Response to Referee # 3

The authors presented an interesting study in particular in revealing new results that have not been published earlier. The manuscript is well designed in structure and clearly presented. To this reviewer, the manuscript is worth being published. However, there are minor issues need to be further clarified or revised. Below, the issues are presented.

The authors thank the reviewer for his/her time and effort in reviewing the paper and making valuable comments about the work. We have revised the manuscript and considered all suggestions. As a result, the paper has been significantly strengthened. Point-by-point answers to the reviewer's comments are provided below:

- ***A.1: Page 3, line 22: For the case of Nysted farm, the wind direction and mean wind direction are given. It would be useful to include the reason of importance of this information.***

  Response A.1: Thanks. We agree with the reviewer on this point. The authors modified the text and now read as:

  Of relevance, the variability in the wind direction pertains to the center of the wake, assesses the wake width, and the character of wake behavior.

- ***A.2: Page 8, line 142: It would be very informative to compute the blockage ratio based on the cross-section area of the tunnel and the turbines' area in order to assess if the ratio is in the acceptable range.***

  Response A.2: Thanks. The blockage ratio for this set of experiments is quite small. Considering a maximum of three wind turbine rotors in a given cross section of the wind tunnel, each with rotor diameter $D = 0.12$ m, the blockage G is approximately 3.5%, given by,

  $$G = (3 * \pi * (D/2)^2)/(1.2 * 0.8) = 0.035.$$

  The text now read as:

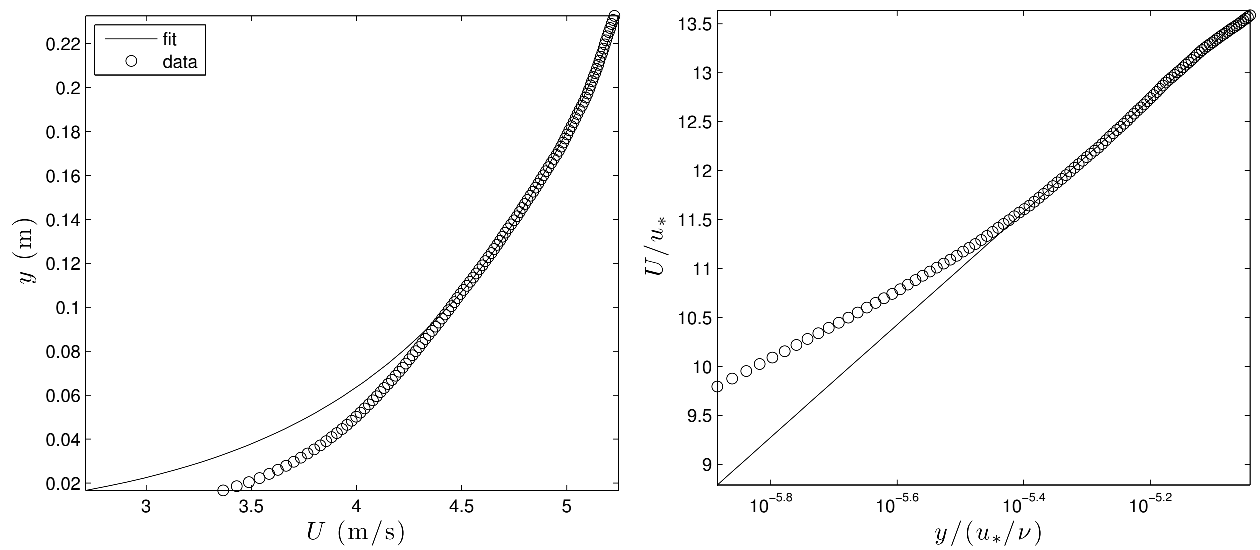
  The blockage ratio is less than 5% in the test section.

- ***A.3: Page 8, line 146: It is stated that acrylic strakes were used to modify the upstream inflow. To this reviewer, it would be helpful to provide information about the velocity distribution upstream the turbines to depict the formation of the boundary layer (B.L.). Furthermore, the relation of the B.L. to the turbines can be compared to the realistic situation.***

  Response A.3: Thank you. A detailed review of the experiment can be found in previous work Hamilton et al. [1]. The attached figures are copied from Hamilton et al. [1] and characterize the inflow to the tunnel-scale array. The figure 1 compares the inflow velocity of the current experiments to a fit for the boundary layer given by,

  $$\tilde{u}(y) = u_\star \left(\frac{1}{\kappa} ln \left(\frac{u_\star y}{\nu} \right) + B - \Delta U^+ \right),$$

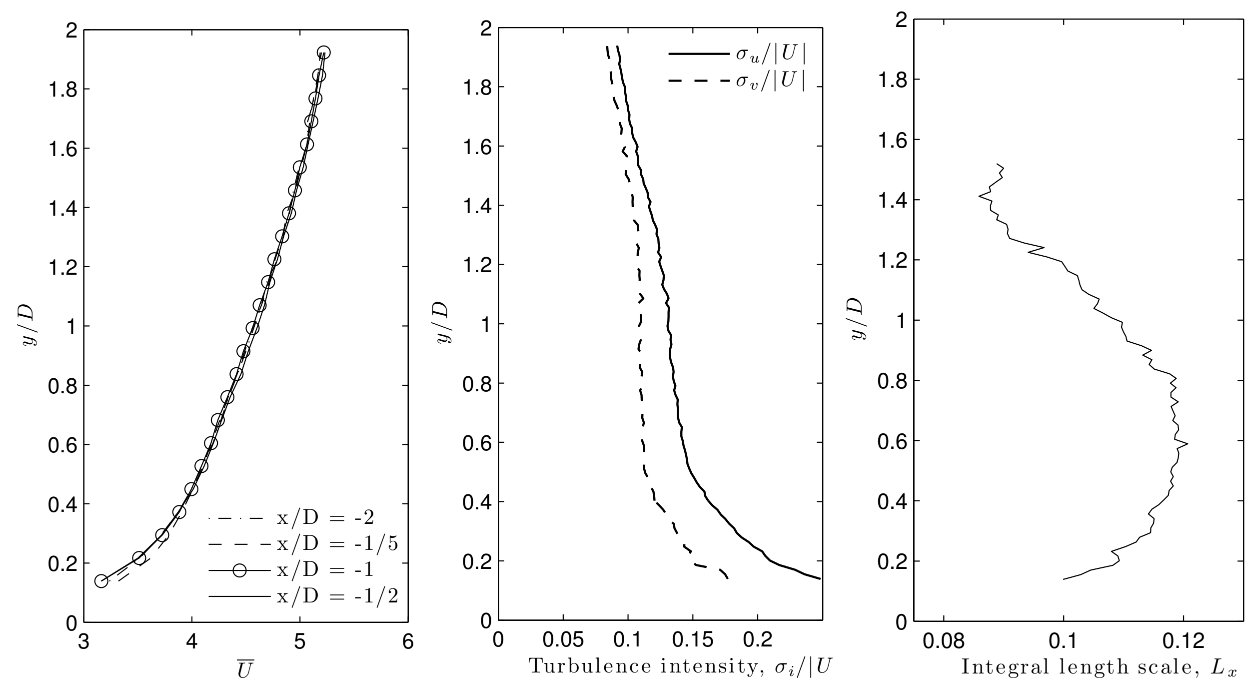
  where $u_\star$ is the friction velocity, ΔU^+ is a velocity deficit, and y_0 is the effective surface roughness. Fitting parameters are $B = 5.5$ and the von Kármàn constant is taken as, $\kappa \approx 0.4$. The figure 2 demonstrates turbulence quantities in the inflow to the model array. Including averaged velocity profiles (subfigure a), turbulence intensity (subfigure b), and an estimate of the integral length scale (subfigure c).



(a)Mean inflow profile of the wind tunnel boundary layer in linear scale.

(b)Normalized inflow profile of the wind tunnel boundary layer in logarithmic scaling.

FIG. 1: The inflow profile.



(a)

(b)

(c)

FIG. 2: Characteristic quantities.

- ***A.4: Page 9, line 150: Based on the provided information, the turbines are miniature ones. To this reviewer, it is necessary to include the assessment of the scaling effects in particular the effect of Reynolds number.***

Response A.4: Thank you. The reviewer is correct to give similarity consideration in the assessment of the work. Reaching full dynamic similarity is one of the key challenges in wind tunnel experiments for wind energy studies. Most often, wind tunnel experiments are considered to have reached a Reynolds number independent range past $\mathcal{O}(10^5)$. In the current work, the Reynolds number of the entrance row turbines based on the hub height velocity and rotor diameter is approximately 3.7×10^4. At this level, the Reynolds number is nearly the same order of magnitude of the Reynolds number independent range detailed in [2].

The text now read as:

In this study, the Reynolds number in the entrance row turbines is approximately the same order of magnitude of the independent range detailed in [2].

- ***A.5: Page 9, line 150: It is mentioned in the manuscript that 3-bladed horizontal axis wind turbines are used in the experiments. Is there any specific design used to construct these turbines? Or they are scaled-down versions of an existing design?***

  Response A.5: Thank you. Model-scaled wind turbines in the current work follow a generic design, patterned after the work by Cal et al. [3] , Kang and Meneveau [4] and Hamilton et al. [1]. Pitch and twist of the blades was investigated in a laboratory setting to reach the expected performance of scaled wind turbines ($\lambda_{tsr} \approx 3.5$ and $c_P \approx 0.25$), detailed in Hamilton et al. [1].

  The text now read as:

  The wind turbine model design used is that presented in Cal et al. [3], Kang and Meneveau [4] and Hamilton et al. [1].

- ***A.6:Page 9, line 166: It would be informative to include the sampling rate of the SPIV system.***

  Response A.6: Thanks. The nominal sampling rate of the SPIV system was fixed at 5 Hz. In reality this speed varied between approximately 3 Hz and 5 Hz based on the memory usage of the system.

  The text now read as:

  The sampling rate of the SPIV system is fixed at 5 Hz.

- ***A.7:Page 9, line 176: To this reviewer it would useful to provide error calculation for the PIV measurements.***

  Response A.7: To this point, the reviewer is again referred to previous work from the same set of experiments, where it was found that the error of the SPIV measurements was on the order of 3%, with the greatest uncertainty pertaining to the out-of-plane (spanwise) component. This error was approximated using a variability estimator as in George [5].

  The text now read as:

  Based on the variability estimator [5], the error of the SPIV measurements is on the order of 3%. The major uncertainty pertaining to the out-of-plane (spanwise) component.

- ***A.8: Page 10, FIG 3: According to this figure, the turbines are located close to the lateral walls? How close is this distance? And how much effect was noticed in the measurements?***

  Response A.8: Thanks. The wind turbines closest to the walls of the wind tunnel are approximately 24 cm away from any fixed surface. The boundary layers developing along the wind tunnel walls are rather thin (∼3-6 cm) and do not to alter the results since measurements are focused around the last row-center turbine. In addition, all measurements considered in the current work are along the centerline of the wind tunnel, 60 cm from the walls.

- ***A.9:Page 16, FIG 8, 9 and 10: It would be helpful to include legends for these figures in order to compare different modes.***

  Response A.9: Thanks for the suggestion. This has been addressed.

- ***A.10: As a general recommendation, to this viewer, it is necessary to provide reasonable physical interpretations for curves, profiles and contour maps presented in the manuscript. In other words, it would be more informative to present physical reasons associated with the curves? behaviours. This can be taken into account for example in page 6- FIG 6 (e.g. line 222: ?a reduction in streamwise spacing shows less effect when the spanwise spacing Sz= 1.5D.? what is the physical reason?), and page 18, FIG 11.***

  Response A.10: Thanks for highlighting this points. The physical interpretations are added to the revised manuscript.

  Interestingly, a reduction in streamwise spacing shows less effect when the spanwise spacing $S_z = 1.5D$. This is a result due to constraining the wake as it interacts with wakes from the other various turbines thus suppressing the development in the streamwise and spanwise direction. Therefore, a reduction in the spanwise turbine-to-turbine distance increases the lateral interactions.

  In cases C_{33} and $C_{31.5}$, less energetic features are observed due to the reduced spacing effect that leads to a reduction of the mean velocities within the canopy and an increase in lateral wake interactions. These interactions, which become larger as a result of the accumulated wakes, expand downstream of the rotor.

  The streamwise spacing allows for the flow to recover and therefore produce larger, more coherent structures within the domain, which in comparison eclipses variations produced by the spanwise spacing. Also, the large spacing offers a larger frontal area to the wind coming from above the lateral sides.

  The maximum difference is observed between the reconstructed profiles from modes 5-10 and from 5-25 due to the turbulence kinetic energy contained within these modes.

  The upstream of cases $C_{6\times3}$ and $C_{6\times1.5}$ is representative of the recovering part of the flow, in contrast to the downstream that presents the wake region. This difference in the physical space has an impact in the low number POD modes that show the discrepancy in the coherent structures between the upstream and downstream. In the $C_{3\times3}$ arrangement, upstream and downstream both contain similar behaviors, thus pointing to the resemblance in the structure. Alike observations can be extracted from case $C_{3\times1.5}$. Of note, a difference in sign of the eigenvectors is present, which is one of the POD properties.

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] L. P. Chamorro, R. Arndt, and F. Sotiropoulos, Wind Energy **15**, 733 (2012).
[3] R. B. Cal, J. Lebrón, L. Castillo, H. S. Kang, and C. Meneveau, Journal of Renewable and Sustainable Energy **2**, 013106 (2010).
[4] H. S. Kang and C. Meneveau, Measurement Science and Technology **21**, 105206 (2010).
[5] W. K. George, Chalmers University of Technology (2013).