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WIND ENERGY SCIENCE DISCUSSIONS

Interactive comment on "First Identification and Quantification of Detached Tip VorticesBehind a WEC Using Fixed Wing UAS" *by* Moritz Mauz et al.

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Thank you for the detailed review of the manuscript. In the following I will comment on each point. The referee's comments will be repeated in italic before the answer.

General comments

The manuscript by Mauz et al. describes in-situ measurements of wind turbine tip vortices with a UAS. From these measurements, circulation of the vortices is calculated using the Burnham-Hallock wake vortex model. These measurements are unique and I do not know of any other study in which a UAS operated in such close proximity to an operating wind turbine and even in its wake. The authors can convincingly show that wake vortices can be measured with the UAS. The presentation of the methods of analysis and the results however needs some significant improvement:

- *In the introduction and throughout the text I miss more thorough references to the state-of-the-art. For example, other methods to measure full-scale wind turbine wakes with remote sensing are not mentioned at all, but are carried out all the*

time and in multiple ways. What can a UAS do that is not possible with remote sensing?
Remote sensing methods (e.g. LIDAR) can not resolve turbulence in such a small scale as a UAS is capable of. LIDARs usually cycle cone measurements that resemble averages over a huge volume compared to a UAS line measurement. However, the method of operation allows for long term measurements whereas UAS excels at in-situ small scale measurements. Appropriate literature will be added. The lack of references is also contributed to the lack of publications of remote sensing experiments that try to resolve small scale turbulence in wakes. The wakes itself can be measured by LIDAR but focus of this manuscript is the identification of tip vortices that only have been verified qualitatively by Subramanian et al.

- *The structure of the text is sometimes confusing and much information is given in the results and discussion and outlook section that should have been introduced before. I provide details in the specific comments.*
  Thank you for the feedback. I will try to improve the structure of the text. Also by implementing the specified suggestions.

- *A major problem of the manuscript is that all the analysis is only done for a single sample of a wake vortex pair. If possible at all I would strongly urge the authors to investigate if they can maybe use some other flights. Maybe even flight levels above or below hub height could still be valuable.*
  Additional vortex measurements are available. In those flight legs usually the vortex pairs are visible. However, an evaluation of the core radius and vortex strength is mainly not possible due to the distance of the UAS being larger than

r_c. From all the available data only one flight leg showed two vortices were the evaluation method presented in the manuscript was feasible.
The aim of this manuscript is to establish an evaluation method for MASC-3 to later examine future wake measurements and then be able to establish a statistic for near wake vortex behaviour (e.g. turbulence and stratification dependent). However there is the need for an improved flight strategy in the future.

- *It is known that the estimation of the UAV attitude is a major source of error for the wind calculation. It is also known that navigation systems are less precise in dynamic flight manoeuvrers. I would therefore at least expect that attitude angles as well as airspeed and flow angles during the flight through the vortex are shown. The authors raise the issues themselves in the discussion, but I think it is necessary to include a proper analysis of this in the manuscript, including an estimation of uncertainty of the wind vector and thus the circulation.*
  The attitude angles of the UAS will be shown in an extra evaluation (e.g. subsection) also including an error estimation of the wind velocity and the measured circulation. See also Fig. 1 and Fig. 2 for a first look.

- *I recommend some copy-editing to be done on English grammar and expressions.*
  I will look into that.

figure-1.pdf

Fig. 1. Wind angles and true air speed (TAS) of the 5-hole probe for the evaluated vortex measurements. Grey dashed line shows the calibration limit of -20 to 20 degrees. Overstepped angles are interpolated.

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figure-2.pdf

Fig. 2. Attitude angles of the UAS for the vortex measurement flight. The entry and exit of the wake can be seen. The UAS remains on a stable flight path through the wake.

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Specific comments

[] Abstract

1. *The abstract should be rewritten with more statements about the hypotheses that were investigated in the study. A description of the results / conclusion is missing. p.1,ll.1ff: wind converter should be either wind turbine or wind energy converter. Preferable: "rotor blade of a wind turbine". The whole first sentence is very hard to read and grammatically wrong. Starting with the relevance for numerical models in the abstract is misleading, because numerical models are not the topic of the paper.*
   p.1,l.6: what is the difference between atmospheric and meteorological quantities?
   The abstract will be rewritten. All other annotations concerning the abstract have been implemented.

Introduction

2. *p.2,ll.9-13: this paragraph should go into the description of the aircraft (Sect. 2.1)*
   p.2,ll.14-21: this paragraph could go in the experiment/site-description in Section 2
   p.2,ll.22-31: here, a lot more literature should be referenced. Wake vortices are a major field of research and the state-of-the-art has not been evaluated at all.
   All annotations have been addressed. Additional references and literature has been added.

Section 2

3. *I miss a detailed description of the atmospheric conditions during the flight. Stratification, turbulence in the inflow, etc. which are important for the wake development are not given but should be available from the data.*
The day the tip vortex measurement flights took place, only measurements at three different heights were made. The flight strategy was aiming on capturing tip vortices at hub height, and at the top and bottom of the wake. Since the distance to the nacelle is 0.25D or about 27 m the stratification of the atmosphere should not have a significant influence on the wake development. Also there is the possibility that the tip vortices were not yet fully detached, since the measurements took place in such close vicinity to the nacelle.

4. *A list of available flights and an explanation why only a single flight leg is analysed is missing.*
A total of five flight legs at 0.25D are present. From these measurements only in one leg the criterion of $\Delta y < r\text{c}$ was met.

5. *p.3,ll.3-8: Here, description of the aircraft is mixed with operational procedures. I feel like this should be separated.*
A new subsection has been added 'Available data' where the data availability and the atmospheric condition are mentioned.

6. *p.3,l.11: Since RTK GPS is mentioned here and is not a standard feature of UAS in atmospheric research, some additional information would be appreciated: what kind of receiver is used (L1 or L1/L2 phase); is a local base station or RTCM-services used for correction data / what is the baseline? What is the advantage of the very accurate flight path in atmospheric measurements?*
RTK was not used during the flight and will not be mentioned in the manuscript any more.

7. *Fig.3: I think a more schematic background (not Google Earth) with a better scale and legend would help*
   Google Earth map/image was replaced with a schematic map of Germany (cf. Fig. 3).

   Section 3

8. *Fig.6: It is unclear how TKE has been calculated. How large is the averaging window?*
   The TKE calculation serves a qualitative purpose. Therefore an averaging of 1 s (100 data points) has been found to be sufficient. The integral length scale was not calculated.

9. *Fig.7: Nice figure, but watch out for which lines cross in front of or behind other lines to get the 3D visualization right. I think the red rectangle encloses the blue vortex, right? And "distance" should probably get a variable name or could even be left out.*
   First of all, thank you for the compliments. The line issue has been addressed. They should now support the viewer's perspective. 'Distance' has been removed. An updated figure will be found in the new manuscript (cf. Fig. 4).

10. *p.9,l.5: Except that the vortices along the horizontal axis are not generated at the same time for the WEC.*
    In the specific line it is talked about the x-axis: Along the x axis, which is also the flight path of the UAS (pointing east with the main wind direction approximately 10° north), the vortices indeed show a little temporal delay. The first encountered vortex travelled a bit farther than the second vortex. This should be mentioned and could also explain the smaller core radius of the second vortex.

figure-3.pdf

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figure-4.pdf

Fig. 4. Simplified sketch of a vortex pair passed by the UAV to the right. In reality it would rather have a helical pattern than a ring shape. Velocities and axis according to meteorological standards, therefore axis and orientation according to the in-situ conditions. y axis pointing north, x axis pointing east. At hub height the w component (along z axis) vanishes. The red rectangle illustrates a top view of a tip vortex with distance Δy to the UAS.

Section 4

11. *p.14,l.1: What is the vortex coordinate system and which angles are used for the rotation? This has not been introduced before.*
    Thank you for this comment. 'Vortex coordinate system' might really be the wrong expression here. What I was trying to say is that the 'horizontal wind data' have been rotated into the vortex rotational plane. So after this rotation the horizontal wind plane is parallel to the rotational plane of the tip vortex. The rotation was accomplished by rotating the x and y axis (u and v wind component respectively). This information will be added in the new version of the manuscript.

12. *p.14, ll.26ff: this needs to be introduced and explained in more details in the methods section. Why can this correction not be done for other flight levels to increase the number of samples of tip vortices?*

    In principle it is possible to look at different altitudes. The flight strategy was to concentrate on measurements at hub height, since the probability to hit a tip vortex is the highest at this level. Also the introduced simplification of the vortex only rotating in two dimensions is mainly true at hub height.
    The rotation into the vortex rotational plane only makes sense, when the vortex has passed with the necessary criterion ($\Delta y < r_\mathrm{c}$). Otherwise an evaluation of Γ and r_c is not possible.

13. *Fig.16: I think this figure is not necessary.*
    This figure has been removed.

14. *p.15, l.5: "rotated slightly" $\rightarrow$ what does that mean?*
    Done. The wind is rotated into the wake direction.

15. *p.15, l.10ff: It is said that the wind speed deficit plays an important role for the tip vortex, but this is not discussed any further. Is BH even an appropriate model*

under these circumstances?
The short answer is 'yes'. The u component of the model is not affected by the deficit, especially since the data has been rotated into the wake direction. Also the peak position (on the x axis) for the v component in the BH model is also not affected. Only the slope and magnitude.

16. *Fig.18: not sure if this figure is necessary*
Will be dropped from the manuscript. It was simply thought to be a visualisation of the applied correction.

Section 5

17. *p.19,l.7f: These are too strong statements for an experiment with a single sample*

18. *p.19,l.15ff: The issues that are raised here are not insignificant and call for some more analysis and quantification.*
Attitude angles and true air speed variations will be analysed and the results addressed accordingly in the new manuscript.

Section 6

19. *p.19,l.21: What is the equation by Sorensen et al. (2014) that is meant here?*
Done. Eq. 20. Reference has been added.

20. *p.19,l.23: "aggravates an evaluation" - what do you mean by that?*
The evaluation is done mainly graphically. The second tip vortex is embedded in a relatively high level of turbulence (wake deficit, shear, etc.). The second tip vortex does not show a clear border to the undisturbed atmosphere as tip vortex

1 does. The reference velocity levels for the evaluation are therefore harder to extract from the measurements.

21. *p.19,ll.27ff: The information about the 5-hole probe calibration range and why other flights could not be used should be given in Section 2 already. In section 2, it was said that the UAV operated with RTK GPS which is contradicted here.* The subsection 'Data availability' has been added in Section 2 where I explain briefly why no other vortex examples are available. The RTK GPS mentioning will be stripped. I will link to a recent MASC-3 paper by Rautenberg et al. 2019.

Technical corrections

22. *p.1,l.1ff: wind converter should be either wind turbine or wind energy converter. Preferable: "rotor blade of a wind turbine". The whole first sentence is very hard to read and grammatically wrong. The second sentence raises problems of numerical simulations that are not the topic of the paper.*
p.1,l.6: what is the difference between atmospheric and meteorological quantities?
p.1,l.8: u,v,w, italic please
p.2,l.3: underestimate
p.2,l.4: "Another way" or "Another method"
p.8,l.7: "several analytical models are available"!?
Fig.8: x-axis should be labelled r
p.11,l.18: L is not proportional to the velocity ratio → The velocity ratio is a function of L.
p.14,l.10f: "In Fig.14 shown as a solid purple line." What is?
p.14,l.21: "clear and sharp jump" - strange expression
p.14,l.22: Fig. 16 appears before Fig. 15 in the text.
Fig.17: What is u and what is v should be mentioned in the caption. the same

line style should be used for the same analysis method, i.e. dashed line for simple BH, and dotted for corrected version for example.
All corrections have been adopted and implemented in the new manuscript.

23. *p.1,l.18: "their individual capacity and diversity" (what do you mean by diversity?)*
Here I wanted to point out that there are different WEC designs for different terrain (complex vs. homogeneous) with all their challenges (high wind speeds, high turbulence and increased stress on blade structures etc.) The paragraph has been rewritten.