Evaluation of iSpin anemometry uncertainty analysis

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Executive summary

ECN has evaluated the uncertainty assessment of ROMO Wind's iSpin anemometry comprising the iSpin uncertainty contributions, the iSpin uncertainty in the measured horizontal wind speed and the uncertainty in iSpin applications as for instance in nacelle power curves, etc. This work is based on the documentation provided by ROMO Wind and mainly conducted by DTU.

Regarding the uncertainty contributions ECN believes that the provided set-up is a comprehensive inventory of uncertainty components and a thorough assessment of their contributions to the overall uncertainty budget. ECN believes that the only significant flaw is the currently unexplained wind tunnel results regarding the angular response. We recommend that more sensors be subjected to angular response tests in the wind tunnel and ideally the source of the deviations be explained.

In addition, some of the theory for uncertainty estimation is based on potential flow theory for ideal fluids on a sphere. ROMO Wind specifies in their requirements that the "turbine should have an aerodynamic, symmetrical spinner". ECN recommends that the spinner shape requirements be defined in terms of the limitations of the flow model. Moreover, it is recommended to specify how the uncertainty assessment is affected if the spinner does not have a spherical shape.

In DTU's report, the uncertainty contributions lead to an equation that expresses the horizontal wind speed as a function of nine key variables following the widely used and ISO 17025 related GUM method. In order to come to concrete values for specific cases DTU has developed a complex numerical model to estimate the overall uncertainty of the horizontal wind speed. This model is relatively hard to be applied by parties other than DTU or ROMO Wind.

A more practical approach is desirable that does not rely on complex models and ideally is a simple set of equations that can be applied to any turbine that meets the spinner geometry requirements. To this end, ECN has evaluated a simplified method presented by Demurtas. ECN believes that the method provides a good basis for a best practice uncertainty assessment method. However, the method currently does not take into account important uncertainty contributions, such as the lateral angular response of the iSpin sensor. Given that the source of the lateral angular response of the iSpin sensor

is currently unclear, this is not a trivial task and may make the evaluation become more complex.

This is a crossroads in our evaluation. On the one hand ECN has seen a complete and thorough uncertainty contribution assessment leading to a complex numerical model that can hardly be applied outside DTU and ROMO Wind. On the other hand ECN has seen a simplified model, which currently does not incorporate all contributions, and which might become complex upon completion.

In communication by telephone professor Pedersen provided an alternative option in which a detailed, complex uncertainty assessment is provided to the user community as a documented computer model. ECN believes this is an interesting proposal and could even imagine a mixed solution in which ROMO Wind utilizes a complex model to provide parameters for a simplified assessment to the end user, i.e. an uncertainty parameter database for each turbine type as a service for their iSpin users.

Both the research of unclear uncertainty contributions, such as the iSpin angular response, and the investigation of a suitable implementation path of the uncertainty assessment are subject of research at DTU within the framework of the Performance Transparency Project led by ROMO Wind.

ECN has also evaluated the iSpin uncertainty assessments for nacelle power curves according to the IEC 61400-12-2 standard. Arguably, this standard has mainly been developed considering nacelle anemometry, so one might question to what extend the uncertainty contributions also apply to spinner anemometry in general and to iSpin technology in particular. Of course this depends on the intended application and three application cases were evaluated.

For the use case of generic application of IEC 61400-12-2 for the estimation of the annual energy production, DTU suggests to neglect the effect that the terrain has on the flow over the nacelle. Although the iSpin anemometer is mounted on the spinner, in front of the nacelle, the local flow conditions may still be affected by the terrain. DTU's claim that "at the spinner, there has not been any flow distortion" lacks a reference to the related work.

The use case on relative power curves deals with uncertainty estimation of power curves obtained from the same turbine. In DTU's estimation of the difference of the computed annual energy production, only uncertainty contributions that are uncorrelated between two power curve measurements are included. ECN believes this approach will hold, as long as the set-up remains unaltered and the calibration of the instruments remains valid. ECN believes that for a quantitative comparison, seasonal uncertainty should be included in the uncertainty as well. The influence of differences in environmental conditions, most notably the turbulence intensity, should be reduced by filtering or normalization.

This is also reflected in the iSpin Guardian approach, where the iSpin nacelle power curve on multiple turbines is determined simultaneously. Here, DTU proposes to exclude the uncertainty of seasonal variability from the nacelle transfer function, because the power curves are measured in the same period. ECN believes that for this application it is valid to exclude seasonal uncertainty from the nacelle power curves, but excluding the influence from the nacelle transfer function should only be considered if it is regenerated each time a nacelle power curve is made.

1

Background

ROMO Wind requested ECN to evaluate the uncertainty analysis for their iSpin anemometry technology. The uncertainty of the measured horizontal wind speed will be assessed in chapter 2. Uncertainty aspects related to power performance assessment and comparison is presented in chapter 3.

1.1 ROMO Wind

ROMO Wind is a Danish-Swiss technology-as-a-service company with headquarters in Switzerland and operations and offices in Denmark, France, Germany, Ireland, Italy, Spain and the UK. In 2011 DTU sold all rights to the spinner anemometer patent [14] to ROMO Wind, which brought the iSpin to the market in 2013.

ROMO Wind initially focused their iSpin services on yaw misalignment correction. ROMO Wind currently seeks to expand the application of iSpin anemometry to improve wind farm performance monitoring. In the future ROMO Wind also aims at applying iSpin technology for improving wind farm control and extending wind farm lifetime.

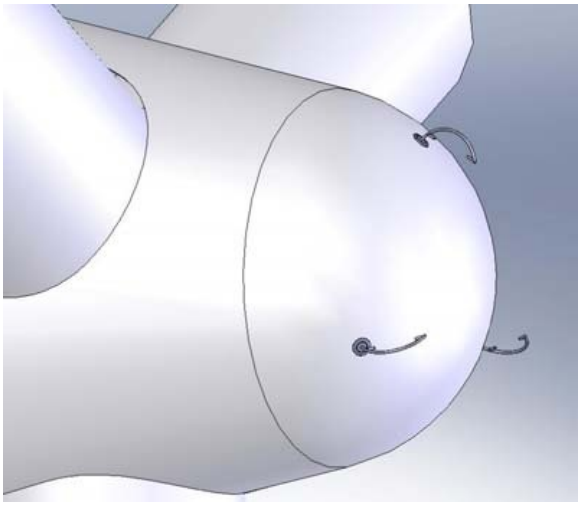
Power performance monitoring can be used to monitor the performance degradation of a single turbine over time. When monitoring the power performance of a farm, ROMO Wind can employ specific benefits of the iSpin anemometry system to compare the relative performance between all turbines in the farm. This concept, called the iSpin Guardian approach, was evaluated by ECN in an earlier report [17].

1.2 iSpin anemometry

The iSpin system consists of three ultrasonic anemometers, mounted on the spinner of the turbine. The sensors are arranged 120° apart, parallel to the rotor plane, as depicted in figure 1.

The iSpin system is an implementation of the more generic patent EP 1,733,241 by Pedersen from DTU [14]. The patent describes an apparatus for measuring wind speed and direction using one or more sensors directly mounted on the rotor of a wind turbine in front of the blades. According to the patent [14, clause 19], an advantage of a spinner

Figure 1: typical mounting example of the iSpin anemometer

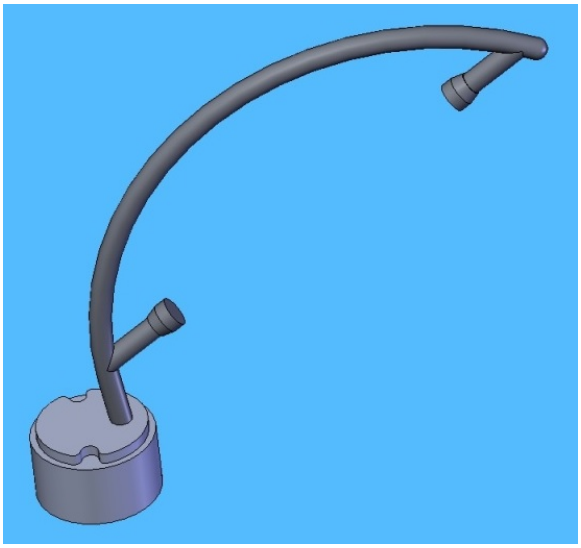


Source: DTU [16]

anemometer in general is that it is undisturbed by the turbulence induced by the blades. The added benefit of a spinner anemometer with three sensors, like the iSpin, is that it can measure the wind speed and directions in three dimensions at each moment [14, clause 25].

The ROMO Wind iSpin anemometry system contains three sonic anemometers, as shown in figure 2. Sonic sensor heads are supplied by METEK, based on their USA-1 sonic anemometers. Each sensor has an accelerometer mounted in its base, which is used for determining the azimuth of the rotor. The system also includes pressure and temperature sensors, which are used to calculate air density, nacelle direction sensor equipment and the required electronics and communication allowing it to operate as a stand-alone system.

Figure 2: iSpin sensor



Source: DTU [15]

The wind speeds measured by the three sensors are converted to the wind speed modulus

and inflow angle using[1] equation 1.1.

$$
\begin{aligned}
V_1 &= U\left(k_1 \cos\alpha - k_2 \sin\alpha \cos\theta\right) \\
V_2 &= U\left(k_1 \cos\alpha - k_2 \sin\alpha \cos\left(\theta - \frac{2\pi}{3}\right)\right) \\
V_3 &= U\left(k_1 \cos\alpha - k_2 \sin\alpha \cos\left(\theta - \frac{4\pi}{3}\right)\right)
\end{aligned}
\tag{1.1}
$$

In this equation set V_1, V_2 and V_3 are the velocities measured in the sonic sensor paths of the three sensors. The constants k_1 and k_2 are obtained through calibration. These are used by equation 1.1 to derive wind speed U, the inflow angle relative to the rotor shaft α and the azimuth position of the flow stagnation point on the spinner θ.

The iSpin calibration is based on extensive research performed at DTU [6]. ROMO Wind, in collaboration with DTU and METEK, provides detailed instructions for the calibration steps [1]:

1. **Zero wind calibration** This calibration test accounts for production uncertainties of the ultrasonic sensors. It is performed at the factory and ensures that the sensor output equals zero in zero wind conditions.
2. **Wind tunnel calibration** In this test the individual iSpin sensors are calibrated in an accredited wind tunnel. The procedure is prescribed by the IEC 61400-12-2 standard and detailed in a clarification sheet [12] published by IECRE.
3. **Internal spinner calibration** After installation, this test normalizes the three sensors against each other. After this step geometric imperfections, such as the spinner shape and mounting errors, no longer results in rotor azimuth dependent variations.
4. **Wind direction calibration** After this calibration the iSpin can correctly measure the inflow angle (such as yaw misalignment). The result of this calibration, k_α, is the ratio between k_2 and k_1.
5. **Wind speed calibration** This calibration yields the k_1 value for the linear wind speed relation. It accounts for spinner shape and sensor mounting errors. This is typically done by only using data acquired at very low and very high wind speeds, for which the rotor induction is negligible.
6. **NTF calibration** The nacelle transfer function (NTF) calibration represents the non-linear relation that accounts for the effect that the rotor induction has on the wind speed at the rotor centre.

[1] Refer to Demurtas' PhD thesis [4, chapter 2, equations 2-4], because the equations in the DTU report [16, equations 2-3, page 8] are incomplete.

2

Wind speed uncertainty

In this chapter we will evaluate the uncertainty analysis of the horizontal wind speed measured by the iSpin anemometry system as performed by DTU. In section 2.1 we review the detailed inventory of uncertainty contributions presented by Pedersen and Gómez Arranz in chapter 3 of their report “Spinner Anemometry - Uncertainty Analysis” [16]. In section section 2.2 we discuss the practical approach for estimating uncertainties as presented by Demurtas et al. [5].

2.1 Review of uncertainty contributions

In chapter 3 of the DTU uncertainty analysis [16] a comprehensive inventory is made of components that contribute to the uncertainty of the horizontal wind speed. This inventory is split up into four categories: calibration, mounting, operational influences and miscellaneous.

Calibration uncertainties

1. **Zero wind calibration** No uncertainty is associated with this calibration step.

2. **Wind tunnel calibration** Apart from the regular wind speed calibration, the clarification sheet requires that the sonic sensor path angle[2] be measured. The uncertainty of the calibration is comprised of the measurement uncertainties of the wind speed and the sonic path angle.

3. **Internal spinner calibration** No uncertainty is associated with this calibration step. This test minimizes 1P variations by making corrections to the k_1 and k_2, so that the output of each sensor yields the same time-averaged value. Therefore, this calibration does not influence the measurement of the average wind speed.

4. **Wind direction calibration** The uncertainty in the obtained k_α is relevant for the wind speed uncertainty as well. The uncertainty of k_α is estimated as $0.1 \cdot k_\alpha$.

[2] This is the angle between the line connecting the sonic sensor heads and the mounting plate. See figure 2. This angle is typically 35°.

5. **Wind speed calibration** No uncertainty is associated with this calibration step. All calibration uncertainty is attributed to the NTF calibration step.
6. **NTF calibration** The uncertainty estimation of the NTF is described in IEC 61400-12-2 [11, annex G].

Discussion of calibration uncertainties

Regarding the wind tunnel calibration, the IEC 61400-12-2 standard states that the wind speed uncertainty for (sonic) anemometers is comprised of the wind speed uncertainty, and the uncertainties of the rotation and tilt tests [11, annex H.4, page 84]. It should be noted that the tilting test is designated as 'recommended'. The DTU uncertainty analysis presents wind tunnel test results for the sonic sensor lateral inflow angle [16, section 3.3.3, page 24-28]. This test coincides with the rotation test. Although the tilt angle variations on the turbine are much smaller than the lateral angle variations[3], it would be interesting to consider a tilt angle response test.

Mounting uncertainties

1. **Longitudinal alignment** Mounting position error; along the direction of the rotor shaft axis.
2. **Direction alignment** Mounting angle error; sensor is rotated along an axis perpendicular to the spinner surface. Very important due to the lateral flow induced by the spinner rotation.
3. **Sensor path angle** Mounting angle error; rotation of the sensor base around an axis that is tangent to the spinner surface and parallel to the rotor plane.
4. **Lateral alignment** Mounting position error; in the direction of the spinner rotation. This results in errors to the wind speed, accelerometer reading and phase shift in the sensor output.
5. **Accelerometer alignment** Misalignment of the accelerometer in the sensor foot influences the determination of the rotor azimuth position, which in turn is used for computing the horizontal wind speed from the measured wind speed modulus.

Discussion of mounting uncertainties

The influence of longitudinal misalignment is estimated from the potential flow theory for ideal fluids on a spherical surface, two assumptions that deserve scrutinization.

Besides the mounting position errors, sensor mounting angle errors are described in two directions. The third possible rotation is not mentioned; a rotation of the sensor base around an axis that is tangent to the spinner surface and in the same plane as the rotor shaft. Admittedly, this rotation would have only a minor effect on the wind speed - apart from the inherent rotation of the accelerometer - compared to the other two directions.

Operational influences

1. **vertical inflow angle** Vertical inflow to the rotor results in varying inflow angles to the sonic sensor path. For realistic vertical inflow angles and if the iSpin sensors are

[3] The lateral angle varies considerably, depending on the rotor speed and inflow angle.

mounted around the 55° mark on a spherically shaped nose cone, the resulting sensor path angle varies only little from 35°. Because the sensors are calibrated for this angle in the wind tunnel, this uncertainty contribution is neglected.

2. **lateral inflow angle** Lateral inflow to the sonic sensors is caused by oblique rotor inflow (relative to the rotor shaft axis) and the spinner rotation. This causes large variations to the lateral inflow angles to the iSpin sensors. The lateral angular response yielded wind speed measurement deviations (from a cosine profile) in excess of 5 % in two different wind tunnel experiments.
3. **turbulence** Modelled as a fluctuation of the horizontal wind speed, the turbulence intensity is expected to only significantly influence the wind speed uncertainty through the variation it causes in the lateral inflow angle of the iSpin sensors.
4. **nacelle vibration** The side-to-side vibration of the nacelle affects the accelerometers used to determine the rotor azimuth.
5. **temperature** The temperature affects the path length through thermal expansion of the sensor arm. Temperature also affects the speed of sound. Both effects are cancelled by the sonic measurement principle[4].
6. **shaft tilt angle** Aerodynamic thrust pushes the tower backwards, results in a tilting of the nacelle. The increased rotor shaft tilt angle is estimated to be 1°.

Discussion of operational influences

The lateral angular response of the iSpin sensors observed in the wind tunnel experiments deserves further investigation. The results obtained for the three sensors are especially diverse at low wind speed (4 $\mathrm{m/s}$). Whether this is the result of manufacturing tolerances or mounting differences in the wind tunnel, the sensor appears to be sensitive to such small variations.

Considered as an ideal gas, the speed of sound in air is only a function of temperature as demonstrated by equation 2.1. In reality the speed of sound is also affected by other atmospheric conditions, such as pressure and humidity. However, like the temperature effect, these influences are eliminated by the sonic measurement principle.

$$c = \sqrt{\frac{\gamma \cdot p}{\rho}} = \sqrt{\frac{\gamma \cdot k_B \cdot T}{M}} \approx 20.0 \cdot \sqrt{T} \tag{2.1}$$

miscellaneous uncertainty components

1. **data acquisition** The uncertainty associated with the data acquisition system is approximated as 0.0006 $\mathrm{m/s}$.
2. **default constants** The uncertainty due to the use of default k constants is considered negligible.
3. **spinner geometry** The operation of the iSpin anemometry system heavily depends on the spinner geometry. If the NTF measured on the reference turbine is to be transferred to another turbine of the same type, deviations of the spinner geometry should be investigated in detail.

[4] The wind speed is determined from two time-of-flight measurements between the sonic heads, once in either direction.

4. **rotor induction** The rotor induction can be influenced by changes to the blades or pitch control strategy. Such changes may render the NTF invalid.

5. **conversion algorithm** The theoretical model used to compute the horizontal wind speed from the iSpin measurements is based on a laminar flow model near the spinner surface. This model breaks down at large inflow angles. This may affect the k_α calibration, which is performed at large misalignment angles. Only a small uncertainty contribution is expected.

Discussion of miscellaneous components

The IEC 61400-12-2 standard [11, annex C.4] specifies the allowable geometric variations of the nacelle as 100 mm. The DTU uncertainty analysis states that for the application of iSpin NTF transfer, the requirements for the spinner should be more strict, but does not provide a criterion. It is suggested to use overlay photography to compare the spinner geometries. ROMO Wind addresses this issue by prescribing various dimensions to be measured during the installation [3]. In communication by telephone ROMO Wind stated that a tolerance of 20 mm is used for these dimensions.

The DTU uncertainty analysis also discusses the uncertainty contributions due to seasonal variability and flow distortion due to the terrain. These contributions are directly related to the IEC 61400-12-2 standard and will be discussed in chapter 3.

Final remarks

ECN believes that the inventory of uncertainty contributions presented by DTU is a thorough one. It certainly appears that all aspects related to the wind speed measurement that are specific to the iSpin anemometry were addressed.

Some of the theory for uncertainty estimation is based on potential flow theory for ideal fluids on a sphere. In an EWEC 2007 publication [13], DTU and its research partners investigated the validity of their flow model using FEM computer simulation and wind tunnel experiments for the spinner of a 300 kW wind turbine, which has a spherical tip. The calibration constants k_1 and k_2 should allow for different spinner geometries. However, ROMO Wind specifies in their requirements that the "turbine should have an aerodynamic, symmetrical spinner" [9, table 2]. We recommend that the spinner shape requirements be defined in terms of the limitations of the flow model. Moreover, it would be useful to specify how the uncertainty assessment is affected if the spinner does not have a spherical tip.

The DTU uncertainty analysis report does contain an uncertainty assessment. However, the results will not be evaluated here, because the assessment is based on a numerical simulation. In chapter 4 of the DTU report an equation is derived that expresses the horizontal wind speed as a function of nine key variables:

V_1, V_2, V_3 : the calibrated wind speed along the sonic iSpin sensor paths

k_1 : spinner anemometer algorithm constant

k_α : spinner anemometer algorithm constant (equal to k_2/k_1)

δ : rotor shaft tilt angle

P_1, P_2, P_3 : output of the three acceleration sensors

Due to the wide range of variation of these variables, it is considered very difficult to determine sensitivities according to the ordinary GUM method [7]. The numerical simulation of the uncertainty assessment is executed for measurements performed on a 2.3 MW wind turbine. This exercise resulted in an uncertainty for the iSpin horizontal wind speed (not including the NTF) of about 1.4 %.

The uncertainty assessment method provided in the DTU uncertainty analysis report is thorough, but labour intensive and hard to be applied by parties other than DTU or ROMO Wind. A more practical approach is desirable that does not rely on complex models for estimating the wind speed uncertainty. Such an approach is presented in the next section.

2.2 Review of uncertainty estimation

Demurtas et al. presented a practical method for estimating the wind speed uncertainty in section 9 of their paper "Nacelle power curve measurement with spinner anemometer and uncertainty evaluation" [5], which is also part of Demurtas' PhD thesis [4, chapter 5].

Calibration uncertainties

All calibration uncertainties to which the DTU uncertainty analysis assigns an uncertainty contribution are addressed.

- **wind tunnel calibration** Wind speed uncertainty from tunnel calibration certificate. Sensor path angle uncertainty from protractor accuracy.
- **wind direction calibration** The uncertainty of k_α is estimated as $0.1 \cdot k_\alpha$ as in the DTU uncertainty analysis [16].
- **NTF calibration** as described in IEC 61400-12-2 [11, annex G].

Mounting deviations

Only the longitudinal alignment error was considered (and corrected for). The alignment was observed through photography from ground level.

From the missing contributions, the most notable are probably the sensor path angle uncertainty and the direction alignment uncertainty, because these proved to be the most significant mounting related uncertainty contributions (along with the longitudinal alignment) in the DTU uncertainty analysis [16, table 11].

Other influences

Like most of the mounting deviations, no other uncertainties regarding the operational influences and miscellaneous contributions are discussed in this paper. The reason for this is that the work presented in the paper that is the topic of this section actually predates the DTU uncertainty analysis discussed in section 2.1.

Propagation of uncertainties

The conversion algorithm for propagating the uncertainty in sonic sensor measurements to an uncertainty in the horizontal wind speed is simplified in two ways.

- The uncertainty in the horizontal wind speed is approximated by the uncertainty in the wind speed modulus.
- The uncertainty in the wind speed modulus is modelled as a simple function of the wind speed. This model was fitted to numerical results obtained for a 6° inflow angle. This value is taken as a worst case average inflow angle.

The latter is expected to have a larger effect on the resulting uncertainty than the former.

2.3 Implementation issues

In order to compose a best practice for iSpin uncertainty assessment, ideally a simple set of equations is available that can be applied to any turbine that meets the spinner geometry requirements. The method discussed in section 2.2 is a good starting point.

However, the method is incomplete with respect to the uncertainty contributions discussed in section 2.1. At the very least an expression is needed to estimate the wind speed uncertainty for the directional alignment uncertainty. Given that the source of the lateral angular response of the iSpin sensor is currently unclear, this is not a trivial task.

In his PhD thesis [4, section 7.2, page 109] Demurtas recommends that "the evaluation of uncertainties shall be simplified further". Although ECN supports this recommendation, some of the simplifications already made are not generically applicable. Add to this the uncertainty contributions that still need to be added, and it is more likely that the evaluation will (initially) become more complex.

This brings us to the crossroads of this evaluation. On the one hand it would be recommendable to simplify the uncertainty assessment to the point where the resulting equations can be published as an easy to apply best practice method. However, simplification for general application will undoubtedly require worst case approximations. This could easily lead to inflation of the resulting uncertainty, which does not do justice to the elaborate uncertainty analysis performed.

In communication by telephone professor Pedersen provided an alternative option in which a detailed, complex uncertainty assessment is provided as a documented computer model. The assessment could then be executed by ROMO Wind or other end users. Both the research of unclear uncertainty contributions, such as the iSpin angular response, and the investigation of a suitable implementation path of the uncertainty assessment are subject of research at DTU within the framework of the Performance Transparency Project led by ROMO Wind.

3
iSpin Application

The IEC 61400-12-2 standard [11] specifies how to establish a nacelle power curve (NPC) with the goal of obtaining an annual energy production (AEP) estimate for that turbine. The prescribed (type B) uncertainty contributions reflect this goal.

These uncertainty contributions may be contested, if properly motivated, for two different reasons.

- Although spinner anemometry is part of the IEC 61400-12-2 standard, it was written mostly with nacelle based cup anemometers in mind. It may well be that some contributions apply to the iSpin anemometer to a lesser extend, or not at all.
- If the goal of the analysis is not to produce an AEP, or at least not in the sense that the result should be comparable to the warranted figure, some contribution may simply prove irrelevant.

In the following sections the uncertainty contributions mentioned in iSpin analysis reports are categorized by application:

- AEP estimation according to IEC 61400-12-2,
- monitoring performance in time on the same turbine,
- comparing performance of like turbines at the same time.

3.1 AEP estimation

The DTU uncertainty analysis [16, page 69] states that "no uncertainty is considered to be added on the NTF due to the terrain for measurement of the NPC, since the wind speed is measured on the spinner and not on the nacelle". This statement is in reference to the uncertainty component for flow distortion due to terrain, $u_{\mathrm{V5},i}$ [11, page 74]. The standard describes this uncertainty source as the term that "captures the influence of the terrain on the flow over the nacelle (upflow, terrain, shear) and subsequent effect on correlation between nacelle wind speed and free stream wind speed as measured during the NTF and NPC". In private communication, professor Pedersen clarified that this

flow distortion due to terrain: $u_{\mathrm{V5},i}$

contribution was deemed not to apply to iSpin anemometers, because they are mounted on the spinner and hence are unaffected by the flow over the nacelle. Finally, the DTU uncertainty analysis [16, section 3.4.7, page 35] claims that "at the spinner, there has not been any flow distortion due to upflow, turbulence and shear". While this argumentation has merit, ECN was expecting a reference to the relevant work.

3.2 Power comparison on same turbine

Comparison of power curves measured on the same turbine can be used to assess performance improvement resulting from modifications applied to the turbine or control strategy, or it can be used to monitor performance degradation over time.

In their report on relative power curves [8], Gómez Arranz and Pedersen from DTU discuss the uncertainty resulting from subsequent power curve measurements on the same turbine. Rather than computing an uncertainty for each resulting AEP, an uncertainty is estimated for the difference between two computed AEP's, $u_{\Delta \mathrm{AEP}}$. As a result, many uncertainty contributions cancel out, because they are assumed to be identical between the two measurement periods. This assumption holds as long as the set-up remains unmodified and calibration of the measurement instruments remain valid. Thus $u_{\Delta \mathrm{AEP}}$ is composed only of those uncertainty components that are uncorrelated between the two power curve measurements.

The dominating uncertainty contributions were found to be:

- the type A uncertainties of the power measurements,
- the operational uncertainties of the iSpin anemometer.

This study did not take into account:

- seasonal variability,
- differences in environmental conditions, especially turbulence intensity.

ECN believes that for a quantitative comparison, seasonal variability should be included, as discussed in section section 3.3.

The differences between environmental conditions could be addressed by filtering, so that both data sets contain a similar range and distribution of e.g. turbulence intensities, as suggested in the report. Alternatively, turbulence normalization might be applied, as specified in the second edition of IEC 64100-12-1 [2, annex M].

Performance change detection

ROMO Wind extends this method in their approach for performance change detection [10]. In their approach the turbine under study, which is to undergo a modification, is compared against a neighbouring turbine that remains unmodified. A power curve measurement is performed on both turbines before and after the modification. The resulting AEP difference for the modified turbine is offset by the AEP difference for the reference turbine.

ECN believes the addition of a reference turbine to be a valuable improvement, yielding more reliable results than in absence of a reference. ECN recommends that when the comparison between the modified and reference turbine is done, the conditions are verified and demonstrated. Example are: similar site conditions and measurement sector, identical turbine conditions and operations and identical data post processing.

3.3 Power comparison between turbines

Comparison of the power curves of turbines is useful for establishing (and monitoring) their relative performance. This is of particular interest for a wind farm in which all turbines are of the same type. ROMO Wind presented such a technique, which leverages specific advantages of the iSpin anemometer, called the iSpin Guardian approach [9]. In an iSpin Guardian campaign, wind speed and power measurements are performed for a certain period of time on multiple turbines simultaneously.

The DTU uncertainty analysis [16, page 69] states that the seasonal uncertainty in the NTF is not included, because the NTF is only considered for the measurement campaign. ECN believes this to be a valid approach for the purpose of this kind of power curve comparison, if the NTF is determined for the same campaign. As addressed in the DTU uncertainty analysis [16, section 3.4.6, page 35], a distinction needs to be made between the uncertainty contribution due to seasonal variability on the NTF and the NPC. The uncertainty of the NPC, referred to in the standard as $u_{\mathrm{M5},i}$ [11, page 75], can be omitted for the purpose of comparing simultaneously measured power curves. The uncertainty of the NTF, referred to in the standard as $u_{\mathrm{M2},i}$ [11, page 73], is more subtle. If the NTF is established once, while the NPC comparison is performed more than once (e.g. at regular intervals for monitoring purposes), then the uncertainty due to seasonal variability should be taken into account for the NTF. It may still be possible to reduce the prescribed estimate of 2 % based on the knowledge of the specific site. As the campaign progresses, the uncertainty may be reduced further due to the increasing range of seasons covered by the measurements. Another approach might be to establish a new NTF for each measurement interval for which an NPC comparison is performed.

seasonal variation on NPC: $u_{\mathrm{M5},i}$

seasonal variation on NTF: $u_{\mathrm{M2},i}$

The DTU uncertainty analysis [16, page 69] further questions the relevance of the following uncertainty contributions.

- uncertainty due to wind speed variations across the rotor due to e.g. shear, while the wind speed measurement is essentially a single point measurement at hub height: $u_{\mathrm{M6},i}$ [11, page 75]
- inaccuracy due to turbulence on the method of bin-wise averaging of the power: $u_{\mathrm{M7},i}$ [11, page 75]

variation to rotor inflow: $u_{\mathrm{M6},i}$

turbulence effect on averaging and binning: $u_{\mathrm{M7},i}$

On both accounts the standard states that the prescribed uncertainties (of 2 % and 1 % respectively) can be relaxed for site specific power curves. However, for the application of power curve comparison, omitting these contributions implies the assumption that all turbines in the farm are exposed to similar turbulence and shear conditions during the campaign. This may hold for a line set-up in non-complex terrain, but in e.g. a rectangular farm, inflow conditions for turbines near the centre are definitely different from those along the edges.

4 Conclusions

ECN has evaluated the current state of uncertainty assessment for ROMO Wind's iSpin anemometry. In this chapter the main conclusions of this evaluation are provided.

4.1 Wind speed uncertainty contributions

We have taken the DTU report on iSpin uncertainty analysis [16, chapter 3] as the reference for our evaluation of the uncertainty contributions identified for the measurement of the horizontal wind speed. As an overall conclusion, ECN believes this to be a comprehensive inventory of uncertainty components and a thorough assessment of their contributions to the overall uncertainty.

The remarks presented in section 2.1 are mostly minor ones.

- A wind tunnel tilt test as recommended by the IEC 61400-12-2 is not reported. Although less relevant than the rotation test, in light of the angular response results it would be interesting to try to perform a tilt test too.
- The uncertainty associated with (longitudinal misalignment) mounting errors is estimated from potential flow theory for ideal fluids on a spherical surface. For general application it would be useful to describe how to obtain an estimate if this approximation cannot be used.
- The mounting angle misalignment of the iSpin sensor is observed in two directions: the yaw and tilt angle. The roll angle is not mentioned, although this is admittedly the least interesting of the three.
- The lateral angular response, which is the response of the sensor to yawed inflow, was observed in wind tunnel experiments to yield deviations from the expected profile in excess of 5 %. Moreover, this response was very different for each of the three sensors tested, especially at low wind speeds. It is unclear what caused these deviations and why the tested sensors behave so differently.

Of these items, ECN believes the last one to be the most influential for the wind speed uncertainty estimate.

The downside to this uncertainty assessment is that it involves a complex numerical model to estimate the overall uncertainty of the horizontal wind speed.

4.2 Wind speed uncertainty estimation

For an uncertainty estimation suitable for implementation we have evaluated the method presented by Demurtas et al. [5, section 9]. ECN believes that the method provides a good basis for a best practice uncertainty assessment method.

The main simplification is introduced by the worst case approximation for the inflow angle. This eliminates the inflow angle as a variable and makes the wind speed uncertainty a pure function of the wind speed modulus. Judging by the case study provided, it appears that the impact on the accuracy of the uncertainty is acceptable.

Because the approximation is turbine-specific, the approximation will have to be derived anew for each turbine type considered. More importantly, the method currently does not take into account some of the important uncertainty contributions identified by the uncertainty analysis discussed in section 2.1. The most important contribution is probably the lateral angular response of the iSpin sensor.

4.3 iSpin application

Whether uncertainty contributions prescribed by the IEC 61400-12-2 standard are relevant, depends on the intended application of the iSpin measurements. We evaluated the uncertainty contributions contested in the DTU uncertainty analysis [16] and a DTU report on relative power curves [8].

For the use case of generic application of IEC 61400-12-2 for the estimation of the annual energy production (AEP), it is suggested to neglect the effect that the terrain has on the flow over the nacelle. Although the iSpin anemometer is mounted on the spinner, in front of the nacelle, the local flow conditions may still be affected by the terrain. DTU's claim that "at the spinner, there has not been any flow distortion" lacks a reference to the related work.

The DTU report on relative power curves [8] deals with uncertainty estimation of power curves obtained from the same turbine. By estimating the difference of the computed annual energy production (AEP), only the uncertainty contributions that are uncorrelated between two power curve measurements are included. ECN believes this approach will hold, as long as the set-up remains unaltered and the calibration of the instruments remains valid. This study did not take into account seasonal variability and differences in environmental conditions. ECN believes that for a quantitative comparison, seasonal uncertainty should be included in the uncertainty. The influence of differences in environmental conditions, most notably the turbulence intensity, should be reduced by filtering or normalization.

An important application of the iSpin anemometer is the measurement of the nacelle power curve (NPC) on multiple turbines simultaneously, as proposed by the iSpin Guardian approach. DTU proposes to exclude the uncertainty of seasonal variability from the NTF, because the NPC's are measured in the same period. ECN believes that for this application it is valid to exclude seasonal uncertainty from the NPC. But excluding the influence from

the NTF should only be considered if the NTF is regenerated each time an NPC comparison is made.

4.4 Steps ahead

ECN believes that DTU has been thorough in the identification of uncertainty components. The only significant flaw is the currently unexplained wind tunnel results regarding the angular response. We recommend that more sensors be subjected to angular response tests in the wind tunnel and ideally the source of the deviations be explained.

For the implementation of the wind speed uncertainty assessment, it would be preferable that a simplified set of equations be derived that can be applied generically. Such simplifications can be obtained by worst case approximations, which come at the cost of inflation of the uncertainty estimate, which might not do justice to the detailed assessment performed by DTU. An alternative, proposed by professor Pedersen, could be to provide the uncertainty assessment in the form of a detailed, complex computer model. We could even imagine a mixed solution in which ROMO Wind utilizes a complex model to provide parameters for a simplified assessment to the end user. (ROMO Wind can build a database of these uncertainty parameters for each turbine type as a service for their iSpin users, as they do for the calibration parameters.)

Both the research of unclear uncertainty contributions, such as the iSpin angular response, and the investigation of a suitable implementation path of the uncertainty assessment are subject of research at DTU within the framework of the Performance Transparency Project led by ROMO Wind.

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