

Reply to reviewers

We thank the reviewers who, with their detailed analyses and constructive inputs, have helped improve the quality of this paper. A list of point-by-point replies to their comments is reported in the following, and a revised version of the manuscript is attached with highlighted changes. In addition, we have taken the opportunity for several minor improvements to the text to increase clarity or form.

Best regards,
The authors

Contents

Reply to reviewers.....	1
Short comment 1 (SC1).....	2
Comment	2
Referee comment 1 (RC1).....	3
General comments	3
Detailed questions.....	4
Minor corrections	8
Referee comment 2 (RC2).....	8
Small comments	9
Referee comment 3 (RC3).....	9
Major comments:.....	10
Minor comments.....	13
Revised version of the manuscript with highlighted changes	15

Short comment 1 (SC1)

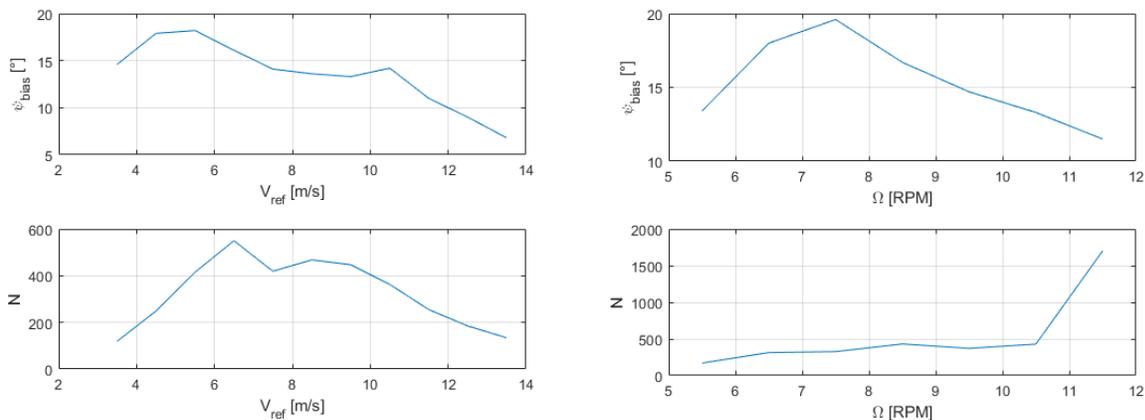
Comment

Dear authors,

You mention on p.10 lines 11-16 the method for eradicating the bias in the azimuth readings, due to the sensors or blade dynamics. Could you please comment why you would expect the bias from ignoring blade dynamics to be a constant, independent of wind speed? It might be a constant for the sensor bias over the period investigated (it might drift with time), but it is hard to see this to be the case for blade dynamics or are the first 7 days representative for the entire measurement period? It would be interesting to plot ψ_{bias} as a function of time or wind speed. It should be simple to incorporate a variable ψ_{bias} in your method and it might be necessary for long-term applications. Thanks

Authors:

Thank you for your comment. Indeed, the azimuth bias can be affected by blade dynamics (and therefore it might also depend on wind or rotor speed). The figures below show the azimuth bias identification for varying wind and rotor speeds using the complete dataset (in 1 m/s and 1 RPM bins respectively, N showing the number of samples in each bin).



As suggested in the comment, a rotor speed or wind speed dependency can be implemented to take such dynamic effects into account, for example using a one dimensional look-up-table. For a long term field implementation such an approach is indeed reasonable and should probably be adopted. However, in this work we preferred the use of a constant average value, mainly to simplify the analysis and discussion, but also because a variable bias does not significantly improve the results. Also, the azimuth bias might change over time, an effect that we were not able to observe with sufficient accuracy because only 41 days were included in the dataset. In fact, for the first 7 days we identified a bias of 14.8 deg, while a bias of 16.3 deg was found for the last 7 days. However, this variation might also have been caused by a different wind/rotor speed distribution, so that we opted even in this case for an average value.

We have updated the manuscript to explain the points above.

Finally, we have found that the manuscript erroneously reported a bias of 11.4 deg for the first 7 days (instead of 14.8 deg). This error has been corrected in all analyses, with no significant effect on the results.

Referee comment 1 (RC1)

General comments

This paper is in the continuity of other studies on the same subject. The objective of this work and the previous ones is to predict the mean wind state inflows (shears and misalignments) from wind turbine loads. Previous works were dedicated on the validation of the method using an aeroelastic simulations, LES simulations and scaled wind tunnel tests .The present work extend the validation using field tests.

Having the knowledge of the flow affecting the entire rotor including its impact on the production for all wind directions/conditions is indeed not trivial with today's sensors that are generally limited spatially (a point measurements with nacelle-mounted wind lidar, some points of the vertical wind profile from a met-mast ...), limited to certain wind directions (met-mast location, scanning lidar position etc ...) and limited in time (met-mast/scanning lidar are generally installed for the certain amount of time). Extract information of the wind inflow from remote sensors on the rotor blades, that can be included in the monitoring set of data (SCADA data), is therefore a very attractive solution.

The use of blade out-of-plane bending moment is demonstrated here to be an interesting quantity for wind inflow analysis. However, a sensor characterization is generally based on measurements redundancy. For this sensor this means a perfect knowledge of the spatio-temporal inflow, which is only partially available from this field test. Also, sensors need to be characterized dynamically which is a quite complex task from field measurements. In antoher hand, reproducing all the physics in wind tunnel or in simulations is still a challenging task and this first application of the method on field test is a real interesting feedback to perform further accuracy evaluations that could be completed off-line in controlled environment using wind tunnel tests, CFD or aero-elastic simulations.

I clearly recommend this paper for publication ...

Authors:

Thank you for your positive review and helpful comments.

... with however some corrections or more details regarding these tow points:

Mean shear trends can be retrieved after however some online calibrations:

- calibration coefficient introduced to compensate the mismatched of the bending moments on the two blades
- calibration coefficient introduced to match the rotor effective speed VTB with the velocity estimated from the bending moment measurement.
- azimuth mean biais of 11.4° is removed (using the average over 7 days).

The origin of the mismatch is not always completely evaluated. If the source of the error dependent on the rotor operation, this will limits the validation of the method to this specific rotor operating point. It would reinforce the strength of the paper to look in more details at the origin of these mismatch.

Authors:

Errors affecting the sensors of different machines could clearly be of different origin and entity. However, the calibration procedures that were used in this paper are general, and could be applied to each different turbine to calibrate its sensors. It should be realized that these calibration procedures are independent from the cause of the miscalibration, which is an important advantage. We do not see the limit mentioned by the reviewer related to the rotor operating point. For example,

the calibration of the load sensors simply enforces the same long-term averages among the various blades, so there is no dependency on the operating point as indeed many different points are used. The calibration of the azimuth bias was also based on a 7-day average (i.e., many different operating points), although a more sophisticated calibration that depends on the rotor speed could be used (see reply above to SC1).

We have improved the descriptions of the calibration procedures, and especially expanded the one of the rotor blades and of the azimuth bias.

For that purpose, it would be interesting to have more informations on the available sensors (type, accuracy, calibration procedure) such as the azimuthal sensor, the sensor available on the mast, the initial strain gauge calibration ... This is particularly important to help to discriminate the error from the model to the measurement and thus to have more inside on the origin of some errors/biais found by the authors.

Authors:

Additional technical specifications of the sensors have now been included in the manuscript. Even more information on the origin of errors and biases would certainly be valuable. However, such information is often unavailable in practical field applications, as also stated by Bromm 2017: “*All sensors are subject to measurement uncertainties, and their perfect mounting and alignment cannot be automatically assumed in a field environment*”. As the sensors can be miscalibrated for many different reasons, this work explicitly proposes methods to correct them in a pragmatic cause-independent way.

Detailed questions

Q1: Measurements used in the paper are 10min averaged data. However, it is particularly interesting to have an estimation of the wind fluctuations at the rotor location for blade load monitoring/alleviation for instance. The highest time resolution for this method/sensor is linked to the strain gauge sensor cut-off frequency, to the structural dynamic response of the blade bending moment, but also to the rotation speed of the rotor. The rotation speed of the rotor is varying with wind inflow according to the control of the turbine, so that the developed sensor has a varying sampling rate. Have you estimated the sampling rate variations? Does it impact the wind estimation? Do you have an estimate of the minimal/maximum time resolution for a given azimuth position (phase measurements)?

Authors:

We have included a new section “3.3 Estimator update frequency” to address the reviewer’s question. In short, we show how even the slowest update frequency (occurring at low rotor speeds) is still capable of resolving the main fluctuations of the inflow.

Q2: p3L22 “ (...) former yields a rotor-effective wind speed (i.e., an average quantity over the entire rotor disk), the latter is used to sample the local wind speed at the azimuth position occupied by a blade.”

With strain gauge sensors only located at the root for root bending moment measurements (with the out-of-plane forces assumed to be homogeneously distributed along the blade), the estimation of the associated wind condition is necessarily averaged along the blade. This method is therefore local in azimuth, but not along the blade. I think this is an important information to be emphasized

as it is more complex to install strain gauge sensors along the blade (for more local estimation) than only at the blade root location.

Authors:

We have updated the description of the formulation to include the point noted by the reviewer.

Q3 P6L22: “All measurements are sampled at 10Hz”.

Why not using the 10Hz data, why only the 10 min average ?

Authors:

The choice of 10 min averages is now explained in more detail. In addition, an analysis of the higher frequency signals has been included and is shown in Section 3.7.

Q4: p6L25: “the relative difference between the two blades can’t be related to a miscalibration of sensors ...”

Why not a small pitch offset between blades? The cross-checking of the the load calibration is given through a comparison between rotoeffective wind speed and the wind from blade loads. However, no information is available on the initial calibration of the strain gauges, which is an important point to evaluate the accuracy of these measurements and thus to discriminate between an error in measurement and a lack in the model development or other source of errors.

Authors:

We agree, the difference might be caused also by a small pitch offset. Possible causes of the miscalibration have now been included in the manuscript.

The initial calibration of the strain gauges is not known to the authors. We agree that a discrimination among the possible sources of error is of potential interest, but such an analysis seems not to be possible with the present data set. In addition, it should be noted that a main goal of this paper is the realistic demonstration of the method – and in a realistic scenario detailed information and root causes of all possible errors are also often unknown (Bromm, 2017).

Q5 p8L25: “including the cases where the blade is partially or fully stalled”

CD and CL are inputs given to the aero-elastic modeling. How these cases are treated ? Is this a LUT of measured CL/CD or a Xfoil simulation ? Or aerodyn from fast ? Or CFD computations ...?

Authors:

We have included an additional paragraph in the manuscript to clarify this point. Note that CL and CD are part of the model, implemented in FAST, and could be identified through experiments or ad-hoc calculations with Xfoil or CFD.

Q6 p8L30: “A direct comparison between VTb and Vb reveals that the latter provides ... are scaled by a factor of $c=0.928$ ”

Why the model used to compute the aerodynamic coefficients is suspected to be the source of error? Is the model used limited? Are the operating AoA in the stall region? Why not a misalignment bias of the rotor or difference of pitch angles between blades during installation?

Authors:

We have updated the manuscript to address these points. Please see also the subsequent paragraph, which discusses the calibration with respect to the met-mast reference also shown in Fig. 4 and 5. Note that the model is not limited to the linear regime, and can also be employed in the stall region (see added paragraph in Section 3.5).

Q7 p10: “possible bias in the measurement of the azimuthal position of the rotor” or “no blade dynamics included in the model”

How the azimuth is measured, is the 11.4° in the error range of the sensor? Why you didn't include the blade dynamic model? This would have been interesting to cross-check your hypothesis and discriminate between a sensor error or a modeling error.

Authors:

The error range of the sensors is unknown to the authors and might depend on the specific installation.

A blade dynamic model has not been used mainly because it would require additional precise knowledge of additional model parameters, which – if not known with sufficient accuracy (as it might very often be the case) – could lead to a complex propagation of errors. As the steady blade out-of-plane bending moments of this study already do not exactly fit the model predictions without ad hoc corrections, we expect additional difficulties when relying on even more rotor parameters. Therefore, our approach was based on the principle that the formulation should not be more complicated than strictly necessary. Section 2.1 has now been expanded to address and explain this choice.

Q8 p15 figure 10: Is it possible to have the floris pictures between instant C and instant 5:00, where there is a peak increase of velocity $V_{s,left}$? It seems to me that the rotor orientation hasn't changed much relatively to the instant C (γ is constant $\sim 145^\circ$) while the $V_{s,left}$ peak is quite significant and the $V_{s,right}$ remain constant (waked condition). This dissymmetry in the wind estimation (and therefore in load bending moments) is quite strange if the wind orientation hasn't changed. Maybe an errorbar in the measurement of the wind orientation may help?

Authors:

Please see Q10 below.

Q9: p15 figure 10.

Another point that is remarkable is instant $\sim 9:00$. While the wind direction is back to the level found after instant C ($\sim 149^\circ$), the deficit is not as high and the dissymmetry between $V_{s,left}$ and $V_{s,right}$ is again present. I suspect a too fast wind direction variation for the wake to develop. In another word, apart from errors in the method, is the wind unsteadiness can be suspected. Standard deviation of the wind direction may help to go a bit further in the analysis. I understand that without reference this is difficult to explain, however this high sensitivity to the time duration within a wind orientation is certainly to be estimated off-line with a dynamic calibration of the sensor method in future work. It should be at minimum reported or commented in the present paper.

Authors:

Please see Q10 below.

Q10 (figure 10): the coefficient k is interesting but not commented, why is that? The passage from a positive shear to a negative shear, the level of the shear at 5:00 compared to 9:00 etc ...

Authors:

The figure has been updated: the yaw orientation has been included, the reference turbulence intensity is indicated and the time instant D has been changed to 5:00. Note that already a few degrees in wind direction change can have a significant effect on wake position (compare the new FLORIS flow fields for C and D). The discussion of figure 10 has also been updated, addressing the questions raised by the reviewer.

Q11 P17L5: “very few measurement points are available” induces “frequent shutdowns of WT1”

Can you be clearer ? I don't understand this logic: even if the wind turbine is stopped you should have bending moments measurement points ?

Authors:

We have not yet developed a wind estimator that would work when the machine is not in power production. In fact, we expect some difficulties at very low or null rotational speeds, when the airfoils might be operating at large angles of attack, possibly in the presence of complex dynamic separation phenomena. We have updated the paragraph to better explain this point.

Q12 p17L10: “Fig. 11, suggests a small bias in the met-mast wind direction measurement and/ or that the wake is not developing exactly along the downstream direction.”

Also suggested by figure 10 with the dissymmetry between $V_{s,left}$, $V_{s,right}$?

Authors:

Yes, the slightly displaced wake (caused by bias in wind direction measurement or wake displacement) in Fig. 13 (formerly 11) may be also present in Fig. 12 (formerly 10). In the latter case, this is however difficult to assess with certainty.

Q13 P17L16: “the scatter ...”

It can also be attributed to the level of the atmospheric turbulence in the inflow, a comparison from std from met-mast and std of $V_{s,right}$ / $V_{s,left}$ may help to assess this point?

Authors:

We have now included the turbulence intensity in Fig. 12 (formerly Fig. 10) and discuss there its effect on wake development.

Q14 p18L25: “The larger fluctuations of the vertical shear compared to the horizontal one are probably caused by varying ambient inflow conditions.”

Depending on the mast instrumentation (sonic or vanes), this point can be assessed by the evaluation of the atmospheric stability and thus possible additional velocity fluctuations in the vertical direction.

Authors:

Unfortunately, we have no additional information and are unable to further comment on this aspect.

Q15:

P19-20: “This indicates that some of the scatter ...proposed method”

P20L4: “Clearly, this is simply a feature of the flow, and not of the method tested here.”

These sentences are very affirmative while there was no clear demonstration on that purpose. Clearly tendencies agree well with what is expected and the method gives interesting results. However, additional measurement points are needed to have an effective measure of the method accuracy in space (more points on the mast in the vertical direction, maybe a mast in the horizontal direction, and some topological analysis of the terrain ...).

Authors:

We have rephrased these sentences.

Q16 p19L4: “(...) waked by a second machine. This feature of the test site has been exploited for demonstrating the ability of the proposed local wind sensing technique to detect wake impingement.”

The measurements available on field test site is not able to perform a direct validation of the method, which would consist on a direct comparison between a full spatio-temporal description of the wind inflow (at least a 2D plan) with the estimated one. The demonstration is rather based on analysis from partially available measurements (mast, SCADA, azimuth, ...) completed with wake estimation from FLORIS. More specifically, there is no way to validate the horizontal shear (wake) with inflow measurements (only one point). Tendencies are clearly coherent to what we would expect, but a precise evaluation of the method accuracy (in time and space) is not feasible. The term “demonstrating” is therefore a bit strong here, especially for the wake detection.

Authors:

We have rephrased this sentence.

Minor corrections

C1: In equation 1a, V should be replaced by VTB and in equation 1b, V should be replaced by V_i

Authors:

The coefficients are defined with respect to the ambient uniform wind speed (same for the tip-speed-ratio and dynamic pressure later on). VTB and V_i are estimated through Eq. (2).

C2: Usual conventions for wind roses representations are: North corresponds to $0^\circ/360^\circ$, East to 90° , South to 180° and West to 270° . In figure 2, $0^\circ/360^\circ$ corresponds to South.

Authors:

Indeed we follow this convention. Note that Figure 2 includes arrows, to correctly indicate wind directions.

Referee comment 2 (RC2)

Thank you for this paper. I apologize up front that due to school closures and work hour impacts, this will be a brief review. That said, the paper is of high quality such that I have very little in the way of criticism. The paper follows a set of earlier papers (described in the introduction) which develop the methods tested in this paper, and evaluate it in aero-elastic, LES and wind tunnel

testing. The current paper tests the estimation approaches on a full-scale test site. The results are completely convincing. The presence of the nearby met mast offers a very good validation to compare estimation of speed, shear and wake position and the analysis is clear and direct to follow, the conclusions well-justified by the presented figures. Finally, the introduction and literature are well covered, and the paper put well in the context of the broader research areas which could utilize estimation like this. I checked the equations and didn't notice any obvious errors. Recommend accepting.

Authors:

Thank you for your positive review.

Small comments

- 1) Is the cone coefficient a standard value, or an innovation of an earlier paper in this series?

Authors:

The cone coefficient was introduced in one of our previous papers. This fact has now been clarified in the updated manuscript.

- 2) Section 3.6: "Using again the first 7 days of measurements, the azimuth bias was identified as $\psi_{bias} = 11.4$ deg. In the remainder of this work, the sector-effective wind speeds and the two shears are computed using the corrected azimuth signal $\psi_{corr} = \psi + \psi_{bias}$." This was interesting, as it reminds me off the offset value one might compute in the design of standard IPC controllers for 1P or 2P decoupling. Is this the same value?

Authors:

We are not familiar with the offset mentioned by the reviewer. The azimuth bias in this work is likely caused by a measurement bias and by having neglected blade dynamics (see also the discussion on this point above).

Referee comment 3 (RC3)

The manuscript entitled "Field testing of a local wind inflow estimator and wake detector" deals with the full-scale experimental validation of estimator concepts based on the use of the rotor as a wind sensor. The methods are based on the processing of the blade load fluctuations, and particularly the blade out-of-plane bending moments. Since 2010, the research team lead by Bottasso developed, improved and validated the concept of using the rotor as a wind sensor and the present paper is in line with this continuous process. It reaches a new step, by performing the demonstration and partial validation of the concept at full scale, on utility-scale wind turbines. The main challenges are then to obtain statistically converged, reliable and exploitable results when the boundary conditions of the experiments are non-controllable and partially known (onsite environmental and atmospheric conditions) and when the prototype is not specifically designed and equipped for R&D purpose experiments (utility-scale wind turbine). These aspects lead to the need for an extensive preparation of the database by using massive data pre-processing (ad-hoc calibrations and corrections, sample rejections, filtering, classification, etc.). In the present paper, these unavoidable pre-processing steps, as well as the actual data processing steps, are well argued,

described and illustrated. The obtained results are on general, well explained and prove the feasibility of the “WT as a wind sensor” concept. On the other hand, a lack of information on the experimental set-up and on the site description affect sometimes the reliability of the results interpretation, leading the authors to use too frequently “likely”, “would”, “seems to”, “could be due to”. Mainly, a better knowledge of the site properties (terrain and micrometeorology) can help in some interpretations. This can be provided a posteriori using geographical and meteorological databases and it is essential to add them to the manuscript.

Authors:

Thank you for your positive review and helpful comments. We have expanded the manuscript by adding more information on the experimental set-up and by improving the site description.

Major comments:

- A thorough description of the experimental set-up must be added: measurement device (anemometers, strain gages, etc.) descriptions (type, brand, accuracy, cut-off frequency, etc.)

Authors:

Please see the updated manuscript and our reply to the general comments of RC1.

- A thorough description of the site properties must be added: type of terrain surrounding the site (type of vegetation, associated roughness length), atmospheric boundary layer properties (wind rose, averaged power law and turbulence intensity at hub height for the studied wind directions, thermal stability encountered during the selected periods, etc.). If not findable by the measurement campaign itself, meteorological information can be extracted from global meteorology reanalysis database as MERRA2 or ERA5.

Authors:

We have included additional information in the manuscript and refer to Bromm 2017, which describes the same site with reference to another research study. We believe that the new description is sufficient for the scope of this work.

- §3.3 Reference inflow & Figure 3 : it is written that the wind speed is measured at three different heights on the met-mast but two of them are located at 2m of each other. Therefore, one cannot consider that one has three distinct values to assess the power law exponent, but only two. What is the consequence on the accuracy of the obtained power law exponent?

Authors:

The power law exponent can be estimated using only 2 measurement heights, as it depends on only two free parameters. The two measurements located at 2m of each other could be combined into one mean measurement without a significant change in the power law exponent estimation. This point has been added to the manuscript.

- Figures 7 and 8: The obtained values for the power law exponent (mainly between 0.2 and 0.4) are particularly high for such an open-field terrain, as it seems to be on the satellite picture. These values are usually encountered on rough to very rough terrains (forest or

city). Again, a better description of the terrain fetch and of the local atmospheric boundary layer properties would help to justify the results reliability.

Authors:

The site is not completely flat and open (see updated description). We also added a summary of the atmospheric conditions that were reported in Bromm 2017.

- Page 12, lines 9-10: “This difference could possibly be caused by a non-ideal power law inflow profile, leading to a biased met-mast reference shear, although a definitive explanation of this mismatch could not be reached with the present data set.”. I would recommend to make a sensitivity analysis on the power law exponent to the number and position of the used anemometers

Authors:

Please see the comment before the previous one. Also note that we include a reference to Møller 2020, which nicely shows such non-ideal power law profiles.

- Pages 12-13: “Considering that all wind directions are for un-waked met-mast and turbine, these results suggest the presence of a spatial shear variation, probably caused by the local vegetation.” Again, a better description of the terrain fetch and of the local atmospheric boundary layer properties would help to justify this assumption.

Authors:

The description of the site has been expanded, and this sentence has been updated.

- It is written on page 8, lines 4-5, “Measurements taken during yawing manoeuvres were also discarded, as additional induced loads can pollute the estimates”. On the other hand, on Figures 6 and 10, the wind direction progressively changes from 240_ to 200_ during 6 hours, and from 100_ to 175] in 12 hours, respectively. Yaw manoeuvres should appear during these periods. It sounds in opposition of the first statement. Could you please add the wind turbine orientation time series to these plots and explain how you did the data analysis during these periods?

Authors:

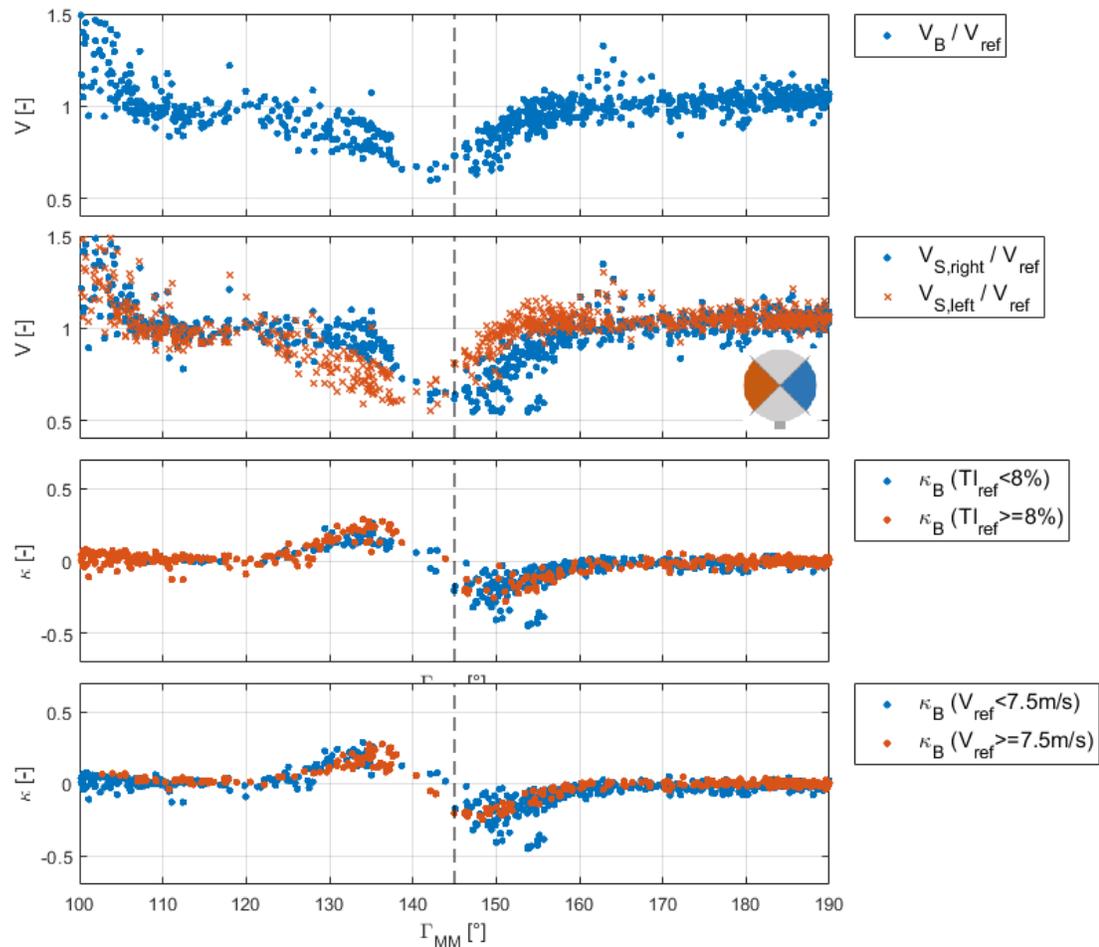
We updated the description on how the consecutive 10-min averages have been computed, and provided a clearer explanation of the effect of yaw maneuvers.

- Figure 11 : would it be possible to classify the results considering the incoming wind speed category (and so the wind turbine operating point). One could expect that the wake is more or less intense, depending on the wind turbine operating point and that the wake detector is more or less efficient.

Authors:

Below you can find a classification of the results in terms of turbulence intensity (higher turbulence should enhance wake recovery and therefore lead to less intense but wider wakes) and in terms of wind speed (note that there are almost no data points above rated wind speed for these wind directions). However, conclusions are difficult to obtain, perhaps due to the very limited amount of data.

As a side-note, please notice that the sign of the horizontal shear is now the opposite of the one of the original manuscript, for consistency with other publications.



- Page 17, lines 10-12: “the wake is not developing exactly along the downstream direction. Indeed, the latter is a well-known phenomenon observed in vertically sheared flow (Vollmer et al., 2016).” Yes, it is true for yawed wind turbines, or for un-yawed ones in very stable atmospheric conditions but cannot be considered as a universal explanation for the bias in the present results.

Authors:
We updated the text.

- Page 18, lines 24-25: “The larger fluctuations of the vertical shear compared to the horizontal one are probably caused by varying ambient inflow conditions.” It is not clear what this sentence means exactly. Could you elaborate more on these “varying ambient inflow conditions”? Again, a better knowledge of the local atmospheric boundary layer properties can help to justify some results.

Authors:
We rephrased this sentence.

- Conclusions: some conclusions are not new (i.e. “rotor-effective wind speed can be estimated from blade out-of-plane bending moments, with a quality that is nearly indistinguishable from the well-known torque-balance method”), since already drawn by previous papers from the same research team. What is new is to make the full-scale demonstration/validation of these different concepts.

Authors:

We have reformulated the conclusions.

Minor comments

- Page 3, line 17: remove A in the q formula

Authors:

Thank you.

- Page 4, line 3-4: “A rotor-effective wind speed can also be obtained from the blade-effective ones by simple averaging over all (three) blades”. One expects that the dynamics of the rotoreffective speed is quite low (cut-off frequency linked to the rotor diameter, whereas the dynamics of the blade-effective ones must be higher. Do you get the right rotoreffective speed dynamics by averaging the three blade-effective wind speeds?

Authors:

The polar inertia of the rotor is certainly much higher than the flap inertia of each blade, so it is indeed possible that the two estimators have different cutoff frequencies. However, we have not investigated this point in detail, nor this comparison between the two methods is very relevant for the scope of the present paper. Also note the new section “3.3 Estimator update frequency”, which shows that the wind estimation based on flapwise loads is capable of following relatively fast fluctuations of the inflow.

- Page 4, line 17-18 “the smaller inertia and high damping of this degree of freedom makes this more sophisticated approach superfluous”: Please add a reference to prove this statement.

Authors:

We have updated this paragraph.

- Page 5, figure 1: the reference framework (x,y,z) is not direct. Considering the naming convention in the downstream viewing direction, one assumes that x is in the downstream direction too. Then y, should be oriented on the left

Authors:

We have updated the reference frame. Note that we also changed the horizontal shear definition for consistency with other publications.

- Page 9, lines 7-8: add this information into the experimental set-up description

Authors:

We have updated the experimental set-up description.

- Figures 4& 5: should be written in the captions that it is after correction

Authors:

We have updated the caption of Fig. 6 (formerly 5) only as the V_{TB} in Fig. 5 (formerly 4) is not affected by corrections.

Revised version of the manuscript with highlighted changes

Field testing of a local wind inflow estimator and wake detector

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Abstract.

This paper presents the field validation of a method to estimate the local wind speed on different sectors of a turbine rotor disk. Each rotating blade is used as a scanning sensor that, travelling across the rotor disk, samples the inflow. From the local speed estimates, the method can reconstruct the vertical wind shear and detect the presence and location on an impinging wake shed by an upstream wind turbine. Shear and wake awareness have multiple uses, from turbine and farm control to monitoring and forecasting.

This validation study is conducted with an experimental data set obtained with two multi-MW wind turbines and a hub-tall met-mast. Practical and simple procedures are presented and demonstrated to correct for the possible miscalibration of sensors.

Results indicate a very good correlation between the estimated vertical shear and the one measured by the met-mast. Additionally, the proposed method exhibits a remarkable ability to locate and track the motion of an impinging wake on an affected rotor.

1 Introduction

Knowledge of the wind turbine inflow can ~~empower~~enable several applications. For example, a turbine controller can be improved when scheduled as a function of wind speed (Østergaard et al., 2007). Similarly, a farm controller benefits from knowledge of the atmospheric stability ~~,with~~because of its strong effect on wake recovery, and from an improved understanding of wake position (Vollmer et al., 2017) ~~,with~~because of its crucial implications on power output and loading. Apart from control applications, other usage scenarios include lifetime assessment and fatigue consumption estimation, which are clearly dictated by the inflow conditions experienced by each turbine (Ziegler and Muskulus, 2016). Moreover, wind farm power and wind forecasting, ~~site assessment for wind farm extensions~~post-construction site assessment, sector management triggered by wake detection for closely spaced turbines, and estimation of available wind farm power are all additional applications that can profit from knowledge of the inflow affecting each single turbine. Unfortunately, this information is not available on today's wind turbines that, as a consequence, operate "in the dark" based only on a limited awareness of the environment in which they are immersed.

Indeed, turbines are equipped with wind sensors, typically located on the nacelle or the spinner, which are used for aligning the rotor axis into the wind and for identifying whether the cut-in or cut-out wind speeds have been reached. Even though these measurements might be accurate enough for these simple tasks, the actual complexity of the turbine inflow remains

completely beyond the reach of such sensors. In addition, wind vanes and anemometers provide pointwise information, while wind conditions exhibit significant spatial variability not only at the large scale of the farm, as in off-shore plants (Peña et al., 2018) and at complex terrain sites (Lange et al., 2017; Schreiber et al., 2019), but also at the smaller scale of the individual turbine rotor disk (Murphy et al., 2019). More sophisticated measurements can be provided by lidars (Held and Mann, 2019) and other remote sensing technologies, which are however still costly and —being mostly used for assessment, validation and research— are not yet commonly used for production installations.

The concept of using the wind turbine rotor as a wind sensor has been proposed to improve wind condition awareness (Bottasso et al., 2010; Simley and Pao, 2016; Bertelè et al., 2017). In a nutshell, wind sensing uses the response of the rotor —in the form of loads, accelerations and other operational data— to infer the characteristics of the wind blowing on the turbine. Therefore, wind sensing is a sort of model inversion, where the response of the system is used to estimate the disturbance (in this case, the wind). The simplest and probably most widely used wind sensing technique is torque-balance estimation (Ma et al., 1995; Soltani et al., 2013). Thereby, turbine power or torque are used to estimate the rotor-effective wind speed by the power curve or power coefficient. The concept has been more recently extended to estimate other characteristics of the inflow, notably the wind directions and shears, as reviewed in Bertelè et al. (2017).

This paper considers the approach first formulated by Bottasso et al. (2018). Through an aerodynamic “cone” coefficient, this method uses the blade out-of-plane bending moment to estimate the local wind speed at the position occupied by a blade. The method is very similar to the torque-balance estimation of the wind speed, with the important difference that it produces a localized speed estimate instead of a rotor-effective one. The rotating blades therefore operate as scanning sensors that, travelling across the rotor disk, sample the local variability of the inflow. In turn, the local wind speed estimates are used for obtaining two key pieces of information on the inflow: the vertical shear, which is an important load-driver and an indicator of atmospheric stability, and the horizontal shear, which can be used to detect the presence and location of an impinging wake. Today, only a scanning lidar would be able to provide similar information on the inflow, albeit not exactly at the rotor disk —as done here, as the rotor itself is the sensor in this case— and with a very different level of complexity and cost.

The present method has some very interesting features. First, it is model-based, and therefore it does not necessitate of extensive data sets for its training. Second, it is based on an extremely simple model of the rotor (expressed through the cone coefficient), which can be readily computed from a standard aeroelastic model of a wind turbine. Third, the resulting estimator is in the form of a simple look-up-table that is computed off-line, resulting in an on-line on-board implementation of negligible computational cost. Fourth, when load sensors are already installed on the turbine for load-alleviating control or monitoring, this wind sensing technique requires no additional hardware, and therefore its implementation simply amounts to a software upgrade. The wind sensing method considered here has already been tested with ~~Blade Element Momentum~~ [blade element momentum](#) (BEM) aeroelastic simulations (Bottasso et al., 2018), large eddy simulations (Schreiber and Wang, 2018), and scaled wind tunnel tests (Campagnolo et al., 2017). Applications related to wake position tracking within a wind farm have been presented in Schreiber et al. (2016) and Bottasso and Schreiber (2018).

Goal of the present paper is to validate the wind sensing approach of Bottasso et al. (2018) in the field. To this end, the method is exercised on a data set obtained with two 3.5 MW turbines, one of which has two blades equipped with load sensors,

and a meteorological mast (met-mast). Since a perfect calibration of the sensors cannot always be guaranteed, another goal of the paper is to present and demonstrate simple and effective methods to correct the measurements and improve accuracy.

The paper is organized as follows. First, the formulation of the wind sensing method is reviewed, including the estimation of rotor-effective and sector-effective wind speeds, as well as of horizontal and vertical shears. Next, the experimental setup is described, including the site layout and the available measurements. The ~~results~~result section represents the core of the paper, and illustrates in detail the performance of the wind sensing technique. A first part of the analysis is concerned with the validation of the vertical shear estimates. Then, the attention is turned to the detection of wake impingement, which is studied by exploiting the waking induced at the site for some wind directions by a neighboring turbine. Finally, the effects of cross-flow are considered, demonstrating that the typical inevitable misalignments between turbine and wind vector do not pollute the estimates. Conclusions and an outlook on future work are given in the last section.

2 Methods

2.1 Rotor and blade-effective wind speed estimation

Considering a steady and uniform wind speed V , the power coefficient C_p and cone coefficient C_m ~~coefficients~~(as introduced in Bottasso et al. (2018)) are defined as

$$C_p(\beta, \lambda, q) = \frac{T_{\text{aero}}\Omega}{0.5\rho AV^3}, \quad (1a)$$

$$C_m(\beta, \lambda, q, \psi_i) = \frac{m_i}{0.5\rho ARV^2}, \quad (1b)$$

where β is the blade pitch angle, $\lambda = \Omega R/V$ the tip speed ratio, Ω the rotor speed, R is the rotor radius and $A = \pi R^2$ the swept disk area, ρ is the air density and ~~$q = 1/2\rho AV^2$~~ $q = 1/2\rho V^2$ the dynamic pressure, while T_{aero} is the aerodynamic torque. The azimuthal position of the i th blade is given by ψ_i , while m_i is its out-of-plane root bending moment. Coefficients C_p and C_m are readily computed using an aeroelastic model of the turbine, today customarily based on a BEM method that, in the present work, is the one implemented in the FAST code (Jonkman and Jonkman, 2018).

Different approaches to estimate wind speed from the power coefficient are reviewed in detail by Soltani et al. (2013). However, following Bottasso et al. (2018), here we use both the power and the cone coefficients: while the former yields a rotor-effective wind speed (i.e., an average quantity over the entire rotor disk), the latter is used to sample the *local* wind speed at the azimuthal position occupied by a blade. A local radial sampling would require a more sophisticated approach and additional sensors along the blade span, with increased complexity and cost. Given coefficients C_p and C_m computed for a reference air density ρ_{ref} , look-up-tables (LUTs) are generated that return wind speeds given measured loads T_{aero} and m_i , blade pitch β , rotor speed Ω and air density ρ . Noting the rotor-effective wind speed estimated from the torque balance

equilibrium as V_{TB} and the one from blade loads as V_i , the inversion of Eqs. (1) yields

$$V_{TB} = \text{LUT}_{C_p}(\beta, \Omega, T_{\text{aero}}, \frac{\rho}{\rho_{\text{ref}}}), \quad (2a)$$

$$V_i = \text{LUT}_{C_m}(\beta, \Omega, \psi, m_i, \frac{\rho}{\rho_{\text{ref}}}). \quad (2b)$$

Instead of the simple non-linear model inversion adopted here for simplicity, more sophisticated methods can be used, for example based on Kalman filters or input observers (Soltani et al., 2013), which may slightly improve the results at the cost on an increased complexity. A rotor-effective wind speed can also be obtained from the blade-effective ones by simple averaging over all (three) blades:

$$V_B = 1/3 \sum_{i=1}^3 V_i. \quad (3)$$

Although in a non-uniform inflow the two rotor-effective speeds V_{TB} and V_B are not necessarily identical, they are in practice very similar, as shown later on in the results section. The redundancy offered by V_{TB} and V_B offers opportunities for sensor calibration, as also described later on.

In Eq. (2a), T_{aero} is computed from the dynamic torque balance equilibrium $J\dot{\Omega} = T_{\text{aero}} - T_{\text{meas}} - T_{\text{loss}}$, where J is the total rotor, drive-train and generator rotational inertia, while $\dot{\Omega}$ is the rotor acceleration and T_{meas} is the measured torque at the generator. Mechanical losses in the ~~whole~~ drive-train are taken into account by the term T_{loss} (Soltani et al., 2013). Here, for the accuracy of the wind speed estimate, a dynamic model is used to compute the aerodynamic torque. In fact, the energy converted into rotor acceleration or deceleration is typically large, given the large rotational inertia of the system.

A simpler approach is used for Eq. (2b), where the blade dynamic equilibrium is neglected. This way, the out-of-plane bending moment is directly set to the corresponding measured load, i.e. $m_i = m_{i,\text{meas}}$, where $m_{i,\text{meas}}$ is provided by blade-mounted strain gages, optical sensors or similar devices. ~~Although even in this case one could include~~ The introduction of a flapwise dynamic equilibrium equation, similarly to what done for the torque balance case, the smaller inertia and although certainly possible, would not be straightforward because of the coupling with the tower fore-aft motion and the need to estimate additional relevant modeling parameters. Therefore, in the interest of simplicity and practical applicability, the phase delay caused by the dynamic response of the blade was taken into account by estimating an azimuth bias in the response, as described in §3.7. Due to the high damping of this the flap degree of freedom makes this more sophisticated approach ~~superfluous~~, even the present simplified method seems able to provide accurate results, as also shown in previous simulation studies (Bottasso et al., 2018).

The power and cone coefficients of Eqs. (1) are computed when the rotor axis is aligned with the ambient wind direction. Hence, strictly speaking, Eqs. (2) can be used to estimate wind speeds only in the same aligned conditions. However, this is typically not the case in practice, as turbines are often misaligned with respect to the wind by several degrees. It will be shown later on that moderate misalignments do not significantly affect the estimation of wind speeds, and that the effects of larger misalignments can be corrected for.

2.2 Sector-effective wind speed estimation

An average wind speed over a rotor sector can be readily computed by averaging the blade-effective estimate V_i between two azimuthal angles ψ_a and ψ_b :

$$V_S = \int_{A_S} V_i(\psi) dA_S, \quad (4)$$

- 5 where $A_S = (\psi_b - \psi_a)R^2/2$ is the area of the sector. A new sector-effective speed estimate is generated as soon as a blade leaves the sector.

The sector width can be arbitrarily defined. Figure 1 shows the case of the four equally-sized 90-degree-wide sectors used in this work, yielding the four sector-effective wind speed estimates $V_{S,\text{left}}$, $V_{S,\text{right}}$, $V_{S,\text{up}}$, and $V_{S,\text{down}}$. Clearly, a finer sampling of the inflow over the rotor disk can be achieved by using smaller sectors. With three blades, each of the sectors is updated
 10 three times per rotor revolution. With one single instrumented blade, the update frequency reduces to once per revolution. [The effects of sampling frequency on the local wind speed estimates is analyzed in §3.3.](#)

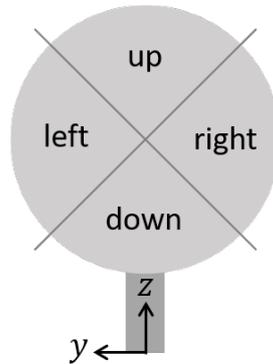


Figure 1. Wind turbine rotor disk with sectors and inflow coordinate system. This naming convention is in the downstream viewing direction.

It was shown in Bottasso et al. (2018) that, for a linear inflow shear and a 90-degree-wide sector, the sector-effective wind speed corresponds to the inflow speed at a distance of approximately $2/3R$ from the hub center.

2.3 Shear estimation

- 15 The vertical wind shear is modeled as a power law profile with exponent α , while the horizontal shear is assumed to be linear with coefficient κ . The inflow wind speed V can therefore be written as

$$V(z, y) = V_H \left(\left(\frac{z}{z_H} \right)^\alpha + \kappa \frac{y}{R} \right), \quad (5)$$

where z and y are the vertical and lateral coordinates, respectively, with origin at the turbine foundation, as shown in Fig. 1. Furthermore, V_H is the speed at the hub center, which is located at $z = z_H$ and $y = 0$.

Assuming that the sector-effective speed samples the inflow profile at $\pm 2/3R$ along the z and y axes, according to Bottasso et al. (2018), the shear coefficients can be estimated from the sector-effective wind speeds by using Eq. (5), which yields

$$\alpha_B = \ln \left(\frac{V_{S,\text{up}}}{V_{S,\text{down}}} \right) \left(\ln \left(\frac{z_H + 2/3R}{z_H - 2/3R} \right) \right)^{-1}, \quad (6a)$$

$$\kappa_B = \frac{3}{2} \frac{V_{S,\text{right}} - V_{S,\text{left}}}{V_{S,\text{right}} + V_{S,\text{left}}} \frac{V_{S,\text{left}} - V_{S,\text{right}}}{V_{S,\text{left}} + V_{S,\text{right}}}. \quad (6b)$$

5 This way, the vertical shear is estimated by using the top and bottom sectors, while the horizontal shear by using the two lateral sectors. One could also use all four sectors together, and solve Eq. (5) simultaneously in a least squares sense for both α_B and κ_B . However, this does not lead to appreciable differences in the results of this paper.

The vertical shear estimate is validated in this work by comparison with an IEC-compliant met-mast, reaching up to hub height. However, shears computed over the whole rotor or over only its lower half can be significantly different; therefore, one should not compare the full-rotor shear obtained by Eq. (6a) with a lower-half-rotor shear provided by a hub-tall met-mast. To address this issue, a *lower-half-rotor shear estimate* is defined here. This quantity is computed by first averaging the two lateral (left and right) sectors to provide a hub-height speed that, together with the lower sector, is then used to estimate the shear on the sole lower portion of the rotor disk. Using Eq. (5), the lower-half-rotor shear estimate is obtained as

$$\alpha_{\text{lower},B} = \ln \left(\frac{V_{S,\text{left}} + V_{S,\text{right}}}{2V_{S,\text{down}}} \right) \left(\ln \left(\frac{z_H}{z_H - 2/3R} \right) \right)^{-1}. \quad (7)$$

15 3 Results

3.1 Experimental setup

This validation study is conducted using an eno114 wind turbine manufactured by eno energy systems GmbH. This turbine, in the following named WT1, has a rated power of 3.5 MW, a rotor diameter $D = 114.9$ m, a hub height $z_H = 92$ m ~~and it is~~ . Two of the blades are equipped with blade load sensors ~~on two of its three blades. The turbine is installed close to Brusow (Germany), in a flat terrain site approximately~~ , mounted in close proximity of the root and capable of measuring the two flapwise and edgewise components.

The site is located approximately 10 km south of the Western Baltic Sea ~~, in a slightly hilly terrain without abrupt changes in elevation, approximately 1 km east of the village of Brusow (Germany), as described by Bromm et al. (2018). During the time of the year of the test campaign, the site is~~ characterized by prevailing westerly wind directions ~~, mostly neutral atmospheric stratification, and wind veers between 0 and 10 deg (Bromm et al., 2018).~~

At the site, a second turbine of the same type, named WT2, and a meteorological mast are also installed. Figure 2 shows a satellite image of the site, including the waking directions and distances among the three installations. WT1 is downstream of the met-mast for a wind direction $\Gamma_{\text{MM} \rightarrow \text{WT1}} = 192.5^\circ$ $\Gamma_{\text{MM} \rightarrow \text{WT1}} = 192.5$ deg, while WT1 is waked by WT2 for $\Gamma_{\text{WT2} \rightarrow \text{WT1}} = 145^\circ$ $\Gamma_{\text{WT2} \rightarrow \text{WT1}} = 145$ deg. The met-mast is equipped with ~~anemometers at three~~ anemometers at three ~~a wind vane (manufactured by Thies GmbH, catalogue number 4.3150.00.212) installed at 89.4 m and three cup anemometers (also manufactured by Thies~~

[GmbH, catalogue number 4.3351.00.000](#)) at different heights, the topmost reaching 91.5 m, which is just half a meter shy of the turbine hub height. The relevant heights of the turbine and met-mast [anemometers](#) are shown in Fig. 3.

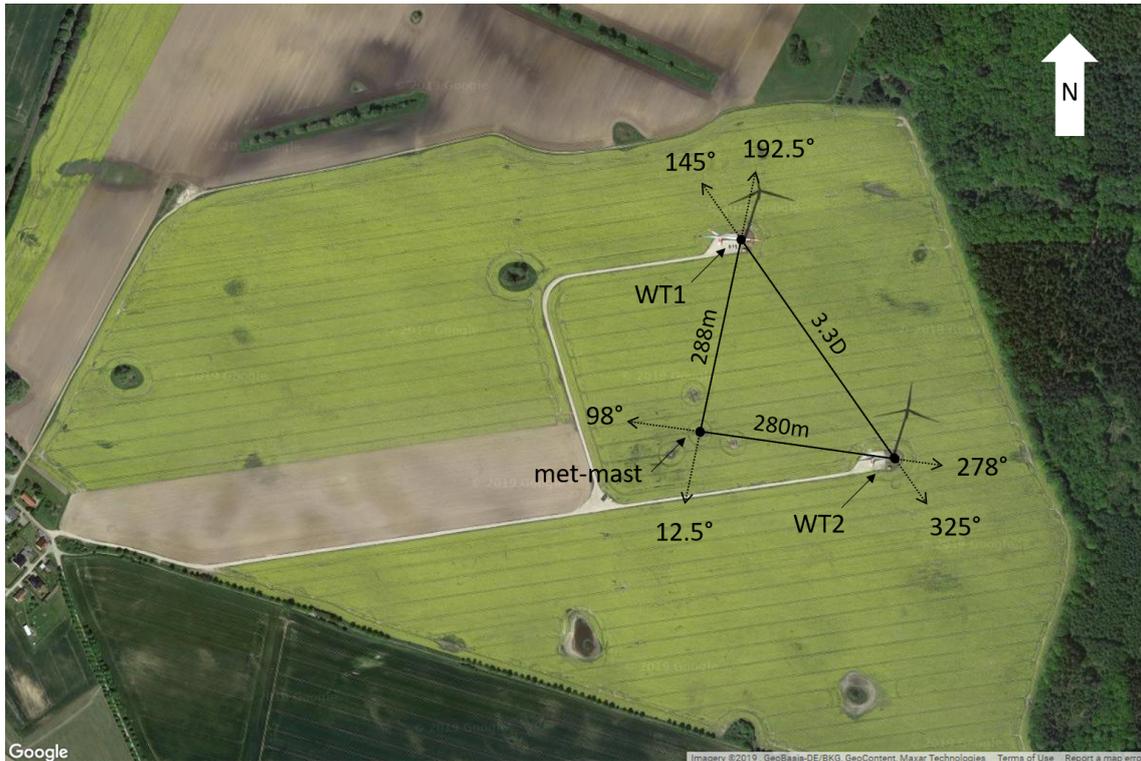


Figure 2. Satellite image with WT1, WT2 and met-mast, including waking directions and distances ([© Google Maps](#)).

3.2 Measurements

Synchronized measurements of WT1 and the met-mast were made available by the turbine manufacturer and operator for 41 days from October 19 to November 29, 2017. The measurements include main shaft torsion T_{meas} , blade root out-of-plane bending moments for two blades $m_{1,2}$, rotor speed Ω , blade pitch β , and rotor azimuth position ψ . The air density ρ was computed by the ideal gas law using measured air pressure and temperature. Met-mast measurements include wind speed $V_{\text{MM},1-3}$ at the three heights $z_{\text{MM},1-3}$, and wind direction Γ_{MM} at ~~the single height~~ $z_{\text{MM},2}$ [89.4 m](#).

All measurements ~~are~~ [were](#) sampled at 10 Hz. To eliminate higher frequency turbine dynamics and measurement noise, the rotor speed and torque signals were low pass filtered using a fifth order Butterworth filter with a -3 db cut-off frequency of 6 rpm.

The long-term average readings of the two blade load sensors are expected to be equal. However, when comparing the mean sensor values for any of the available days, the relative difference between the two blades was found to be between 4.8 and 5.8%, whereas the absolute differences varied between -100 and -300 kNm. This mismatch between the two blades

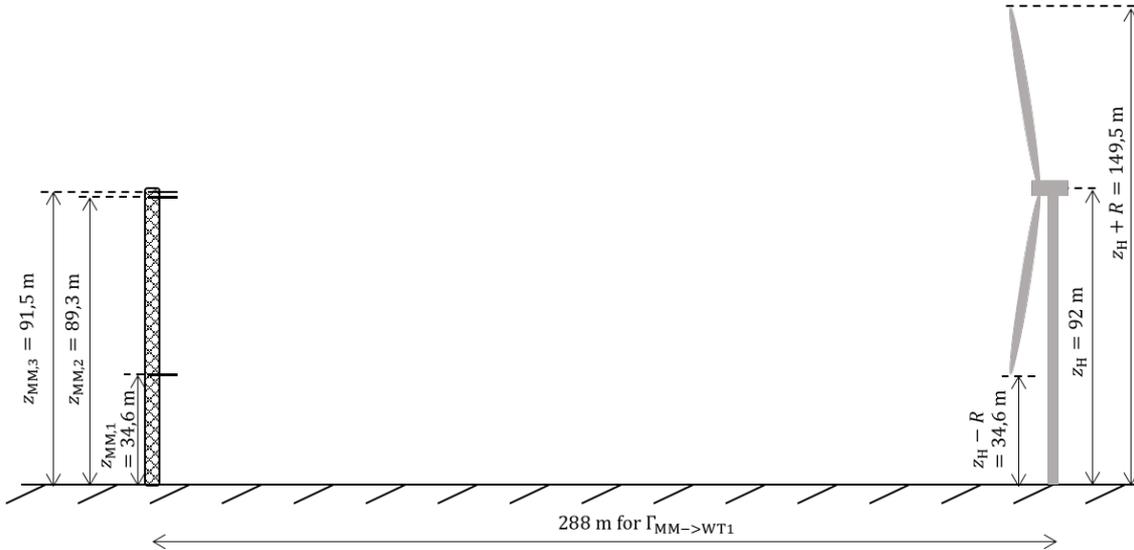


Figure 3. Sketch (to scale) of met-mast and WT1 with relevant dimensions.

suggests a consistent ~~miscalibration of the sensors. To correct for this, the~~ measurement error of one or both sensors. The cause for this error could not be ascertained, but might be due to miscalibration, sensor drift, or pitch misalignment. As an exact determination of the root reason of such inconsistencies is often difficult in a field environment (Bromm et al., 2018), a cause-independent correction method was used here. The first 24 hours of data were used to identify a scaling factor $s = 0.0274$ such that $\bar{m}_1(1 + s) = \bar{m}_2(1 - s)$, where (\cdot) indicates a mean value. This scaling factor was then used to correct the sensor readings for the whole data set. For a long term implementation, a similar correction could be applied periodically to compensate time drifts. Notice that this scaling simply ensures consistent measurements between the two sensors, but not their absolute accuracy, which is corrected later ~~on by comparison with in §3.6 by comparison between~~ the rotor-effective wind speed speeds V_{TB} and V_B . In fact, as ~~this quantity is based on an independent set of measurements through the torque balance equation, it provides for~~ these two quantities are based on independent measurements (torque and blade loads), they provide an opportunity to calibrate ~~the blade load sensors one or the other sensor.~~

The data set was filtered, retaining only measurements corresponding to normal turbine operation with pitch and rotor speed within the LUT limits (see ~~Sect. §3.5~~). Measurements taken during yawing manoeuvres were also discarded, ~~as additional induced loads can pollute the estimates.~~ In fact, yaw generates additional loads on the blades that would be erroneously interpreted by the observer, resulting in a pollution of the wind estimates. For an observer to accurately estimate wind even during yaw maneuvers, yaw-induced loads could be pre-computed and stored into a look-up table; during operation, one could interpolate within the table in terms of the current yawing rate and possibly wind speed (in case also yaw-induced aerodynamic loads, in addition to the inertial ones, need to be taken into account), and remove the resulting loads from the measured ones. This procedure was however not tested in this work, and therefore yaw maneuvers were eliminated from the data set. After each discarded measurement, an interval of ~~± one~~ one minute for the estimator re-initialization was accounted for.

The statistical analysis reported below is conducted with 10-minute averages—, which are standard in several wind energy applications. However, higher frequency estimates are indeed possible, as shown in §3.7. Of the initial data set, a total of 4,279 consecutive 10-minute quantities were obtained, representing approximately 30 days of operation.

3.3 Estimator update frequency

- 5 The sampling rate of the sector-effective wind estimator varies depending on rotor speed and the number of instrumented blades. For the present case, where only two blades are equipped with load sensors and the rotor speed varies between 5 and 12 rpm, the wind speed estimate update frequency varies approximately between 0.17 and 0.4 Hz. Notice that, since only two out of three blades are instrumented, the update frequency is not constant—even at constant rotor speed.

10 To quantify the effects of a limited update frequency, Fig. 4 shows the met-mast-measured shear coefficient. The solid black line represents the shear computed based on the signals provided by the cup anemometers at a 10 Hz sampling frequency. The red dashed line reports that same signal downsampled at 0.17 Hz, which is the estimator update frequency for low rotational speeds. A comparison between the two curves shows that even this slowest update frequency is high enough to capture the most energetic fluctuations of the inflow.

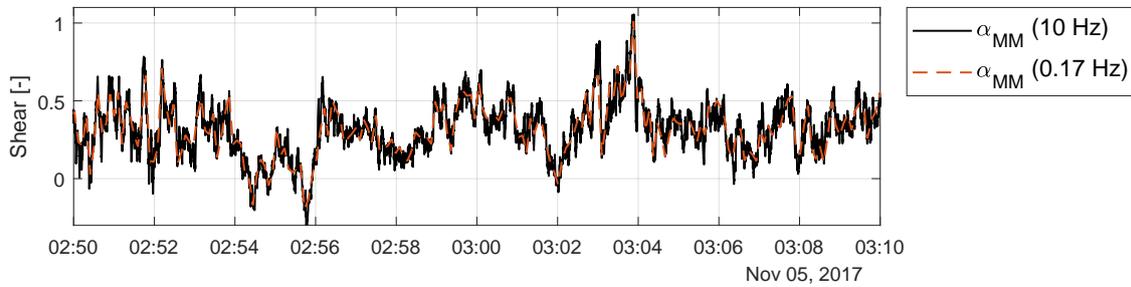


Figure 4. Time series of the met-mast-measured shear coefficient, at the original acquisition frequency of the cup-anemometers (10 Hz) and downsampled at 0.17 Hz, which is the sector-effective wind estimation frequency for low rotor speeds.

3.4 Reference inflow

- 15 The ambient inflow measured by the met-mast is assumed to obey the vertical power law given by Eq. (5). Consequently, the met-mast-measured hub-height reference speed V_{ref} and power exponent α_{MM} were computed as best fits of the mast speed measurements at the three different available heights, i.e.

$$(V_{\text{ref}}, \alpha) = \arg \min_{V_{\text{ref}}, \alpha} \sum_{i=1}^3 (V_{\text{PL}}(z_{\text{MM}, i}, V_{\text{ref}}, \alpha) - V_{\text{MM}, i})^2. \quad (8)$$

Only two measurements at two different heights are strictly necessary in order to compute the two parameters of the power law V_{ref} and α . In the present case three measurements are available, although the highest two anemometers, being only about 2 m apart, essentially provide the same information.

Depending on wind direction, the met-mast is located up to 288 meters upstream of WT1, as shown in Fig. 2 for $\Gamma_{\text{MM} \rightarrow \text{WT1}}$.

- 5 To synchronize met-mast and turbine measurements, assuming Taylor’s frozen turbulence hypothesis, each 10-minute met-mast measurement was time-shifted by $\Delta t = s_{\text{MM} \rightarrow \text{WT1}} / V_{\text{ref}}$, where $s_{\text{MM} \rightarrow \text{WT1}}$ is the downstream distance from met-mast to WT1.

3.5 Look-up-table implementation

10 An aeroelastic model of the turbine was provided by the turbine manufacturer, implemented in the software FAST (Jonkman and Jonkman, 2018). To compute the power and cone coefficients of Eq. (1), a total of 10,626 dynamic simulations were performed in steady and uniform wind conditions for all combinations of $\beta \in [0 : 1 : 20]^\circ$, $\beta \in [0 : 1 : 20]$ deg, $\Omega \in [3 : 0.5 : 14]$ rpm and $V \in [1 : 1 : 22]$ m/s, which took just a few hours on a standard desktop PC. Eliminating the tower and drive-train dynamics, a converged periodic response was achieved in three rotor revolutions.

15 Considering the last revolution, the power coefficient was computed from the mean torque, while the cone coefficient was obtained from the blade root out-of-plane bending moment of one of the blades as a function of ψ . The look-up-tables were compiled, for each β , Ω and —if applicable— ψ , by computing speed as a function of load, ~~including the cases where the blade is partially or fully stalled~~. If the blade is stalled or partially stalled, the speed-load relationship is non-monotonic. When this happens, the rotor-effective wind speed V_{TB} of Eq. (2a) can be used to resolve the indeterminacy and identify the correct speed corresponding to the measured load.

20 3.6 Validation of rotor-effective wind speed estimation

First, the rotor-effective speed estimates V_{TB} (computed through the torque balance equilibrium by Eq. (2a)) and V_{B} (computed using blade bending moments by Eq. (3)) are compared to each other and to the reference met-mast speed given by Eq. (8). A direct comparison between V_{TB} and V_{B} revealed that the latter provides systematically slightly higher wind speeds than the former. This discrepancy may be caused by ~~improper blade load sensor calibration (see Section 3.2)~~ sensor drift, miscalibration,
25 pitch misalignment and/or deficiencies of the simulation model used to compute the aerodynamic coefficients. Unfortunately, the root causes of the discrepancy could not be determined within the scope of the present work, nor the simulation model could be systematically validated; this is probably the norm rather than the exception also in many practical cases when working in the field. To pragmatically correct these sources of estimation bias, all speed estimates (V_{B} , $V_{\text{S,left}}$, $V_{\text{S,right}}$, $V_{\text{S,up}}$ and $V_{\text{S,down}}$) in the remainder of the paper ~~are were~~ scaled by a factor $c = 0.928$. This scaling ensures the best correlation between V_{B} and
30 V_{TB} , and was identified based on the first 7-seven days of measured data. Note that a direct scaling of the load measurements is also possible and potentially even more accurate.

It is worth pointing out that the redundancy of the two estimates V_{B} and V_{TB} offers the opportunity to ensure the consistency between different sets of sensors (the ones measuring blade loads and the ones providing rotor torque). For example, here the

torque sensors were properly calibrated, as indicated by the independent measurements of the met-mast, while the blade load sensors were not. Therefore, the redundancy was used to calibrate the load sensors against the torque ones. Similar recalibration procedures might be used also in situations ~~were~~ where a met-mast is not available, if one can ensure that at least one set of sensors is properly calibrated.

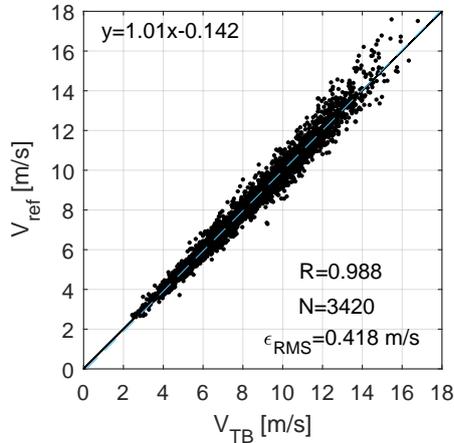


Figure 5. Torque-balance-based rotor-effective wind speed V_{TB} (Eq. (2a)) vs. met-mast reference wind speed V_{ref} (Eq. (8)).

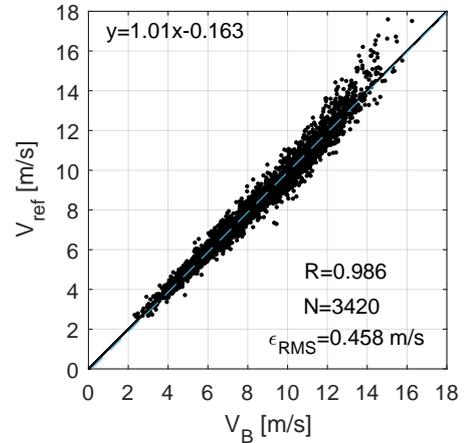


Figure 6. ~~Bending-load-based~~ Corrected bending-load-based rotor-effective wind speed V_B (Eq. (3)) vs. met-mast reference wind speed V_{ref} (Eq. (8)).

- 5 After correction, a comparison between met-mast reference speed V_{ref} and torque balance estimates V_{TB} and V_B is shown in Figs. 5 and 6, respectively. These results include only 3,420 data points where the met-mast wind direction lies between ~~$\pm 80^\circ$~~ 180 and 337.5 deg, to avoid conditions where the turbine or the met-mast operate in the wake of either WT1 or WT2 (assuming a ~~$\pm 35^\circ$~~ ± 35 deg margin). The Pearson correlation coefficient R is approximately equal to 0.99, while the root mean squared error is $\epsilon_{RMS} \approx 0.44$ m/s and the linear best fit ($y = ax + b$) has a slope $a = 1.01$ and an offset $b \approx -0.15$ m/s.
- 10 These results indicate that, after calibration, the two methods correlate well with the (approximate) ground truth provided by the met-mast, and that both yield very similar estimates.

3.7 Validation of vertical shear estimation

- After discarding waked conditions from turbine WT2 (with a ~~$\pm 35^\circ$~~ ± 35 deg margin), an analysis of the long-term mean horizontal shear revealed it to be non-zero. This finding is in contrast with expectations. In fact, while for a narrow wind
- 15 direction sector some horizontal shear due to local orography or vegetation can be expected, such effects should disappear considering the complete wind rose.

This behavior can be explained by a possible bias in the measurement of the azimuthal position of the rotor, which has the consequence of generating a non-zero horizontal shear and reducing the vertical one. In addition, another effect should

be considered: as no blade dynamics were included in the model (see Sect. 2.1), the response of the blade is assumed to instantaneously follow a wind speed change. This is in reality not true, and the actual response will have a phase delay, which appears as yet another source of azimuthal bias.

The expected behavior of the horizontal shear can be used for eliminating these effects. In fact, enforcing a null long-term average horizontal shear corrects both for azimuth sensor bias and for having neglected blade dynamics. To this end, the vertical and horizontal shears were rotated by ψ_{bias} , until a null mean horizontal shear was obtained. Accordingly, the mean vertical shear also reached its maximum. Using again the first 7-seven days of measurements, the azimuth bias was identified as $\psi_{\text{bias}} = 11.4^\circ$ $\psi_{\text{bias}} = 14.8 \text{ deg}$. In the remainder of this work, the sector-effective wind speeds and the two shears are computed using the corrected azimuth signal $\psi_{\text{corr}} = \psi + \psi_{\text{bias}}$.

The effects of blade dynamics would be more precisely rendered by a rotor-speed-dependent azimuth bias. In fact, by repeating the shear rotation for binned values of the rotor speed, a clear bias/rotor speed correlation was observed, with bias values in the range between about 12 and 19 deg. In addition, other effects could cause the azimuth bias to drift over time; indeed, a bias of 16.3 deg was found by using the last seven days of data, a slightly different value than the one obtained using the first seven days. However, these slight variations of the bias and its variability with rotor speed have only a very limited effect on the quality of the results. Therefore, for simplicity, it was decided to use the constant average value of 14.8 deg.

As previously discussed, the reference inflow profile measured by the met-mast ~~through with~~ Eq. (8) only includes measurements up to hub height. Accordingly, the load-based lower-half-rotor vertical shear $\alpha_{\text{lower,B}}$ (computed by Eq.(7) in terms of the two horizontal and the bottom sectors) is the only shear that can be validated with respect to met-mast measurements.

A 12-hour excerpt from the complete set of results is shown in Fig. 7, where 10-minute means of measurements and estimates are provided as functions of time. Notice that the data points are not equally spaced because of the elimination of yawing maneuvers and other conditions not accounted for in the LUTs.

The top subplot shows the wind direction Γ_{MM} measured at the met-mast and the turbine yaw orientation γ_{WTI} ; the direction for which the met-mast is directly upstream of the sensing turbine is $\Gamma_{\text{MM} \rightarrow \text{WTI}} = 192.5^\circ$ $\Gamma_{\text{MM} \rightarrow \text{WTI}} = 192.5 \text{ deg}$, and it is shown by a horizontal solid line.

The second subplot from the top shows the reference wind speed V_{ref} measured at the met-mast, together with the torque-balance V_{TB} and blade-load-based V_{B} rotor-effective speeds. As already noticed, both methods provide very similar results; in addition, especially for wind directions where mast and turbine are nearly aligned, both follow the reference very closely.

The third subplot from the top shows again the met-mast reference wind speed at hub height (solid line) and the one at $z_{\text{H}} - 2/3R$ (dashed line). The respective load-based estimates are indicated with a blue solid line and \bullet symbols for the hub height-hub-height speed, and with a red solid line and \times symbols for the lower-height-lower-height speed. Both estimates correlate well with their respective references, especially when mast and turbine are aligned. The small rotor icon shows, using the color code of the subplot, the two horizontal sectors (used to estimate the hub height wind speed $1/2(V_{\text{S,left}} + V_{\text{S,right}})$) and the lower sector.

The last subplot finally shows the mast vertical shear α_{MM} and the load-based estimate $\alpha_{\text{lower,B}}$, computed based on the data shown in the third subplot using Eq. (7). Except for some small underestimation and noise, the load-based shear follows

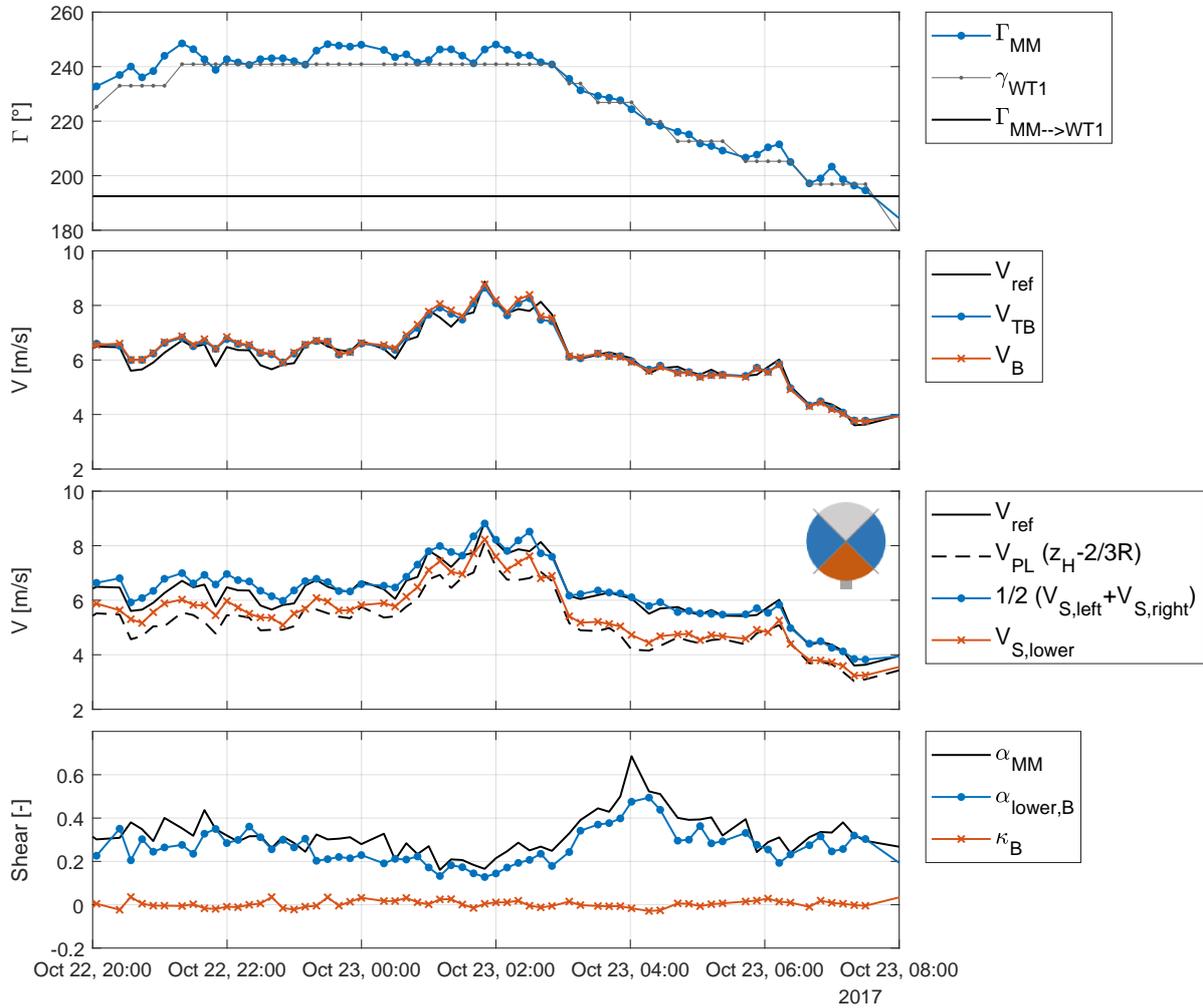


Figure 7. Time series reporting met-mast wind direction [and turbine yaw orientation](#) (top subplot), met-mast and estimated rotor-effective wind speeds (second subplot), speeds at different heights (third subplot), and met-mast and estimated vertical and horizontal shears (bottom subplot).

the reference quite accurately. The load-based horizontal shear κ_B is also reported in the same figure. Although no met-mast reference is available in this case, as expected the horizontal shear is always essentially null.

Figure 8 shows the correlation between the lower-half-rotor shears $\alpha_{\text{lower},B}$ and α_{MM} . Only wind directions from ~~190°~~ 190 up to 200 deg are included in the figure, resulting in $N = 155$ 10-minute data points. These conditions contain the direction where the met-mast is directly upstream of WT1. The Pearson correlation coefficient is $R = 0.92$. The shear is underestimated with respect to the met-mast reference by a factor $1/a = 0.88$, obtained by the linear best fit ($y = ax + b$) shown in the figure with a blue dashed line. By looking at the third plot from the top in Fig. 7, a comparison of the wind speed at hub height and at $z_H - 2/3R$ with their respective met-mast references indicates that the former is quite accurate, while the latter has a small positive bias. This difference could possibly be caused by a non-ideal power law inflow profile (Møller et al., 2020), leading to a biased met-mast reference shear, although a definitive explanation of this mismatch could not be reached with the present data set. Figure 9 shows the correlation between the full-rotor shear $\alpha_{\text{lower},B}$ and the lower-half-rotor shear α_{MM} . As the two shears are computed over two different vertical distances, their correlation is lower than in the case of Fig. 8, as expected.

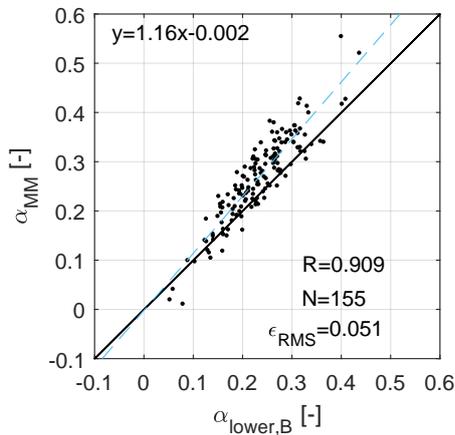


Figure 8. Correlation between the lower-half-rotor vertical shear $\alpha_{\text{lower},B}$ and the met-mast shear (up to hub height) α_{MM} , for wind directions from ~~190°~~ 190 to 200 deg.

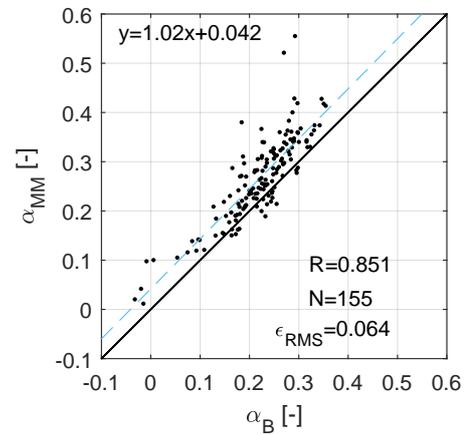


Figure 9. Correlation between the rotor-equivalent (full rotor) vertical shear α_B and the met-mast shear (up to hub height) α_{MM} , for wind directions from ~~190°~~ 190 to 200 deg.

A more complete overview of the results, including a broader range of wind directions, is shown in Fig. 10. The x -axis reports wind directions from ~~180° to 340°, in 10°-wide~~ 180 to 340 deg, in 10 deg-wide bins. All results of Fig. 8 fall in the second bin from the left. The number of available measurements N within each bin is shown in the first subplot from the top. The second subplot shows the Pearson correlation coefficient R , between the met-mast reference α_{MM} and the load-based shear estimate $\alpha_{\text{lower},B}$. Here and in the other plots, a blue solid line indicates results for the lower-half-rotor shear, while a red dashed line is used for the full-rotor shear. The best correlation is achieved for the wind direction where the met-mast is

directly upstream of the turbine ($\Gamma_{MM \rightarrow WT1} = 192.5^\circ$ $\Gamma_{MM \rightarrow WT1} = 192.5$ deg). For the same wind direction bin, also the minimum root mean squared error is achieved, as shown in the third subplot from the top. Considering that all wind directions are for unwaked met-mast and turbine, these results suggest the presence of a spatial shear variation, probably caused by the local vegetation -and/or the village in the west that is partially visible in Fig. 2. This interpretation is also confirmed by the last two subplots, which show the linear best fit coefficients a and b . For wind directions up to 235° 235 deg, the slope coefficient a achieves values between ~~1.01 and 1.16~~ 1.02 and 1.18, increasing up to ~~1.64~~ 1.67 in the remaining wind directions. The constant b is nearly zero for all wind direction values.

Looking at the plots, it appears that the full-rotor shear differs from the lower-half-rotor shear, as already reported by Murphy et al. (2019) and as also observed earlier here in Fig. 8. The validation of the full-rotor shear estimated by the proposed method would necessitate a met-mast reaching the rotor top height or a velocity-azimuth display (VAD) lidar, which however were not available ~~in-for~~ the present research. Nonetheless, the results obtained for the lower-half-rotor shear appear to be very encouraging, and there is no technical reason why similar results should not be achievable for shear estimates over the entire rotor disk.

Finally, the effects of a higher temporal resolution are considered. Figure 11 compares the 10 Hz lower-half-rotor vertical shear to the met-mast reference; this figure is therefore similar to the last subplot in Fig. 7, which was however obtained with 10-minute averages. Within the 20 minutes considered in the figure, the wind direction was approximately constant and equal to 190 deg, resulting in the met-mast being 2D directly upstream of the turbine, while the wind speed was approximately equal to 7 m/s. Based on the wind speed, the met-mast signal was time-shifted assuming Taylor's frozen turbulence hypothesis. The plot shows that the load-based estimate $\alpha_{lower,B}$ follows the main trends of the met-mast reference α_{MM} . There are however discrepancies at the higher frequencies. It is not possible to conclusively determine the causes of these differences based exclusively on the available data. However, the non-colocation of the measurements might clearly be among the reasons. For example, the spike of the met-mast shear at 03:04 is not visible in the load signals, which might indicate a local turbulent fluctuation at one of the met-mast anemometers not rigidly convecting downstream to the turbine rotor.

3.8 Validation of wake detection

As no measured reference for the horizontal shear was available for this study, the wake of the second turbine was used for a qualitative validation. This wake interference study nicely illustrates the very interesting wake detection capabilities of the proposed method.

Figure 12 reports a time series corresponding to 12 hours of operation, which experienced wind direction changes from approximately ~~100° to 180°~~ 100 to 180 deg. This data subset includes a significant duration where WT1 is waked by WT2. The first subplot from the top shows the met-mast wind direction Γ_{MM} and turbine yaw orientation γ_{WT1} , where the waking direction $\Gamma_{WT2 \rightarrow WT1}$ is reported as an horizontal solid line (cf. also Fig. 2). The second subplot shows the reference met-mast wind speed V_{ref} , as well as the load-based rotor-equivalent estimates V_{TB} and V_B . The reference 10-minute turbulence intensity TI_{ref} computed from V_{ref} is shown on the right y -axis. The third subplot shows the sector-effective wind speeds $V_{S,right}/V_{ref}$ and $V_{S,left}/V_{ref}$ for the two horizontal sectors, non-dimensionalized by the met-mast reference wind speed. The small rotor

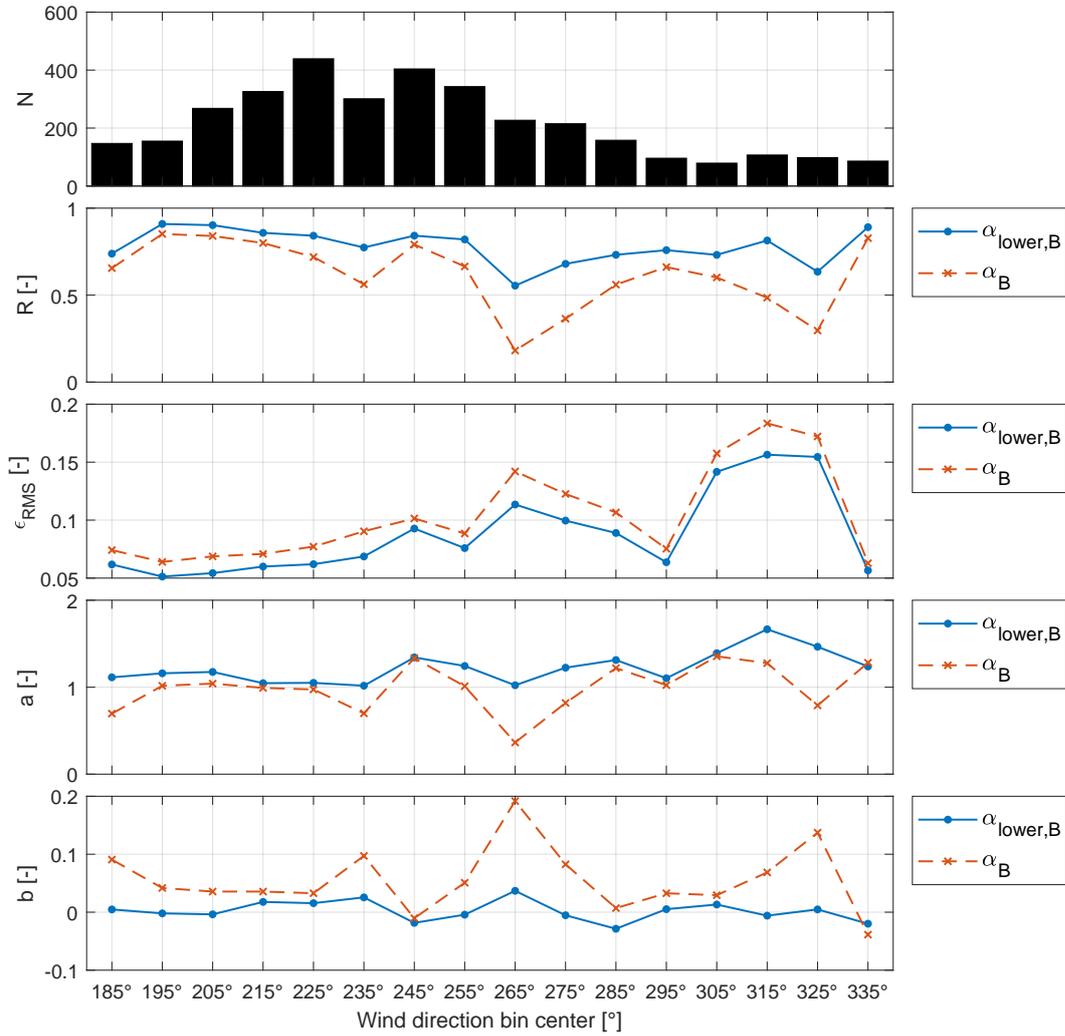


Figure 10. Statistics of the shear estimates as functions of wind direction. Blue solid line: lower-half-rotor shear; red dashed line: full-rotor shear. Top subplot: number of 10-minute data points; second subplot: Pearson correlation coefficient; third subplot: root mean squared errors; fourth and fifth subplots: linear best fit coefficients ($y = ax + b$).

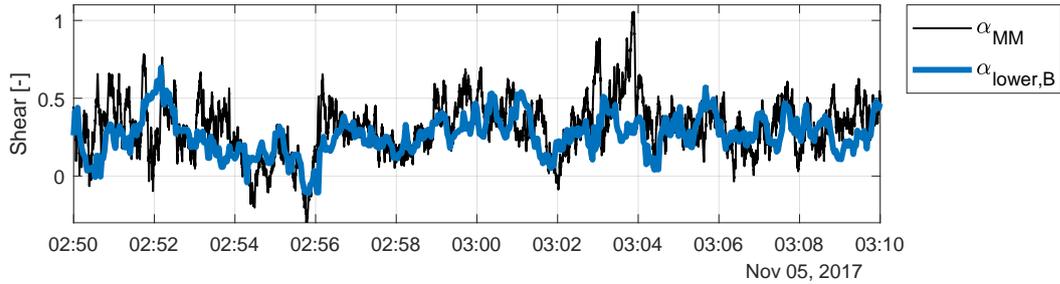


Figure 11. Comparison of 10 Hz met-mast vertical shear α_{MM} with lower-half-rotor shear $\alpha_{lower,B}$ during a period of 20 minutes.

icon shows, using the color code of the subplot, the left (red) and right (blue) sectors. The last subplot reports the horizontal shear estimate κ_B computed according to Eq. (6b).

Vertical dashed lines are used to highlight four time instants, labelled with the letters from A to D. For each of these time instants, the position of the wakes of the two turbines is visualized in the lower part of Fig. 12 using the FLORIS wake model (Doekemeijer and Storm, 2019). The yellow color indicates the ambient wind speed, while the blue color is used for the lower speed in the wakes. The rotor disk of WT2 is shown with a solid black line, while a red line is used for the left sector of WT1 and a blue line for the right one. Finally, the small cross symbol indicates the met-mast (MM) position.

At instant A (time equal to 02:05), Fig. 12 shows that the wind direction reaches 130° – 130 deg and the left sector of WT1 gets waked by WT2, as clearly illustrated by a reduced speed in the left sector and a ~~positive~~–~~negative~~ horizontal shear. At time instant B (02:35), the wind direction has turned back to 122° – 122 deg: as the turbine is not waked anymore, the estimated shear is null and an equal wind speed is estimated on both the left and right sectors. The rotor-effective wind speed is slightly smaller than the met-mast reference value; however, for this wind direction, the met-mast is not aligned with the turbine, which might explain this small discrepancy. At time instant C (03:45), the wind direction has increased and WT1 is waked again ($F_{WT2 \rightarrow WT1} = 145^\circ$ – $T_{WT2 \rightarrow WT1} = 145$ deg): after an initial reduction in the left sector speed, also the right sector is affected (dropping below 0.7), indicating a full waked condition. This is further confirmed by the reduction in the rotor-effective wind speeds with respect to the one measured by the met-mast. Later, a wake impingement on the right sector is observed at time D (05:00), followed by a second full waking at time 05:30. At ~~instant D (06:20)00~~, the wind direction has ~~increases to~~–~~increased to~~ 159° – 156 deg and both sectors operate again in nearly free stream. Accordingly, the rotor-effective wind speeds increase to reach the met-mast reference. Later again, the wind direction varies slightly, leading to partial wake impingements on the right side until, finally (at ≈ 12.00), the wind direction increases further and the horizontal shear becomes almost zero.

Note that the horizontal shear deviates slightly from 0 between 06:00 and 10:30 even though the wind direction is approximately constant around 155 deg. An explanation can be potentially found in the increased turbulence (after sunrise, at around 07:58).

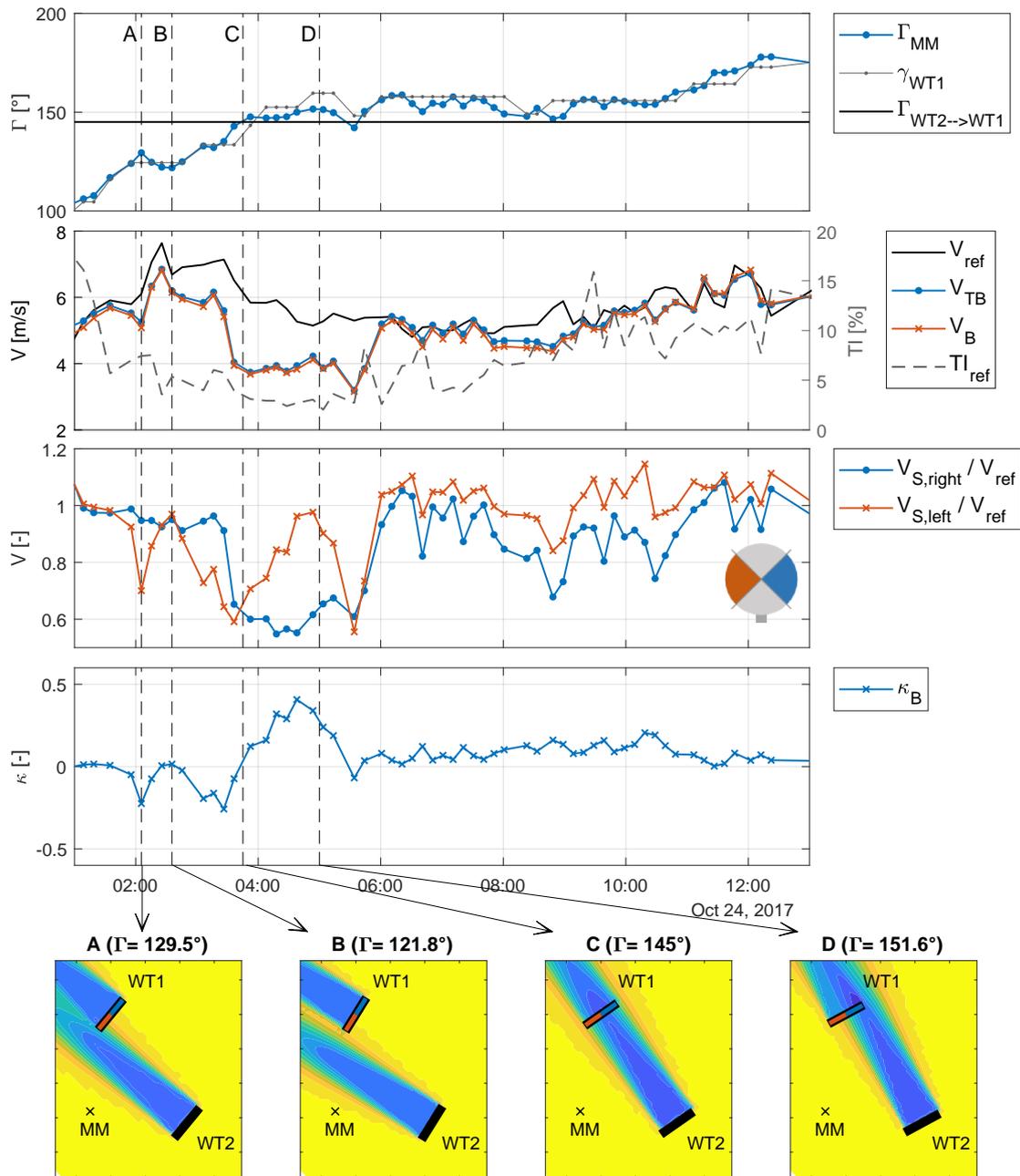


Figure 12. Time series characterized by varying wake interference conditions, with met-mast wind direction and turbine yaw orientation (first subplot from the top), reference met-mast wind speed and rotor-effective wind speed estimates and reference turbulence intensity (second subplot), left and right sector-effective speed estimates (third subplot), and horizontal shear estimate (fourth subplot). Lower part of the figure: wake visualizations based on the FLORIS model for different wind directions at time instants A through D.

that might enhance wake meandering and increase the expansion of the wake. The high turbulence before 02:00 can be attributed to the met-mast being affected by WT2.

This time series very nicely illustrates how the horizontal sector-effective wind speeds and the horizontal shear can be used to understand the instantaneous position of a wake with respect to an affected turbine rotor disk.

- 5 Figure 13 reports extended results, showing all available 10-minute values as functions of met-mast wind direction within the range from $\Gamma_{WT2 \rightarrow WT1} - 45^\circ = 100^\circ$ to $\Gamma_{WT2 \rightarrow WT1} + 45^\circ = 190^\circ$. The waking wind direction from WT2 onto WT1 ($\Gamma_{WT2 \rightarrow WT1}$) is indicated by a vertical dashed line.

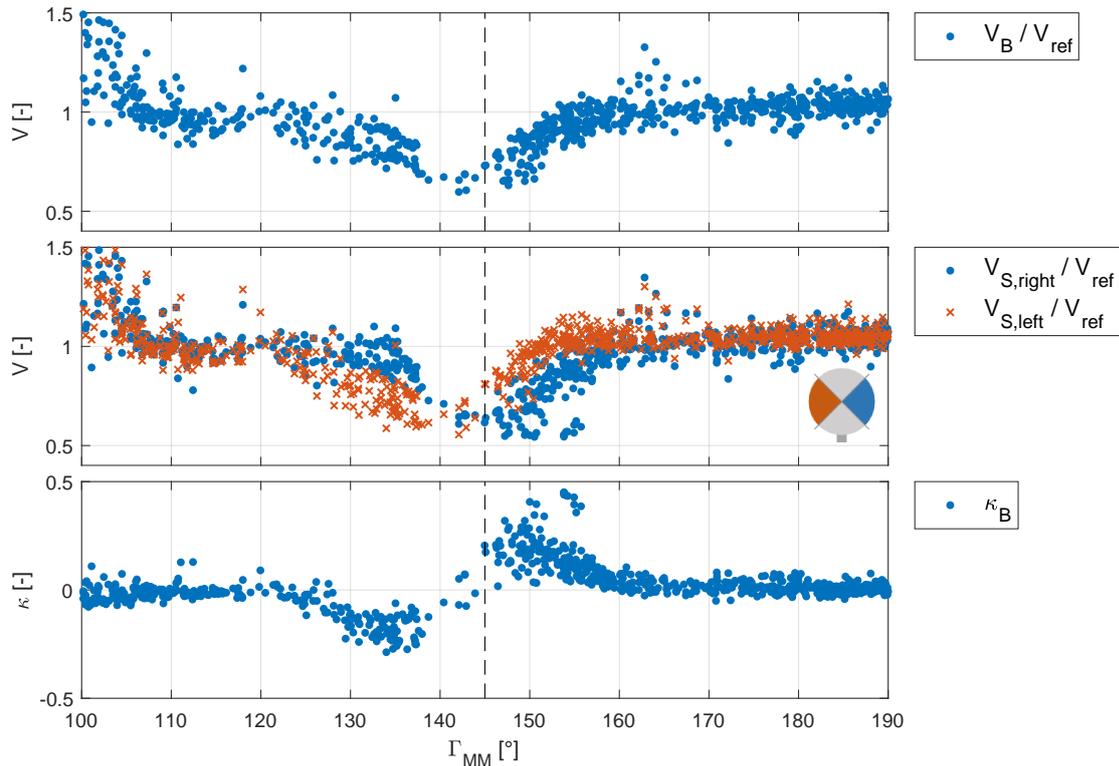


Figure 13. Wind speeds and shear at the WT1 rotor disk as functions of wind direction. Top subplot: non-dimensional load-based rotor-effective wind speed. Central subplot: left and right sector-effective wind speeds. Bottom subplot: horizontal shear.

The first subplot from the top shows the rotor-effective wind speed V_B/V_{ref} , non-dimensionalized by the reference speed of the met-mast. Values larger than one can be observed for wind directions close to 100° , as the wake of WT2 is affecting the met-mast (see Fig. 2). For wind directions close to 145° , lower speeds are observed, caused by the wake of WT2 impinging on WT1. For other wind directions, the speed stays close to one, even though some scatter can be observed.

The central subplot shows the non-dimensional sector-effective wind speeds $V_{S,right}/V_{ref}$ and $V_{S,left}/V_{ref}$. The small rotor icon shows, using the color code of the subplot, the left (red) and right (blue) sectors. For wind directions between $\approx 125^\circ$ and

$140^\circ \approx 125$ deg and 140 deg, the local wind speed is smaller in the left sector, indicating that the wake of WT2 is affecting mainly that portion of the rotor disk. Similarly, for wind directions between 145° and $\approx 160^\circ$ 145 and about 160 deg, the right sector is affected by the presence of the wake.

The bottom subplot shows the horizontal shear estimate. This quantity is close to zero for all wind conditions, except around the waking direction. **Positive-Negative** values indicate a left-sided wake impingement, while **negative-positive** values a right-sided one. Note that the scatter observed in the first two subplots, e.g. for wind directions between 160° and 170° 160 and 170 deg, seems not to be caused by wake interaction but rather by variations in the reference wind speed, as the horizontal shear is not affected.

For wind directions close to 140° 140 deg, only very few measurement points are available. This suggests that the lower-than-ambient wind speed within the wake of WT2 triggers frequent shutdowns of WT1. **The load-based estimator does not operate during turbine shutdowns.** Figure 14 shows in 2° -wide- 2 deg-wide bins the probability of the WT1 status indicating “no operation”. Wind directions were **based-on-obtained from** the met-mast, using all available days without discarding any data point. Indeed, mean direction bins close to $F_{WT2 \rightarrow WT1} = 145^\circ$ $F_{WT2 \rightarrow WT1} = 145$ deg support the hypothesis of frequent wake-induced turbine shutdowns. Additionally, Fig. 14 reports a maximum for the bin centered at 141° 141 deg. This, together with the shear shown in Fig. 13, suggests a small bias in the met-mast wind direction measurement and/or that the wake is not developing exactly along the downstream direction. Indeed, the latter is a **well-known** phenomenon observed in **vertically sheared flows (Vollmer et al., 2016)** **stable atmospheric conditions when the flow presents a significant vertical shear (Vollmer et al., 2016; Bromm et al., 2018).**

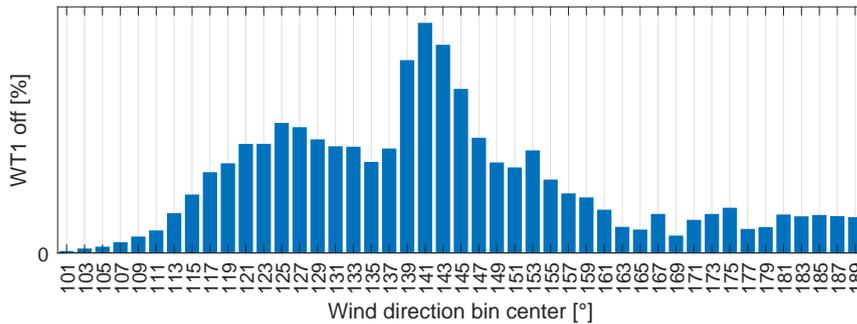


Figure 14. Probability of WT2 being in “no operation” state as a function of met-mast wind direction (using 10 Hz measurements of all available days).

These results demonstrate a remarkable ability of the proposed local speed and shear estimates to identify whether and to which extend a downstream turbine operates in the wake of an upstream machine. Note also that the met-mast reference wind direction is just a point measurement at one single height above the ground. In addition, other unknown inflow parameters, such as for example veer, may affect wake development. Therefore, the scatter of some of the data points in Fig. 13 is not necessarily

due to inaccuracies of the wind estimator, but might be rather due to the indirect, incomplete and pointwise measurement of the reference wake position.

3.9 Effect of turbine misalignment on estimates

As previously mentioned in ~~Seet-~~ §2.1, in theory the present method is formulated for turbines aligned with the ambient wind direction. However, in practice this happens only quite rarely, as every turbine in general operates with some degree of misalignment with respect to the incoming wind vector. This is mainly due to two reasons. First, the on-board wind vane(s) may not always provide an exact measurement of the local wind direction. Second, yaw control strategies generally avoid an excessively aggressive tracking of ~~changes in wind direction~~ wind direction changes. In fact, a turbine will typically yaw only when its misalignment with the wind has been above a certain threshold for a long-enough duration of time. This is done to limit duty cycle and yaw expenditure, given the very considerable mass of the rotor-nacelle system and the rather modest power capture loss caused by a misalignment of a few degrees.

Since the hypothesis on which the theory is based differs from the situation encountered in practice, it is necessary to show that the typical misalignments of normal turbine operation do not pollute the speed and shear estimates provided by the proposed method. This is ~~done~~ achieved here by showing that shears and misalignment are indeed uncorrelated.

To this end, Fig. 15 shows the rotor-effective wind speed as well as the horizontal and vertical shear estimates as functions of the turbine-wind misalignment angle $\Gamma_{\text{rel,WT1}}$. The misalignment is measured using the on-board wind vane. As this instrument may be not always very precise on some turbines, the misalignment angle was also computed by using the met-mast wind direction together with the turbine absolute orientation; however, in the present case no significant difference was observed between these two methods of computing the misalignment angle. The results of the figure only include data points for wind directions between ~~180° and 337.5°~~ 180 and 337.5 deg, to avoid waked conditions.

The first subplot reports the non-dimensional rotor-effective wind speed V_B . This quantity decreases for increasing misalignment angle, as shown by the second order polynomial fit reported with a dashed line. Such behaviour is completely expected and can be corrected for, if the misalignment is known, by using the cosine law (Gebraad et al., 2015; Fleming et al., 2017; Schreiber et al., 2017).

As shown, the rotor-equivalent wind speed is clearly correlated with misalignment, because the effective speed orthogonal to the rotor plane varies as a function of this angle. However, there is no reason why the vertical and horizontal shears—which are physical characteristics of the inflow—should also exhibit a similar dependency. To verify this fact, the central subplot shows the horizontal shear estimate κ_B , which is almost constant with respect to misalignment angle (and also very close to zero). Finally, the bottom subplot shows the vertical shear α_B . It appears that both shears have only a very marginal dependency on wind misalignment, as shown by the parabolic best fits reported with dashed lines in the plots. The larger fluctuations of the vertical shear compared to the horizontal one are probably caused by ~~varying time-varying~~ ambient inflow conditions, as also visible in Fig. 9.

The data shows that the shears are essentially uncorrelated with misalignment. These results demonstrate that the proposed method works without significant errors for turbine-wind misalignment angles up to $\approx \pm 10^\circ \approx \pm 10 \text{ deg}$.

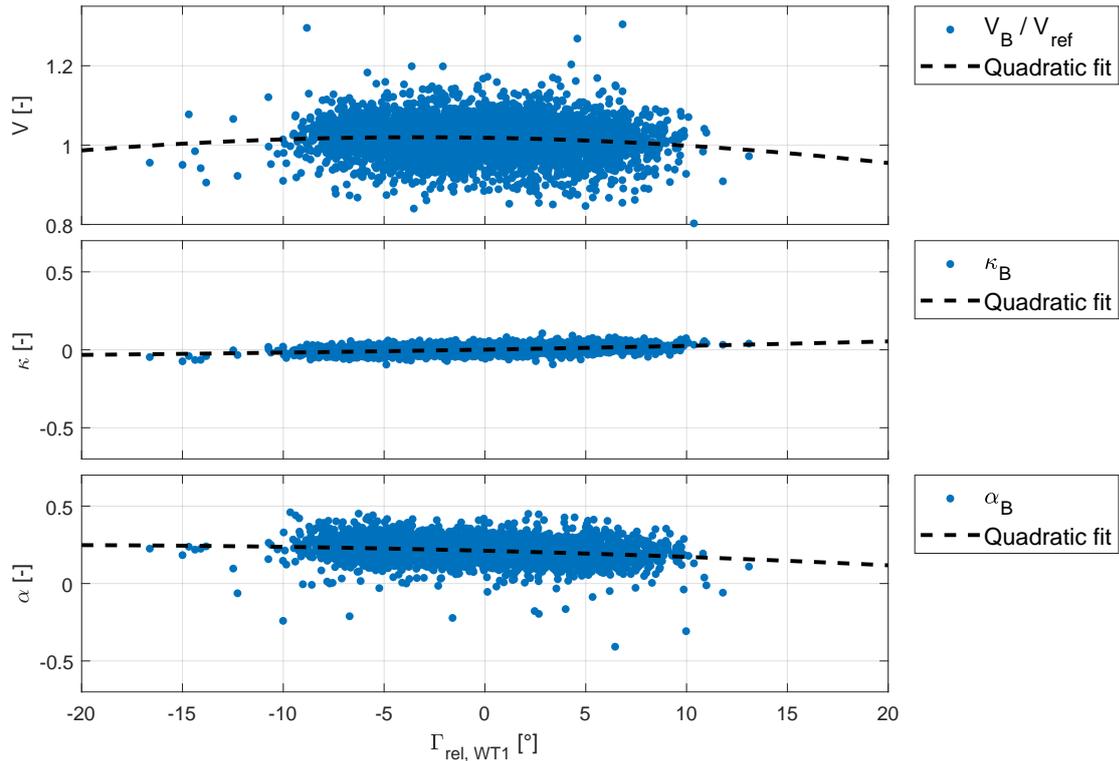


Figure 15. From top to bottom: rotor-effective wind speed V_B , horizontal shear κ_B and vertical shear α_B , all plotted as functions of wind turbine misalignment angle $\Gamma_{\text{rel, WT1}}$.

Larger turbine misalignment angles would be necessary for wake steering control (Fleming et al., 2017), where the rotor is intentionally pointed away from the wind to deflect the wake laterally. The performance of the proposed method could not be tested in such conditions within the present research, as no large misalignment angles were present in the available data set. However, even in that case, the procedure illustrated here could be used for pragmatically correcting possible errors caused by misalignment. In fact, by plotting shears as functions of misalignment angle, a best-fit correction function could be readily derived and used for correcting the estimates, if necessary.

4 Conclusions

A method to estimate the local wind speeds over sectors of the rotor disk has been tested on a 3.5 MW wind turbine. Results have been compared to reference values obtained with a nearby met-mast. For some wind directions, the sensing turbine is waked by a second machine. This feature of the test site has been exploited for demonstrating to test the ability of the proposed local wind sensing technique to detect wake impingement.

The wind sensing method has been previously studied and evaluated in simulations and scaled experiments. The present work has presented a first full-scale demonstration. Based on the field test results ~~showed~~ shown herein, the following conclusions can be drawn:

- 5 – A rotor-effective wind speed can be estimated from blade out-of-plane bending moments, with a quality that is nearly indistinguishable from the well known torque-balance method.
- The vertical wind shear estimated from out-of-plane bending moments correlates very well with the met-mast reference. The best results were obtained when the mast is directly upstream of the turbine. This ~~indicates~~ suggests that some of the scatter in the results ~~is simply~~ might be due to a lack of knowledge of the exact ground truth, rather than to a lack of accuracy of the proposed method.
- 10 – The vertical shear measured by the met-mast up to hub height differs from the shear measured over the whole rotor disk. ~~Clearly, this is simply~~ This is likely a feature of the flow, and not of the method tested here.
- The local wind speeds estimated on two lateral sectors of the rotor disk show the clear fingerprint of an impinging wake shed by a neighbouring turbine. By looking at the two sectors, one can distinguish left, right or full wake overlaps.
- Simple and very practical techniques can be used to correct for various sources of error, including not perfectly calibrated
15 load or azimuth sensors, as well as model approximations.

The present load-based wind estimation method provides for a remarkably simple and effective opportunity to estimate atmospheric inflow conditions on operating turbines. The method is based on readily-available quantities that can be easily computed from a standard model of a wind turbine, and does not need to be trained from extensive data sets. The on-board implementation uses pre-computed look-up-tables. and hence has a negligible computational cost. When load sensors are
20 already installed on a turbine, for example for load-reducing control, this novel wind sensing capability is simply obtained as a software upgrade. Wind sensing opens up a number of opportunities that can profit from a better knowledge of the inflow, including turbine and wind farm control, lifetime consumption estimation, predictive maintenance and forecasting, among others.

Code and data availability. The operational data and turbine model used in this research are the property of eno energy systems GmbH. An
25 implementation of the estimator can be obtained by contacting the authors.

Nomenclature

BEM	Blade Element Momentum
LUT	Look-up-table
MM	Met-mast or meteorological mast

	WT1	Wind turbine 1 (sensing turbine)
	WT2	Wind turbine 2
	a	Linear best fit constant ($y = ax + b$)
5	A	Rotor disk area
	A_S	Sector area
	b	Linear best fit constant ($y = ax + b$)
	C_m	Cone coefficient
	C_p	Power coefficient
10	c	Speed estimate scaling factor
	D	Rotor diameter
	J	Total rotational inertia
	m_i	Blade root out-of-plane bending moment of blade i
	$m_{i,meas}$	Measured blade root out-of-plane bending moment of blade i
15	N	Number of measurements
	q	Dynamic pressure
	R	Rotor radius or Pearson correlation coefficient
	s	Load scaling factor
	$s_{MM \rightarrow WT1}$	Downstream distance between met-mast and wind turbine WT1
20	T_{aero}	Aerodynamic torque
	T_{meas}	Measured torque
	$\frac{TI_{ref}}{V}$	<u>Met-mast measured reference turbulence intensity</u> Wind speed
	V_B	Blade-load estimated rotor-effective wind speed
25	V_H	Wind speed at hub height
	V_i	Blade-effective wind speed estimate of blade i
	$V_{MM,i}$	Met-mast measured wind speed at height i
	V_{PL}	Power law inflow profile
	V_{ref}	Met-mast measured reference wind speed of inflow profile
30	V_S	Sector-effective wind speed
	$V_{S,left/right/up/down}$	Load-based estimation of left/right/up/down sector
	V_{TB}	Torque-balance estimated rotor-effective wind speed
	y	Lateral position
	z	Height above ground
35	z_H	Hub height

	$z_{MM,i}$	Installation height of sensor i on met-mast
	α	Vertical shear exponent
	α_B	Load-based estimated vertical shear exponent
5	$\alpha_{\text{lower},B}$	Load-based estimated vertical shear exponent on lower half of rotor disk
	α_{MM}	Met-mast-measured vertical shear exponent
	β	Blade pitch angle
	γ	<u>Turbine yaw orientation (clockwise from due North)</u>
	Γ	Wind direction (clockwise from due North)
10	$\Gamma_{A \rightarrow B}$	Direction of wind blowing from point A to B (clockwise from due North)
	Γ_{MM}	Wind direction at met-mast
	$\Gamma_{\text{rel},WT1}$	Relative wind direction at nacelle of WT1
	Δt	Time delay between measurement at met-mast and turbine
	ϵ_{RMS}	Root mean squared error
15	κ	Horizontal shear coefficient
	κ_B	Load-based estimated horizontal shear coefficient
	λ	Tip speed ratio
	ρ	Air density
	ρ_{ref}	Reference air density
20	ψ	Blade azimuth position
	ψ_a	Blade azimuth position, beginning of sector
	ψ_b	Blade azimuth position, end of sector
	ψ_{bias}	Blade azimuth measurement offset
	ψ_{corr}	Corrected azimuth measurement
25	Ω	Rotor speed
	$\dot{\Omega}$	Rotor acceleration

Author contributions. JS conducted the main research work and prepared a first draft of the manuscript. CLB developed the core idea of load-based wind sensing, supervised the research and contributed to the writing of the paper. MB assisted in the measurement post-processing and analysis. All authors provided important input to this research work through discussions, feedback and by improving the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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