12.01.2022

Dear Editor,

we would like to sincerely thank the Reviewers for their time and constructive feedback regarding the paper "Vortex identification methods applied to wind turbine tip vortices".

We have tried our best to modify the manuscript according to the suggestions. Along with the present document, we are attaching a revised version of the manuscript, where all changes are tracked (wes-2021-104-tracked_changes.pdf) and a clean version of the same manuscript (wes-2021-104-Clean.pdf) with all the changes incorporated.

In the following, Reviewers' comments are reported in black-colored text, while authors' answers are in blue-colored text. Additionally, new sections added in the manuscript that refer to each comment are provided between quotation marks, for convenience.

We believe that Reviewers' comments have helped us making significant improvements in the paper possible. We thus hope that the study can now meet the high standards of WES journal.

Best regards,

Rodrigo Soto-Valle, Stefano Cioni, Sirko Bartholomay, Marinos Manolesos, Christian Navid Nayeri, Alessandro Bianchini, and Christian Oliver Paschereit

Reviewer #1

RC1.1 While the paper provides very interesting insights on the use of the different VIMs for vortex tracking, the novelty of the article is still unclear. The advantages of the Graftieaux's approach, which is hailed by the authors as the most suitable approach are already known. The authors should expand more on the novelty of their article in the introduction section since it is for now not very apparent.

The Reviewer's comment prompted us at trying to better highlight the impact and novelty. A dedicated part has been added to the scope and is reported below for convenience.

"Several vortex identification methods (VIMs) have been employed so far. However, consensus on the most suitable methodology for the study of vortices in the wake of a wind turbine has not been found yet, as shown in Table 1. Furthermore, upon examination of the literature, it is apparent that many studies do not provide the complete implementation methodology, such as the differentiation scheme, thus hindering an extensive comparison between methods.

This paper aims at comparing different VIMs to evaluate their suitability to study specifically the tip vortices of a wind turbine. The methods are applied to velocity field planes that were obtained through PIV in the near wake of a wind turbine model located in a wind tunnel facility. Compared to previous investigations, the present study offers in a depth comparison, commonly used VIMs on the same wind turbine tip vortex measurement data set. The main goal is to identify similarities and differences of the methodologies, i.e., providing a direct insight into their application. Furthermore, a rigorous comparison of VIM application is provided, with the simultaneous study of six tip vortex parameters, namely: (1) streamwise location; (2) lateral location; (3) streamwise velocity; (4) lateral velocity; (5) core radius; and (6) jittering.

Thanks to the large number of analyzed samples, a statistical analysis is also included in order to give more insights into the challenges of each methodology. Three different VIMs are compared:

vorticity, Q-criterion and Graftieaux. The first two VIMs require differentiation, thus, the application of six different schemes is examined. Moreover, Graftieaux's methodology is also tested in different scenarios. In this way, a total of 14 cases are presented, where each of the six parameters is investigated. This represents an important source of information to support future wind turbine tip vortices analyses in both experiments and simulations as the implementation is scalable and only requires velocity fields input."

RC1.2 The effects of experimental uncertainty are lacking in the paper. The SPIV data has some level of uncertainty in the results and how this gets propagated in the methods that are being proposed is not very clear. At the very least, a discussion of these effects should be made. This could also have an impact on the Graftieaux approach used. The literature on the uncertainty on PIV should be thoroughly reviewed in order to be able to support your discussion of the effects.

Thank you for the right comment. The discussion about measurement uncertainty has been improved throughout the paper based on three main actions: 1) Table 1 has been updated highlighting the number of samples of each research, i.e., giving an overview of their repeatability; 2) The literature review has been updated including important references about uncertainty. 3) Additional details about experiments have been included, from which the uncertainty levels, based on the error of the velocity field, have been reported. Modifications made on the paper are given below for the completeness of this document.

"It is worth remarking that, once comparing the methods the inherent error introduced by the PIV technique must be accounted for. Table 1 includes the number of samples (or pair-samples in Stereo-PIV) used to analyze each contribution. The latter is a well-known parameter, directly related to the uncertainty level. This has been extensively used in literature to give a quantification of the uncertainty in PIV experiments (Grant and Owens, 1990; Micallef, 2012; Del Campo et al., 2014; Micallef et al., 2016), Eq. 1 shows an example of the error in a measured velocity u by Sherry et al. (2013b).

$$\epsilon_u = \frac{z\, I_u}{\sqrt{N}}, \qquad (1)$$

where z is the confidence coefficient or critical value (normal distribution), I is the turbulence intensity and N is the number of samples. Moreover, it is overall agreed that actions to reduce uncertainty levels could be (1) the maximization of the number of samples to ensure repeatability and convergence of the results (Uzol and Camci, 2001; Ostovan et al., 2019); and (2) the use of subpixel algorithms (Scarano, 2001) giving errors below 0.1 px (Del Campo et al., 2014; Sciacchitano et al., 2013; Beresh, 2008; Fouras and Soria, 1998; Scarano, 2001)"

Table 1. Wind turbine tip vortices studies employing the PIV technique and VIM details.

contributor	test facility[a]	diameter [m]	N	VIM	scheme
Whale et al. (2000)	WC	0.18	6	vorticity magnitude	fifth order polynomial
Maalouf et al. (2009)	WT, closed-loop	0.50	95	circulation	integration
Xiao et al. (2011)	WT, open jet	1.25	n.s.	vorticity magnitude	n.s.
Yang et al. (2011)	WT, closed-loop	0.25	1000	vorticity magnitude	n.s.
Micallef et al. (2014)	WT, open-jet	2.00	100	vorticity magnitude	central difference
Meyer et al. (2013)	WC	0.38	100	vorticity magnitude	n.s.
Sherry et al. (2013a)	WC	0.23	25	Graftieaux's method	solid-body rotation
Sherry et al. (2013b)	WC	0.23	300	swirling strength criterion	Richarson extrapolation
Ning and Yang (2013)	WT, open-jet	0.25	960	vorticity magnitude	n.s.
Jin et al. (2014)	WT, closed-loop	0.15	300	vorticity	n.s.
Ostovan et al. (2019)	WT, open jet	0.94	1000	zero induced velocity	central difference
Soto-Valle et al. (2020)	WT, closed-loop	3.00	1200	Q-criterion	central difference
Fontanella et al. (2021)	WT, closed-loop	2.38	100	vorticity magnitude	central difference

(a) WT: wind tunnel, WC: water channel. n.s: not specified.

Table 3. Operation and image acquisition details.

operation parameters		PIV parameters	
cross-section area	$4.2 \times 4.2\, m^2$	cameras	PCO 2000
BeRT rotor radius	$1.5\, m$	lens focal length	$100\, mm$
blockage ratio	40%	resolution	$2048 \times 2048\, px^2$
freestream speed	$6.5\, ms^{-1}$	field of view	$435 \times 435\, mm^2$
rotational speed	$3\, Hz$	recordings	1200
tip speed ratio	4.35	laser pulse separation	$150\, \mu s$
turbulence intensity[a]	$3 - 6\%$	interrogation window	$24 \times 24\, px^2$ (50% overlapping)
phase-locked angle	$\phi = 40°$	spatial resolution	$3.6\, mm$

(a) reported by Bartholomay et al. (2017)

"Based on the selected operational parameters (see Table 3), the uncertainty of the velocity magnitude is below $\pm 0.4\%$ of the freestream velocity (see Eq. 1), which is equivalent to $0.026 ms^{-1}$ with a 98% confidence. This uncertainty level does not affect the location of the vortex centers of the averaged velocity field or the other studied parameters, as they rely on the vortex center location. For completeness, a statistical analysis of the instantaneous velocity fields is done and is presented in the following section."

RC1.3 Figure 10 – It is recommended to remove the line plot and use a scatter plot for such representations.

The Reviewer's correction is right. Both convection velocity plots were updated using bars instead of a continuous line. The new Figure is reported below for convenience.

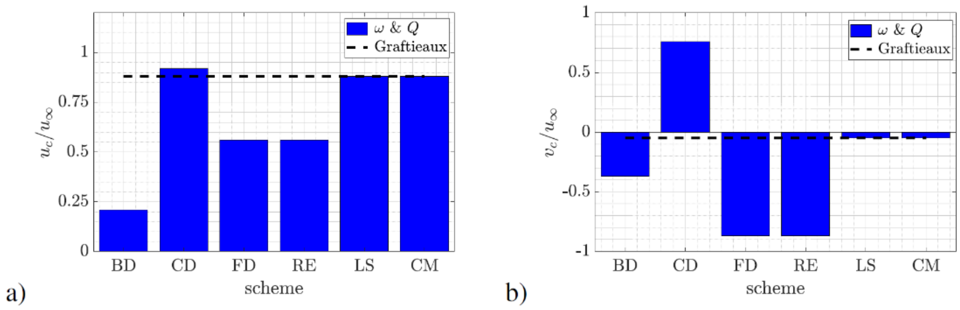

Figure 10. Average convection velocities.

RC1.4 Line 264-267 – The following sentence should be clarified further "Alternative methods such as the prediction from time series vortex locations might be also successful using the rest of the schemes due to the small discrepancy between the vortex center locations between VIMs and schemes; however, more than one vortex age is needed."

The original paragraph referred to the possibility of calculating the convection velocity between two or more consecutive vortex center locations by means of a fitting curve between either streamwise or lateral locations over time. In particular, the streamwise location of the vortex presents a linear behavior over time. In the revised manuscript this part has been rewritten and two references where this methodology is applied were added. The rephrased paragraph is given below for convenience:

"Therefore, the estimation of the convection velocity is recommended with the smoother VIMs and schemes, i.e., the Graftieaux method or vorticity, and Q-criterion while employing LS or CM schemes. Additionally, since there is a low scattering in vortex locations among VIMs and schemes, the convection velocity can be alternatively calculated by comparing several vortex locations over time, fitting streamwise and lateral locations separately (Snel et al., 2007; Soto-Valle et al., 2020). However, more than one vortex age is needed."

RC1.5 Figure 17 – For completeness the figure needs a colorbar.

Figures 9 and 17 were updated with their respective colorbars. Both Figures are shown here for convenience.

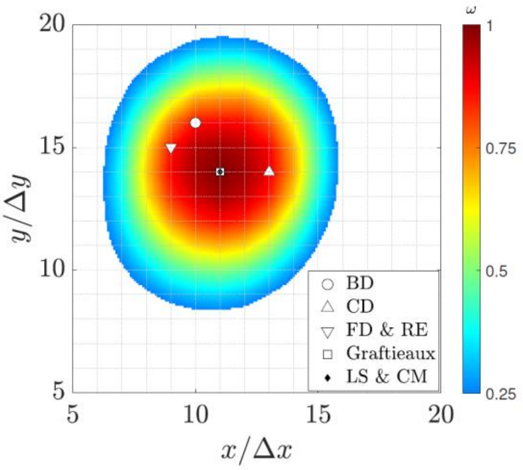

Figure 9. Vortex center locations for different differentiation schemes. The vorticity magnitude contour based on the least squares scheme is shown.

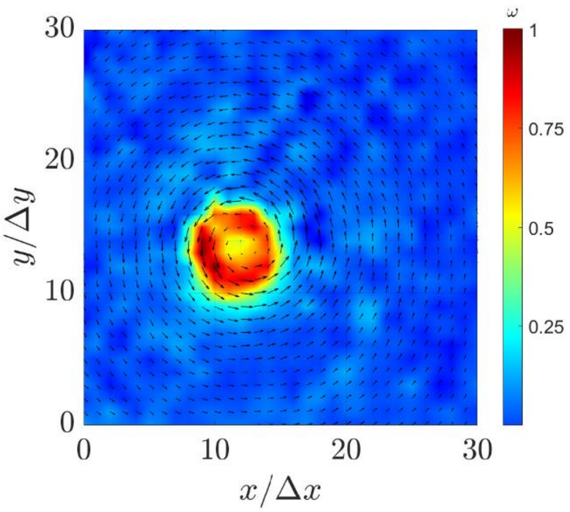

Figure 17. Instantaneous vorticity magnitude with the central differentiation scheme and quiver lines of the velocity field.

RC1.6 Line 343 – Do you here mean for vortex kinematics analysis or do you really mean that the methods are simply not suitable for establishing both position and motion of the tip vortices? "In fact, both schemes ignore information either forward or backward from the grid on the implementation of differentiation. Therefore, they are not suitable for vortex analysis."

The sentence was unclear, and it has been rephrased according to the findings of the work. It is reported below for convenience:

"Based on the above and due to the large values of SD after the application of these schemes, they are not recommended for vortex analysis"

RC1.7 Line 333 – It is not very clear whether the authors are rejecting the uneven shedding effects on the observed double peak results.

Conclusion - For the most part it is felt that the issue of the double peak has remained unresolved in this work. The authors seem to attribute these to purely numerical artefacts. Do the authors feel confident about this conclusion? Could experimental uncertainties also be responsible for this?

The two hypotheses of multiple peak results are now in separated paragraphs to make their formulation clearer. The supported hypothesis is now explicitly reported in the manuscript in both the averaged and statistical results. For convenience, the relevant paragraphs are given below. Additionally, the title of Section 5 has been updated to: Results and discussion.

"The presence of multiple maxima and the ring-like distribution of the ω and Q parameters can be explained through different hypotheses. On the one hand, the cause could be the level of noise in the vortex core because of the lack of seeding (Foucaut and Stanislas, 2002; van der Wall and Richard, 2006). The rotational motion of the fluid causes the seeding particles to be pushed at the edges of the vortex. For this reason, the velocity vectors shall be evaluated through interpolation, introducing a further source of uncertainty in the results. In this way, the contours of ω and Q have a single peak concentration for the schemes with the lowest uncertainties (LS and CM) while two peak concentrations appear for the schemes with higher uncertainty (CD, RE, BD and FD).

On the other hand, the presence of multiple maxima might also be due to small-scale structures within the vortex, as suggested by Bonnet (1998). It is conceivable that these structures might originate during the shedding of the tip vortex from the blade. Certainly, the pressure difference between the pressure and suction sides of the blade is only one of the many effects that take part in the formation of the tip vortices. Several experiments show that the flow at wingtips involves the interaction of multiple vortices, shear layer instabilities, flow separation and re-attachment (Giuni and Green, 2013a; Devenport et al., 1996; Micallef, 2012). The involved structures are also affected by the blade shape, tip geometry, Reynolds number, and load distribution (Giuni and Green, 2013a) and generally merge into a single structure. In conclusion, the multiple peaks could be caused by the uneven shedding of vorticity in the chordwise direction. In the work of Micallef et al. (2014), a study of the formation of the tip vortices in a horizontal axis wind turbine, a complex vorticity distribution along the blade chord is observed, which seems to cause multiple vorticity peaks inside the core. These multiple peaks can be identified in the vortex core even after the tip vortex has been shed from the blade. In present results, the same effect is obtained when the high uncertainty schemes are applied (CD, RE, BD and FD).

Among these hypotheses, the first one seems the most suitable. It is possible that artifacts are produced on some of the schemes applied, where the concentration of seeding is diminished. These artificial peaks are not present in the results using the Graftieaux method because the methodology includes information from a larger amount of grid points.

In fact, eight and 24 points are employed to estimate the parameter Γ_1 ***. In the case of BD, CD and FD only two grid points are considered. RE and LS schemes use four grid points, with the difference that in the first case the inner points are considerably weighted more (see Table 2); the opposite happens for the LS case. CM scheme employs six grid points. Therefore, either weighting more the outer part of the derivative estimation (LS scheme) or considering more grid points (CM scheme) contribute to repairing the artifacts and put in evidence that the issue only occurs in the inner part of the vortex."***

[...]

"The visible ring-like concentration in Fig. 17 contrasts the uneven shedding hypothesis previously formulated in the average results, supporting the idea of an artifact of the schemes, as it preserves the same ring-like structure even when an instantaneous velocity field is analyzed."

RC1.8 Line 25 – "It is shown, by using the vorticity to identify the vortices, a high variation in the position of the tip vortices."

The sentence has been rewritten and is given below for convenience:

"A high variability of the position of the tip vortices is shown by using the vorticity in the identification"

RC1.9 Line 237 – Change "are originated" to "might originate"

The comment has been implemented and is given below for convenience:

"It is conceivable that these structures might originate during the shedding of the tip vortex from the blade."

RC1.10 Line 269 – Sentence structure is poor here: "the Graftieaux 24-points as well only vorticity magnitude cases are presented."

The sentence has been rewritten and is given below for convenience:

"For readability, only the Graftieaux 24-points and vorticity VIMs are presented"

RC1.11 Line 365 – "The two peaks found in the jittering…" – please rephrase

The sentence has been rewritten and is given below for convenience:

"The multiple peaks, found in some identification parameters, are determined as an artifact produced by certain schemes"

Reviewer #2

RC2.1 The authors should explain their contribution to the field more clearly. The paper definitely needs more description in terms of its novelty and how it distinguishes itself from previous literatures. In particular, the methods and their applications have been already addressed by other researchers; hence, the authors should demonstrate their contribution.

The Reviewer's comment prompted us at trying to better highlight the impact and novelty. A dedicated part has been added to the scope and is reported below for convenience.

"Several vortex identification methods (VIMs) have been employed so far. However, consensus on the most suitable methodology for the identification of vortices in the wake of a wind turbine has not been found yet, as shown in Table 1. Furthermore, upon examination of the literature, it is apparent that many studies do not provide the complete implementation methodology, such as the differentiation scheme, thus hindering an extensive comparison between methods.

This paper aims at comparing different VIMs to evaluate their suitability to study specifically the tip vortices of a wind turbine. The methods are applied to velocity field planes that were obtained through PIV in the near wake of a wind turbine model located in a wind tunnel facility. The main goal is to provide similarities and differences of the methodologies after being applied to the same dataset, i.e., providing a direct insight into their comparability. The application of the methodology is based on six tip vortex parameters, namely: (1) streamwise location; (2) lateral location; (3) streamwise velocity; (4) lateral velocity; (5) core radius; and (6) jittering.

Thanks to the large number of analyzed sample, a statistical analysis is also included in order to give more insights into the challenges of each methodology. Three different VIMs are compared: vorticity, Q-criterion and Graftieaux. The first two VIMs require differentiation, thus, the application of six different schemes is examined. Moreover, Graftieaux's methodology is also tested in different scenarios. In this way, a total of 14 cases are presented, where each of the six parameters is investigated. This represents an important source of information to support future wind turbine tip vortices analyses in both experiments and simulations as the implementation is scalable and only requires velocity fields input.”

RC2.2 In the introduction section, the authors addressed different PIV measurements performed by previous investigators particularly those focused on tip vortex flow. However, to this reviewer, there are more studies, also worked on the behavior of tip vortices, that can be included in the literature review.

Thank you for the comment. The literature review has been improved including more studies about tip vortices and uncertainty evaluation. Moreover, Table 1 has been updated, with these studies. One column has been also added to the Table, to display the number of samples used by each of the contributors in their analysis. Both the updated literature and Table 1 are given below for convenience.

“The wake of a wind turbine is characterized by a massive presence of vortex structures. Two main types of concentrated vortices can be identified, which are shed from the root and the tip region, respectively. The latter form strong helical structures that influence the wake of the wind turbine.

The tip vortices are generated by the pressure difference between the top and lower side of the blade tip, which lead to a flow from the pressure side to the suction side of the blade (Karakus et al., 2008; Sherry et al., 2013b). In this way, the tip vortices of a wind turbine represent a source of energy loss (Shen et al., 2005) and noise (Arakawa et al., 2005). Moreover, the wake development needs proper consideration in the layout of a wind park (Marten et al., 2020), as it can affect the performance of wind turbines located downstream. Therefore, a more detailed characterization of the wind turbine wake vortices does represent a relevant research topic.

Since the first introduction of Particle Image Velocimetry (PIV) applied to wind turbine aerodynamics by Smith et al. (1990), many experimental investigations have been performed and a variety of methods have been employed to identify the vortex center and other characteristics. Yang et al. (2012) studied the formation and evolution of helical tip vortices of a wind turbine model under atmospheric boundary layer wind. A high variation of the position of the tip vortices is shown by using the vorticity in the identification. This effect is known as wandering or jittering and it is related to turbulence, vibrations of the model turbine (e.g., blades and tower) and the PIV system. Additional investigations (Maalouf et al., 2009; Soto-Valle et al., 2020) show the same effect using different identification methods such as the Q-criterion or circulation-based methods.

Micallef et al. (2014) studied the mechanism of formation of the tip vorticity on a wind turbine blade. The findings showed how the vorticity is convected and forms a unique and symmetrical tip vortex

behind the trailing edge. The location of the vortex center, identified by the maximum vorticity value, was found to be slightly inboard the rotor. In agreement with the previous finding, Xiao et al. (2011), by means of vorticity, reported that the motion of the tip vortices moves first inward and then outboard of the rotor swept area, highlighting its importance in the aerodynamic modelling of the wake.

Studies have also been carried out in water channels facilities. Sherry et al. (2013a) studied tip vortices from a submerged wind turbine model. Results highlighted the breakdown of the wake due to the mutual interaction between the helical structure of the tip vortices, which is highly dependent on the tip-speed ratio. Additionally, the jittering of the tip vortices was also detected. Meyer et al. (2013) tracked the tip vortices from a wind turbine model using the vorticity magnitude. The procedure was done by choosing a reference vorticity magnitude, after visual inspection. Then, the location was estimated by averaging the positions where the vorticity magnitude is larger than the considered reference. Moreover, several studies rely on the identification of the wind turbine tip vortices to assess retrofits such as winglets (Ostovan et al., 2019), rime ice effects (Jin et al., 2014) or surge motion impact (Fontanella et al., 2021).

It is worth remarking that, once comparing the methods the inherent error introduced by the PIV technique must be accounted for. Table 1 shows the number of samples (or pair-samples in Stereo-PIV) used to analyze each contribution. The latter is a well-known parameter, directly related to the uncertainty level. This has been extensively used in literature to give a quantification of the uncertainty in PIV experiments (Grant and Owens, 1990; Micallef, 2012; Del Campo et al., 2014; Micallef et al., 2016), Eq. 1 shows an example of the error in a measured velocity u by Sherry et al. (2013b).

$$\epsilon_u = \frac{z\, I_u}{\sqrt{N}}, \tag{1}$$

where z is the confidence coefficient or critical value (normal distribution), I is the turbulence intensity and N is the number of samples. Moreover, it is overall agreed that actions to reduce uncertainty levels could be (1) the use of subpixel algorithms (Scarano, 2001) giving errors below 0.1 px (Del Campo et al., 2014; Sciacchitano et al., 2013; Beresh, 2008; Fouras and Soria, 1998; Scarano, 2001); and (2) the maximization of the number of samples to ensure repeatability and convergency of the results (Uzol and Camci, 2001; Ostovan et al., 2019)."

Table 1. Wind turbine tip vortices studies employing the PIV technique and VIM details.

contributor	test facility[a]	diameter [m]	N	VIM	scheme
Whale et al. (2000)	WC	0.18	6	vorticity magnitude	fifth order polynomial
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Yang et al. (2011)	WT, closed-loop	0.25	1000	vorticity magnitude	n.s.
Micallef et al. (2014)	WT, open-jet	2.00	100	vorticity magnitude	central difference
Meyer et al. (2013)	WC	0.38	100	vorticity magnitude	n.s.
Sherry et al. (2013a)	WC	0.23	25	Graftieaux's method	solid-body rotation
Sherry et al. (2013b)	WC	0.23	300	swirling strength criterion	Richarson extrapolation
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Ostovan et al. (2019)	WT, open jet	0.94	1000	zero induced velocity	central difference
Soto-Valle et al. (2020)	WT, closed-loop	3.00	1200	*Q*-criterion	central difference
Fontanella et al. (2021)	WT, closed-loop	2.38	100	vorticity magnitude	central difference

(a) WT: wind tunnel, WC: water channel. n.s: not specified.

RC2.3 The authors have presented an extensive description of VIM methods which predict vortex behaviors. It would be very informative to include analytical approaches such Rankine model which predict tangential velocity profiles of vortex and compare your results with those that can be obtained from those models.

The Reviewer's comment is very interesting and could represent a very engaging continuation of the research. A reference on this has been added to the paper and is given below. Such models would extend, however, the paper in an analytical benchmarking direction, probably lowering the focus on the experimental part.

"The convection velocity presented a higher dependency on the VIM and scheme applied. Therefore, and keeping in mind that the results have shown good comparability regarding the vortex center locations, it is recommended to use the information of several vortex ages instead of the swirling velocity approach to estimate the convection velocity. Conversely, the vortex core radius only showed a grid step variation between VIMs and schemes. Further studies might include analytical approaches which predict the tangential velocity profiles of a vortex from which is estimated the vortex core to also check their applicability."

RC2.4 Experimental details:

*The authors are well familiar with the fact that there are two governing parameters, i.e. local Reynolds number and tip speed ratio that affect the flow structure of the turbine including tip vortices. The authors need to discuss further about the role of tip speed ratio in their assessments of vortex location, vortex core radii and vortex jittering.

*The authors have employed the results obtained from a PIV measurement to perform their analysis. However, they should present more specifications of the PIV test such the sampling rate of the measurement, the phase phase-lock process and the number image pairs per second for each azimuth angle of the blade.

*Page 7, line 145: what is the tip speed ratio of the turbine? Is it smaller or bigger than the design tip speed ratio?

*Page 7, line 150: More clarification about the experiment set-up and process is required, such as the sampling rate, frequency of the laser and camera as well as error analysis.

*Page 7, line 155: How was the process of phase-lock measurements performed?

*Page 7, Figure 2: the location of the camera is not clear in the figure.

*The authors should provide enough information if during the measurements the turbine was subjected to any blockage effect in the wind tunnel or not. Regarding that, they should calculate blockage ratio of the turbine based on the tunnel cross section area and considering the tip speed ratio at which the turbine is performing, they should discuss whether the turbine is experiencing blockage effect. If the blockage effect is high, it would affect the experimental results including the velocity field and wake expansion (which also determines the vortex location) significantly.

The authors would like to thank the Reviewer for his/her right suggestion. The following actions have been taken: 1) All additional details on experiments have been added in the paper; 2) A summary Table has been included; and 3) Figure 2 has been updated. All changes are given below for convenience:

"The experiments were carried out in the closed-loop wind tunnel at the Technische Universität Berlin. The wind turbine, Berlin Research Turbine (BeRT) (Pechlivanoglou et al., 2015), is a three-bladed, upwind horizontal axis wind turbine model. Blades are twisted, tapered, and based on Clark Y airfoil profile along the full span. Moreover, the blade-tip is sword-shaped and the Reynolds number, based on the circulation of the tip vortices, is $Re_\nu \approx 10^5$ (Soto-Valle et al. (2020)). The freestream velocity and rotational frequency are fixed giving a tip speed ratio of 4.35, which is the design-rated condition of the turbine. The latter provides a constant operational condition to all the studied vortices. Table 3 reports details of the experimental setup.

The wind turbine model produces a 40% blockage ratio in the wind tunnel, while this is quite relevant for performance measurements, it is thought to be acceptable for this study as all the identification methods and schemes are applied to the same dataset and with the focus of highlighting the differences in their outcomes. Therefore, conclusions should not be altered by this effect.

The stereo-PIV system consisted of a Quantel Dual-Nd:Yag double laser with energy of 171mJ, a mirror arm, the laser sheet optics and two cameras (CCD-chip). Additionally, an ILA synchronizer receives information of a reference blade azimuthal angle from a light sensor located in the nacelle. In this way, the phase-locked measurement is achieved by coupling the laser and blade position. Table 3 provides details of the PIV system.

The measurement plane was horizontal and was centered on the tip location when the blade was in the horizontal position. In this study, only one vortex age is analyzed, $\phi = 40°$, consequently, all the studied parameters belong to the same vortex age, shed from consecutive rotations. A total of 1200 image pairs are recorded in the phase-locked position, this ensures enough information to obtain converged statistics of the results (Uzol and Camci, 2001; Ostovan et al., 2019). The image postprocessing is done with sub-pixel precision by three-point Gaussian fit using the software PIVview3C (PIVTec GmbH). Figure 2 shows a sketch of the facility together with details of the camera and the calibration procedure."

Table 3. Operation and image acquisition details.

operation parameters		PIV parameters	
cross-section area	$4.2 \times 4.2\ m^2$	cameras	PCO 2000
BeRT rotor radius	$1.5\ m$	lens focal length	$100\ mm$
blockage ratio	40%	resolution	$2048 \times 2048\ px^2$
freestream speed	$6.5\ ms^{-1}$	field of view	$435 \times 435\ mm^2$
rotational speed	$3\ Hz$	recordings	1200
tip speed ratio	4.35	laser pulse separation	$150\ \mu s$
turbulence intensity[a]	$3 - 6\%$	interrogation window	$24 \times 24\ px^2$ (50% overlapping)
phase-locked angle	$\phi = 40°$	spatial resolution	$3.6\ mm$

(a) reported by Bartholomay et al. (2017)

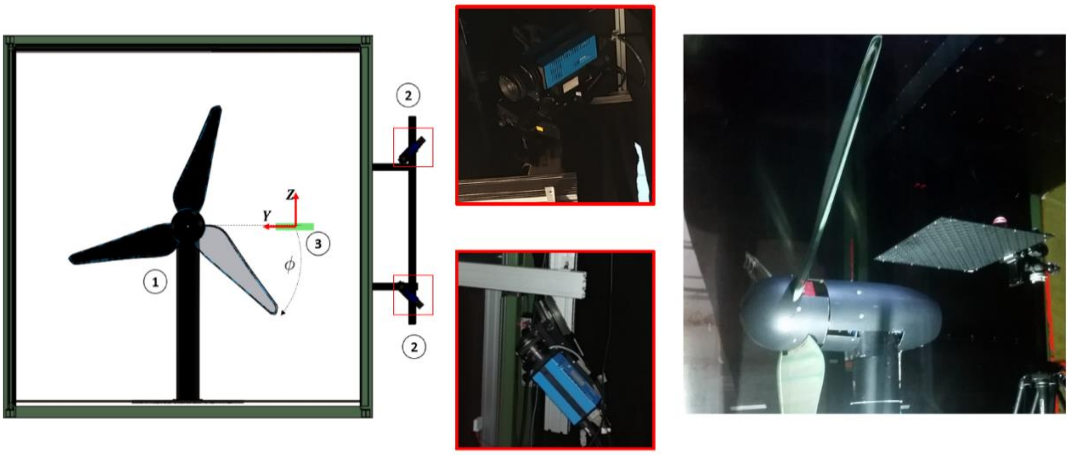

Figure 2. Front view sketch of Berlin Research Turbine ① (BeRT), cameras ② and laser sheet ③, left. Cameras system, middle. BeRT and calibration target in the test section.

RC2.5 The authors should demonstrate more clearly that how the convection velocity has been estimated, particularly from the PIV data. Did you consider the sampling rate of the measurements for each azimuth angle of the blade? How did you make sure that you are tracking the same vortex as moving from one image pair to the next one?

To address this comment, subsection 4.2, which contained the methodology for the vortex center and convection velocity, was split. Now, the convection velocity is reported in a separate subsection, which is given below for convenience. Additionally, the experimental details provide information about the recording procedure (see previous comment):

"4.2 Convection velocity

The tip vortex, after being shed, is both translating and rotating at the same time. Considering this, the convection velocity (downstream, x and outboard directions, y) is estimated as the velocity magnitude corresponding to the vortex center location, Eq. 8. The latter is a common estimation in the literature (van der Wall and Richard, 2006; Yamauchi et al., 1999) and it has the advantage that only one vortex age is needed. However, the estimation is also affected by both the VIM and the scheme chosen on their application."

RC2.6 Page 3, line 70: what is ΘM?

The description has been added and is given below for convenience:

"where P is a fixed point to evaluate, $\overrightarrow{U_M}$ is the velocity of the M surrounding points to P in the surface S, $\overrightarrow{PM}$ is the radius vector that connects the point P with M. N is the total number of points considered in the surrounding of P, and z is the unit vector, normal to the surface plane S. The angle θ_M is formed by the vector $\overrightarrow{PM}$ and $\overrightarrow{U_M}$."

RC2.7 Page 10, line 195: what is v(x,y)? it is mentioned that v(x,y) is induced velocity; however, at line 185 induced velocity is represented by u'(x,y). Which one is the correct one? It is confusing.

The notation has been corrected and it is given below for convenience

"a) Induced velocity field $v'(x, y)$ b) Swirling velocity with the x-axis shifted to the corresponding vortex center."

RC2.8 Page 11, line 230: It is mentioned that "the presence of the multiple maxima and the ring-like distribution of the parameters ω and Q can be explained through different hypothesis. On one side, the cause could be the level of noise in the vortex core because the lack of seeding." If this can be one of the reasons, why you do not get the similar behavior in Figure 6?

The supported hypothesis is now explicitly reported in the manuscript in both the averaged and statistical results. For convenience, the relevant paragraphs are given below. Additionally, the title of Section 5 has been updated to: Results and discussion.

"The presence of multiple maxima and the ring-like distribution of the ω and Q parameters can be explained through different hypotheses. On the one hand, the cause could be the level of noise in the vortex core because of the lack of seeding (Foucaut and Stanislas, 2002; van der Wall and Richard, 2006). The rotational motion of the fluid causes the seeding particles to be pushed at the edges of the vortex. For this reason, the velocity vectors shall be evaluated through interpolation, introducing a further source of uncertainty in the results. In this way, the contours of ω and Q have a single peak concentration for the schemes with the lowest uncertainties (LS and CM) while two peak concentrations appear for the schemes with higher uncertainty (CD, RE, BD and FD).

On the other hand, the presence of multiple maxima might also be due to small-scale structures within the vortex, as suggested by Bonnet (1998). It is conceivable that these structures might originate during the shedding of the tip vortex from the blade. Certainly, the pressure difference between the pressure and suction sides of the blade is only one of the many effects that take part in the formation of the tip vortices. Several experiments show that the flow at wingtips involves the interaction of multiple vortices, shear layer instabilities, flow separation and re-attachment (Giuni and Green, 2013a; Devenport et al., 1996; Micallef, 2012). The involved structures are also affected by the blade shape, tip geometry, Reynolds number, and load distribution (Giuni and Green, 2013a) and generally merge into a single structure. In conclusion, the multiple peaks could be caused by the uneven shedding of vorticity in the chordwise direction. In the work of Micallef et al. (2014), a study of the formation of the tip vortices in a horizontal axis wind turbine, a complex vorticity distribution along the blade chord is observed, which seems to cause multiple vorticity peaks inside the core. These multiple peaks can be identified in the vortex core even after the tip vortex has been shed from the blade. In present results, the same effect is obtained when the high uncertainty schemes are applied (CD, RE, BD and FD).

Among these hypotheses, the first one seems the most suitable. It is possible that artifacts are produced on some of the schemes applied, where the concentration of seeding is diminished. These artificial peaks are not present in the results using the Graftieaux method because the methodology includes information from a larger amount of grid points.

In fact, eight and 24 points are employed to estimate the parameter Γ_1. In the case of BD, CD and FD only two grid points are considered. RE and LS schemes use four grid points, with the difference that in the first case the inner points are considerably weighted more (see Table 2); the opposite happens for the LS case. CM scheme employs six grid points. Therefore, either weighting more the outer part of the derivative estimation (LS scheme) or considering more grid points (CM scheme) contribute to repairing the artifacts and put in evidence that the issue only occurs in the inner part of the vortex."