Reviewer Comments to "Controls-Oriented Model for Secondary Effects of Wake Steering"

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The authors appreciate the feedback from the reviewers and believe that the manuscript has been much improved based on the reviewer comments. In particular, a reformulation of secondary steering and yaw-added recovery have been included that have proven to be more robust to varying wind farm configurations. Answers to the individual reviewer comments can be seen below.

Immediate improvements can be seen in the model in this figure:

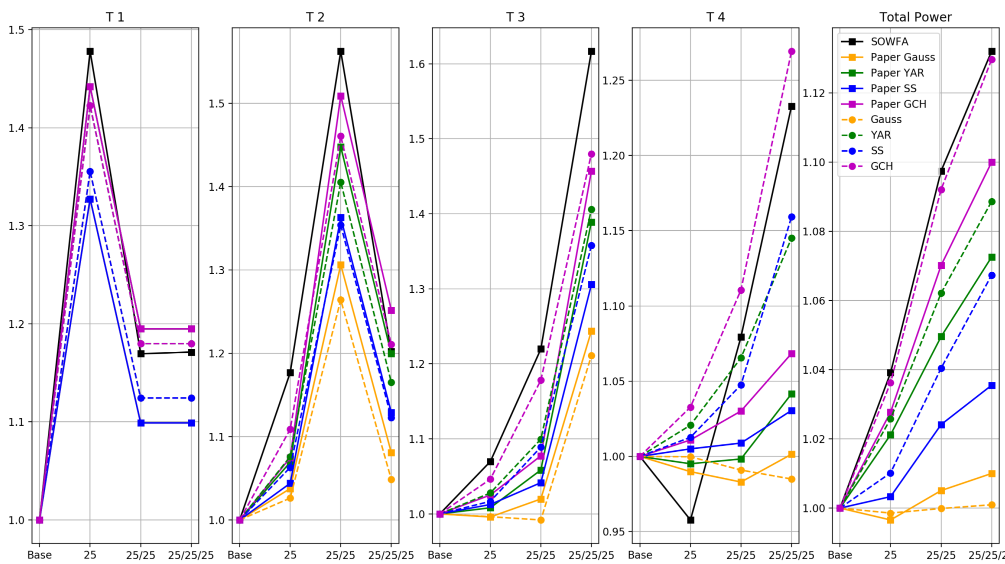

Figure 1: This figure shows the previous version of the model compared to the improvements made to the model based on reviewer suggestions.

Reviewer 1

I read your article with great interest. You present a very important contribution to the literature, being a surrogate wind farm model that incorporates the effects of secondary steering. I find the translation of secondary steering to an "effective" yaw angle a very interesting, eloquent, and novel solution. This work will surely improve wind farm control algorithms and AEP predictions with such models. I envision that the proposed GCH model will replace the standard Bastankhah (Gaussian) wind farm model as the literature standard in the near future. My comments remain largely minor. That being said, I have a number of suggestions that may improve the clarity. and correctness of the article.

Comments

- Generally, the manuscript needs to be proofread. Some sentences can be rephrased in a clearer manner and there is still a handful of spelling errors in the manuscript. Similarly, in figures, axis labels legends, captions, and subfigure titles need to be reconsidered and may. be made more clear. Note units and the size of text in figures compared to the regular manuscript font. Further, to simplify descriptions of simulation setups such as the first paragraph in Section 5, the authors could consider putting such information in a table instead.

  The figures have been modified. In particular, figures 2, 3, 4, 7, and 14 have been added or modified to enhance the narrative of the manuscript.

- Section 2 would greatly benefit from adding a figure that demonstrates the definition of various variables. Generally, I found it difficult to follow the derivations shown in this section. A figure or perhaps some restructuring of the text may benefit clarity. Also, please have a look at the consistency in definitions when moving from a single-wake model (Equation 1) to the wind farm model. In Equation 1, y is defined as zero at the turbine while this is not necessarily the case in Equation 11, for example. Moreover, is it not true that $M_0 = C_T$?

  The authors agree that a figure would be helpful to provide some useful context. Figure 1 has been added to address these issues. In addition, equation 1 has been updated and M_0 has been removed from the text everywhere..

- Figure 1 shows the time-averaged flow fields from transient, turbulent SOWFA simulations. From what I am seeing here, and based on my own experience, I observe the following. The precursor simulation in SOWFA has a constant west inflow, I am assuming (270 degrees). This may cause certain faster regions of flow to "stack up" in the precursor simulation due to the cylcic boundary conditions. This explains why you have a higher inflow wind speed to the left and right side of your turbines (based on what I see in the plots of Figure 1). Now, since you are specifically looking at secondary steering effects, this may actually have an impact on your work. The ambient wind speeds are already higher to the left and right of the turbine due to the non-homogeneous mean inflow wind speeds in the precursor, and therefore also to the left and right of the downstream wake. This may induce more or less wake deflection than in a precursor without such "stack up" effects. I am not sure if you can address this in the current work, but you should consider this for future work.

The authors agree with this assessment. The authors will be making the domains bigger in the future so that these streaks dissipate more and the authors can simulate cases at different spanwise locations to provide "bounds" on the simulations to make sure that these streaks are not exacerbating, or muffling, the effects of wake steering.

- The GCH model is compared to the Gaussian model in Figure 4. It may be nice to (instead) show the wake outlines (centerline + σ_y, centerline - σ_y) of the two models in a single plot to more clearly show the additional deflection achieved with the GCH model. This would also show that the wake behind turbine 1 is identical between the two models.

  The authors really appreciate this insight and have added these figures for the 3 turbine and the five turbine case that shows the influence of secondary steering from GCH. See figures 3, 4, and . A figure has been added to target the centerline. The boundaries of the wakes do not change significantly between models and were left off the figure to minimize clutter.

- Figure 8 shows the power values measured from SOWFA. The default SOWFA implementation on Github has a bug where the generatorPower file in the turbineOutput folder is erroneously multiplied with a factor fluidDensity. This causes the power measurements to be a factor 1.225 too high in our own simulations, for which we have to correct manually. Have you considered this in your own work? It makes no difference in the other figures in which relative power productions are shown, but it does in Figure 8 where absolute values are shown.

  Yes, this has been corrected in the version of SOWFA that is being used for this paper.

- Sections 3-6 show a thorough analysis of the GCH and the Gaussian model, their differences, and how this reflects in simulation. This is very valuable. Though, due to the sheer amount of results, it can be a bit overwhelming. I wonder if the observations made in the 2- and 3-turbine analysis can also be made by only looking at the 5-turbine analysis.

  The authors have removed the two turbine results and focused on three turbine, five turbine, and the wind farm results. The three turbine results were kept because of the sweep of yaw angles at the low turbulence intensity case is helpful in visualizing the asymmetry that is achieved with this model. See Figure 6.

- What is the difference in computational cost between the GCH and Gaussian model? You can find a highlighted manuscript with more detailed comments in the attachment.

  A speed test was conduced and GCH is 3.5x slower than the standard Gaussian model due to the computation of V and W. This has been noted in the text.

Reviewer 2

This manuscript presents an improved wake model, denoted as Gauss-Curl Hybrid (GCH) model, which is obtained by coupling the existing Gaussian wake model and the curl model. The main objective of the proposed wake model is to improve accuracy in predictions of wakes and turbine power capture in presence of yaw steering and more importantly, the secondary steering on downstream turbines induced by upstream yawed rotors. From field experiments, the secondary wake steering seems beneficial to enhance power capture for wind farms.

After a comprehensive introduction, the Gaussian model and the curl model are reviewed in Sect. 2. Subsequently, the GCH model is introduced by coupling the two previous models. In Sect 3, the first analysis consists of the case with two turbines. Sects. 4 and 5 show the results for a three and 5 turbine cases, respectively. Finally, a wind farm case is analyzed in Sect. 6.

Major Comments

- How much of the physics is preserved through this model, such as mass conservation, momentum budgets? In other words, should this model be considered an analytical or empirical model?

  It is noted in the text that mass conservation and momentum budgets are not obeyed in this paper. The reviewer is referred to `https://arxiv.org/pdf/2011.00894.pdf` to see the authors' ongoing work to attempt to preserve more physics in this model.

- Sect. 4 (Figs. 3 and 4) - An initial comparison is done visually between the wake velocity fields obtained from SOWFA and the models. I recommend visualizing the error between the models and the reference SOWFA data. You can also provide some global parameters, such as mean absolute percentage error. 3.

  The authors agree that figures 3 and 4 could be more descriptive. The authors have updated Figures 3 and 4 to include the differences between the Gaussian model and the GCH model in terms of wake centerline. While the flow field is important to match, these analytical models are focused on making sure the powers are computed accurately at each turbine.

- Figs. 5, 6 - While for positive yaw angles, the GCH model performs very well, for negative angles besides the large error, even the trend is completely missed. You should comment, if I did not miss it, how this under-performance affects applications for control or wind farm design.

  Based on another Reviewer's comments, the authors have taken out the two-turbine section, but have made a comment in the three turbine section about not always predicting the negative yaw angles correctly. Typical yaw controllers are mostly focused on positive yaw angle implementations; however, the authors note that this is an important phenomenon to understand and will be the subject of future research.

Minor Comments

- Equation 1 - cross-check it, I guess brackets are missing in the exponential.

  This was fixed. See Equation 1

- P3 L22, there is a typo at σ_z.

  This has been fixed.

- P8 L8 - "Published in literature"; add some references.

  Since the first draft of this paper was written, a few of the parameters in the turbulence model have been slightly updated as the authors have acquired more large eddy simulation and field results. However, the values used in the velocity deficit and the velocity deflection model are the same as used in Bastankhah 2016 and Niayfar 2015 and is now indicated in the text.

Reviewer 3

In this paper, a new analytical model (GCH) which takes into account the yaw added wake recovery and the secondary wake steering effects is proposed to predict the wind farm power production under active yaw control. Overall, it is an interesting and promising piece of work. Nevertheless, the equations in this paper are in a mess. Some are wrong. Some are given without rigorous theoretical justification. These issues bother the reviewer a lot and have to be fixed prior to publication. Detailed comments are as follows:

Major Comments

- Equations (11) - (18) are incorrect. Take equation (11) as an example. The induced spanwise velocity (V) should be related to the vertical distance to the vortex center (z-z_h), instead of the spanwise distance (y-y_0). The correct form is:

  $$V_{\text{wake rotation}} = \frac{-\Gamma_{wr}(z - z_h)}{2\pi\left((y - y_0)^2 + (z - z_h)^2\right)}(\ldots)$$

  The authors note the inconsistencies in the paper and have corrected these equations as the reviewer indicates.

- Substituting equation (4) into Equation (3), we obtain $M_0 = C_T$. Why introduce two symbols to represent the thrust coefficient?

  The authors have removed M_0 and C_0.

- In Equation (6), the physical meaning of u_0 is the wake velocity at the onset of the far wake, instead of "the velocity behind the rotor" given by the authors.

  This has been fixed.

- Equation (9) is different from that in Bastankhah and Porte-Agel (2016). The authors changed the original term $1.6\sqrt{\frac{\sigma_y \sigma_z}{d^2 \cos\gamma}}$ to $1.6\sqrt{\frac{\sigma_y \sigma_z}{\sigma_{y0}\sigma_{z0}}}$. This doesn't hold, as $\sigma_{y0}\sigma_{z0} \neq d^2 \cos\gamma$. In fact, they differ approximately by a factor of 10.

  The authors note the difference. However, the authors were referring to equation 5.8 from (Bastankhah 2016, see reference below). There are other differences between the two equations that must take care of this difference although the authors admit they have not worked through this by hand.

  Bastankhah, M. and Porté-Agel, F.: Experimental and theoretical study of wind turbine wakes in yawed conditions, Journal of Fluid Mechanics, 806, 506–541, 2016

- In Section 2.3, the authors conjectured a new effect called "added wake recovery due to yaw misalignment" and stated "the wake recovers more when the turbine is operating in misaligned conditions..." In order to make such a statement, the authors should provide some quantitative evidences, or at least give a reference. Additionally, if this effect does exist, instead of using a complex equation (equation (23)), why not just increase the wake recovery rate, k_y?

  After some rigorous testing, the authors agree that the current approach was not robust to all wind farm layouts. The authors have since improved this formulation as the reviewer suggests to more directly affect the recovery rate through an increase in TI as described in Section 2.3.

- Equation (23) is given without rigorous theoretical derivation, which is unacceptable to the reviewer. What is the exact control volume used to apply momentum conservation? Why an artificial parameter, α_r is introduced? Detailed theoretical derivations should be given in the appendix.

  The authors understand this confusion and have changed the formulation of the yaw added wake recovery from a control volume analysis to effectively increasing the turbulent mixing behind the rotor as indicated in Section 2.3.

- In Section 2.3.1, instead of computing the effective yaw angle based on equation (24), why not directly use the ratio of total transverse velocity to freestream velocity to estimate γ_{eff}?

  The authors have updated the way that the effective yaw angle is computed by directly using spanwise velocity. Although this might not be exactly what the reviewer had in mind, it provides a more robust solution than the previous iteration of the paper.

- The figures in this paper are not well presented. Labels are hardly recognizable and the information in figures 2, 12, 13, and 14 can't be grasped at first sight.

  The authors have done their best to address the readability of each of the figures as well as add a few figures to address the model setup and more clearly address the differences between the Gaussian and the GCH model.

- Line 22 on page 3: $sigma_z$

  This has been addressed.