# Comments on the review by Reviewer 1 of “Evaluation of tilt control for wind-turbine arrays in the atmospheric boundary layer”

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I thank Reviewer 1 for the many constructive comments and suggestions which have helped to improve the manuscript.

During the revision process I became aware that most of the simulations had problems in the roughness lengths values selected by the input files (in particular the roughness lengths of the precursor simulation where different from those of the simulations with the turbines). All the simulations have therefore been repeated with consistent correct values ($z_0 = 0.001$) and the manuscript has been modified accordingly. The main results are not changed, so that the conclusions of the study are not affected by these updated results (but, where appropriate, some quantitative values have been updated in the revised manuscript, as can be seen in the highlighted copy of the manuscript).

Following the referees comments and suggestions, the manuscript has undergone a non-negligible revision, where the main modifications are the following:

- All figures and tables have been updated with the results from the new simulations (with the correct consistent value of $z_0$). Changes resulting from these new simulations are updated in the revised manuscript.
- Additional simulation have been performed to further analyze power gains that can be obtained with $C_T' < 3$ values. These additional results are presented and discussed in the newly-added Appendix B and are mentioned in the main text when appropriate.
- The need for a detailed structural load analysis is further emphasized in the conclusions.

Each issue raised by a specific comment in the report is addressed in detail below. Modifications of the manuscript can be tracked in the highlighted version of the revised article (red = removed, blue = added or modified).

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*The paper uses Large Eddy Simulations to study the effect of rotor diameter, boundary layer height, and wind veer on power gains from tilt-misalignment in a wind farm. Several interesting insights are gained, indicating the relation between streak amplification in the boundary layer, and tilt-induced power gains. The paper is well written. The reviewer has some minor comments/ questions.*

I am glad of this positive general opinion on the manuscript. The comments/questions are addressed below.

*- Line 96: The actuator disk models are simulated with a constant ratio between thrust coefficient and power coefficient. When the author choses to run wind turbines at a higher thrust coefficient, how is the power coefficient modeled? If it is modeled with the linear dependence on thrust coefficient as described in the text, the power coefficient will be*

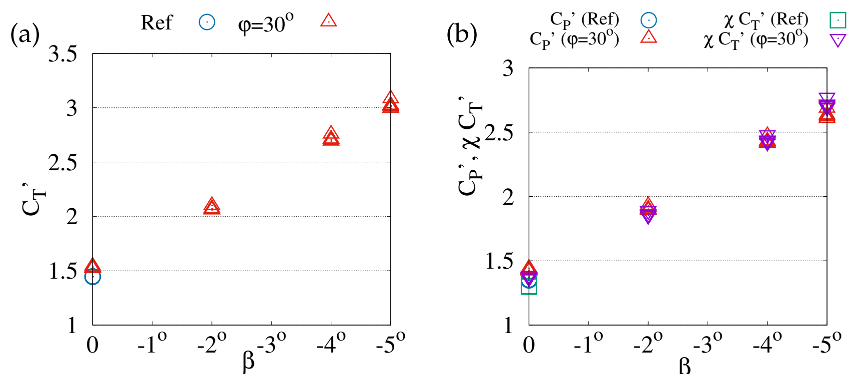


Figure R1.1 Dependence of local thrust (panel $a$) and power (panel $b$) coefficients $C'_T$, $C'_P$ of the rotor-based power coefficient on the rotor-collective blade-pitch angle ($\beta$) computed from simulation data on SOWFA's original ADM model of the NREL-5MW turbine, based on the blade element method. Power coefficient predicted from the thrust coefficient as $\chi C'_T$ (with $\chi = 0.9$) are also reported for comparison in panel $b$. The results shown pertain to time-averaged $C'_T$ and $C'_P$ values computed for each turbine of the upwind (front) row of the array in the reference case (no tilt no pitch) and for the $\varphi = 30^o$ tilted case for a range of $\beta$ values.

*unrealistically high for the case of CT′=3? It would be helpful if the author can explain in the text how the power coefficient is modeled when the thrust coefficient is increased past CT′=2, and how a higher thrust coefficient can be practically applied in a real wind farm.*

There are many questions nested in this point. Let me address them separately:

−The power coefficient is always (even when $C'_T > 2$) modeled as $C'_P = \chi C'_T$ with $\chi = 0.9$, as described in the text.

− The $C'_P = \chi C'_T$ modeling is accurate according to Munters & Meyers (2017, cited in the manuscript) who test, by LES, the same simplified actuator disk model used in the present study against theoretical predictions (see their Appendix A). I have further checked this by performing simulations with SOWFA's original actuator disk model, which is based on the blade-elements method, using the rotor-collective blade-pitch angle $\beta$ to change the turbine load and then computing $C'_T$ and $C'_P$ from simulation outputs. The computed $C'_T(\beta)$ and $C'_P(\beta)$ data are shown in Figure R1.1 for the case of tilt control in a two-rows array of NREL 5-MW wind turbines with the same spacing ($4D - 7D$) and flow parameters as in the present study for the $H = 750\,m$ ABL (the $C'_T$ data are reproduced from the study "Wake redirection at higher axial induction" which is currently under review in Wind En. Sci., DOI: 10.5194/wes-2020-111, cited as Cossu, 2021 in the manuscript). From this figure it can be verified that the relation $C'_P = \chi C'_T$ (with $\chi = 0.9$) is a good approximation of the data even for $C'_T > 2$.

−For $C'_T = 3$, the power coefficient is $C'_P = 2.7$ (as shown above) which is not unrealistic. As mentioned, the additional simulations I have performed by means of SOWFA's model of the NREL-5MW turbine, show that the large $C'_T = 3$ value can be obtained with a rotor-collective blade-pitch angle $\beta = -5^o$. Furthermore, many other studies use such large values of $C'_T$ in numerical simulations of wind farm control. For instance, Goit & Meyers (2015, cited in the manuscript) show that large $C'_T$ values (up to $C'_T = 4$) can be accessed by modified NREL-5MW models by increasing the wind-tip speed ratio or/and the blades chord length (see their Appendix A). Munters in his PhD dissertation (2017, cited in the manuscript) shows that such large values of $C'_T$ can be obtained by simply increasing the tip speed ratio provided that the mean wind speed is not too large (see his Figure 2.4) and Munters & Meyers (2017, cited in the manuscript, and a few other papers), indeed enforce a maximum value $C'_T = 3$ in their computations.

− In the revised manuscript it is now mentioned (in the new Appendix B) that high $C'_T$ values could be obtained by acting on the rotor-collective blade-pitch angle and/or increasing the tip speed ratio of typical existing wind turbines or, in the design phase, by increasing chords lengths (lines 310-312). It is also mentioned that: (a) one does not necessarily need to enforce values as high as $C'_T = 3$ because significant power gains can already be obtained for lower values of $C'_T$ (lines 230-232) and (b) the issue of structural loads for higher $C'_T$ high-tilt turbines has to be addressed mostly for next-generation wind turbines (lines 282-289).

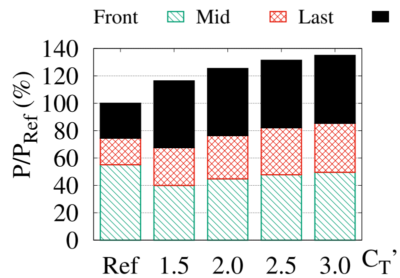


Figure R1.2 Influence of $C'_T$ on the average power extracted with $\varphi = 30^o$ tilt control from D=126m turbines in the H=750m ABL decomposed into front, middle and last row contributions (the baseline, no-tilt $C'_T = 1.5$, case "Ref" is also displayed for comparison).

*- If the power coefficient indeed increases to an unrealistically high value for CT'=3, it would mean that the power of the first row of turbines is overestimated? Maybe the author can add a plot of average row power also for the case of CT'=1.5?*

As discussed in the previous point, I am not convinced that $C'_P$ grows to an unrealistically high value for $C'_T = 3$. However, I understand the concern that $C'_T = 3$ might be considered unfeasible lacking additional studies on the feasibility of turbines capable of high positive tilt angles combined with overloading. I have therefore added a plot of average row power not only for $C'_T = 1.5$, as suggested, but also for the intermediate values $C'_T = 2$ and $C'_T = 2.5$ in the new Fig.B1$a$, reproduced here in Fig.R1.2. From this figure it can be seen that significant power gains can be obtained also at intermediate $C'_T$ values and that only (roughly) half of the power gains enhancements obtained by increasing $C'_T$ do come from first-row turbines.

For the same reason, I have added further additional results in Appendix B showing that: (a) non-negligible power gains are obtained by tilt control operating the turbines at the reference $C'_T = 1.5$ value, (b) significant power gain enhancements are already obtained by operating tilted turbines at $C'_T = 2.25$ (instead of the almost borderline value $C'_T = 3$) and (c) the optimal $D/\delta_2$ ratio where tilt-control power gains are maximized is not sensitive to the $C'_T$ operational value used in tilted turbines.

*- One focus of this paper is quantifying' or estimating' power gains from tilt misalignment. (see line 62) However, Large Eddy Simulations are not perfect, as small scale turbulence is missing. Subgrid scale modeling can have an effect on the turbulent diffusion of the counter rotating vortex pairs, leading to an over-estimate of the downstream dominance of the counter rotating vortex pair. Furthermore, the wind turbines are modeled by actuator disk models. It would be helpful for the reader if the author gives a brief discussion on the limitations of this study.*

I agree that some of the potential limitations of the study were not mentioned or discussed enough in the original manuscript. That further investigations removing these limitations are needed is mentioned in the conclusions of the revised manuscript (lines 263-276).

*- Line 104: 'spanwise turbine spacing $\lambda_y = 4D$': It is mentioned later in the text, but it would be helpful to mention here the typical spanwise spacing for 'streak generators' as described non-dimensionally in the respective papers, instead of converted into wind turbine diameters for this specific case.*

The streaks generators used in previous flat-plate investigations and mentioned in the manuscript were wall-mounted cylinders of diameter $d$, spanwise spacing $\Delta z$ and height $k$ (see Fig. R1.3). During long preliminary work to the 2004 paper it was found that streaks with most of the energy in the first spanwise harmonic (i.e. with the streamwise velocity profile approaching a pure sinus in the spanwise direction) could be obtained when $d/\Delta z \approx 1/4$.

Considering wind turbines, the formation mechanism of the streamwise vortices (by lift induced by the tilted rotors) is different from the one of the roughness elements (which is probably a mix of horseshoe vortex formation and lift-induced mechanisms) but the initial spanwise spacing of the two counter-rotating vortices is roughly $D$ for the turbines (even if tilted, the rotor spanwise size is always $D$) as in was $d$ for the roughness elements (the spanwise size of the roughness elements is the cylinder diameter). This is why the same terminology and adimensionalisation is used here.

As this was probably unclear in the manuscript, the explanation has been made more precise in the revised manuscript (line 108) by mentioning that the roughness elements are circular and that D is their diame-

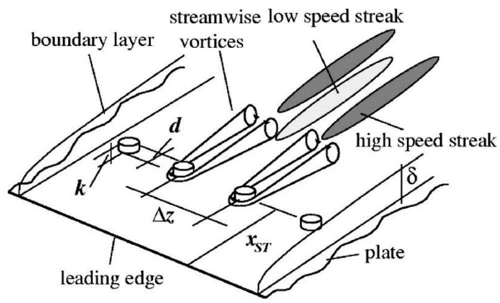


Figure R1.3 Scheme of the spanwise array of wall-mounted cylindrical roughness elements used to generate streamwise streaks in the flat-plate boundary layer (reproduced from Fig. 13 in Fransson et al. 2004, cited in the manuscript ).

ter/width.

*- Wind veer is relatively limited in the considered boundary layer conditions. Does the author expect a bigger impact on power improvement from tilt when wind veer would be stronger?*

This is a very interesting question. I would expect that a stronger wind veer would result in an increased lateral deviation of the high-speed streaks because the higher-speed fluid which is pushed down by the vortices has a stronger lateral component. This would probably require to combine tilt-control with an additional yaw adjustment able to counter this lateral displacement. This is mentioned in the conclusions of the revised manuscript (line 261).

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I hope to have clarified the main issues raised in the report. I thank again Reviewer 1 for his/her remarks and suggestions which have helped to improve the manuscript.