

## ***Interactive comment on “Wind tunnel experiments on wind turbine wakes in yaw: Effects of inflow turbulence and shear” by Jan Bartl et al.***

### **Anonymous Referee #2**

Received and published: 26 February 2018

The paper covers the very relevant topic of wake steering, through a fundamental analysis of the wake physics behind the wind turbine in yaw. The detailed results of the cross-sections of the wake regarding velocity deficit and turbulent kinetic energy levels are a rich addition to our understanding of the complex wake aerodynamics involved in the wake steering process. The systematic investigation of flow cases with increased complexity (no turbulence, turbulence, turbulence with shear) is also very welcoming, as it allows to distinguish between the different phenomena which drive the wake deflection. The introduction is very well written and covers the state-of-the-art as it is today. An important remark is made about the triviality of wake deflection and wake expansion methods used in contemporary literature, and a well-considered attempt is made to base the definition of deflection on the integrated power levels in the wake.

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This notion about definitions and parameters involved in wake deflection certainly requires a lot more discussion by the wind energy community. Below I have stated remarks related to the content of the report, as well as technical remarks including quite some spelling mistakes. Note, p99.l99 stands for page 99, line 99.

Remarks about the content:

In the introduction, p1.l20, you state wake redirection techniques, which intentionally apply an uneven load distribution. Instead of an uneven loading, I would say that key to wake steering is the tilting of the thrust vector. For instance, cyclic pitching results in a large uneven loading, but marginal steering, while yaw results in a much smaller uneven loading, but a large thrust vector tilting.

On page 11, in the subsection about the tower wake deflection, you discuss several factors that contribute to the tower shadow deflection. You mention the influence of the lateral offset between the rotor and the tower during yawing, and the effect of the CVP (Counter-rotating Vortex Pair) on the wake opposite tower wake direction. What I suspect here is that the bottom of the two counter-rotating vortices is in strong interaction with its mirror image underground (i.e. the ground effect), thereby forming another CVP, but in opposite direction to the main CVP involved in the wake steering. This could hypothetically boost the deflection of the wake shadow in opposite direction to the main wake deflection.

On page 12, the insignificant influence of the moderately sheared inflow on the wake shape is addressed. However, this can only be stated about the shear inflow under high turbulence conditions, as that is the only case you analysed. It might be the case that shear does have a significant contribution for low ambient turbulence levels, as the inflow shear in combination with the wake shear results in a distinctively high velocity gradient near the top of the wake (as shown by many researchers), thus increasing turbulence levels there. By the way, you mention this notion in the discussion about the TKE results later on in the paper.

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For completeness, it is important that the parameter settings for the JMC and BPA models is provided.

On page 14, you note that the wake deflection of a non-yawed turbine is assumed to stem from the interaction of the rotating wake with the turbine tower. The fact that the wake of a counter-clockwise rotating turbine (thus with a clockwise rotating wake swirl) deflects in positive z direction, sounds to me as originating from the interaction between the wake swirl and the ground: the root vortex forms a CVP with its mirror image underground from the ground effect, with its deflection direction in positive z direction. This was also discussed by e.g. Fleming (2014) and BPA (2016).

On page 14, you mention that the differences are small for the wake deflection as compared between a high and low turbulence inflow. Here it would be helpful to present results of the streamwise vorticity for both cases and for several downstream positions. Maybe the diffusion of vorticity under self-induced turbulence is already very significant for low ambient turbulence levels, which would explain why both cases are then so similar. In the end, the analysis of streamwise vorticity is key to understand, as the streamwise vorticity forms the CVP which is the driving force behind both the wake deflection and the shape deformation.

In figure 11, vertical lines of the standard deviation are given, but it is unclear how the mean and standard deviation are defined here. After all, the Gaussian fit curves applied here are clearly not symmetric, thus I assume those are from a fit with multiple Gaussians, for which it is less trivial to define a mean and standard deviation. Apart from that, there is a lot of information in this figure, and it took me a while to comprehend it fully.

Technical remarks:

P3.14 – “donstream” -> “downstream” P3.124 – remove “used in” P3.127 – “a NREL” -> “an NREL” Table 1 – add full stop Figure 2 – add full stop Table 2 – “CT” -> “CÂÑÃÑT” Table 2 – add full stop P7.13 – “a HBM” -> “an HBM” P8.114 – “a eight” -> “an eight”

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P8.I16 – remove “these” before “all these” P8.I16 – remove “as a result” (duplication with “is obtained”) P9.I22 – “an solid” -> “a solid” P11.I10 – add “been” in between “previously investigated” P12.I13 – remove “in” P13.I9 – add “the” before “BPA-model” P13.I9 – lowercase for “Available” P13.I16 – duplicate of the word “complex” P13.I20 – “a input” -> “an input” P15.I13 – remove “and” Figure 10 – add full stop Figure 11 – remove “a” before “TKE profiles” P18.I16 – “slight” -> “slightly” P19.I2 – “shown” -> “show”

Comma’s could be used more extensively to increase readability. For instance, see the first paragraph of section 4.1: “At the top, the”; “As the rotor thrust is reduced, a”; “For a yawed rotor, a”; “Due to this lateral force component, the”; “Comparing the wake contours [. . .] , an asymmetry” . . .

Sometimes it would make the text more easily readable if the text would be broken up into several paragraphs. For instance, p13.I18: “Secondly, the wake. . .” is a confusing construction, as there is no “firstly” defined in your text. Moreover, this sentence refers to a new comparison, so to clarify the text it would be better to break it up into two sections.

At p2.I18, “The measured circulation in the wake showed clear asymmetries for positive and negative yaw angles”. This is about the asymmetry of the wake regarding the kidney shape, but this sentence could also be read as an asymmetry between the values for positive and negative yaw (i.e. yaw dependency).

In figure 1, a clockwise rotating turbine is presented in the left subfigure, while the other two subfigures depict an anti-clockwise rotating turbine. Although it was clearly mentioned in the text that the results were for a turbine that is anti-clockwise rotating, it was a bit confusing for me at first to see the picture for the clockwise rotating turbine (which I assume is the second turbine used for the experiments later on in the paper).

At page 6, it would be good to add the approximate values for  $\cos^2(30)$  and  $\cos^3(30)$  in the main text to get a feeling for their magnitude (0.75 and 0.65 respectively).

In figure 5 you apply a very fine gradient scaling with contour lines added, but it is hard to extract the true magnitude from these plots. You might change these plots to one where you have much fewer gradient colors (let's say about 10), and change the colorbar accordingly (which is completely smooth in the current visualization).

In section 4.1, the subsection about the curled wake shape, you mention “. . . a kidney-shaped velocity deficit is observed. . .”, without referring to a figure number. The same applies for the subsection about the tower wake deflection on the next page.

In general, it comes more natural for the understanding of the reader if the lateral direction was defined as  $y$  and the vertical direction as  $z$  instead.

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Interactive comment on Wind Energ. Sci. Discuss., <https://doi.org/10.5194/wes-2017-59>, 2018.

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