions of the two methods it is unclear what this phrase means and it confused me slightly.*

Yes, thanks for pointing this out. The original wording was intended to describe that while Rott et al. applies the Gaussian convolution when predicting optimal yaw setpoints, in Simley et al. the convolution is applied as a postprocessing step on the intended yaw setpoints to achieve a better fit with the yaw offsets that were actually achieved by the turbine. In order to remove any ambiguity or confusion the sentence has now been changed to 'Simley et al. (2020) used a similar approach to achieve a better fit between numerical and experimental data by proposing that the achieved yaw offsets were a convolution of the Gaussian yaw error distribution and the intended yaw setpoints.'

- *Line 133: A constant temperature profile with height of 288.15 K is applied, so I believe  $dT/dz = 0$ .*

Yes, thanks for pointing this out, we have corrected the description. The intended meaning was indeed that the potential temperature is constant with height up to 600 m.

- *Figures 3-5: I would suggest referring to the plane position as  $0.5D$  instead of  $1R$  because  $R$  hasn't been defined yet.*

Thanks for pointing out the inconsistency. We have changed the captions for Figures 3-5 to be in terms of diameter.

- *Line 267: Is this semicolon here by mistake?*

It was meant to be a colon rather than a semicolon and has now been changed.

## **Questions:**

- *Line 113: Is there a reason why a 22MW turbine was chosen in this case study? Do the authors expect any changes in the trends of their results for a smaller turbine, say in the 5MW range, that is more common presently?*

Research projects, including SUDOCO, often choose a specific wind turbine for the research

activities, where it is often prioritized to future proof the research results. We expect the size of the wind turbine has minimal impact on the results in the present case. Figure 1 shows that the velocity profile is near logarithmic below the capping inversion and the wind direction change is nearly constant with height, so following van der Laan et al. (2020), we expect wake behaviour would be very comparable for modern turbines of 5-22MW. We have added a comment on this in the Discussion (Section 4.2).

- *Line 151: What does “the cell sizes are stretched to the domain boundaries” mean? I assume that there is more than one cell outside of the refined region, so does this mean that the cells are progressively stretched from the refined size to the background size?*

Yes, this is exactly what it means, the cell size is progressively increased towards the boundaries. This is done to minimize the total number of cells while keeping numerical blockage low.

- *Line 154: How were these times decided upon? Are the wakes considered developed after a certain number of flow through periods at the rotor height, and was any analysis of the wake velocity deficits used to make this determination?*

The transient time allows the inflow to propagate through the domain and the wakes to fully develop. The 1500 s used in this case corresponds to a full flow-through of the total domain (length 13490m) at  $U_{hub} = 9.2 \text{ ms}^{-1}$ , or a full flow-through of the refined region (length 9940 m) at  $0.7U_{hub}$  (to account for wakes). This explanation has now been added to the Simulation Setup section. Qualitative assessment of the flow development and wake dynamics were used to corroborate that this flow time was sufficient.

- *Line 221: What does area-normalized histogram mean? Is this the wind direction averaged over the rotor area?*

The histograms are normalized by the area, so that the integral is 1. We have added a small comment to clarify.

- *Line 227: Which statistics are calculated with a moving average, and which are not? There are several means and standard deviations introduced in the text and I found myself getting mixed up, especially here where there are two different standard deviations with a 1 minute time average.*

Some more text has been added to this paragraph to help clarify the differences between the stated standard deviations. The moving mean is only applied to the data in the context of Figure 5, as it helps to clarify the trends in the distributions. In order to compare the wind direction variability present in the LES with other work, it is more appropriate to use the raw 1 Hz data instead, which is now explained. Both the 1 and 10-min standard deviations of the raw data are stated (which are very similar to each other) and it is the 10-min standard deviation of the 1 Hz raw freestream wind direction which is used throughout the work to characterise the flow and compare with other work.

- *Figure 10: My main conceptual question regards this idea of how additional wind direction uncertainty is estimated based on the existing simulations. The authors refer to the Rott and Simley papers, so I recognize that this method has been applied before, but I am skeptical of how well this Gaussian process approach can capture all of the non-linearities of the power response to wind direction. I agree with the trends that are elucidated by this experiment, namely that increased wind direction uncertainty reduces the benefits or viability of wake steering. I would be interested in seeing the actual power production results from simulations with the increased standard deviation, but this would be outside the scope of the current work. Perhaps this concern already falls under the discussion starting at Line 430, or the authors could add a note discussing this to Section 4.1.*

Yes, we agree that the the Gaussian convolution approach to estimating wind direction vari-

ability is a simplification which has limitations, which the Discussion section ‘Limitations and Further work’ (now Section 4.2 rather than 4.1) examines in detail. From the authors’ point of view, the main limitation, rather than being related to non-linearities in power with wind direction (which are likely to be small at the offsets studied), is that the Gaussian distribution represents 10-min variability in wind direction. As explained in the Discussion, with a flow-through time of the 4-turbine row of more than 10 mins, the Gaussian convolution may therefore exaggerate the impact of wind direction variability on the power gains. However, this overestimation is set against other underestimates and assumptions in the simulations, such as having no nacelle position error (e.g., all turbines face directly into the oncoming wind). We completely agree that running additional simulations with higher wind direction variability would be of interest, however it is out of scope of the current study.

- *Line 374: I agree that it is an interesting idea to consider yawing to decrease fatigue loads despite a decrease in total power, but I wonder if yawing would increase other relevant loads on the turbines besides the flapwise bending moment?*

Yes, we agree that other loads are likely to increase as a result of applying static yaw control. It has now been clarified in the Discussion that we are specifically referring to damage equivalent loads of flapwise bending moment when making those comments, and a note about the likelihood of other loads increasing has been added.

## **Reviewer 2:**

**General Comments:** *In the manuscript by Hodgson and Andersen, the authors conduct a numerical study on the effect of wind direction uncertainties on wake steering. The LES study considers a single column of 4 turbines in a conventionally neutral ABL, and three wake steering configurations. Six different inflow wind directions are considered by changing the layout of the turbines in the same ABL condition. Their findings indicate that wake steering is beneficial within a narrow window of 7.5 degrees, and using Gaussian convolution to extrapolate to larger amounts of wind direction uncertainty leads to a decrease in the effective window and the overall power gains.*

*Overall, the study is systematic and methodically conducted, and the conclusion the authors deliver is an important point which deserves attention – wake steering is very sensitive to wind direction and inflow condition uncertainty, and gaining control over these uncertainties will be important for wake steering to be successful. However, there are some considerations which might help to strengthen the study and help generalize its findings, or at least point to several areas which are necessary for future studies.*

We thank the reviewer for the constructive and insightful comments. The points raised have helped strengthen the manuscript. Detailed responses are provided below.

## ***Major Points:***

- *The current study is focused on a single column of turbines with 7D streamwise spacing. While this is a relatively clean and simple configuration for this study, realistic wind farm layouts may see interactions with neighboring columns, such that at larger wind directions, downstream waking can occur even if it is not from the turbine immediately upstream. For the larger offshore turbines like the IEA22MW, 7D spacing (1988 m) may not be achievable, and turbine spacings may be closer. In section 4.0, a discussion of shorter turbine spacings is presented, but it may be worth considering how these findings hold deep within the center of larger wind farms, and how much the benefits might decrease with neighboring, closely spaced turbines.*

The 7D spacing was selected as one which is reasonable and representative of current wind farms, however we understand that shorter spacings are also increasingly common for larger

turbines and hence included a discussion on the possible implications of short spacing in the Discussion (Section 4.1). An extra paragraph has now been added to the Discussion (Section 4.2) in which the implications for larger wind farms are also discussed. For example, wake steering may not be effective in the centre of a large wind farm, both due to high uncertainty in wind direction and also as the flow redirection only serves to move the wake impingement to other turbines rather than mitigate it. Additionally, that high mean wind direction offsets in a wind farm may lead to other configurations of wake interactions, rather than resulting in more turbines experiencing the freestream flow. However, regardless of these factors, we believe that the overall conclusions - that wake steering is highly sensitive to mean inflow wind direction and wind direction variability - are relevant to all wind farm and turbine sizes.

- *The neutral ABL used in this study, while convenient to setup and use in LES, may not be a representative condition for offshore wind farms in reality. Truly neutral conditions may only last for a few minutes per day as measured in the field, as the ABL transitions from stable to unstable conditions or vice-versa. However, simulations in this study are run for 5100 of flow time, with averages over 3600 seconds used for the statistics, which produces very clear contrasts between the different wake steering configurations. This idealization is discussed in section 4.1, where it is mentioned that more common 5 or 10 min statistics contribute to the uncertainty in measurements. However, it may be worth discussing how an LES study might be conducted so that more realistic wind direction, wind speed, or ABL stability changes can be taken into account, and how an optimal wake steering strategy could be determined in the face of these complex uncertainties.*

We agree that the atmosphere is significantly more complex and transient than what is represented in a neutral ABL. In this study, we utilize a CNBL, which is has near-neutral conditions near the ground capped by an inversion and stable conditions above. As shown in Hodgson et al. 2025, it is possible to model a diurnal cycle in LES and study wake steering across changing atmospheric stability conditions, but the transient nature makes statistical treatment more challenging. Here the aim was to isolate the impact of the mean and variability of inflow wind direction, and hence using a quasi-steady ABL flow allowed a clear comparison to be performed. A CNBL is also more representative of what engineering wake models capture. However, we completely agree that accounting for transient development of atmospheric conditions (in LES, engineering models and through improved measurements from real wind farms), is an important area of further work to help increase the potential of wake steering. This is now addressed in additions to the Discussion (Section 4.2).

- *In section 3.2, a Gaussian convolution approach is used to extrapolate the wind direction uncertainty from the 2.3 degrees in the LES to higher values of uncertainties. In this analysis, it may be important to acknowledge the larger values of wind direction variability can be connected to changes in the inflow atmospheric stratification, which in turn change the wake behavior. As an example, unstable ABL conditions might have larger values of  $\sigma_{WD}$ , but are also associated with faster wake recovery and shorter wakes. Thus, it may not be appropriate to extrapolate the neutral LES results to larger WD uncertainties while assuming the wake properties are constant.*

Yes, thanks for this comment. We completely agree that the wind direction variability in the atmosphere is likely to be linked to a number of other important factors such as stability, and recognise a number of limitations with the Gaussian convolution approach, as mentioned in Section 4.2. Part of the logic of extrapolating up to  $\sigma_{WD} = 4.5^\circ$  is to represent the ranges reported from measurement data ( $2 - 6^\circ$ ), which are also the typical values used in engineering models when using this approach. The  $\sigma_{WD} = 2.3^\circ$  achieved in the LES is relatively low in comparison to this range, despite the fact that the reported  $\sigma_{WD}$  values from literature are often in connection with studies where wake steering may be beneficial (hence

not unstable BLs or with high turbulence intensity). In fact, the relationship between ABL stability, TI, short- and long-term wind direction variability, and any possible limitations of LES in modelling that (e.g. through not including a mesoscale coupling), are to the authors' knowledge not an area that has received much research. Comments have been added to the discussion to mention this.

- *The LES simulations use an actuator disk approach to model the IEA22MW turbine forces in a highly yawed configuration (-20 degrees), and both the power and DEL are reported based on the HAWC2 solver coupled to the AD model. It may be useful to include additional information on the performance of the AD model under such conditions, compared to higher fidelity models such as actuator line models. Of potential concern is whether the blade loading is accurately captured under high yaw, and thus if the turbine torque or thrust are properly calculated through the CFD (and thus, if the downstream wake is properly initialized).*

Yes, we agree that it is important that the AD model is sufficient to model the setups investigated, particularly related to the applied yaw angles. As described in Section 2.2, in the AD coupling, velocities are extracted from the three blade locations and transferred to HAWC2, which calculates the loads and deflections - which provide the AD body forces and positions. These forces are then smeared over three overlapping 240 deg segments to create the AD, with forcing decreasing linearly from a maximum at the blade location to a minimum at the neighbouring blades. One benefit of this AD model is that it closely resembles the AL formulation (with the final smearing to form the disc added, and a different tip correction) and therefore is able to capture the azimuthal loading variation induced by shear or yaw, which has been clarified in Section 2.2. Verifications of the thrust, loading and wake predictions of the AD in non-yawed (both with and without shear) configurations are present in Hodgson et al. 2021 and 2023. Recent internal unpublished comparisons between the AD and AL for sheared laminar inflows and high yaw angles show that the total thrust, blade loads and azimuthal variation compare well between the two models. The thrust comparison between AD and AL at  $\gamma = 0^\circ$  and  $\gamma = -20^\circ$  is provided in Figure 1, which shows a constant difference of  $\approx 2.5\%$  between the two models, regardless of yaw angle.

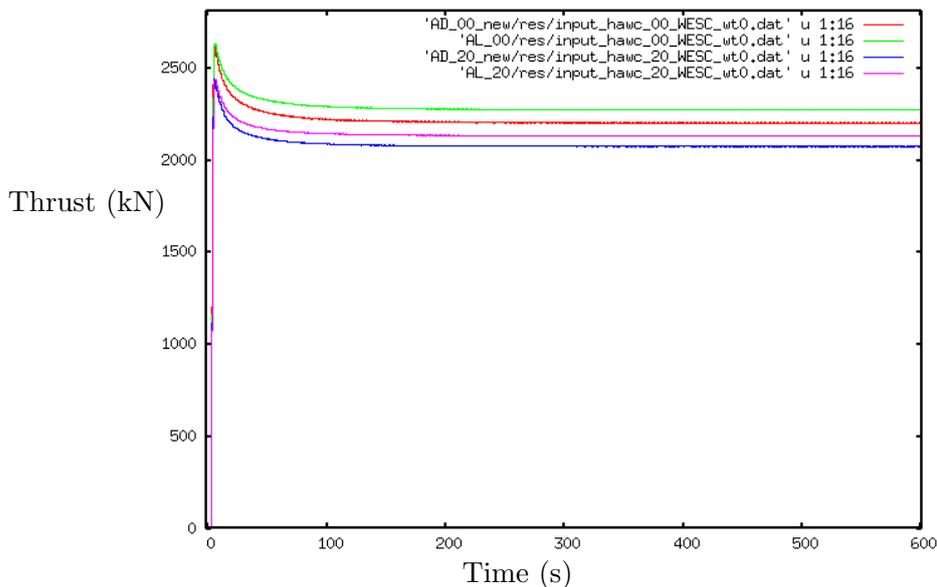


Figure 1: Comparison of Thrust (kN) between AD and AL in sheared, laminar  $8 \text{ ms}^{-1}$  inflow for  $\gamma = 0^\circ$  and  $\gamma = -20^\circ$ . Red: AD,  $\gamma = 0^\circ$ ; green: AL,  $\gamma = 0^\circ$ ; blue: AD,  $\gamma = -20^\circ$ ; pink: AL,  $\gamma = -20^\circ$ .

### **Minor Points:**

- *Introduction, line 42, minor stylistic point "Concerning the former, imperfect response to a control input can occur" – imperfect may not be the best adjective to use here, as it implies there is a perfect yaw control response.*

This sentence has now been rephrased.

- *Section 2.2 – It may be worth explicitly stating if a yaw controller is active during the IEA22MW simulations – it appears that a constant, fixed yaw is always applied to each turbine. How much would the wake steering benefits change if the yaw controller is active? By default, the IEA22MW turbine, if using the ROSCO turbine controller, activates yaw only if misalignment exceeds 4 degrees, so it may be interesting to consider how long it takes the turbines reach their intended set point once the wake conditions are detected.*

It is now stated at the end of Section 2.2 that there is no turbine yaw controller included in the simulations. The inclusion of one would not change the results of this study; firstly as the setup is designed assuming zero nacelle orientation error with regard to the inflow (however, the implications of this assumption for wake steering effectiveness are discussed in Section 4.2). Secondly, as the secondary steering effects are not large enough to trigger a realignment of the downstream turbine nacelles (which with our wind direction controller would occur if the filtered inflow wind direction exceeded 4 deg for over 180 s).

- *Section 2.3, line 133: "temperature profile  $dT_0/dz = 288.15K$ " – that is probably a typo, it might be temperature profile  $T(z) = 288.15$*

Yes, that was a typo and the sentence has now been corrected.

- *Section 2.3 – Some additional information on how the ABL conditions were chosen may be useful to the reader, including the choice of the geostrophic wind values, the wall roughness, etc.*

The choices of roughness, temperature and geostrophic wind (and more importantly the resulting boundary layer flow) are designed to represent offshore conditions in Northern Europe, which has now been stated with citations in Section 2.3. The explanation of the general appropriateness of the CNBL at the end of Section 2.3 has also been expanded, to note that the precursor was designed to result in conditions ideal for wake steering, so that the uncertainties present even in a favourable flow scenario could be investigated.

- *Section 2.3 – It may be useful to add how the lower boundary conditions were enforced in the precursor ABL and wind farm simulations.*

The instantaneous shear stress is calculated using the log law, and is applied at the lowest grid cell. This is explained in Section 2.1.

- *Section 2.4 – line 150: " $dx = dy = dz = 32/D$ " – possibly a typo, and meant  $D/32$*

Yes, that was a typo and has been corrected to  $D/32$ .

- *Section 2.3/2.4 – What were the mesh sizes and timesteps used in the simulations?*

The mesh sizes ( $\approx 266$  millions cells for the precursor and  $\approx 116$  million cells for the successor) and the timesteps (1 s for the precursor and 0.5 s for the successor) are now included in sections 2.3 and 2.4.

- *Section 3.1 line 222 – typo, "infront" is two words*

All instances of this typo have now been fixed.

- *Section 3.1, figure 5 – The histograms of the wind direction were created by sampling a single point velocity at  $0.5D$  upstream of the turbine rotor. A single point, upstream measurement of wind direction may be susceptible to influences from turbine induction and veer, and is generally not available to turbines operating in the field. It may be interesting to consider a*

*measurement of the wind direction based either on rotor disk averages, or for more realism, and virtual nacelle vane measurement that would be used by the turbine controller.*

Yes, we agree that this upstream measurement would not be available in reality. In general it is not trivial to define a location on which to characterise the ‘inflow’ to a turbine when operating inside a wind farm, so the  $0.5D$  distance was chosen as a reasonable compromise. However, during the initial analysis of the results several different points and distances in front of the turbine were investigated (including the rotor centre), and showed very similar standard deviations, means and trends; therefore, in LES the precise location of this sampling point does not substantially influence the results.

- *Section 3.1, line 234 – “for  $WD = 8$  degrees, there is very little wake impingement on the downstream turbines”. This conclusion may be limited to this specific configuration of a single column of 4 turbines. In a larger wind farm array, for instance, in a  $4 \times 4$  array, even if there is not direct downstream waking, there may be wake effects from neighboring turbine columns (see major point above).*

Yes, we agree that the exact range of wind directions where wake impingement occurs and where wake steering is beneficial is highly dependent on the turbine spacing, as is mentioned in the abstract, discussion and conclusion. As this remark is describing what is visible in the plot (which is of the specific case studied), the specificity of the statement was intended to be implicit. However, the qualifying remark ‘...for this spacing of  $7D$ ...’ has been added to further clarify.

- *Section 3.2, line 253 – “tends back to that of the baseline” – optional, perhaps reword this sentence to avoid awkward phrasing*

This phrasing was used twice in the paper, and both have now been rephrased to ‘converges towards the baseline’.