Carlo Cossu
*Directeur de recherche CNRS*
*Head of the Urban & Coastal Atmospheric Dynamics Group*
LHEEA, CNRS - Centrale Nantes
1 rue de la Noë, 44300 Nantes, France
☎ +33(0)240376824, ✉ carlo.cossu@ec-nantes.fr

Prof. Johan Meyers
Associate Editor
*Wind Energy Science*

Nantes, 13 January 2021

Dear Pr. Meyers,

I thank you and the reviewers for having examined the manuscript entitled "Wake redirection at higher induction" and for the rapidity of the review process.

Both reviewers have raised a number of issues which have been addressed in the revised manuscript and in the reply to each reviewer. As you can read in the posted author's comments, I have followed most of the suggestions of Prof Munters (Reviewer 1) while I found it more difficult to follow all the suggestions of Reviewer 2. All the comments, nevertheless, have helped to improve the quality of the manuscript that I'm resubmitting for publication in *Wind Energy Science*.

During the revision process I have also realized that most of the turbine simulations were performed with an erroneous roughness length which was larger than the one used in the precursor simulation. I have rerun all the simulations with the correct value and updated the paper figures accordingly, but, luckily, the results do not change much.

Following the many reviewers' comments and suggestions, and the updated results from the new simulations, the manuscript has undergone a major revision, the main modifications being the following ones:

- All the presented results have been updated with the new simulations (with the correct $z_0$). The new results, reported in the revised manuscript, are mostly similar to the previous ones so that the main conclusions of the manuscript do not change. Changes resulting from these new simulations are updated in the revised manuscript.
- Additional simulation have been performed to analyze the role of the used turbine model, and in particular the effect of including wake rotation effects. The new results are presented and discussed in the new Appendix B and mentioned in the manuscript when appropriate.
- New figures have been added showing the mean streamwise vorticity and velocity fields in the cross-stream planes to highlight the role of the counter-rotating streamwise vortices forced by the tilt or yaw misalignement and discuss the role of wake rotation. A scheme has been added to define the tilt and yaw angles.
- The abstract and conclusions have been modified to make them more clear following reviewers' comments and suggestions.

All the modifications of the manuscript can be tracked in the highlighted revised version of the manuscript which has also been posted (red = removed, blue = added or modified).

I hope that you and the reviewers will find this revised version suitable for publication.

Yours sincerely,

# Comments on the review of "Wake redirection at higher axial induction" - Reviewer 1, Wim Munters

Carlo Cossu
Laboratoire d'Hydrodynamique Énergetique et Environnement Atmosphèrique (LHEEA)
CNRS - Centrale Nantes, 1 rue de la Noë 44300 Nantes, France

January 13, 2021

I thank Prof. Munters for the many constructive comments and suggestions and I appreciate the rapidity of the refereeing process. Each issue raised by a specific comment is addressed in detail below.

This reply has taken longer than expected because during the revision, in relation to the performed additional simulations and to the question on the used roughness length, I became aware that most turbine simulations input files were bugged leading to the inconsistent use of roughness lengths $z_0 = 0.15$ that were larger than the value used in the precursor simulation. I therefore had to rerun all the simulations with the correct value $z_0 = 0.001$, postprocess the results and redraw all the figures.

The manuscript has undergone a major revision, the main modifications being the following ones:

- All the presented results have been updated with the new simulations (with the correct $z_0$). The new results, reported in the revised manuscript, are mostly similar to the previous ones so that the main conclusions of the manuscript do not change. Changes resulting from these new simulations are updated in the revised manuscript and are discussed, when appropriate, below.
- Additional simulation have been performed to analyze the role of the used turbine model, and in particular the effect of including wake rotation effects. The new results are presented and discussed in the new Appendix B and mentioned in the manuscript when appropriate.
- New figures have been added showing the mean streamwise vorticity and velocity fields in the cross-stream planes to highlight the role of the counter-rotating streamwise vortices forced by the tilt or yaw misalignement and discuss the role of wake rotation. A scheme has been added to define the tilt and yaw angles $\varphi$ and $\gamma$.
- The abstract and conclusions have been modified to make them more clear following reviewers' suggestions.

---

*In the manuscript Wake redirection at higher induction, the author describes a study into combining wake redirection techniques from yaw and tilt control with increased turbine induction. The study is well-described and the structure and elaboration of the manuscript is very clear and easy to read. The overall contribution to the field is rather limited and incremental, i.e. tilt control at higher induction has been shown in an earlier study of the same author (albeit using a different turbine model); and combined yaw and induction control has been shown in earlier studies by Park Law and Munters Meyers (albeit using different ways of generating control strategies). That being said, the current work is still highly relevant to the general community and I believe the topic is suitable for publication in Wind Energy Science. However, I feel there are several points for improvement of the quality and novelty of the considered work, as detailed below in my comments*

I am glad that the study is found relevant and the topic suitable for publication in Wind Energy Science. While I agree with most of the comments, which have led to an improvement of the manuscript, I do not completely agree with the perceived lack of novelty/relevance of some of the results, and in particular those pertaining to the overinductive yaw control, as discussed below.

*The added contribution of the current paper is relevant but incremental: overinduction has already been shown to work for yaw and tilt control in earlier LES-based studies (Cossu 2020b and Munters and Meyers 2018 respectively. The author shows that this strategy also works in his current setup (with a slightly different turbine model for tilt, and a static vs dynamic control strategy for yaw).*

I agree that the contribution could be perceived as incremental in what concerns the tilt case. For the yaw-control results, however, I do not completely agree and I still am quite excited about the results. What is substantially new, relevant and the main step forward is, in my view, that the proposed overinductive yaw-control is static and, as such, immediately implementable in existing yaw-control settings. That this is the case, could not be clearly deduced from previous results with dynamic induction control where one could not exclude that the coordinated dynamical evolution of $C_T'(t)$ played a major role in the power gains. Also, the results of Park et al. (2015), which were obtained in the static-static case, seem to converge towards an underinductive regime for the front-row turbines in the wind-aligned case, probably because of their simplified wake model. Besides, the finding that a simple static open-loop overinduction control is able to significantly and systematically increase yaw-control power gains, and does so even for relatively small overinduction, also shows that the physics behind it is quite robust.

These points, not emphasized enough in the original manuscript, are more explicitly highlighted in the revised manuscript (lines 55-63 and 68-70).

*The added value of the current paper over existing literature would benefit from a more detailed flow analysis of the current LES results. For example, it would be interesting to see expand Figure 1 with additional flow field sections...*

I agree with this comment which has led to an improvement of the quality of the manuscript.

The flow analysis of the current results has been expanded by adding, in the additional figures 2,6 and B1 of the revised manuscript, cross-stream sections of the mean streamwise vorticity and velocity. These additional figures, and the associated discussion, show the effect of the tilt- and yaw-induced mean streamwise vortices and are allow to explain the important role of wake rotation in the newly added Appendix B.

*...and compare to results from Cossu 2020b, which would allow to show effects of wake rotation on tilt-based redirection.*

Thank you for this suggestion. As it is difficult to directly compare the present results to those of Cossu (2020b) because they are obtained for different array configurations (2 vs 3 rows), I have performed additional simulations with the same turbine model used in Cossu 2020b for the 2-rows layout considered in the present study. These results are discussed in the revised manuscript in the newly added Appendix B and mentioned in the main text (lines 154-159). It is, in particular, shown and discussed how the wake rotation induces a strong asymmetry of the induced streamwise vortices resulting in an oblique downwash and therefore in a loss of efficiency in the displacement of the high-speed fluid towards the downstream rotors.

*Further, a flow-based comparison between the differences for yaw and tilt control would be very interesting. For example, the author mentions in line 160 that the shift of larger optimal angles after including pitch is present for tilt but not for yaw, and that this can probably be explained by observing that vertical shear is not exploited by yaw. The author has the data to show this quantitatively, and I feel this could be an important addition to the current work.*

In the updated numerical simulations (using a consistent $z_0$) results, the mentioned shift to larger tilt angles is less pronounced than in the original manuscript. Furthermore, the newly discussed effect of wake rotation on the direction of the downwash in the tilt-induced case adds complexity to the interpretation because the shear direction to be considered is not vertical for the tilt case, which also probably introduces a further dependence on the streamwise turbine spacing. In the revised manuscript I have therefore removed the emphasis that was put on the shift to larger angles, as these shifts appear to be a relatively minor and probably non-generic effect.

*The first goal of the study is to assess whether additional gains in overinductive tilt control still hold up when considering realistic turbine models closer to reality. However, I believe that this goal is only partially achieved and the step forwards from the Cossu 2020b study is relatively small. A significant step forward would have been made using an actuator line model instead of an actuator disk model. The limitations of an actuator disk model should be mentioned earlier in the study (currently they are left to the conclusions).*

I do not completely agree on this point. This paper is mainly concerned with power gains in wind turbine arrays where turbines are not closely spaced. As these are time-averaged effects and they concern the interaction of far wakes with downstream rotors, I think that the actuator disk model is completely adapted to the purpose of this study and I do not think that any qualitative improvement would come from the use of at actuator line model. Furthermore, the high computational resources required in ALM simulations, which require grid refinements and much smaller time steps, would have restricted the analysis to a much more limited set of $\varphi - \gamma, \beta$ combinations.

The use of an ALM will of course be necessary for further highly suitable investigations of the structural loads and aeroelastic response of tilted and yawed turbines operated at higher induction. This is now mentioned in the revised manuscript (lines 225-227).

*Some comments related to this:*
*– In the conclusion, the author mentions that the absolute level of power gains is larger in Cossu 2020a, b. Unless Im mistaken, this is not mentioned in the main text. The author should attempt to explain this. Could this be due to the different turbine model (e.g. accounting for wake rotation), or a different wind-farm setup (i.e. 2 rows vs 3 rows)?*

This is an interesting suggestion which is closely related to an already discussed point.

In previous investigations of tilt-control it was found that power gains obtained in 3-turbines (3-rows) layouts were larger than those found in 2-turbines (2-rows) layouts, so this must certainly play a role in the difference in power gains. However, the respective role of the different number of rows and of the turbine model can not be isolated by a quantitative comparison of the present results with the mentioned previous ones, as both the array configuration and the turbine model have been changed. To isolate the role of the turbine model, additional simulations have thus been performed on the 2-rows configuration used in the present study but using the same turbine model (ADMC) used in Cossu 2020a,b (and in numerous previous investigations) as already mentioned in one of the previous points. These additional simulations show that the inclusion of wake rotation leads to a non-negligible decrease of the absolute level of power gains explaining the lower absolute values of tilt-induced power gains observed in the present study.

These additional results are reported in the newly added appendix B and are mentioned in the main text (lines 154-159).

*– The increase of $C_T'$ shown in Figure 3b requires some further explanation, is this caused by a change in the effective angle of attack of the blades?*

When the tilt angle $\varphi$ is changed at constant rotor collective blade pitch angle $\beta$ (and blade-twist $\theta$) the angle of attack $\alpha = \phi - (\beta + \theta)$ of the blades can change only because of a change in the angle $\phi$ formed by the wind with the rotor plane. The change in $\phi = \tan^{-1}(U_n/\Omega r)$, where $U_n$ is the velocity component normal to the rotor, is therefore a consequence of the change of $U_n$ and of the rotor angular speed $\Omega$ which not only depend on $\varphi$ but also on the load and torque on the turbine rotor (and therefore on $C_T'$) therefore forming a sort of closed loop. I therefore prefer to avoid explaining the change of $C_T'$ as caused by a change of $\alpha$. Furthermore, things are complicated by the fact that $\Omega$ is determined by the particular controller used for the specific turbine under consideration, that $U_n$ is not uniform on the disk and that wake rotation effects should also be included in the computation of $\phi$.

A probably simpler explanation (and also a check that the observed increase of $C_T'$ with $\varphi$ is not some kind of artifact) can be obtained by considering the direct dependence of $C_T'$ on $\varphi$ and on the change of the induction factor $a$ induced by the tilt. $C_T'$ can be expressed as a function of $\varphi$ and $a$ by e.g. rearranging Eq. (2.13) of Shapiro et al. (2018):

$$C_T' = \frac{4a}{(1-a)\cos^2\varphi} \tag{1}$$

I have then plotted this predicted $C_T'$ in Fig. R1.1 as a function of $\phi$ by using axial induction factors $a$ based on the simulation data for $u_d$ as $a(\varphi) = u_d(\varphi)/(U_\infty \cos\varphi)$.
In Fig. R1.1 a trend very similar to the one of Fig. 3*b* of the original manuscript is observed despite the strong simplifying assumptions implied by Eq. (1) such as the neglect of the effects of wind shear, turbulent fluctuations and the radial dependence of the loads on the actuator disk. This detailed discussion is not included in the revised manuscript to keep the focus on the most important points but it is now mentioned that the increase of $C_T'$ with $\varphi$ is related to the combined effect of the tilt and of the associated decrease of the induction factor (revised manuscript, lines 147-148).

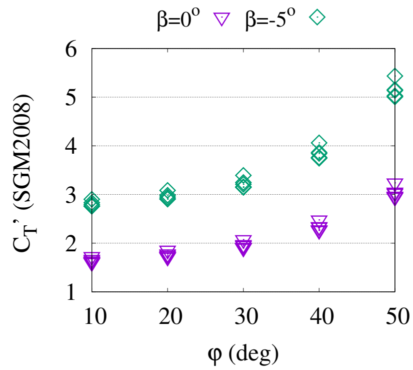


Figure R1.1 Dependence of $C'_T$ computed with Eq. (1) for each turbine of the upwind row using the $u_d(\varphi)$ data from the simulations for $\beta = 0^o$ and $\beta = -5^o$.

*- The author shows the dependency of $C'_T$ on different control parameters, but there is no mention of how e.g. the pitch angle affects the power coefficient $C_P$ (or $C'_P$ if you will). This should be clearly mentioned*

The dependence $C'_P(\beta)$ is shown in Figure R1.2 below for both tilt and yaw control. From this figure it can be verified that the relation $C'_P = \chi C'_T$ is a good approximation of the data (with $\chi = 0.9$).

This is now mentioned in the revised manuscript (lines 100-102).

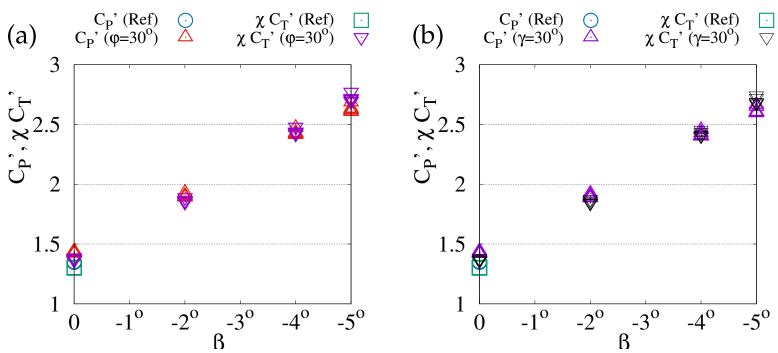


Figure R1.2 Dependence $C'_P(\beta)$ of the rotor-based power coefficient on the pitch angle. Power coefficient predicted from the thrust coefficient as $\chi C'_T$ (with $\chi = 0.9$) are also reported for comparison. Panel $(a)$: tilt control. Panel $(b)$ yaw control

*The author frequently mentions achieving doubled or tripled power gains in high induction compared to baseline tilt/yaw control. Please be more specific in phrasing here to avoid confusion: mention explicitly the percentages, and the setup (e.g. Cossu 2020b has a three-row setup, achievable power gains are different than when looking at two rows as in the current study).*

This is done in the revised manuscript.

*Starting from line 131, the author discusses that he believes increasing thrust in tilted conditions should not impact turbine loading compared to standard operation, since the overall thrust force would not be higher than in the latter. However, Fleming et al (Renewable Energy 2014), have shown that tilt control can have a significant influence on blade bending and drivetrain torsion. Further increasing thrust could aggravate such issues. I believe that turbine loading could be an issue at higher induction scenarios such as considered here, and that conclusive statements warrant a detailed analysis using aero-elastic codes. This should be mentioned in the manuscript.*

This is right. Trying to modify the manuscript in this direction, however, I have realized that even with the suggested additions, the only partial discussion of turbine loading in tilted/yawed conditions remained at best only qualitative and at worst potentially misleading, so that I have completely removed this discussion in the revised manuscript where the need for further studies of the turbine structural loading is now clearly mentioned.

*Line 59: typo oveinductive should be overinductive*

Right. This is corrected in the revised manuscript.

*Line 82, the formula for $C_T'$ contains a $\pi$ which shouldnt be there*

Right. This is corrected in the revised manuscript.

*The appendix states use of a Schumann BC at the wall. What is the roughness length imposed at the bottom and, more importantly, what is the resulting turbulence intensity at turbine height? This tends to have a significant impact on power deficits and hence achievable gains.*

I thank you for this comment which has led me to find inconsistencies in the simulations input files. The used $z_0 = 0.01$ and the associated turbulence intensity (5.7% at hub height) of the incoming flow are mentioned in the revised manuscript (lines 109-110).

*A 3x3 km periodic precursor domain is probably too small to generate fully realistic turbulent flow structures. Does the author expect this to affect results in any way?*

Intuitively, I do not expect that running simulations in longer/wider domains would significantly affect the results, especially for the considered configuration, where the spanwise spacing of the turbines are smaller than those of natural large- (LSM) and very large scale motions (VLSM) of the boundary layer. In this case, indeed, a possible locking of the LSM and VLSM to the computational box should not have a significant influence on the global power gain. Furthermore, the fact that statistics are accumulated for more than one and a half hours (6000s) ensures their acceptable convergence as can be seen in all figures where data for each of the upwind-row turbines are shown and where it can be observed that the spread of data among turbines is small.

*The author rightfully mentions surprisingly little research efforts into combining yaw and induction control. An additional study that could be mentioned here is Munters, Meyers, 2018, Optimal dynamic induction and yaw control of wind farms: effects of turbine spacing and layout. J Phys Conf. Ser 1037, 032015, which investigates combined dynamic yaw and overinduction for a series of different wind-farm layouts*

This is right. This paper is now cited in the revised manuscript (lines 58, 210, 359-360).

---

I hope to have clarified the main issues raised in the report. I thank again Prof. Munters for his remarks and suggestions which have helped to improve the manuscript.

# Comments on the review of "Wake redirection at higher axial induction" - Reviewer 2

Carlo Cossu
Laboratoire d'Hydrodynamique Énergetique et Environnement Atmosphèrique (LHEEA)
CNRS - Centrale Nantes, 1 rue de la Noë 44300 Nantes, France

January 13, 2021

I thank Reviewer 2 for his/her comments and suggestions and I appreciate the rapidity of the refereeing process. Each raised issue is addressed in detail below.

The reply process has been longer than expected because during the revision, in relation to the performed additional simulations and to a question raised by Referee 1 , I became aware that most turbine simulations input files were bugged leading to the inconsistent use of roughness lengths $z_0 = 0.15$ that were larger that used in the precursor simulation. I therefore had to rerun all the simulations with the correct value $z_0 = 0.001$, postprocess the results and redraw all the figures.

The manuscript has undergone a major revision, the main modifications being the following ones:

- All the presented results have been updated with the new simulations where the bug on the $z_0$ value was fixed. These corrected results, reported in the revised manuscript, are mostly similar to the previous ones so that the main conclusions of the manuscript do not change. Changes resulting from these new simulations are updated in the revised manuscript and are discussed, when appropriate, below.
- Additional simulation have been performed to analyze the role of the used turbine model, and in particular the effect of including wake rotation effects. The new results are presented and discussed in the new Appendix B and mentioned in the manuscript when appropriate.
- New figures have been added showing the mean streamwise vorticity and velocity fields in the cross-stream planes to highlight the role of the counter-rotating streamwise vortices forced by the tilt or yaw misalignement and discuss the role of wake rotation. A scheme has been added to define the tilt and yaw angles $\varphi$ and $\gamma$.
- The abstract and conclusions have been modified to make them more clear following reviewers' suggestions.

---

*1. The abstract mainly provides general introduction and the past research of the author. Please discuss the findings of the current research. You can quantify and further discuss the power gains due to tilted rotor and yaw control.*

I agree. The abstract has been largely rewritten accordingly.

*2. It is not clear why you have considered just two rows of turbines. I do not see any technical challenge in simulating for wind farms with more rows.*

I agree that the two-rows configuration is highly idealized and, as such, it is not representative of a typical wind farm and that technically I could have considered more turbine rows. However, the problem of considering many rows is that the results depend on the specific tilt/yaw angles enforced in each row. Thus, if I had considered more than two rows, the effect of increasing the induction in tilted/yawed turbines (which is the main message of this paper) would have been blurred by considerations/analyses of the optimal combinations of tilt/yaw angles to be enforced in each row. I have therefore chosen to consider only two rows for which the results in term of $\beta$ and (a single value of) $\gamma$ or $\varphi$ remain relatively easy to interpret. The chosen configuration is indeed similar to the two-turbines case considered by Fleming et al. (2015) except for the fact that spanwise periodic distributions of turbines (the two rows) are considered instead of only two turbines. This was explained in the original manuscript (lines 61 to 64).

*But in case you think two-row wind farm simulation is sufficient, please discuss how you can link your findings to larger wind farms.*

Actually, I do not think that two-rows simulations are sufficient but that they are necessary. Indeed, in addition to the considerations discussed in point n.2, one should also consider that the computation of the optimal overinductive tilt or yaw control for realistic turbine arrays, where the optimal combination of tilt, yaw and pitch angles of all turbines has to be computed for a large number of wind directions and intensities, would be too computationally demanding if performed by means of large eddy simulations. This type of analysis is customarily based on less computationally demanding simplified sets of equations where the accurate modeling of the controlled wakes is of primary importance. In this context, the results presented in the present study should be used to improve/validate the existing simplified wake models in moderate to high-tilt/yaw and pitch angles regimes, particularly in the case of significant overinduction. Indeed, simplified models which are unable to reproduce the power gains results for the set of $\varphi, \gamma, \beta$ combinations and the idealized two-row array considered here would probably be unfit to predict annual power gains in more realistic settings.

This said, I agree, however, that the link between the studied idealized array and realistic configurations was not clear enough in the idealized manuscript. I have therefore summarized these points in the conclusions of the revised manuscript (lines 228-237).

*3. Line 81 to 83: Please add more explanation to clarify the relation between $\beta$ and $C'_T$. You can use blade element momentum (BEM) theory in order to describe the relations between $\beta$, lift and drag coefficients and the thrust coefficient.*

Additional explanations have been added to Appendix A (lines 265-270).

*4. Line 84 to 91: Add LES and other relevant equations.*

As in this study I have used the standard SOWFA code without changing its formulation, I prefer to refer the reader to the original papers to keep the focus on the main scopes of the study. The same is done in the many related studies based on SOWFA such as the cited ones of Fleming et al. (Renew. En. 2014) and Fleming et al. (Wind En. 2015) who also refrain from reproducing all the details of the formulation and refer to Churchfield et al. for the full details on the used formulation, including the LES equations. However, I agree, that section 2 lacked even some of the most basic information. This is fixed in the revised manuscript where more details on the used model (filtered Navier-Stokes equations with Boussinesq approximation) are now mentioned in section 2, lines 88-92 (they were briefly mentioned only in Appendix A in the original manuscript).

*Adding a schematic for the computation domain will be helpful too.*

The velocity fields reported in Figs. 1 and 4 of the original manuscript (Figs. 2 and 6 of the revised manuscript) show the full computational domain. This is now mentioned in the revised manuscript (line 118 and near the end of the caption of Fig.2).

*5. This may be beyond the scope of this manuscript, but how practical do you think it is to tilt blade by $\varphi = -30^o$? Higher tilt angle will significantly increase the flapwise bending and reduce the blade lifetime. You have mentioned about gravity load in line 137, but that is not very clear.*

I agree that the mention of loads, and gravity loads in particular was unclear in the original manuscript. I have removed it from the revised manuscript to avoid a potentially misleading only partial discussion of the structural turbine loading.

I also completely agree that the issue of the practicality of tilting turbines is important and deserves further investigations that are beyond the scope of this paper. However, let me note that given that positive tilt is not immediately implementable in most of the installed horizontal axis wind turbines with upwind-directed rotor, possible drawbacks of the tilt on blade loads could be addressed in the design phase of a new generation of turbines with downwind-oriented rotors and highly flexible blades such as those discussed by Loth et al. (Downwind pre-aligned rotors for extreme-scale wind turbines, Wind Energy, 20, 12411259, https://doi.org/10.1002/we.2092, 2017).

That additional studies should consider the influence of overinduction combined to tilt and yaw on loads and the full aeroelastic response of the blades is now mentioned in the revised manuscript (lines 222-227).

*6. Line 116 to 122 and Figure 3(a): I do not understand why increasing $\beta$ (making it more negative) increases the power from the first turbine row. Wind turbines are usually optimized for the pitch angle around $0^o$. If that is the case with your turbine too, power output should be lower for $\beta < 0^o$. Increased thrust coefficients -for negative blade pitch angles- are simply caused by increased drag coefficients, and they will not necessarily translate into the higher power output.*

This is an interesting point [you are probably referring to Figure 2(b)]. I agree that it seems strange that more power can be produced by first-row turbines for the suboptimal values $\beta < 0^o$. There are however two reasons that can explain this apparently counterintuitive result:

(a) For the NREL5 turbine $\beta = 0^o$ corresponds, by design, to the maximum $C_P$ (at the optimal wind-tip speed ratio) but only for the reference case $\gamma = 0^o$, $\varphi = -5^o$ for which the optimization was performed. However, the data in Figure 2(b) do not pertain to reference values but to $\varphi = 30^o$ for which there is no guarantee that the maximum $C_P$ is obtained for $\beta = 0^o$.

(b) For the case of a (single) row of closely spaced (non-tilted/non-yawed turbines) Strickland & Stevens (Effect of thrust coefficient on the flow blockage effects in closely-spaced spanwise-infinite turbine arrays, J. Phys. Conf. Ser. 1618, 2020, doi:10.1088/1742-6596/1618/6/062069) show that "the power production of turbines in the row increases approximately linearly with $C_T'$ when compared to the production of a free-standing turbine". It is therefore possible that also in the present case the slight blockage effect of the first row increases when $C_T'$ is increased leading to an increase in the power production.

A note mentioning this has been added to the revised manuscript (bottom of page 7).

*7. You have not discussed how the tilt control and the yaw control influence the flow fields inside the wind farm. How do turbulence fields and shear stresses change as a result of those controls should be presented.*

I do not completely agree that I have not discussed how the tilt control and the yaw control influence the flow fields inside the wind farm because this is precisely what was done in Figs. 1 and 4 and the related discussion. Additional flow fields and discussion have, however, been added to the revised manuscript where the mean streamwise vorticity and velocity fields are now shown in crossflow planes in Figs. 3, 7 and B1 in order to better discuss the role of wake rotation.

I have shown the mean streamwise velocity fields because they are the ones which influence the mean power output which is the main subject of this study. I do not show the turbulence fields because they are mainly relevant for the analysis of the power and load *fluctuations*, an analysis which goes beyond the scope of the present study. However, that additional studies of load fluctuations for the presented overinductive tilt and yaw control is now mentioned in the revised manuscript (lines 222-227).

*Minor comments and corrections: 1. Line 10: an high $\rightarrow$ a high.*

Right. This is fixed in the revised manuscript.

*2. Line 8: of the produced $\rightarrow$ of that produced*

Right. This is corrected in the revised manuscript.

*3. Line 110: Is it $\varphi = -30^o$? You can add a schematic describing positive and negative directions for yaw, tilt and pitch angles.*

Actually, it is a positive tilt angle $\varphi = +30^o$ (see e.g. the discussion of Fleming et al. 2015 who write "With a positive tilt angle, the rotor would face downward, and for conventional upwind turbine designs, this would cause the blades to hit the tower").

A schematic describing positive and negative directions for yaw and tilt has been added in an additional figure (Fig. 1 of the revised manuscript). The schematic for the rotor collective pitch angle has not been added because it would have required a long discussion to avoid misunderstandings (indeed in a plot one should also discuss the local twist angle, the aerodynamic angle of attack and its definition, etc.). These angles are now mentioned in Appendix A (lines 267-270).

---

I hope to have clarified the main issues raised in the report. I thank again Reviewer 2 for his/her many remarks and suggestions which have helped to improve the manuscript.

# Wake redirection at higher axial induction

Carlo Cossu

Laboratoire d'Hydrodynamique Énergetique et Environnement Atmosphèrique (LHEEA)
CNRS - Centrale Nantes, 1 rue de la Noë 44300 Nantes, France

**Correspondence:** Carlo Cossu (carlo.cossu@ec-nantes.fr)

**Abstract.** The energy produced by wind plants can be increased by mitigating the negative effects of turbine-wakes interactions. In this context, axial induction control and wake redirection control, obtained by intentionally yawing or tilting the rotor axis away from the mean wind direction, have been the subject of extensive ~~investigations. We have recently shown that the combination of static tilt control with static axial over-induction results in significant power gains. However, these early results were based on idealized turbine models where wake-rotation effects, radial force distributions and realistic turbine controller effects were neglected~~research but only very few investigations have considered their combined effect. In this study we ~~therefore~~ compute power gains that ~~can be~~ are obtained by operating tilted and yawed rotors at higher axial induction ~~for the more~~ by means of large eddy simulations using the realistic native NREL 5-MW ~~turbine~~ actuator disk model implemented in SOWFA. We ~~then extend this approach to the case of yaw control. We show that power gains~~ show that for the considered two-rows wind-aligned array of wind turbines the power gains, of approximately 5%, obtained by standard wake redirection ~~based on yaw or tilt control are highly enhanced when the yawed or tilted turbines are operated~~ at optimal tilt or yaw angles and reference axial induction can be more than tripled, to above 15%, by operating the tilted or yawed turbines at higher axial induction. ~~These results confirm our early findings for the case of tilt control and extend them to the case of yaw control suggesting an high potential for the practical application of overinductive wake redirection~~It is also shown that significant enhancements of the power gains are obtained even for moderate overinduction. These findings confirm the potential of overinductive wake redirection highlighted by previous investigations based on more simplified turbine models that neglected wake rotation effects. The results also complement previous research on dynamic overinductive yaw control by showing that it leads to large power gain enhancements also in the case where both the yaw and the overinduction controls are static hopefully easing the rapid testing and implementation of this combined control approach.



## 1 Introduction

In wind farms, wind turbines shadowed by the wakes of other upwind turbines experience a decrease of the mean available wind speed and an increase of turbulent flucutuations resulting in decreased extracted wind power and increased fatigue loads (see Stevens and Meneveau, 2017; Porté-Agel et al., 2019, for a review). In currently installed wind farms, however, each turbine is typically operated in "greedy" mode maximizing its own individual power production. As the greedy operation mode does not generally lead to the global optimal, where the energy production of the whole wind farm is maximized (see e.g. Steinbuch et al., 1988), a number of different approaches have been proposed where the collective control of all turbines is used to increase the power production of the whole wind farm by mitigating the negative effects of turbine-wake interactions (see Knudsen et al., 2015; Boersma et al., 2017, for a review). Among the many proposed approaches, two have received particular attention: axial induction control and wake redirection control which can be static (the control is steady if the incoming wind conditions are) or dynamic (the control can be unsteady even for steady incoming wind conditions).

In axial induction control the induction factors of selected (usually upwind) turbines are steered away from the greedy operation mode in order to increase the power production of other (usually downwind) turbines. While static axial induction control has not demonstrated significant power gains in realistic settings (Knudsen et al., 2015; Annoni et al., 2016), dynamic axial induction control has shown promise for significant power gains (Goit and Meyers, 2015; Munters and Meyers, 2017). In wake redirection control the intentional misalignment of rotor axes from the wind direction is used to deflect turbine wakes in the horizontal or in the vertical direction by acting on yaw or tilt angles respectively with a documented increase of the global power produced by the wind farm (Dahlberg and Medici, 2003; Medici and Alfredsson, 2006; Jiménez et al., 2010; Fleming et al., 2014, 2015; Campagnolo et al., 2016; Howland et al., 2016; Bastankhah and Porté-Agel, 2016).

In two recent studies (Cossu, 2020a, b) we have shown that an appropriate combination of (static) tilt and (static) axial induction control results in a significant enhancement of the global power gains obtained in spanwise-periodic wind-turbine arrays. In ~~particular~~these studies, for the considered three-rows turbine arrays, power gains were observed to be highly enhanced (up to a factor of 2 or 3) when the turbines with rotor tilted by the optimal angle ($\varphi \approx 30^o$) were operated at disk-based thrust coefficient $C_T' = 3$ higher than in the baseline case ($C_T' = 1.5$).

~~These early results~~ The results reported in these previous studies (Cossu, 2020a, b) were obtained with an actuator-disk model where wake-rotation and the radial distribution of actuator-disk forces were neglected and the turbines were assumed to operate at constant given $C_T'$. This highly idealized setting, used in many previous investigations (e.g. Calaf et al., 2010; Goit and Meyers, 2015; Munters and Meyers, 2017), has been instrumental in obtaining general results not depending on the specific turbine control law and blade design but calls for confirmation on more realistic turbine models. Hence, a first goal of this study is to determine the power gains that can be obtained with high-induction (overinductive) tilt control when realistic turbine models are used that take into due account blade-design, wake-rotation and ~~controller specificities~~the controller specificity. This goal is addressed in the first part of this study, by making use of SOWFA's (Churchfield et al., 2012) native actuator disk model for the NREL 5-MW turbine. In this implementation of the turbine model the radial dependence of the actuator disk force as well as wake rotation and $C_T'$ are computed from turbine blades properties by means of a blade-element approach and NREL 5-MW's five-region realistic controller (Jonkman et al., 2009) is used.

In the second part of the study we address the case of yaw control. Indeed, the increased power gains obtained by operating tilted turbines at higher thrust coefficients mostly result from the increase of wake deviations obtained without a penalization of the power production of the tilted turbine. Overinductive wake deflection could therefore be beneficial also in the case of yaw-control where it is known that higher thrust coefficients also result in larger wake deviations (Jiménez et al., 2010; Howland et al., 2016; Shapiro et al., 2018). Surprisingly, however, only ~~a~~ very few studies have investigated the potential benefits of combining axial induction control and yaw control~~: Park and Law (2015)show that significant power gains can be obtained in this way.~~. Park and Law (2015), based on simplified wake models and advanced optimization techniques, show that significant power gains can be obtained by the combining static yaw and induction control but they do not analyze the respective effects of yaw and induction~~while Munters and Meyers (2018b) find~~ ; furthermore, their optimal solutions in the aligned case converge to an underinductive operation mode for yawed turbines. Munters and Meyers (2018a, b) show, by means of adjoint methods with full-state information and an actuator disk turbine model where wake rotation is neglected, that high power gains result from the combination of ~~*dynamic*~~ dynamic yaw and axial induction ~~control and highlight~~ controls with Munters and Meyers (2018b) highlighting the potential of quasi-static yaw control in the (dynamic) overinductive regime. From these previous studies, thus, it is not clear if significant power gains could be realized in the overinductive regime when both the yaw and the axial induction control are static, nor to what extent the neglected wake rotation effects are important.

The second ~~, probably most important,~~ objective of the present study is therefore to ascertain if significant power gains can be obtained, with a combination of static yaw control and static axial induction control, by operating yawed turbines at higher axial induction and including the effect of wake rotation in the turbine model. An affirmative answer would allow to isolate the mean wake redirection as the most relevant physical effect at play (instead of e.g. the dynamical adaptation to the incoming wind) and that it is robust with respect to the inclusion of wake rotation effects. Furthermore, if successful, static overinductive yaw control could be easily implemented by simply updating existing yaw-control protocols with a prescription on the suitable turbine rotor-collective blade-pitch angle (controlling the axial induction and the thrust coefficient) for each accessible yaw angle.

The potential of ~~oveinductive~~ static overinductive wake redirection will be investigated by computing power gains that can be obtained in a wind-turbine array composed of two spanwise-periodic rows of wind-aligned turbines where the same control is applied to all upwind-row turbines while downwind-row turbines are left in default operation mode. This idealized configuration, which is an extension to the spanwise-periodic case of the two-turbine configuration considered by Fleming et al. (2015), is chosen in order to keep simple the physical interpretation of the results by isolating the effects of tilt or yaw angle and axial induction of the upwind turbines without entering the problem of the optimization of these parameters ~~in multi-row configurations~~ encountered in more realistic configurations with more rows. As such, this approach is a necessary first step needed to isolate the main trends at play before considering more realistic settings. Importantly, the relevance of these power gains will be tested without excessive assumptions by means of large-eddy simulations in the atmospheric boundary layer using a turbine model which includes the effects of wake-rotation, radial force distribution and a realistic turbine controller.

We anticipate that substantial enhancements (up to a factor of 3) of the power gains induced by wake redirection are found when operating the tilted or yawed turbines at higher axial induction.

The formulation of the problem at hand is introduced in §2. Results are reported in §3 and further discussed in §4. Additional details on used methods are provided in ~~the appendix~~Appendix A and additional results about the effect of using a less realistic turbine model, where wake rotation effects are neglected, are reported in Appendix B.

## 2 Problem formulation

We address the case of two spanwise-periodic rows of wind turbines immersed in a neutral atmospheric boundary layer (ABL) at latitude $41^o$N. The flow is simulated by means of large-eddy simulations (LES) with SOWFA ~~(see Appendix A and Churchfield et al., 20~~ (the Simulator for On/Offshore Wind Farm Applications developed at NREL, see Churchfield et al., 2012) which solves the filtered Navier-Stokes equations including the Coriolis acceleration associated to Earth's rotation and the compressibility effects modeled by means of the Boussinesq approximation (see Appendix A for more details and Churchfield et al., 2012, for the explicit expres .

NREL 5-MW turbines (Jonkman et al., 2009) are considered, which are modeled with SOWFA's native actuator disk method where wake rotation, the radial distribution of aerodynamic forces and the thrust coefficient are all computed from blade properties providing a reliable descriptions of the wake structure except in the near-wake region. We also make use of SOWFA's native implementation of NREL 5-MW's realistic five-region turbine controller based on generator-torque control in the Region-II regime corresponding to the mean wind speeds considered in the following; in this regime we modify axial induction by changing the rotor-collective blade-pitch angle $\beta$. Higher axial inductions are obtained by enforcing negative values of $\beta$ (see Appendix A), resulting in higher local thrust coefficients $\cancel{C'_T = 2T/(\pi\rho u_n^2 A)}$$C'_T = 2T/(\rho u_n^2 A)$, where $T$ is the thrust magnitude and $u_n$ is the disk-averaged wind velocity component normal to the rotor disk of area $A = \pi D^2/4$.

For all the considered cases the local power coefficient $C'_P = 2P/(\rho u_n^3 A)$ is well approximated as $C'_P = \chi C'_T$, with $\chi = 0.9$; results on $C'_P$ trends will, therefore, not be shown in the following. The incoming flow, generated by means of a precursor simulation in a 3km x 3km domain in the absence of turbines, has a 100m-thick capping-inversion layer centered at H=750m separating the neutral boundary layer with constant potential temperature ($\theta$=300K) from the geostrophic region above where the vertical potential temperature gradient is positive $(d\theta/dz)_G = 0.03K/m$. In the capping-inversion layer this gradient is $(d\theta/dz)_{CI} = 0.03K/m$. In the precursor simulation, the ABL is driven by a pressure gradient adjusted to maintain ~~an~~ a horizontally-averaged mean of 8m/s from the west at z=100m (a few meters above hub height $z_h$=89m). In the region spanned by the turbines ($z <$152m) the streamwise mean velocity is well approximated by the logarithmic law and the vertical wind veer is less than $4^o$ (see Cossu, 2020b, where the same ABL has been already considered). The streamwise turbulence intensity of the incoming wind at hub height is of 5.7% for the enforced low roughness length ($z_0 = 0.001$m) typical of offshore conditions.

Simulations in the presence of wind turbines are repeated in the same 3km x 3km domain starting from the solution of the precursor simulation at $t_0$=20000s, corresponding to a well developed ABL, up to $t_1$=30000s. Statistics are computed starting from $t$=24000s, when turbine wakes are fully developed. The pressure gradient issued from the precursor simulation is enforced during the simulation with turbines and the (previously stored) ABL solution at $x$=0 (west boundary) is used as inflow boundary condition.

In each (spanwise-periodic) row, turbines are spaced by $4D$ in the spanwise direction (where $D$=126m is the rotor diameter) and the two rows, are spaced by $7D$ in the streamwise direction with corresponding turbines of each row aligned with respect to the mean-wind direction (see Fig. 2, where the full computational domain is shown). Downwind-row turbines are always

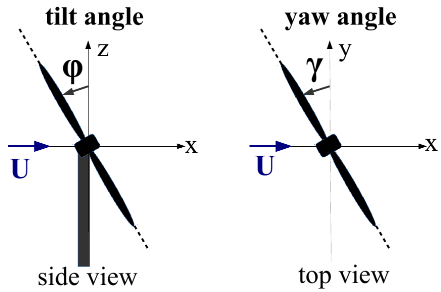


**Figure 1.** Definition of the positive rotor tilt and yaw angles $\varphi$ and $\gamma$ used in the present study. Positive tilt angles can be obtained for downwind-oriented rotors to avoid blade-tower hits.

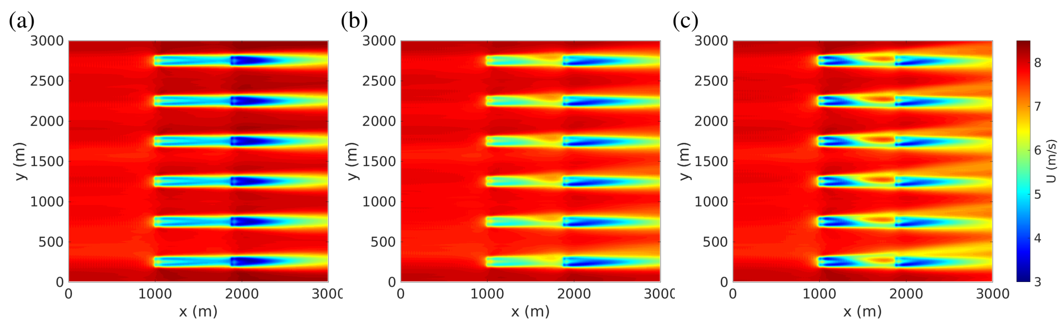


**Figure 2.** Tilt control: Mean (temporally averaged) streamwise velocity field in the horizontal plane at hub height obtained ($a$) in the baseline case where all turbines are operated in default mode, ($b$) with upwind turbines tilted by $\varphi = 30^o$ and operated at the default rotor-collective blade-pitch angle $\beta = 0^o$ and ($c$) with upwind turbines tilted by $\varphi = 30^o$ and operated at higher induction ($\beta = -5^o$). The mean wind is from the west (from the left, parallel to the $x$ axis). Note that the entire 3km x 3km computational domain is shown in the figure and that periodic boundary conditions are applied on the north and south boundaries.

operated in default mode with the rotor axis at zero yaw angle $\gamma = 0^o$ (aligned with the mean wind at z=100m), tilt angle $\varphi = -5^o$ ~~(~~to prevent rotor-tower hits (see Fig. 1 for a definition of $\varphi$ and $\gamma$) and rotor-collective blade-pitch angle $\beta = 0^o$. In the baseline (reference) case upwind-row turbines are also operated in default mode. The baseline case is then compared to a set of controlled cases where all the turbines of the upwind row are operated at the same non-zero tilt or yaw angle and, possibly, non-zero ~~pitch angle~~rotor-collective blade-pitch angle.

## 3 Results

### 3.1 Effect of overinduction on tilt control

In the baseline case (all turbines operated with $\gamma = 0^o$, $\varphi = -5^o$, $\beta = 0^o$), the usual situation is found where the turbines of the downwind row see a strongly reduced mean wind (see Fig. 2$a$ and Fig. 3$b$) therefore producing only ≈30% of the total power,

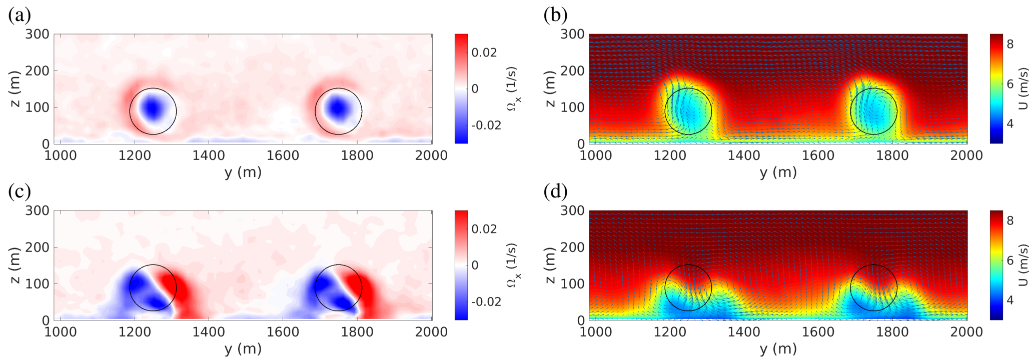


**Figure 3.** Tilt control: Cross-stream view of the mean streamwise vorticity and velocity fields in the in the baseline case (top panels $a$ and $b$) and with upwind turbines tilted by $\varphi = 30^o$ and operated at $\beta = -5^o$ (bottom panels $c$ and $d$). From the streamwise vorticity fields (left panels $a$ and $c$), extracted $3D$ downstream of the first turbine row, the negative streamwise vorticity in the wake core associated to wake rotation can be clearly seen in the baseline case (panel $a$) as well as its combination with the two counter-rotating streamwise vortices forced by the tilted rotor (panel $c$). Streamwise (color scale) and cross-stream (arrows) velocity fields (right panels $b$ and $d$) are extracted $D/2$ upstream of the second row of turbines; to improve readability only the fields of the two central turbines columns (between $y = 1000m$ and $2000m$) are shown. The circles in black represent the perimeter of downstreamn rotors.

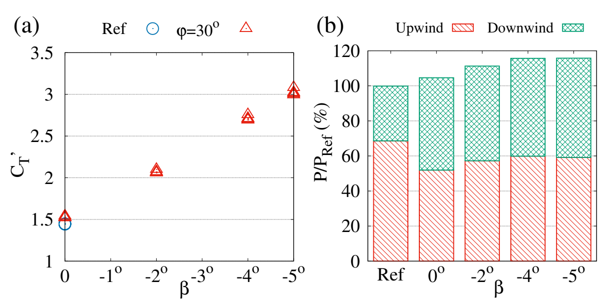


**Figure 4.** Effect of enforcing negative rotor-collective blade-pitch angles $\beta$ on upwind-row turbines tilted by $\varphi = 30^o$. Panel $(a)$: (temporally-averaged) local thrust coefficient $C_T'$ of the individual turbines of the upwind row. Panel $(b)$ wind power extracted by the upwind (hatched red) and downwind (cross-hatched green) rows of turbines normalized by the total power $P_{Ref}$ produced in the baseline case (Ref).

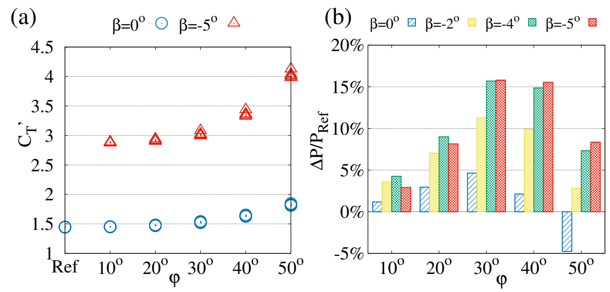


**Figure 5.** Effect of the tilt angle $\varphi$ on: $(a)$ the ~~total power gain $(P-P_{Ref})/P_{Ref}$ for selected values of $\beta$; $(b)$ the~~ local thrust coefficients $C_T'$ of upwind-row turbines when they are operated with $\beta = 0^o$ (default axial induction) or with $\beta = -5^o$ (strongly overinductive regime), $(b)$ the total power gain $(P - P_{Ref})/P_{Ref}$ for selected values of $\beta$.

i.e. ≈40% of ~~the~~ that produced by the upwind row of turbines (see Fig. 4$b$). The effect of wake rotation is clearly discernible in the mean streamwise vorticity field (see Fig. 3$a$). In the following, power gains will be computed with respect to the mean power $P_{Ref}$ produced in this baseline case.

We then consider the case where upwind-row turbines are tilted by $\varphi = 30^o$, an angle in the range where best power gains have been found in previous studies (Fleming et al., 2014, 2015; Cossu, 2020a, b), while keeping their rotor-collective blade-pitch angle at the default value $\beta = 0^o$. In this case, the wakes of the upwind turbines are pushed down by the tilt-induced downwash increasing the mean wind available to downwind turbines (see Fig. 2$b$). The tilt-induced decrease of power produced by upwind-row turbines is compensated by the increase of the power produced by downwind-row turbines resulting in ~~an~~ global power gains of ≈5% ~~global power gain~~ for $\varphi = 30^o$ ~~tilt angles~~ (see Fig. 4$b$).

In a further step, the rotor-collective blade-pitch angle of the tilted upwind-row turbines is changed. Enforcing increasingly negative values of $\beta$ (i.e. increasing the mean angle of attack of all rotor blades, as explained in Appendix A) results in increased thrust coefficients (increased axial induction) which, starting from $C_T' = 1.5$ in the baseline case ($\beta = 0^o$), attain $C_T' = 3$ for $\beta = -5^o$ in turbines tilted by $\varphi = 30^o$ (see Fig. 4$a$).

The effect of the increased thrust is twofold: ~~it reinforces the downwash , further increasing the available wind and extracted power in downwind turbines~~ (a) the downwash associated to the stronger tilt-induced streamwise vortices is reinforced (see Fig. 3$c$,$d$), which increases the mean wind speed seen by downstream rotors (see Fig. 2$c$ and Fig. 3$d$) and their extracted power despite the higher wake deficit of upwind turbines (compare Fig. 2$c$ to Fig. 2$b$) ~~but it also (more slightly)increases~~ and (b) the power produced by tilted turbines ~~(~~is also (slighlty) increased[1] (see Fig. 4$b$). The combination of these two effects results in optimal power gains which are highly enhanced (almost tripled) ~~power gains~~with respect to those obtained by tilt without overinduction.

[1] This might be related to blockage effects which induce an increase with $C_T'$ of the power produced by an (upwind) spanwise-periodic row of turbines as shown by Strickland and Stevens (2020) and it is not surprising given that for the NREL5 turbine $\beta = 0^o$ corresponds, by design, to the maximum $C_P$ (at the optimal wind-tip speed ratio) for an isolated non-tilted turbine but not necessarily so when $\varphi = 30^o$.

Finally, a full set of $\varphi$-$\beta$ combinations is considered. ~~From~~ For these simulations we observe that, for turbines operated at constant $\beta$, the increase of $C_T'$ with $\varphi$ is noticeable only for $\varphi \gtrsim 30^o$, as shown in Fig. 5$a$ (we have verified that this increment is consistent with the effects of changing the tilt angle and the associated change of the induction factor). Considering the $(P-P_{Ref})/P_{Ref}$ power gains with respect to the baseline case, from Fig. 5$b$ it can be seen that ~~tilt-induced~~ the maximum power gains are ~~highly enhanced (more than doubled) even with the moderate~~ reached for $\varphi \approx 30^o$ with optimal values obtained with significant overinduction (power gains larger than 15% for $\beta \approx -5^o$) which are almost three times those ($\approx 5\%$) obtained with tilt control at reference induction rates ($\beta = 0^o$). This effect of overinduction in tilt control is very strong: from Fig. 5$b$ it is indeed also seen that at $\varphi = 30^o$, even with the moderate rotor-collective blade-pitch angle $\beta = -2^o$ ~~and that optimal $\beta$ values do depend on $\varphi$ ($\beta = -2^o$ is the best for $\varphi = 10^o$, $\beta = -4^o$ is the best one for $\varphi = 20^o$, while $\beta = -5^o$ appears well adapted for $\varphi \gtrsim 30^o$).~~ power gains have already almost doubled with respect to standard tilt control with $\beta = 0^o$. ~~Maximum power gains are reached for $\varphi \approx 40^o$, a value larger than the optimal $\varphi \approx 30^o$ found when $\beta = 0^o$. This is probably related to the fact that for a selected fixed value of $\beta$, the local thrust coefficient $C_T'$ remains almost constant with the tilt angle up to $\varphi \approx 30^o$ but increases for higher values of $\varphi$ (see $b$)leading to a stronger downwash which more efficiently exploits the vertical velocity gradient. Smaller values of the optimal tilt angle $\varphi$ would probably be found if $C_T'$ was held constant instead of $\beta$ (as in Cossu, 2020b).~~

~~Contrary to a first intuition, increasing the local thrust coefficient $C_T'$ is not an issue for mean turbine loads because turbines are tilted. Indeed, when turbines are tilted at the default $\beta = 0^o$, their mean load (essentially the thrust force) decreases because of the reduced incoming mean wind $u_n$ normal to the rotor. For the considered cases, the increase of $C_T'$ obtained with negative values of $\beta$ counteracts this thrust decrease but the thrust magnitude remains almost unchanged (within 5%)~~ The high enhancement of power gains obtained by combining overinduction with tilt control with respect to ~~the baseline case for $\varphi \lesssim 30^o$ when optimal $\beta$ values are used for each $\varphi$ and is reduced for larger $\varphi$ values (not shown). Thrust magnitudes exceed that of the baseline case by more than 5% only when a (suboptimal) excessive induction is enforced for $\varphi \lesssim 20^o$. Note also, that in tilted turbines an important part of the thrust force is directed along the (positive)vertical direction compensating the gravity force; the remaining horizontal part of the thrust force is therefore always reduced in turbines operated at the optimal $\beta$.~~ those obtained by standard tilt control at baseline induction is consistent with that found in our previous studies (Cossu, 2020a, b) therefore confirming the robustness of this trend. The absolute levels of power gains are, however, smaller than those reported by (Cossu, 2020a, b) both because two-rows arrays are considered here instead of the previously considered three-rows arrays (which have higher power gais, see e.g. Annoni et al., 2017) and because wake-rotation effects, neglected in the previous studies, are here taken into account (see Appendix B for further details).

### 3.2 Effect of overinduction on yaw control

~~To evaluate the effect of overinductive operation on yaw control we~~

We now evaluate the benefits of combining static yaw control with static overinduction. We proceed similarly to the tilt-control case by using the same precursor simulation and the same baseline case where all turbines operate at default values $\gamma = 0^o$, $\varphi = -5^o$, $\beta = 0^o$.

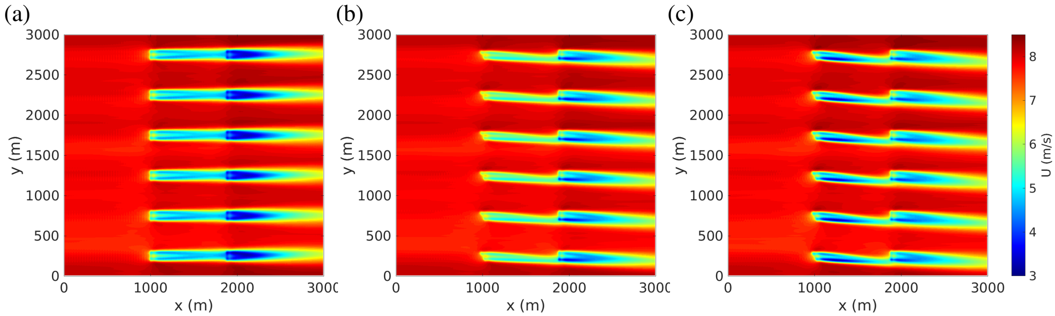


**Figure 6.** Yaw control: Mean streamwise velocity field in the horizontal plane at hub height obtained $(a)$ in the baseline case where all turbines are operated in default mode ($\gamma = 0^o$, $\beta = 0^o$ same as Fig. 2$a$, reproduced here to ease the comparison), $(b)$ in the case with upwind turbines yawed by $\gamma = 30^o$ and operated at the default $\beta = 0^o$ and $(c)$ with upwind turbines yawed by $\gamma = 30^o$ and operated at higher induction (~~$\beta = -5^o$~~$\beta = -4^o$).

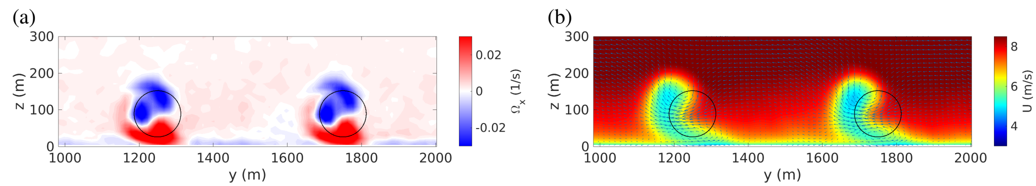


**Figure 7.** Yaw control: Cross-stream view of the mean streamwise vorticity and velocity fields with upwind turbines yawed by $\gamma = 30^o$ and operated at $\beta = -4^o$. The signature of the two vertically-staked counter-rotating streamwise vortices forced by the yawed rotor combined with wake rotation is clearly visible in the streamwise vorticity field (panel $a$) extracted $3D$ downstream of the first turbine row. Their effect on the lateral displacement of the wake is clearly discernible in the streamwise (color scale) and cross-stream (arrows) velocity fields (panel $b$) extracted $D/2$ upstream of the second row of turbines. Only the fields of the two central turbines columns (between $y = 1000m$ and $2000m$) are shown.

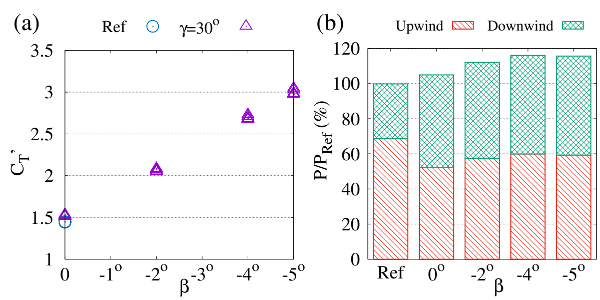


**Figure 8.** Effect of changing the rotor-collective blade-pitch angle $\beta$ of turbines yawed by $\gamma = 30^o$. Panel $(a)$: local thrust coefficient $C'_T$ of the turbines of the upwind row. Panel $(b)$: wind power extracted by the upwind (hatched red) and downwind (cross-hatched green) rows of turbines normalized by the total power $P_{Ref}$ extracted in the baseline case.

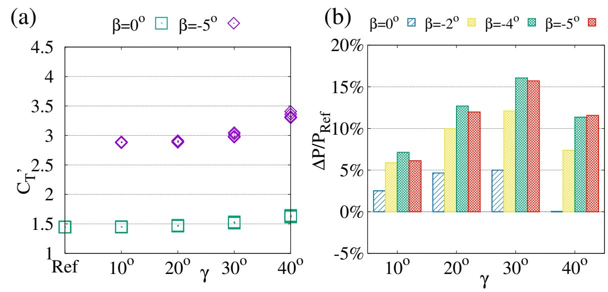


**Figure 9.** Effect of the yaw angle $\gamma$ on: ($a$) the local thrust coefficients $C'_T$ of upwind-row turbines when they are operated at $\beta = 0^o$ or at $\beta = -5^o$, and ($b$) power gains for selected values of rotor-collective blade-pitch angle $\beta$.

We first simulate the standard yaw control where the yaw angle $\gamma$ of upwind-row turbines is changed (while keeping unchanged the other parameters $\varphi = -5^o$, $\beta = 0^o$) resulting in the well known horizontal deviation of upwind-row turbine wakes and the increase of the mean wind speed seen by downwind rotors (see Fig. 6$b$). From Fig. 8$b$ it is seen that ~~, in this case,~~ the increase of the power produced by downwind-row turbines compensates the reduction of the power produced by the yawed (upwind-row) resulting in maximum power gains of ≈5% obtained for ~~$\gamma = 20^o - 30^o$ (see $a$)~~ $\gamma \approx 30^o$, similarly to the values found by Fleming et al. (2015) for the two-turbines case.

Increasing the local thrust coefficient $C'_T$ by means of increasingly negative blade-pitch angles in yawed turbines (see Fig. 8$a$) has effects similar to those observed for the tilt-control case: an increase of ~~wake~~ velocity deficits in upwind-row turbine wakes but also their higher deviation away from downwind turbines (see Fig. 6$c$ and Fig. 7$b$) induced by the stronger yaw-induced vertically-staked counter-rotating streamwise vortices (see Fig. 7$a$) resulting in an increase of the mean power produced by all turbines ~~($b$)~~ with respect to the standard yaw-control case with $\beta = 0^o$ (Fig. 8$b$).

The analysis of ~~power gains obtained with different~~ a full range of $\gamma$-$\beta$ combinations, leads to results similar to those obtained for the tilt-control case. A non-negligible increase of $C'_T$ is observed for large yaw angles $\gamma \gtrsim 30^o$ when operating at constant $\beta$, as reported in Fig. 9$a$, ~~reveals that~~ and global power gains obtained by yaw control are highly enhanced when yawed turbines are operated at higher induction ~~. Power gains are indeed~~ (more negative values of the rotor-collective blade-pitch angle $\beta$). Also similarly to the tilt-control case, maximum power gains are obtained for $\gamma \approx 30^o$ regardless of the $\beta$ value. Overall optimal power gains (above 15%) are reached for relatively high overinduction ($\beta \approx -4^o$). Also in this case, power gains obtained by $\gamma = 30^o$ yaw control are more than doubled already for $\beta = -2^o$ and ~~are~~ almost tripled for the optimal ~~yaw-pitch combination $\gamma = 30^o$,~~ value $\beta = -4^o$ ~~.~~

~~Similarly to the tilt-control case, at higher induction the optimal yaw angles are higher ($\gamma \approx 30^o$) than in the standard yaw-control case ($\gamma \approx 20^o$ for~~ with respect to the standard operation mode ($\beta = 0^o$) ~~. However, differently from the tilt control case, the optimal pitch angle is not very sensitive to the yaw angle, $\beta = -4^o$ being the optimal value for all considered tilt angles and the increase of $C'_T$ observed for $\gamma \gtrsim 30^o$ (see $b$) does not result in a shift of optimal yaw angles to values larger than $30^o$ even for the highest considered $\beta = -5^o$. This can be probably explained by observing that the vertical wind shear is not~~

~~exploited by yaw control and thus, in the yaw-control case very large wake deviations are less beneficial than in~~ at the same yaw angle $\gamma = 30^o$.

These results confirm the first intuition that, also in the static yaw-control case, static overinduction leads to a substantial improvement of the power gains which is based on the same mechanisms discussed for the tilt-control case confirming that these mechanisms are quite robust.

~~Effect of changing the $\beta$ of turbines yawed by $\gamma = 30^o$. Panel $(a)$: local thrust coefficient $C_T'$ of the turbines of the upwind row. Panel $(b)$: wind power extracted by the upwind (hatched red) and downwind (cross-hatched green) rows of turbines normalized by the total power $P_{Ref}$ extracted in the baseline caseEffect of the yaw angle $\gamma$ on $(a)$ power gains for selected values of $\beta$ and $(b)$ on the local thrust coefficients $C_T'$ of upwind-row turbines when they are operated at $\beta = 0^o$ or at $\beta = -5^o$.~~

## 4 Conclusions

The main goal of this study was to assess the magnitude of global power gains that can be obtained in wind turbine arrays by combining static wake redirection control and static axial induction control operating tilted or yawed turbines at higher axial induction (overinduction). Results have been obtained by means of large-eddy simulations of a two-rows array of NREL 5MW turbines in a neutral atmospheric boundary layer.

In a first part of the study we have considered the effect of higher induction on tilt-control by using an actuator disk model less idealized than the one used in our previous studies of this approach. The results confirm that, also with this more realistic turbine model, power gains can be highly increased by operating tilted turbines at higher induction (power gains above 15% are found, to be compared to ≈5% obtained with default induction, for the considered set of parameters). This substantial enhancement of power gains due to the use of overinduction in tilt control is consistent with those found in our previous studies ~~(the absolute level of power gains was, however, larger in Cossu (2020a, b) where three rows of turbines were considered instead of the two rows considered here). It is also found that $\beta$ (and therefore local thrust coefficients $C_T'$) maximizing global power gains do increase with the rotor tilt angle $\varphi$ suggesting that an optimized law $\beta(\varphi)$ depending on the specific turbine design should be used in tilt-control operation. Our result also indicate that the use of such an optimized law would also guarantee that the thrust magnitude in overinductive tilt-control does not exceed the one of the baseline case by more than 5%~~but the absolute levels of the power gains are smaller because of the differences in array configurations and in the used turbine models. Indeed, when included in the turbine model, wake rotation results in an inclination of the formerly vertical downwash which displaces higher-altitude higher-speed fluid towards downstream rotors and, as a consequence, a decrease of tilt-induced power gains.

In the second part of the study we have ascertained if ~~the overinductive wake redirection approach results in power gain enhancement also in the case of~~ similar power gain enhancements could be obtained by combining static overinduction with static yaw control. To this end, we have first considered the standard case where ~~yaw~~ yawed turbines are operated at the ~~standard~~ reference rotor-collective blade-pitch angle $\beta = 0$ finding power gains of the order of 5%, similar to those found in ~~numerous~~ many previous studies (e.g. Fleming et al., 2015, for the two-turbines case). We then show that a very significant increase of power gains (almost threefold, up to $\approx$15% for the cases considered) is obtained by operating yawed turbines at higher induction, similarly to what found for tilt control.

The findings concerning the static overinductive yaw control are probably the most relevant of this study ~~. They could, indeed, provide an explanation for the high power gains found by Park and Law (2015) and Munters and Meyers (2018b) (by means advanced optimization techniques where both yaw angles and axial inductions were used as control variables) showing that similar~~ for short-term applications because they show that significant power gains can be realized with ~~simple static open-loop~~ a simple static overinductive yaw control in a realistic model (the atmospheric boundary layer with NREL 5-MW turbines simulated with SOWFA) ~~. Furthermore, yaw control can be tested and applied in most of currently installed wind farms,~~ where wake rotation effects are fully taken into account. They also probably isolate the main physical mechanisms underlying the significant power gains found by Munters and Meyers (2018b, a) by means of combined (dynamic and static) yaw and (dynamic) induction control using adjoint methods with full state information on large-eddy simulations where the turbines were modeled with a simplified actuator disk method neglecting wake rotation effects. Furthermore, static overinductive yaw control is suitable for immediate experimental testing with most existing standard horizontal axis wind turbines unlike tilt control which is promising for specifically designed future generation downwind-oriented and/or floating turbines (Bay et al., 2019; Nanos et al., 2020).

Another important result, obtained for both tilt and yaw overinductive controls, is that while maximum power gains ($\approx 15\%$) are obtained for relatively large rotor-collective blade-pitch angle ($\beta = -5^o$) for the optimal large tilt and yaw angles ($\varphi, \gamma \approx 30^o$), significant power gains ($\approx 10\%$) are already obtained for smaller values $\beta = -2^o$ showing the robust beneficial effect effect of even moderately overinductive turbine operation.

It is also to be noted that here we have considered only two rows of turbines and for a single configuration with a small value of the $D/\delta$ ratio of rotor diameters to the ABL thickness but that higher power gains can be expected for a larger number of turbine rows (Park and Law, 2015; Annoni et al., 2017; Cossu, 2020a) and for larger values of $D/\delta$ (Cossu, 2020a, b).

Additional investigations are, however, necessary to further refine, in many directions, the conclusions of the present study. ~~Quantitative refinements~~ A first important issue is to understand what are the effects of overinduction on the static and dynamic structural loads experienced by the blades of tilted and yawed turbines. A complete aeroelastic analysis based on higher-fidelity simulations making use of the actuator line method, ~~and necessarily~~ requiring more refined grids ~~, would be welcome~~and time steps and larger computational resources, is highly desirable, especially for the largest considered values of the yaw, tilt and pitch angles where the near- and middle-wake ~~structure is~~ structures are probably more sensitive to details of the turbine model.

~~Another issue is the wind direction~~ Other issues are wind direction and array configuration. The present study is limited to a two-rows array in the wind-aligned case, but it is, of course, important to evaluate power gains in arrays with many more rows also in non-aligned configurations. Such kind of analysis, where the optimal combination of tilt, yaw and pitch angles of all turbines has to be computed for a high number of wind directions and intensities, would be too computationally demanding if performed by means of large eddy simulations and is customarily based on less computationally demanding simplified sets of equations where the accurate modeling of the controlled wakes is of primary importance (see e.g. Boersma et al., 2017). In this context, ~~an improvement of existing~~ the results presented in the present study could be used to help in the improvement and validation of simplified wake models in ~~high-tilt~~moderate to high tilt/~~yaw and pitch angles regime would make possible a more precise prediction~~ yaw- and pitch-angle regimes, particularly in the case of significant overinduction. Such improved models would allow for more reliable predictions of annual energy production gains obtained with overinductive yaw or tilt control for realistic wind roses and wind farm configurations by using advanced optimization methods such as those used by Park and Law (2015).

Finally, it would be very interesting to ascertain if additional power gain enhancements could come from the simultaneous activation of tilt, yaw and axial induction control. It might indeed be possible that, as a consequence of the symmetry breaking associated to wake rotation effects and Coriolis acceleration, optimal power gains are obtained with "hybrid" yaw-tilt rotor-axis rotations even in wind-aligned configurations. This is the subject of current intense research effort.

## Appendix A: Methods

~~Large-eddy simulations~~ The large-eddy simulations presented in this study are performed with SOWFA~~(the Simulator for On/Offshore Win~~ ~~. SOWFA~~ , a set of libraries and codes able to simulate atmospheric flows over wind turbines (Churchfield et al., 2012), that is based on ~~OpenFOAM, which solves~~ the OpenFOAM software environment designed to solve partial differential equations ~~based on a~~ by means of finite-volume ~~framework~~ spatial discretizations on unstructured meshes (Jasak, 2009; OpenCFD, 2011). The filtered Navier-Stokes equations are solved using the Smagorinsky (1963) model to approximate subgrid-scale stresses ~~.~~ ~~Compressibility effects are included with~~ with compressibility effects accounted for by means of the Boussinesq approximation and ~~the horizontal component of Coriolis acceleration is included~~ Earth's rotation effects accounted for by the Coriolis acceleration term in the equations (see Churchfield et al., 2012, for all details on the used formulation and for a validation of the code in t . Schumann (1975) stress boundary conditions, modeling the effect of ground roughness, are applied near the ground and slip boundary conditions are enforced at at the top of the solution domain. The solutions are advanced in time using the PIMPLE scheme.

Periodic boundary conditions are applied in the $x$ (west-east) direction for the preliminary 'precursor' simulations where the atmospheric boundary layer flow is computed in the absence of wind turbines in order to generate realistic inflow wind conditions (Keating et al., 2004; Tabor and Baba-Ahmadi, 2010; Churchfield et al., 2012). The mean pressure gradient is adapted in order to maintain ~~a~~ (horizontally-averaged) mean westerly winds of 8m/s ~~wind~~ at $z = 100m$. The time-history of the mean pressure gradient and of the solution at $x = 0$ are stored and then used in the simulations with wind turbines which are run in the same domain with the same grid but removing the periodicity constraint in the streamwise direction and replacing it with an inflow condition enforcing the solution found $x = 0$ in the precursor simulation. Periodic boundary conditions are applied in the $y$ (south-north) direction for both precursor simulations and simulations with turbines.

The solution domain extends 1km in the vertical direction and 3km x 3km along the $x$ and $y$ axes and is discretized with cells extending 15m x 15m in the $x$ and $y$ directions and $7m$ (near the ground) to $21m$ (near the top boundary) in the vertical direction. $\Delta t = 0.8s$ time steps are used to advance the solution. These parameters keep manageable the amount of data stored in the precursor simulation.

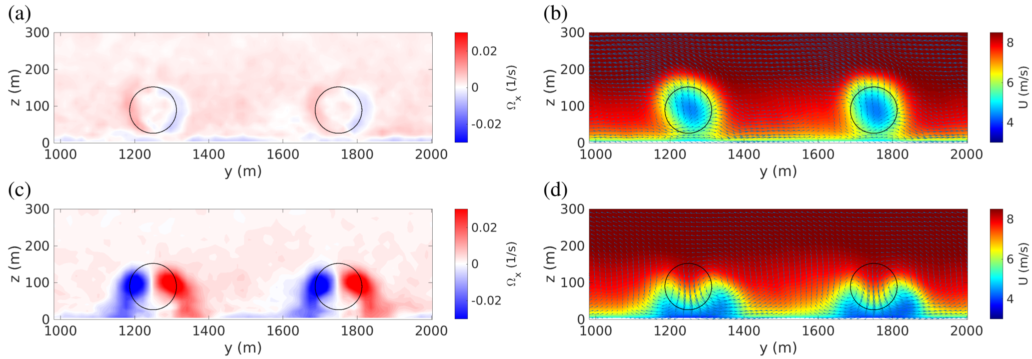


**Figure B1.** Tilt control: Cross-stream view of the mean streamwise vorticity and velocity fields obtained by using the ADMC turbine model in the baseline case where all turbines are operated at $C_T' = 1.5$ with no tilt or yaw (top panels $a$ and $b$) and with upwind turbines tilted by $\varphi = 30^o$ and operated at $C_T' = 3$ (bottom panels $c$ and $d$). The streamwise vorticity fields (panels $a$ and $c$) are extracted $3D$ downstream of the first turbine row, while the streamwise velocity fields (panels $b$ and $d$) are extracted $D/2$ upstream of the second row of turbines.

~~The aerodynamics forces~~ The aerodynamic forces developing on NREL 5-MW turbines, having a $D$=126m rotor diameter and $z_h$=89m hub height (Jonkman et al., 2009), are modeled with SOWFA's native actuator disk method ~~where aerodynamic forces are computed from the characteristics of~~ based on the blade-element method (BEM). The forces exerted on the fluid are computed for each radial blade section by using the lift and drag coefficients $c_L(\alpha)$, $c_D(\alpha)$ associated to the local NREL 5-MW blade profiles ~~, rotational speed and the resolved wind velocity. A~~ and the local angle of attack $\alpha = \phi - (\theta + \beta)$ computed as the difference between the angle $\phi$ formed by the relative wind seen by the blades with the rotor plane and the local pitch angle which is the sum of the local twist angle $\theta$ of the blades and the rotor-collective blade-pitch angle $\beta$ (the reader is referred to e.g. Burton et al., 2001; Sørensen, 2011, for a detailed discussion of turbines modeling in general and of the BEM . The Gaussian projection of the discretized body forces proposed by Sørensen and Shen (2002) is also used with a smoothing parameter $\varepsilon = 20m$ ~~is also used~~ to avoid numerical instabilities (Martínez-Tossas and Leonardi, 2013).

The NREL 5-MW five-region controller implemented in SOWFA is used to control the turbines rotational speed and axial induction. In the Region II regime, the one accessed in the presented simulation, the turbine is driven to the design point (tip-speed ratio and thrust coefficient corresponding to the maximum power coefficient for an isolated non-tilted non-yawed turbine) by means of generator-torque control at the default rotor-collective blade-pitch angle $\beta = 0^o$. In this regime, ~~the static~~ we enforce the axial induction control ~~is applied~~ by changing the rotor-collective blade-pitch angle $\beta$ while leaving unchanged the other parameters of the generator torque controller.

The local thrust coefficient is retrieved from the computed turbine thrust magnitude and rotor-averaged normal mean wind speed $u_n$ by making use of its definition $C_T' = 8T/\pi\rho u_n^2 D^2$.

## Appendix B: Effect of the used turbine model on tilt-control

A quantitative analysis of the effect of the improved ADM model used in the present study by means of a direct comparison with the results obtained in Cossu (2020b) is not possible due to the difference of the considered array configurations (two arrays here, three in Co . Additional simulations of tilt-control have therefore been performed by using the same turbine model (ADMC) used in Cossu (2020b) for the same array configuration used in the present study. We recall that, contrary to SOWFA's ADM used in the present study, in the ADMC model wake rotation effects are neglected and a uniform load is assumed over the rotor disk that is assumed to operate at constant $C_T'$.

First a baseline case has been simulated with all turbines operated at the reference values $C_T' = 1.5$, $\varphi = -5^o$, $\gamma = 0^o$. Then, a standard tilt-control case has been considered with upwind-row turbines operated at $C_T' = 1.5$, $\varphi = 30^o$ (and $\gamma = 0^o$) obtaining a power gain $\Delta P/P_{Ref} \approx 11\%$. Finally, overinductive tilt control has been tested by operating at $C_T' = 3$ the upwind row turbines tilted by $\varphi = 30^o$ obtaining a power gain of $\approx 27\%$.

For the 2-rows array layout, therefore, the ADMC model also predicts that power gains obtained by overinductive tilt control are much larger than those obtained by standard tilt control (by a factor of ≈240% for the ADMC turbine model and by a factor of ≈330% with SOWFA's ADM for $\varphi = 30^o$). However, the absolute levels of power gains computed with the ADMC model are higher than those computed with SOWFA's ADM turbine model. In this context, the effect of wake rotation appears to be important. In the ADMC model which applies a uniformly distributed force purely normal to the rotor disk, wake rotation effects are indeed neglected, resulting in a negligible mean axial vorticity in the rotor wake in the baseline case and in almost-symmetric counter-rotating vortices in the tilted case (see Fig. B1$a$ and $c$). In the ADMC tilted case, therefore, the downwash associated to the tilt-induced streamwise vortices is purely vertical resulting in a highly efficient displacement of higher-altitude higher-momentum fluid towards the downstream-rotor swept area (see Fig. B1$d$). In the case of the SOWFA's ADM more realistic turbine model, on the contrary, wake rotation effects are fully taken into account, resulting in non-negligible mean axial vorticity in the rotor wake in the baseline case and in strongly non-symmetric counter-rotating vortices in the tilted case (see Fig. 3$a$ and $c$). In the more realistic case, therefore, the tilt-induced streamwise vortices are associated to an oblique downwash which is less efficient in displacing high-momentum fluid towards the downstream rotors (see Fig. 3$d$). This explains that lower absolute values of tilt-induced power gains are obtained when wake-rotation effects are taken into due account.

*Competing interests.* The author declares no conflict of interest.

*Acknowledgements.* I gratefully acknowledge the use of the Simulator for On/Offshore Wind Farm Applications (SOWFA) developed at NREL (Churchfield et al., 2012) based on the OpenFOAM finite volume framework (Jasak, 2009; OpenCFD, 2011).

## References


Annoni, J., Gebraad, P. M. O., Scholbrock, A. K., Fleming, P. A., and van Wingerden, J.-W.: Analysis of Axial-Induction-Based Wind Plant Control Using an Engineering and a High-Order Wind Plant Model, Wind Energy, 19, 1135–1150, https://doi.org/10.1002/we.1891, 2016.

Annoni, J., Scholbrock, A., Churchfield, M., and Fleming, P. A.: Evaluating Tilt for Wind Plants, in: 2017 American Control Conference (ACC), pp. 717–722, IEEE, IEEE, Seattle, WA, USA, https://doi.org/10.23919/ACC.2017.7963037, 2017.

Bastankhah, M. and Porté-Agel, F.: Experimental and Theoretical Study of Wind Turbine Wakes in Yawed Conditions, J. Fluid Mech., 806, 506–541, https://doi.org/10.1017/jfm.2016.595, 2016.

Bay, C. J., Annoni, J., Martínez-Tossas, L. A., Pao, L. Y., and Johnson, K. E.: Flow Control Leveraging Downwind Rotors for Improved Wind Power Plant Operation, in: 2019 American Control Conference (ACC), pp. 2843–2848, IEEE, 2019.

Boersma, S., Doekemeijer, B., Gebraad, P., Fleming, P., Annoni, J., Scholbrock, A., Frederik, J., and van Wingerden, J.-W.: A tutorial on control-oriented modeling and control of wind farms, in: 2017 American Control Conference (ACC), pp. 1–18, IEEE, https://doi.org/10.23919/ACC.2017.7962923, 2017.

Burton, T., Jenkins, N., Sharpe, D., and Bossanyi, E.: Wind energy handbook, John Wiley & Sons, 2001.

Calaf, M., Meneveau, C., and Meyers, J.: Large Eddy Simulation Study of Fully Developed Wind-Turbine Array Boundary Layers, Phys. Fluids, 22, 015 110, https://doi.org/10.1063/1.3291077, 2010.

Campagnolo, F., Petrović, V., Schreiber, J., Nanos, E. M., Croce, A., and Bottasso, C. L.: Wind Tunnel Testing of a Closed-Loop Wake Deflection Controller for Wind Farm Power Maximization, J. Phys. Conf. Ser., 753, 032 006, https://doi.org/10.1088/1742-6596/753/3/032006, 2016.

Churchfield, M. J., Lee, S., Michalakes, J., and Moriarty, P. J.: A Numerical Study of the Effects of Atmospheric and Wake Turbulence on Wind Turbine Dynamics, J. Turbul., 13, N14, https://doi.org/10.1080/14685248.2012.668191, 2012.

Cossu, C.: Replacing wakes with streaks in wind turbine arrays, Wind Energy, pp. 1–12, https://doi.org/10.1002/we.2577, 2020a.

Cossu, C.: Evaluation of tilt control for wind-turbine arrays in the atmospheric boundary layer, Wind Energy Sci. (sub judice), https://doi.org/10.5194/wes-2020-106, 2020b.

Dahlberg, J. Å. and Medici, D.: Potential improvement of wind turbine array efficiency by active wake control (AWC), in: Proc. European Wind Energy Conference, European Wind Energy Association, Madrid, Spain, 2003.

Fleming, P., Gebraad, P. M., Lee, S., van Wingerden, J.-W., Johnson, K., Churchfield, M., Michalakes, J., Spalart, P., and Moriarty, P.: Simulation Comparison of Wake Mitigation Control Strategies for a Two-Turbine Case, Wind Energy, 18, 2135–2143, https://doi.org/10.1002/we.1810, 2015.

Fleming, P. A., Gebraad, P. M., Lee, S., van Wingerden, J.-W., Johnson, K., Churchfield, M., Michalakes, J., Spalart, P., and Moriarty, P.: Evaluating Techniques for Redirecting Turbine Wakes Using SOWFA, Renew. Energy, 70, 211–218, https://doi.org/10.1016/j.renene.2014.02.015, 2014.

Goit, J. P. and Meyers, J.: Optimal Control of Energy Extraction in Wind-Farm Boundary Layers, J. Fluid Mech., 768, 5–50, https://doi.org/10.1017/jfm.2015.70, 2015.

Howland, M. F., Bossuyt, J., Martínez-Tossas, L. A., Meyers, J., and Meneveau, C.: Wake Structure in Actuator Disk Models of Wind Turbines in Yaw under Uniform Inflow Conditions, J. Renew. Sustain. Energy, 8, 043 301, https://doi.org/10.1063/1.4955091, 2016.

Jasak, H.: OpenFOAM: open source CFD in research and industry, Int. J. Naval Arch.Oc. Eng., 1, 89–94, 2009.

Jiménez, A., Crespo, A., and Migoya, E.: Application of a LES Technique to Characterize the Wake Deflection of a Wind Turbine in Yaw, Wind Energy, 13, 559–572, https://doi.org/10.1002/we.380, 2010.

Jonkman, J., Butterfield, S., Musial, W., and Scott, G.: Definition of a 5-MW reference wind turbine for offshore system development, Technical Paper NREL/TP-500-38060, National Renewable Energy Lab.(NREL), Golden, CO (United States), 2009.

Keating, A., Piomelli, U., Balaras, E., and Kaltenbach, H.-J.: A priori and a posteriori tests of inflow conditions for large-eddy simulation, Phys. fluids, 16, 4696–4712, https://doi.org/10.1063/1.1811672, 2004.

Knudsen, T., Bak, T., and Svenstrup, M.: Survey of wind farm control-power and fatigue optimization: Survey of wind farm control, Wind Energy, 18, 1333–1351, https://doi.org/10.1002/we.1760, 2015.

Martínez-Tossas, L. and Leonardi, S.: Wind Turbine Modeling for Computational Fluid Dynamics, Subcontract Report NREL/SR-5000-55054, US National Renewable Energy Laboratory, Golden, CO (USA), 2013.

Medici, D. and Alfredsson, P. H.: Measurements on a Wind Turbine Wake: 3D Effects and Bluff Body Vortex Shedding, Wind Energy, 9, 219–236, https://doi.org/10.1002/we.156, 2006.

Munters, W. and Meyers, J.: An Optimal Control Framework for Dynamic Induction Control of Wind Farms and Their Interaction with the Atmospheric Boundary Layer, Philos. Trans. R. Soc. Math. Phys. Eng. Sci., 375, 20160 100, https://doi.org/10.1098/rsta.2016.0100, 2017.

Munters, W. and Meyers, J.: Optimal Dynamic Induction and Yaw Control of Wind Farms: Effects of Turbine Spacing and Layout, J. Phys. Conf. Ser., 1037, 032 015, https://doi.org/10.1088/1742-6596/1037/3/032015, 2018a.

Munters, W. and Meyers, J.: Dynamic Strategies for Yaw and Induction Control of Wind Farms Based on Large-Eddy Simulation and Optimization, Energies, 11, 177, https://doi.org/10.3390/en11010177, 2018b.

Nanos, E. M., Letizia, S., Barreiro, D. J., Wang, C., Rotea, M., Iungo, V. I., and Bottasso, C. L.: Vertical wake deflection for offshore floating wind turbines by differential ballast control, in: J. Phys: Conf. Series, vol. 1618, p. 022047, IOP Publishing, https://doi.org/10.1088/1742-6596/1618/2/022047, 2020.

OpenCFD: OpenFOAM - The Open Source CFD Toolbox – User's Guide, OpenCFD Ltd., UK, 2.4 edn., http://www.openfoam.org, 2011.

Park, J. and Law, K. H.: Cooperative Wind Turbine Control for Maximizing Wind Farm Power Using Sequential Convex Programming, Energy Convers. Manag., 101, 295–316, https://doi.org/10.1016/j.enconman.2015.05.031, 2015.

Porté-Agel, F., Bastankhah, M., and Shamsoddin, S.: Wind-Turbine and Wind-Farm Flows: A Review, Bound.-Layer Meteorol., https://doi.org/10.1007/s10546-019-00473-0, 2019.

Schumann, U.: Subgrid scale model for finite difference simulations of turbulent flows in plane channels and annuli, J. Comp. Phys., 18, 376–404, https://doi.org/10.1016/0021-9991(75)90093-5, 1975.

Shapiro, C. R., Gayme, D. F., and Meneveau, C.: Modelling Yawed Wind Turbine Wakes: A Lifting Line Approach, J. Fluid Mech., 841, https://doi.org/10.1017/jfm.2018.75, 2018.

Smagorinsky, J.: General circulation experiments with the primitive equations: I. The basic experiment, Mon. Weather Rev., 91, 99–164, https://doi.org/10.1175/1520-0493(1963)091<0099:GCEWTP>2.3.CO;2, 1963.

Sørensen, J. N.: Aerodynamic Aspects of Wind Energy Conversion, Annu. Rev. Fluid Mech., 43, 427–448, https://doi.org/10.1146/annurev-fluid-122109-160801, 2011.

Sørensen, J. N. and Shen, W. Z.: Numerical Modeling of Wind Turbine Wakes, J. Fluids Eng., 124, 393–399, https://doi.org/10.1115/1.1471361, 2002.

Steinbuch, M., De Boer, W., Bosgra, O., Peeters, S., and Ploeg, J.: Optimal control of wind power plants, J. Wind Eng. Ind. Aerodyn., 27, 237–246, 1988.

Stevens, R. J. and Meneveau, C.: Flow Structure and Turbulence in Wind Farms, Annu. Rev. Fluid Mech., 49, 311–339, https://doi.org/10.1146/annurev-fluid-010816-060206, http://www.annualreviews.org/doi/10.1146/annurev-fluid-010816-060206, 2017.

Strickland, J. M. I. and Stevens, R. J. A. M.: Effect of Thrust Coefficient on the Flow Blockage Effects in Closely-Spaced Spanwise-Infinite Turbine Arrays, J. Phys. Conf. Ser., 1618, 062 069, https://doi.org/10.1088/1742-6596/1618/6/062069, 2020.

Tabor, G. R. and Baba-Ahmadi, M. H.: Inlet conditions for large eddy simulation: A review, Computers & Fluids, 39, 553–567, https://doi.org/10.1016/j.compfluid.2009.10.007, 2010.