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Breakdown of the velocity and turbulence in the wake of a wind turbine - Part 2: Analytical modeling.

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Summary:

The manuscript entitled "Breakdown of the velocity and turbulence in the wake of a wind turbine - Part 2: Analytical modeling" endeavors to describe the turbulent velocity field in a wind turbine wake by accounting for energy in both the meandering and fixed frames of reference. The mathematical development is thorough and detailed, even if the presentation is difficult to follow at times. The model development takes cues from some well known approaches in fundamental turbulence (e.g., the Boussinesq Hypothesis) and is almost entirely analytical, leaving very few constants to be tuned empirically. For the most part, the manuscript is well written and clear, although there are a few points that require more discussion.

Comments:

- The manuscript does not adequately contextualize the work with regards to other wake turbulence models. While the work by Ishihara and Qian is mentioned, there are no comparisons to the proposed model and so advantages of the current approach cannot be fully assessed. Moreover, the work by Crespo and Hernandez [1, 2], which remains the prevailing wake-added turbulence model used in the wind energy industry and research communities is not mentioned at all.
- The two parts of the manuscript overlap a great deal. Both parts contain a description of the mean flow, and of components of the turbulence field (meandering and fixed frames of reference). I recommend either combining and consolidating the work into a single article or working to distinguish the content in each.
- The notation $\hat{\cdot}$ is not defined in the current work and requires readers to look at Part I. It's also not clear why the notation must also require subscripts to distinguish between quantities in the meandering or fixed frames if the hat notation does the same job. In some terms, the authors use subscripts for meandering frame and for a reference velocity field, which is the undisturbed ABL. This seems like a contradiction. What is meandering in the reference field?
- Many equations are repeated between the two Parts of the article. Equations 6 and 7 contain many terms that are not given enough description or physical interpretation in Part II. Please add a brief description for each term.
- Equation 7 defines several forms of shorthand for some terms (e.g., $k_m = (\mathrm{III})$). Why are multiple names used?

- The definition of turbulence used by the authors appears to arise from decomposing TKE in a fixed frame into the meandering frame of reference. The turbulence model is only coupled to the velocity model through the decay function $C(x)$ given in Eq. 2. In reality, the turbulence field arises from mean shear gradients, solid body interactions and boundary layers. Is this model sufficient to describe changes in turbulence due to changes in the mean momentum deficit and wake morphology? Does the velocity model depend in any way on the turbulence field?
- On lines 66 and 67, the authors state that the mechanisms for wake meandering and wake expansion are treated independently. This strong assumption is not likely to hold in all cases. Can the authors offer more reasoning for this decision? What are the consequences of treating the mechanisms separately? Are the cross terms in Eq. 7 responsible for the coupling of these mechanisms?
- Neither the velocity model nor the turbulence model make use of the stable simulation discussed in Part I of the paper. The authors state that the stable case is not modeled because veer is not described in the current formulation, but that it could be in the future. This is arguably one of the most important cases to model as it leads to the greatest wind plant wake losses, and should be included in the current work.
- Stability is not described in the models. The changes introduced by stability must then come from the dizzying array of standard deviations listed in the models. Is this level of empiricism a step forward from existing wake velocity and turbulence models?
- The authors state that "only atmospheric parameter that seems to influence ΔTI_{MF} is the shear...". This is not the only boundary condition that should be considered. Even in the neutral case, the roughness length will determine the velocity and turbulence profile, the characteristic length scales of inflow turbulence, correlation lengths for meandering, etc. In stable and unstable cases, the surface heat flux will be important to fully describe the sources/sinks of momentum and turbulent kinetic energy. The authors must discuss limitations in the modeling approach and consequences in the final predictions. These sources of uncertainty may be the limiting factor of the model in the end.
- The wake-added turbulence shown in Figures 3 and 14 does not appear to be fully converged. What is the uncertainty associated with developing the model with poorly converged statistics?
- Eq. 15 is shown in the text and can be removed.
- Are Eqs. 15–17 used to infer a value of l_m? If so, what are the consequences of neglecting so many non-zero gradients in the rate-of-strain tensor? What about using a log-layer estimate of u_0? Finally, is a single value of l_m used for the full model everywhere in the wake? There are challenges and limitations with this approach discussed by Iungo [3, 4] and Martínez [5, 6]. Please discuss the model and assumptions in the context of previous work.
- The notation in Eq. 19 needs to be changed from e to $\exp$ to be consistent with the rest of the manuscript.
- How will the models used in the current work be validated? There are not many sources of utility-scale wind turbine wake turbulence available for research.

References

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[3] Francesco Viola et al. "Prediction of the hub vortex instability in a wind turbine wake: stability analysis with eddy-viscosity models calibrated on wind tunnel data". In: *Journal of Fluid Mechanics* 750 (2014).

[4] Giacomo V Iungo et al. "Data-driven RANS for simulations of large wind farms". In: *Journal of Physics: Conference Series*. Vol. 625. 1. IOP Publishing. 2015, p. 012025.

[5] Luis A Martínez-Tossas et al. "The aerodynamics of the curled wake: a simplified model in view of flow control". In: *Wind Energy Science* 4.1 (2019), pp. 127–138.

[6] Luis A Martínez-Tossas et al. "The curled wake model: a three-dimensional and extremely fast steady-state wake solver for wind plant flows". In: *Wind Energy Science* 6.2 (2021), pp. 555–570.