Response to Referee # 1

This manuscript presents results of an experimental wind tunnel study of four different spacing configurations of a 4 × 3 wind turbine array. The authors investigated the mean and turbulent features of the flow using techniques such as the snapshot POD and anisotropy stress tensor. The manuscript is overall well written, but some major clarifications are needed before it can be published in Wind Energy Science. My main concern about the manuscript is the lack of physical interpretation of POD analysis. Please see my specific comments below.

The authors thank the reviewer for reviewing the paper and making valuable comments about the work. We have revised the manuscript according to the comments, and as a consequence, the paper has been significantly strengthened. Below, point-by-point answers to the comments are provided:

A: Specific comments

- ***A.1: You should mention in the literature review part in Introduction that the spacing between wind turbines and their layout are also function of orography among other things, and not just wind direction. For example, see the following recent reference and references therein: Romanic D, Parvu D, Refan M, Hangan H. 2018. Wind and tornado climatologies and wind resource modelling for a modern development situated in "Tornado Alley." Renewable Energy 115: 97,112. DOI: 10.1016/j.renene.2017.08.026. Then you can say that your paper, however, is restricted to a flat surface and topographic influences are not considered.***

  Response A.1: Thanks for the suggestion. The article makes reference to the suggested peer-reviewed article in two instances. The statements read as shown below.

  "Orography and wind direction are relevant when deciding distance between turbines as well as layout as shown by Romanic et al. (2018)."

  "The tunnel-scaled wind farm is, however, restricted to a flat surface and topographic influences are not considered, although the inflow to the wind farm includes modifications to more closely resemble an atmospheric boundary layer."

- ***A.2: In Eqs. (1) and (2), please explain all variables although some of them might be trivial. What are N, A, Ω? In Line 94, you are explain R that does not seem to appear in the previous equations.***

  Response A.2: All variables are now defined in the manuscript for completeness. Thank you.

- ***A.3: Line 102. The sum in the nominator in equation for η_n shouldn't go to the same value as the index n. Please explain these formulas accordingly.***

  Response A.3: Thanks for pointing this out. The authors have changed the indices of the equations.

  $\eta_n = \sum_{j=1}^{n} \lambda_n / \sum_{j=1}^{N} \lambda_n$ and $\xi_n = \lambda_n / \sum_{j=1}^{N} \lambda_n$.

- ***A.4: What was the blocking ratio for your wind tunnel tests?***

  Response A.4: The blockage ratio is less than 5%. This has been included in the experimental portion of the paper.

  "The blockage ratio is less than 5% in the current analysis"

- ***A.5: Line 159. You are using a closed-circuit wind tunnel where the flow is mechanically generated. What do you mean by neutral stratification? You haven't checked for atmospheric stability or at least I don't see any stability parameters in your paper (e.g. potential temperature profiles, Richardson number, etc.)***

  Response A.5: The statement intends to indicate that no stratification is considered. To avoid confusion, any mention to stratification in regards to the presented work is removed from the manuscript.

- ***A.6: What are the geometric and velocity scales (and thus time scales) in your experiments? You did provide the geometric details of your wind turbine models, but what full-scale wind turbine (or turbines) are you replicating in your wind tunnel experiments.***

  Response A.6: Thanks for the suggestion. This information has been included in the manuscript as well as a citation is provided to discuss the inflow characteristics.

  "The scaled turbine models were manufactured in-house. Based on full scale turbines with a 100 m rotor diameter and a 100 m hub height, the scaled models are at 1:830 scale. The rotor blades are steel sheets laser cut to shape and are 0.0005 m thick. The blades are shaped using a die press. The die press was designed in-house to produce a 15 degree pitch from the plane of the rotor and a 10 degree twist at the tip. Figure 1 presents the schematic of the wind turbine model. Operating conditions for the wind turbines are also scaled, namely the power coefficient, C_p and tip-speed ratio, λ, which are detailed in Hamilton et al. [1]. The streamwise integral length scale is approximately 0.13 m, which is the same order of magnitude as the turbine rotor and representative of conditions seen by full-scale turbines in atmospheric flows.

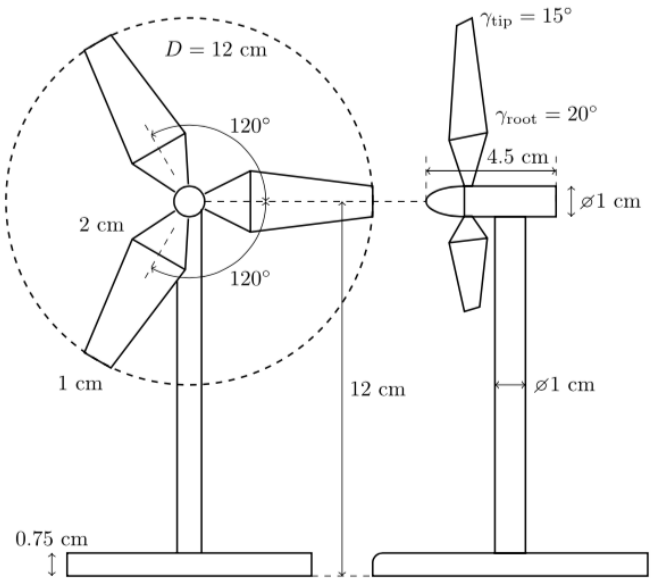

FIG. 1: Schematic representation of the wind turbine model.

- ***A.7: Why is there uncertainty of U_∞ in Line 183? That is, why the value is about 5.5 m s^{-1}? Please provide additional explanation.***

Response A.7: Thanks for the suggestion. The sentence has been modified for clarity and now reads as shown below.

"The inflow mean velocity at the hub height U_∞ is used in the normalization, where $U_\infty = 5.5$ m s^{-1}.

- ***A.8: Figure 11. You use the same color in the insets to represent three different ranges of models so the reader needs to guess which line represents which range. Please introduce either additional colors or use symbols or dashed lines.***

Response A.8: Thanks. The figure has been updated.

- ***A.9: Lines 256-266. You are implying that the 3% difference in the turbulent kinetic energy is large whereas the differences between the cases C6×3 and C6×1.5 are small Since you didn't quantify the differences between the cases C6x3 and C6x1.5, I would argue that the 3% difference is the turbulent kinetic energy is also small.***

Response A.9: The authors mean to imply that there is a close resemblance in shape between cases $C_{6\times3}$ and $C_{6\times3}$, even though the turbulence kinetic energy presented via the POD eigenvalues shows a difference of 3% within the first mode. This has been modified in the updated article. Thanks.

"The resemblance in the shape of the structure is observed between cases $C_{6\times3}$ and $C_{6\times1.5}$ despite the turbulence kinetic energy difference between them being about 3%."

- ***A.10: It is not clear to me from the sentence in Line 256 why did you choose to show only the first, the fifth and the twentieth modes? Why not for example the second mode or eighteenth or any other modes? Please clarify in more details.***

Response A.10: First, fifth and twentieth are considered due to their difference in coherence and inherent flow scales. These provide a range of large and intermediate scales since one of the relevant results is attributing the differences to these intermediate scales. Yet, the reviewer is correct that it could have been the eighteenth mode, for example. If only the first few modes were shown, the contribution of the intermediate modes would be neglected. In describing these, discrepancies among the cases are highlighted as depicted by the eigenvalues.

"These modes were selected because they provide a range of large and intermediate scales, and highlight the discrepancies among the cases. "

- ***A.11: Are there any physical meanings behind the modes that you showed? What flow physics they show if any? It is very important to relate the pure mathematics of POD with the flow physics. That being said, please provide some physical explanations of the modes. Please note that this comment must be addressed seriously before I give a positive recommendation to this manuscript.***

Response A.11: Thanks for highlighting this. In general the POD analysis contains of two parts. First one is quantitative approach describing the turbulence kinetic energy through the eigenvalue matrix of the flow kernel. Second the qualitative representation that presents the dominant structure of the flow as shown mode by mode. In the current work, these coherent structures are assessed based on the spacing effect. POD modes do not carry physical meaning until they are recombined with the respective time coefficients (as we did in reconstruction part) although they do denote the organization of the flow which in itself is physical. The actual physical

contribution of any particular mode is typically determined qualitatively by relating observed full-field dynamics to the structures visualized in each mode. Typically, this is only done for the first few POD modes, describing the most energetic structures (see figure 8). Further, the POD modes give the ability to visualize the decay in organization of the flow. Finally, the POD modes provide a perspective on how wind turbines perturb the flow under different spacing conditions.

" Combining the POD modes with the corresponding time coefficient gives these modes the physical interpretation and shows the contribution of these modes in the flow perturbation. "

- ***A.12: It is typical in the field of fluid dynamics and turbulence to use the terms such as hairpin turbulence instead of cigar-like turbulence. This comment however is just a suggestion so you can keep cigar-like terms if you prefer it.***

  Response A.12: Thank you. Keeping the coined term is consistent with other works such as Klipp [2, 3]. to name two. These citations have been included for reference.

- ***A.13: Section IV E (Anisotropy Stress Tensor). What are you trying to show in this section that would be of importance in wind energy industry? That is, what are the practical applications of your results? In Line 346 you mentioned that it can have implications in the terms of fatigue loads, but the statement is too general. Please provide more explanations and some references would also be very good.***

  Response A.13: Thanks. This point is considered in the revised paper.

  "The ability to identify the turbulence structure allows for identification of its influence on subsequent turbines in terms of fatigue loads [4]. Further, regions of the flow that are characterized by highly anisotropic turbulence are those in which one is likely to find large-scale, coherent turbulence structures. These structures impart the greatest axial and bending loads onto subsequent turbine rotors leading to accelerated fatigue and increased operational and maintenance costs for wind farms. In addition, regions of high anisotropy correlate with gradients in the mean flow and turbulence [5]. These quantities are of particular interest in wind farm modeling and design. Accordingly, the accurate representation of gradients in wind farm design modeling is a necessary check to accurately representing production of and flux by turbulence kinetic energy, wake interaction, and structural loading on constituent turbines. Finally, the stress tensor invariants, by definition, do not depend on reflection or rotation of the coordinate system meaning that they are unbiased descriptive for the turbulent flow [6]".

B: Grammar

- ***B.1: Line 9. "an increase" instead of "an increased"***

  Response B.1: This has been modified. Thanks.

- ***B.2: Lines 15-16. "in turn is a function of the surface roughness"***

  Response B.2: This sentence has been changed. Thank you.

- ***B.3: Line 22. The reference should be in brackets not an in-line format.***

  Response B.3: Done. Thanks.

- ***B.4: If you want to use Roman numbers to denote chapters then remove dots after the numbers.***

  Response B.4: This will be accounted for in the final formatting by the journal. Thank you.

- ***B.5: Line 140. "closed-circuit" instead of "closed- circuit"***

  Response B.5: Done. Thanks.

- ***B.6: When you write ms^{-1}, please have a space between m and s because without the space it looks like millisecond (an example is in Line 183). The same rule applies to other units.***

  Response B.6: This has been updated. Thank you.

- ***B.7: Here I provided just some of the grammatical mistakes that I found. I advise the authors to proofread the manuscript few more times.***

  Response B.7: The proofread has been done. Thank you.

In closing, we thank the referee again for the useful feedback and thorough review of the manuscript.

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[1] N. Hamilton, M. Melius, and R. B. Cal, Wind Energy **18**, 277 (2015).
[2] C. Klipp, in *SPIE Defense, Security, and Sensing.* (International Society for Optics and Photonics., 2012), p. 83800G.
[3] C. Klipp, in *SPIE Defense, Security, and Sensing.* (International Society for Optics and Photonics., 2010), pp. 768505–768505.
[4] S. Frandsen and M. L. Thøgersen, Wind Engineering pp. 327–339 (1999).
[5] N. Hamilton and R. B. Cal, Physics of Fluids. **27**, 015102 (2015).
[6] S. B. Pope, *Turbulent flows* (Cambridge University Press, 2000).