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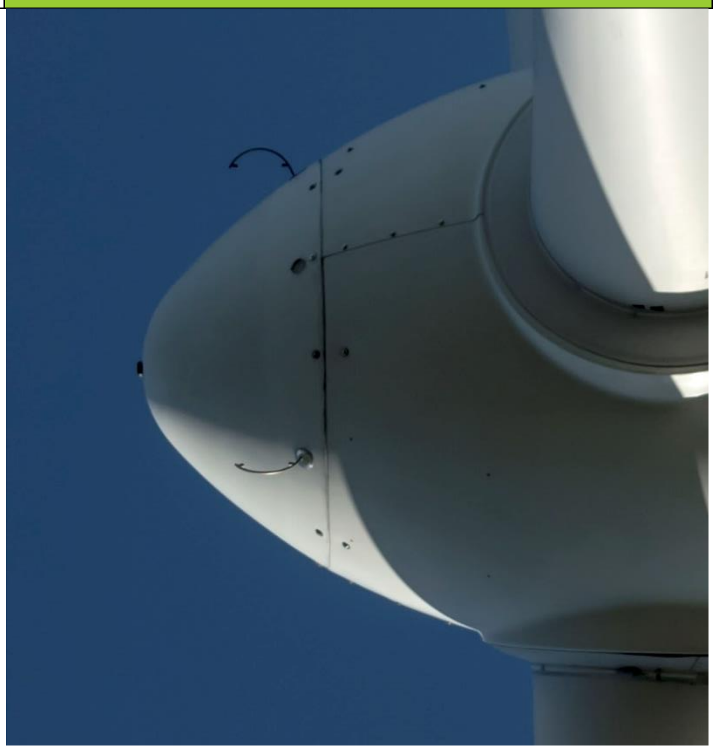
Spinner Anemometry – Best Practice

DTU Vindenergi
Report 2018



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Abstract (max 2000 char.):

Spinner anemometry is used to measure traceable and calibrated wind speed, yaw misalignment and inflow angle. Free wind speed may be measured by application of a spinner wind speed transfer function. Spinner anemometer free wind speed measurements are used in power performance measurements according to the standard IEC61400-12-2 on use of nacelle anemometry. An improved procedure, developed specifically for power performance measurements with spinner anemometry, without considering the use of nacelle anemometry, is the aim of this document. The best practice description for spinner anemometry provides procedures for mounting, calibrations, measurements and uncertainty calculation. As such it could provide input to a separate IEC standard on wind speed, yaw misalignment and inflow angle measurements with spinner anemometry. This best practice procedure for wind measurements is used in the PTP demo project for power performance measurements on 90 wind turbines. The experience from the measurements will be used to demonstrate and support the further development of the best practice procedures.

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Preface

The intension of this report is to summarize the best practice of wind measurements with spinner anemometry. The summarized best practice is based on experience using international standards, improved procedures presented in articles or notes, and through the commercial use of spinner anemometry, documented in internal quality procedures. The best practice report is made as part of the EUDP project PTP in the period 2016 to 2018.

DTU, Risø Campus, April 2018

Content

Abstract

Spinner anemometry is used to measure traceable and calibrated measurements of wind conditions at the rotor centre, including measurement of horizontal wind speed, yaw misalignment and flow inclination angle. The best practice description for spinner anemometry wind measurements provides procedures for mounting, calibrations, measurements and uncertainty calculation. The wind speed measurement can be converted to free wind speed by application of a nacelle or spinner wind speed transfer function. Wind measurements with spinner anemometry may thus be used for a range of applications, including free wind measurements and measurements for control purposes. This report focuses on wind measurements for power performance measurements according to the IEC61400-12-2 standard, including improved methods alternative to the standard. As such it could provide support to a separate IEC standard on wind speed, yaw misalignment and inflow angle measurements with spinner anemometry. This best practice document is used in the PTP demo project for power performance measurements on 90 wind turbines. The experience from the measurements will be used to demonstrate and support the further development of the best practice procedures.

1. Introduction

The purpose of the spinner anemometry best practice report is to provide a uniform methodology of measurement, analysis, and reporting of wind measurements utilizing spinner anemometry. The intent is to ensure that measurement results are as consistent, accurate, and reproducible as possible within the current state of the art of instrumentation and measurement techniques with spinner anemometry. The basic requirements regarding power performance measurements with spinner anemometry references the standard IEC61400-12-2 [1] on power performance measurements with nacelle anemometry. Additional experiences with improved procedures developed during the past years are added.

The best practice report describes all necessary procedures to measure accredited traceable wind measurements with spinner anemometry. The descriptions will refer to relevant documents that may describe procedures in more detail. Requirements for calibration, classification, mounting and uncertainty analysis are described.

2. Scope

Wind measurements carried out according to this best practice procedure are useable for power performance measurements, which is the primary focus of this report. However, the best practice procedures may be used for a range of other purposes, for example: yaw misalignment and inflow angle measurements, measurements of free wind for verification of wind resources and measurements for verification of climatology related to certification, and measurements for control purposes.

3. Measurement principle and measurement parameters

A spinner anemometer is a wind measurement instrument integrated with the spinner of a wind turbine. A spinner anemometer utilises the aerodynamic flow over the spinner surface to determine the wind speed and wind direction at the position of the spinner. Three sonic sensors, mounted at equal azimuthal separation on the spinner, measure directional flow speeds over the surface of the spinner. With these flow speed measurements and a measurement of the rotor azimuth position (based on accelerometer measurements at the foot of each sonic sensor) a conversion algorithm converts the measurements to wind measurements representative to the position of the spinner at the centre of the rotor.

3.1 Definition of wind measurement parameters

The philosophy of the measurement of a power curve is to measure the free wind at the rotor centre as if the wind turbine was not there. This definition of the measured free wind speed requires that the influences on the spinner anemometer measurements from induction due to the blade loads, and the influence from the spinner, the nacelle and the blade roots must be taken into account and corrected for. The influence of induction due to the blade loads is taken care of by a spinner transfer function, STF, similar to a nacelle transfer function, NTF, as defined in the IEC61400-12-2 standard [1]. The influence due to the flow over the spinner, and the induced wind speeds due to the nacelle and blade roots is taken care of by the spinner anemometer algorithm, which converts the local directional wind speeds on the spinner surface and the rotor azimuth position to the wind conditions at the rotor centre. The wind conditions at the rotor centre are thus representable to the free wind when they are applied the nacelle transfer function.

The spinner anemometer sonic sensor measurements are transformed to the wind vector at the rotor centre. However, the wind vector is again transformed to horizontal wind speed, yaw misalignment angle and vertical inflow angle, as these parameters are more representative. The spinner anemometer transformation algorithm uses two constants that depend on the geometry of the spinner, the blade roots and the nacelle, and the position of the sonic sensors on the spinner. Due to the definition of the wind parameters the two constants are ideally calibrated to free wind conditions when the rotor is at standstill, in which case the nacelle transfer function is a 1:1 relationship. However, calibration of wind speed at stand still is very expensive due to lost production, and therefore alternative methods are available.

In addition to the wind conditions at the rotor centre the spinner anemometer measures some secondary parameters. The sonic sensors measure the speed of sound, which is converted to air temperature. The measurement of rotor azimuth position is also converted to rotor speed, which is available.

3.2 Transformation to wind speed and flow inclination angles

The generic relation between the sonic sensor path flow velocities, V_1, V_2, V_3, and the wind vector length U, and its inflow angle to the shaft axis α at the flow stagnation azimuth position on the spinner θ (in the rotating spinner coordinate system) is:

$$V_1 = U(k_1 \cos\alpha - k_2 \sin\alpha \cos\theta) \quad (1)$$

$$V_2 = U(k_1 \cos\alpha - k_2 \sin\alpha \cos(\theta - \frac{2\pi}{3}) \quad (2)$$

$$V_3 = U(k_1 \cos\alpha - k_2 \sin\alpha \cos(\theta - \frac{4\pi}{3}) \quad (3)$$

The generic equations include the two spinner anemometer algorithm constants k_1 and k_2, that must be calibrated for each type of spinner anemometer. The ratio between the two constants $k_\alpha = k_2/k_1$ is another constant that, when calibrated separately, is used to measure and determine flow angles. With k_α calibrated and used in the measurements then k_1 is calibrated, and used to measure and determine wind speeds.

The transformation from sonic sensor measurements to spinner anemometer parameters follows four steps, see Figure 1.

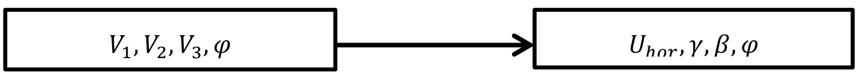

Figure 1 Direct transformation from sonic sensor flow velocities to spinner anemometer parameters

The first transformation step converts the sonic sensor flow velocities V_1, V_2, V_3 to the vector wind speed U, the inflow angle to the shaft axis α and the azimuth position of the flow stagnation point on the spinner θ in the rotating coordinate system:

$$V_{ave} = \frac{1}{3}(V_1 + V_2 + V_3) \tag{4}$$

$$U = \frac{V_{ave}}{k_1 \cos\alpha} \tag{5}$$

$$\alpha = atan2(k_1\sqrt{3(V_1 - V_{ave})^2 + (V_2 - V_3)^2}, \sqrt{3}k_2V_{ave}) \tag{6}$$

$$\theta = atan2\left(V_2 - V_3, \sqrt{3}(V_1 - V_{ave})\right) + \pi \tag{7}$$

The second transformation step converts the parameters to three wind speed components $U_{x,s}, U_{y,s}, U_{z,s}$ in the non-rotating shaft coordinate system taking the rotor azimuth position φ into account:

$$U_{x,s} = U\cos\alpha \tag{8}$$

$$U_\alpha = U\sin\alpha \tag{9}$$

$$U_{y,s} = -U_\alpha \sin(\varphi + \theta) \tag{10}$$

$$U_{z,s} = -U_\alpha \cos(\varphi + \theta) \tag{11}$$

The third transformation step converts the parameters to three ordinary wind speed components U_x, U_y, U_z in a fixed nacelle coordinate system taking the shaft tilt angle δ into account:

$$U_x = U_{x,s}\cos\delta + U_{z,s}\sin\delta \tag{12}$$

$$U_y = U_{y,s} \tag{13}$$

$$U_z = U_{z,s}\cos\delta - U_{x,s}\sin\delta \tag{14}$$

The fourth transformation step converts the parameters into the horizontal wind speed U_{hor}, yaw misalignment angle γ and flow inclination angle β:

$$U_{hor} = \sqrt{U_x^2 + U_y^2} \tag{15}$$

$$\gamma = \arctan(\frac{U_y}{U_x}) \tag{16}$$

$$\beta = \arctan(\frac{U_z}{U_{hor}}) \tag{17}$$

The inverse transformation is made with the four transformation steps in opposite direction as shown in Figure 2.

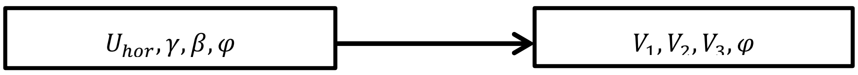

Figure 2 Inverse transformation from spinner anemometer parameters to sonic sensor flow velocities

More details of the transformation steps and derivation of the equations are described in [2].

The azimuth position of the inflow stagnation point on the spinner is defined by the angle from sonic sensor 1 to the position of the stagnation point. Rotor azimuth position is determined from accelerometer measurements in each sonic sensor. Centrifugal and acceleration forces are neutralized in the conversion. The rotor azimuth position angle φ is defined by the angle from vertical to the azimuth position of sonic sensor 1, see Figure 3.

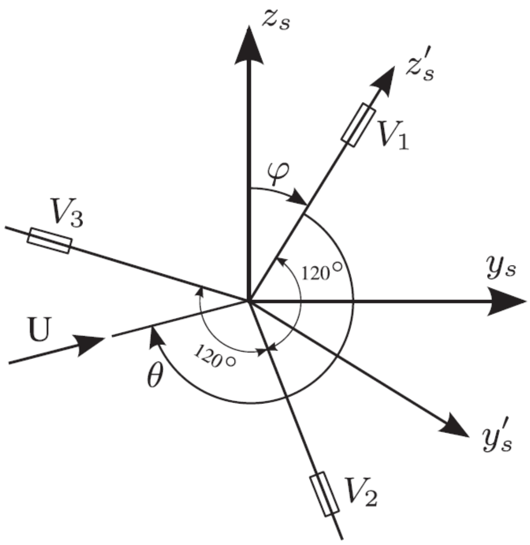

Figure 3 Sketch showing positioning of the three sensors clockwise as seen from the front of the spinner in the non-rotating shaft coordinate system.

3.3 Air temperature

Air temperature is derived from sonic sensor measurements. The sonic sensors measure time of flight from one sensor head to the other and then time of flight the opposite way. The wind velocity and the speed of sound in sensor path i is determined by:

$$V_i = \frac{L_i K_0}{2}\left(\frac{1}{t_{i,to}} - \frac{1}{t_{i,from}}\right) \qquad c_i = \left(\frac{L}{2}\right) * \left(\frac{1}{t_{i,to}} + \frac{1}{t_{i,from}}\right) \tag{18}$$

where L_i is the path length of sonic sensor i and $K_0 = 1.1534$ is a general aerodynamic flow blockage correction factor and c_i is the speed of sound. The "acoustic" temperature in Kelvin is as function of the sound velocity. For each sensor the temperature is calculated with an approximation without taking account of the air humidity:

$$T_i = \left(\frac{c_i}{20.05 m/s}\right)^2 \tag{19}$$

4. Calibration

Calibration of a spinner anemometer is made in six steps in the order shown in Figure 4. The figure shows the calibrations and the system parameters that are involved, see the spinner anemometer manual [3]. However, some calibrations may be omitted dependent on the purpose and requirements of the measurements, see chapter 6.

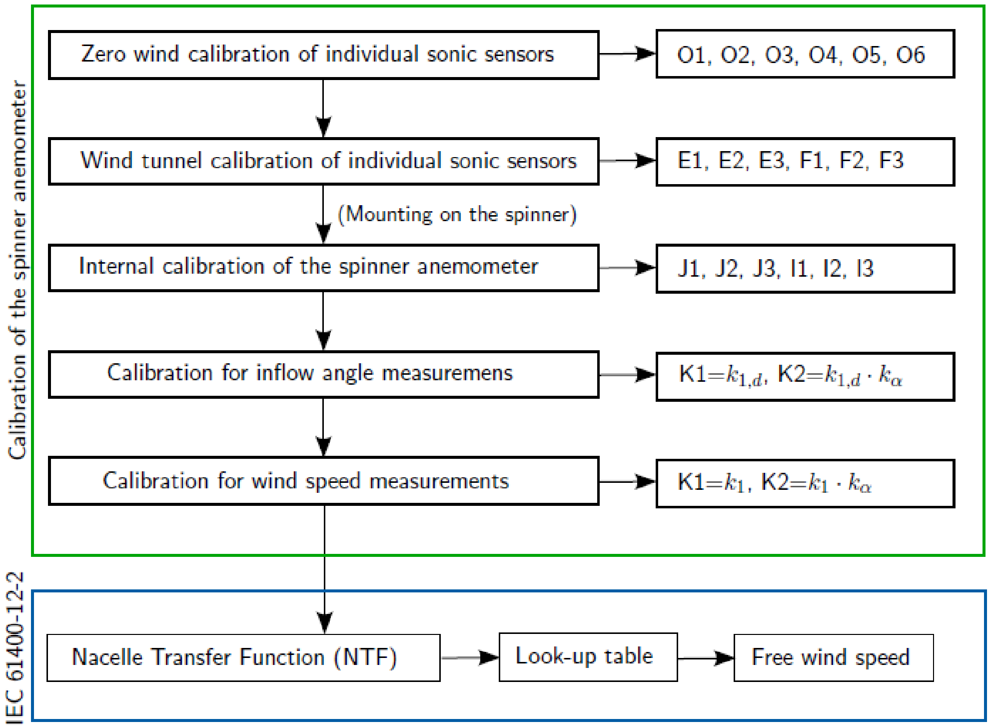

Figure 4 Calibration steps of a spinner anemometer and system parameters

4.1 Zero wind calibration of sonic sensor

Zero wind calibration is a factory calibration that calibrates the instrument at zero wind speed. Procedures are described in an ISO standard [4] and in an ASTM procedure [5]. The calibration is performed with a curtain put around the sensor to make zero wind and the inside temperature is measured, while a calibration at zero wind speed is made by the spinner anemometer. The path length between the two sensor heads is measured and values of the path length and temperature are inserted into the spinner anemometer box. The calibration values are not changeable without doing another zero wind calibration. A new zero wind calibration must be made if a sonic sensor is damaged on the turbine and a substitute sensor is inserted.

4.2 Wind tunnel calibration of sonic sensor

Wind tunnel calibration of a spinner anemometer sonic sensor is made similar to calibration of a cup anemometer, as described in the MEASNET procedure [6], which references the standard IEC61400-12-1 annex F [7]. Calibration of spinner anemometer sonic sensors shall be made according to the clarification sheet [8] as part of the requirements for power performance measurements according to IEC61400-12-2. The document [8] prescribes the use of a special designed plate in the wind tunnel for setup of a spinner anemometer sonic sensor, see Figure 5.

Figure 5 Calibration setup for wind tunnel calibration of a spinner anemometer sonic sensor [8]

The sonic sensor mounting on the plate simulates the mounting on the spinner surface. The sonic sensor path angle must be measured in the actual setup and an uncertainty on the angle must be stated. When converting the wind tunnel calibration result from the calibration certificate to the sonic sensor path the calibration expression shall take account of the actual measured sonic sensor path angle ϕ in the following way:

$$V_n = A_{cal} \cos\varphi \cdot V_{n,meas} + B_{cal} \cos\varphi \quad (20)$$

Where

- V_n is the calibrated wind speed along the sonic sensor path
- $V_{n,meas}$ is the measured wind speed by the sonic sensor
- A_{cal} is the calibration line gain value from the calibration certificate
- B_{cal} is the calibration line offset value from the calibration certificate
- φ is the sonic sensor path angle measured when mounted on the mounting plate

The wind tunnel calibration constants to be inserted into the spinner anemometer box are the sonic sensor path calibration constants $A_{cal} \cos\varphi$ and $B_{cal} \cos\varphi$.

For further details on wind tunnel calibration of spinner anemometer sonic sensors, see [8].

4.3 Internal calibration of a spinner anemometer

An internal calibration of a spinner anemometer shall be made after installation of spinner anemometer sonic sensors on the spinner before calibration for inflow angle measurements. The internal calibration out-compensates the geometric influences such as non-perfect geometry of spinners and non-perfect mounting positions and mounting angles of sensors. The internal calibration minimizes 1P variations in the output signals. A detailed internal calibration procedure is described in [9].

The internal calibration do not influence on 10min average wind speed, yaw misalignment and flow inclination measurements. It does have influence on turbulence measurements by reducing influence of 1P variations due to non-perfect spinner and mounting geometry.

The internal calibration must be made prior to calibration for inflow angle measurements as the non-perfect geometric influences will otherwise depend on the rotor position during the stand-still calibration.

4.4 Calibration for inflow angle measurements

The recommended method for calibration of inflow angles of a spinner anemometer is to calibrate it for yaw misalignment measurements. Inflow angle measurements uses the same algorithm and is therefore calibrated at the same instance. The preferred calibration method is called the “wind speed response method” and is described in [10]. The calibration is made by yawing the stopped wind turbine in and out of the wind (±90°) several times (6-8 times) at moderate wind speeds (>6m/s) while wind speed and yaw misalignment of the wind turbine is recorded at high sample rate (10Hz), see example in Figure 6, left. The measurements of horizontal wind speed are then plotted against yaw misalignment, see Figure 6, right. In the figure it is seen that the wind speed has upwards slopes the further away from zero yaw misalignment you are. An optimization process is now made where F_α is varied until the dependency of the wind speed on the yaw misalignment is minimized, see figureFigure 7. In the figure it is seen how different F_α values influences on the wind speed versus yaw misalignment relationship. The optimization is using the direct and inverse transformations, see former chapter or [2] for the transformation of data in the process. The optimization varies F_α untill the root mean square error of the horizontal linear fit to the horizontal wind speed data is minimized. The calibration for yaw misalignment measurements takes about half an hour to perform in the field dependent on the yaw rate of the wind turbine.

When the angular calibration constant k_α is inserted into the spinner anemometer box as the correct ratio between k_2 and k_1 then yaw misalignment measurements can be made correctly in absolute values. Additionally all wind speed measurements are now linear. This means that the non-linearity of the wind transformation algorithm no longer influences on wind speed measurements, and wind speed measurements can be calibrated by multiplication of the correction factor F_1.

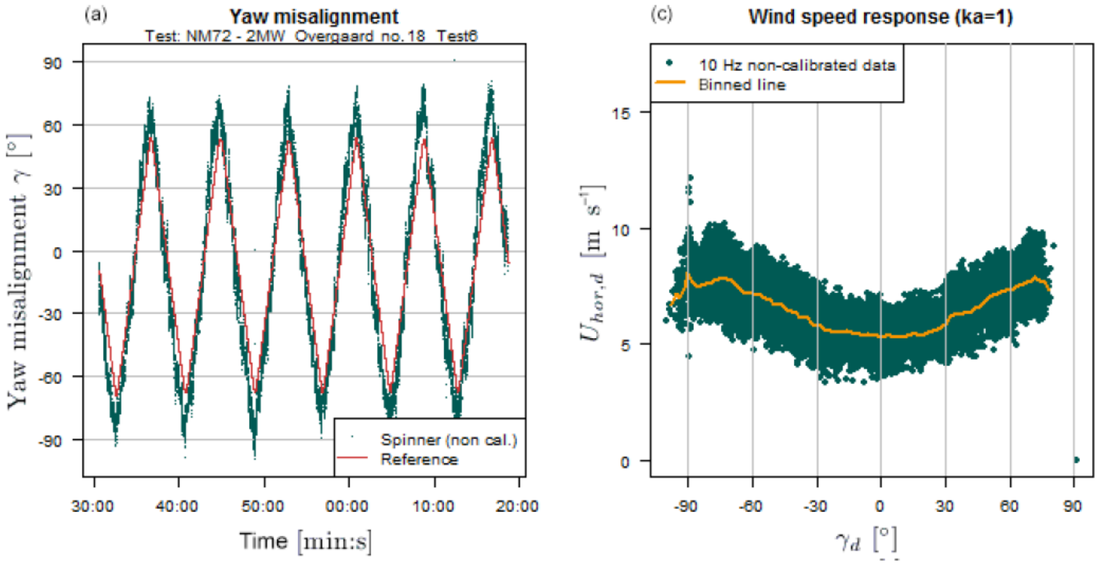

Figure 6 Spinner anemometer yaw misalignment measurements by yawing the wind turbine in and out of the wind, and plot of horizontal wind speed versus yaw misalignment for the default $k_{\alpha,d} = 1$ value, see [10]

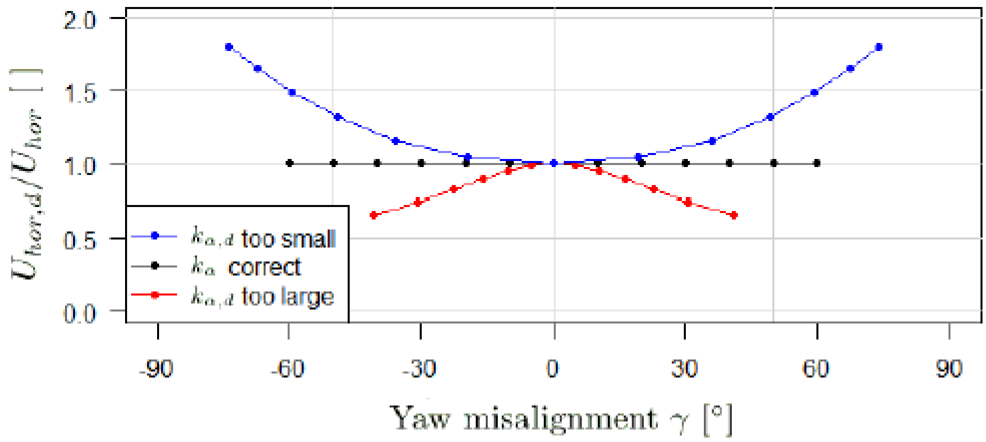

Figure 7 Effect of three different correction factors F_α values; $F_\alpha = 1$ ($k_\alpha = k_{\alpha,d}$, black curve), $F_\alpha = 2$ ($k_\alpha = 2 \cdot k_{\alpha,d}$, blue curve), $F_\alpha = 0.5$ ($k_\alpha = 0.5 \cdot k_{\alpha,d}$, red curve), from [10]

4.5 Calibration for wind speed measurements

The calibration for wind speed measurements of the spinner anemometer is a calibration that determines the correction factor F_1 to correct the default constant $k_{1,d}$ to the calibrated constant k_1 as described in [2]. With calibrated k_α and default k_{1d} constants inserted into the spinner anemometer box the spinner anemometer is ready to be calibrated for wind speed measurements. With a stopped rotor pointing into the wind the spinner anemometer correction factor F_1 can be directly calibrated against free wind hub height mast measurements. In practice, however, it is not feasible to stop a wind turbine for a longer time to make a wind speed calibration, due to costs.

The preferred calibration method of F_1 is to do spinner anemometer measurements against a traceable free met mast hub height cup anemometer during operation of the wind turbine as described in the IEC standard [1]. For practical reasons it is feasible to combine the calibration of F_1 with measurements of the spinner transfer function, STF, as described in [11], but using the method of bins method described in [12] to provide an STF look-up table. An example of measurements of an STF on a V52 wind turbine [13] is shown in Figure 8, where the determined correction factor $F_1 = 1.445$ is indicated with the blue line. The deviation of the data points from the blue line is due to the induction by the rotor. Figure 9 shows the data applied with the correction factor and binned according to [12], red curve. The induction, which is the free wind speed minus the spinner anemometer wind speed, divided by the free wind speed, is shown in Figure 10. The red curve is the binning of the data according to [12] and the pink curve is an alternative fitted function according to the formula:

$$a = B(\frac{U_{SA} - C}{A})^{D-1} \cdot \exp(-\left(\frac{U_{SA} - C}{A}\right)^{D}) \qquad (21)$$

Where $A = 5.71$, $B = 0.449$, $C = 3$ and $D = 2$.

The measurements of the spinner anemometer with F_1 and the STF (the function) applied is shown in Figure 11.

Instead of using a free met mast to measure free wind speed as described in [1] and [11] a nacelle mounted lidar, calibrated according to [14] and [15], may be used, or a ground based lidar, calibrated according to [16], annex L.

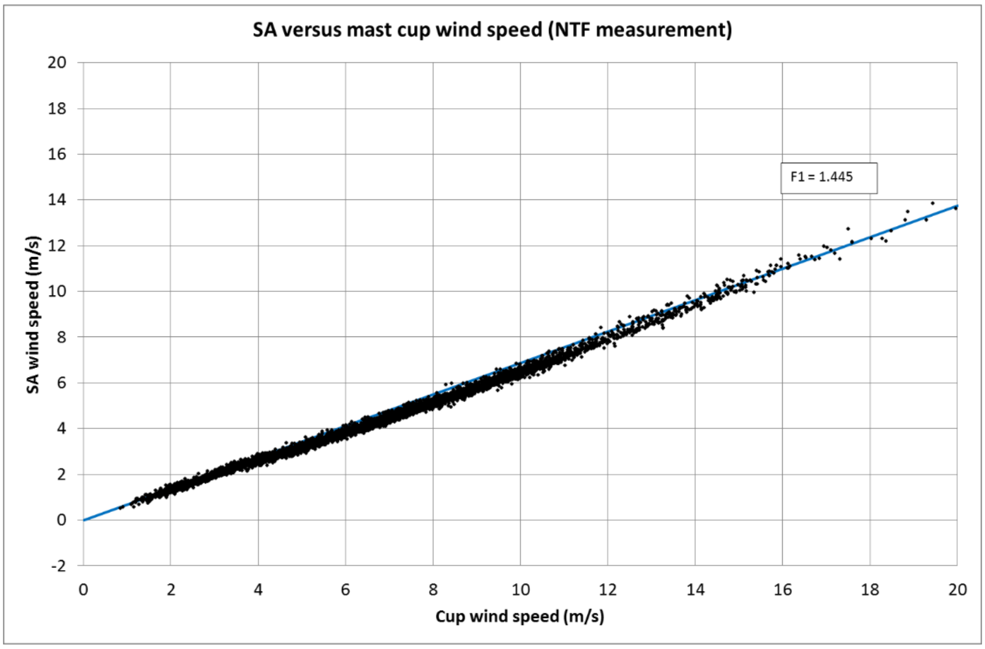

Figure 8 Measurements of spinner transfer function with hub height cup anemometer and spinner anemometer wind speed during operation of a V52 wind turbine [13]

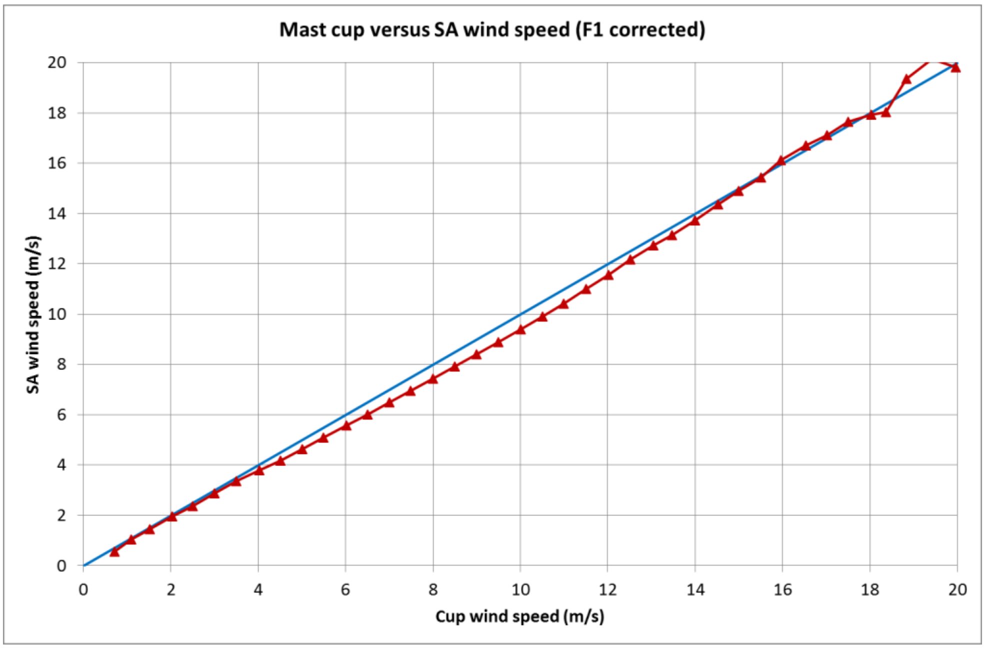

Figure 9 Spinner anemometer corrected ($F_1 = 1.455$) wind speed versus cup wind speed [13], red curve binned according to [13]

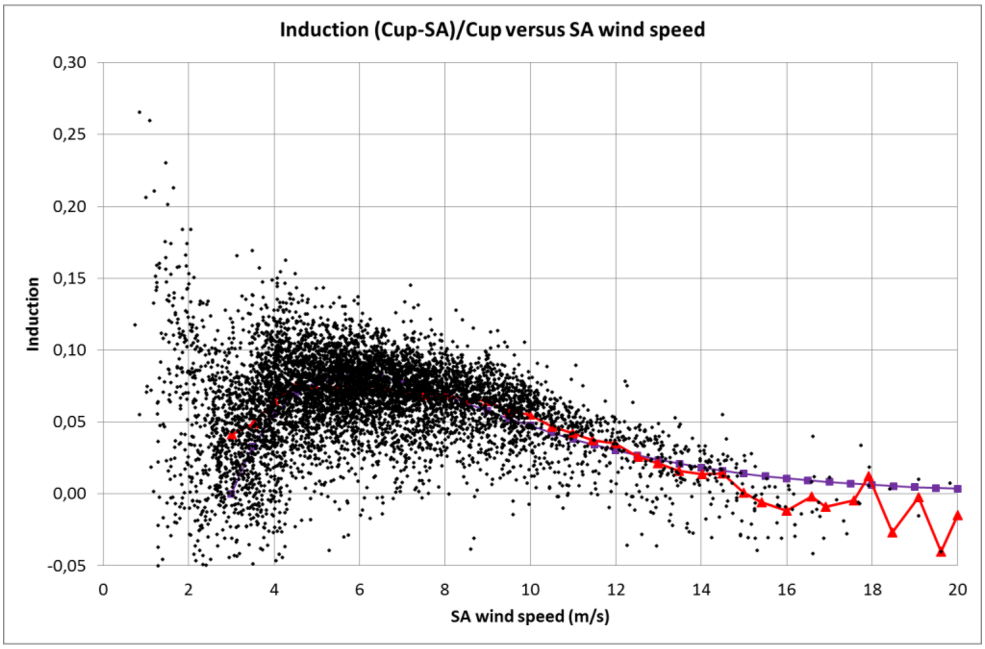

Figure 10 Induction at rotor centre of a V52 wind turbine [13]. The blue curve is the induction found by the method of bins [12]. The red curve is the induction found by fitting a function.

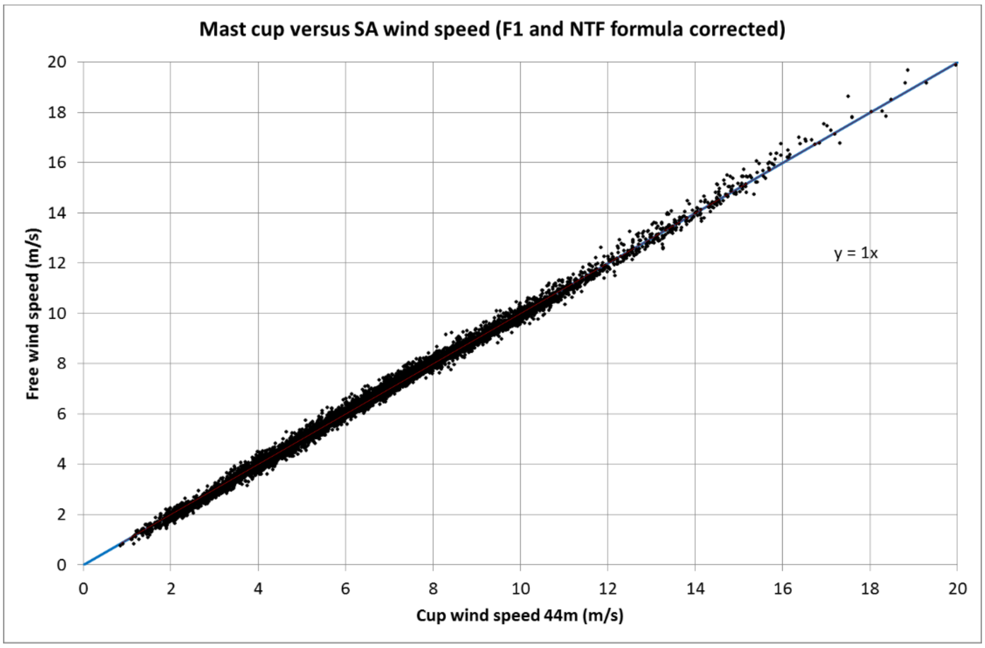

Figure 11 Spinner anemometer wind speed measurements, corrected with F1 and the spinner transfer function STF (function) [13]

5. Mounting of spinner anemometry

The air flow over the spinner is well-defined due to smooth geometry of the spinner. The air flow has a stagnation point at the surface of the spinner nose where the air speed is zero. From the stagnation point the air speed increases over the surface of the spinner until it reaches approximately the double of the free air speed at the edges of the spinner close to the front of the nacelle. The spinner anemometer sonic sensors should be mounted at positions on the spinner surface where the air speed is about the same as the free wind speed. In such case there is room for lower and higher air speeds at the sonic sensors corresponding to variations in inflow angles of the wind with changes in position of the stagnation point. The sonic sensors shall be mounted at azimuth positions exactly in the middle between the blade roots, and at exactly the same distance from the front nose of the spinner and at exactly the same distances from the shaft axis. They shall be pointing forward directly parallel to the shaft axis. As the sensors are mounted with minimum disturbance above the spinner surface they protrude inwards into the spinner. Inside of the spinner there might be structures that prevents the optimal mounting positions and in this case the sensors should be moved forward rather than backwards to avoid collision with the structures.

Mounting of spinner anemometers on different types of wind turbine spinners may vary dependent on the spinner geometry. In order to mount the spinner anemometer sonic sensors systematically in the same way on each individual wind turbine, quality instructions shall be used. Quality instructions shall detail the required skills to do the mounting, the procedure to measure up and document the mounting positions of sonic sensors, the mounting procedure of each sonic sensor, the testing of the spinner anemometer system, and the external verification of the spinner anemometer geometry. The provider of spinner anemometry instrumentation has developed quality instructions for mounting and documentation of installation geometry [17]. An example of documentation for an installation geometry is shown in Figure 12, from [17].

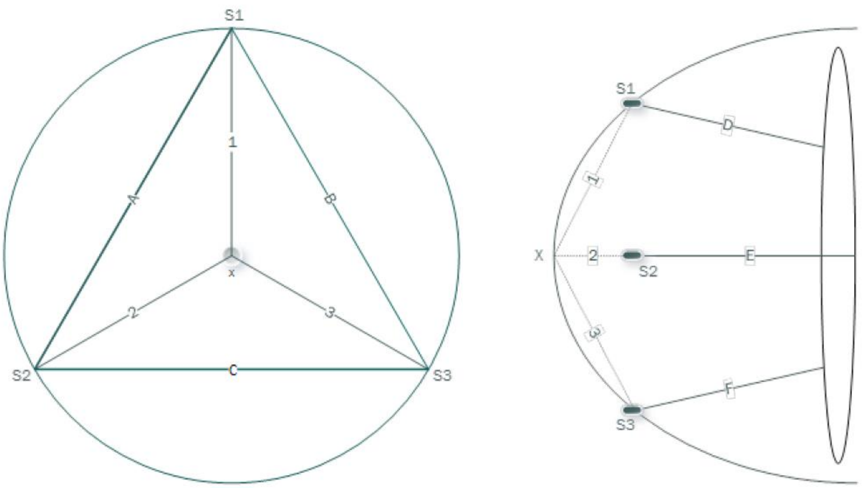

Figure 12 Documentation of mounting geometry on spinner of a wind turbine, from [17]

6. Measurements with spinner anemometry

Spinner anemometry may be used to measure wind speed in different applications. It may be used for measurement that are independent of the operation of the wind turbine and it may be used for wind turbine control. An overview of different measurement applications was made in [18] and is shown in Table 1 with indication of the type of calibrations needed for each type of application.

A spinner anemometer measures wind speed with at least 10Hz frequency. This means that turbulence as well as long term 10min wind statistics can be measured. The use of the STF means that the wind measurements on a wind turbine can refer to free wind measurements. This again means that wind conditions at the position of the wind turbine can be measured “as if the wind turbine was not there”. For example, in wind farms the wind conditions at the location of each wind turbine can be measured and wind conditions can be compared to wind climate predictions. However, regarding turbulence measurements, it should be mentioned that experience have shown, see for example [13], that the standard deviation of the wind speed seems to be the same measured by spinner anemometer and free mast, while the 10min average data must be applied the STF. This means that to get the right free wind turbulence intensity one has to use the standard deviation measured by the spinner anemometer divided by the wind speed measured by the spinner anemometer but applied the STF.

Measurement procedures with spinner anemometer should follow international IEC standards. However, where no international standards are available then well described alternative methods should be applied. Alternative methods may be described in articles, reports or in internal quality procedures.

Table 1 Table of calibrations relevant to different types of measurement applications with spinner anemometers

	Zero wind calibration	Wind tunnel calibration	Internal SA calibration	Inflow angle calibration	Wind speed calibration	STF calibration
Yaw misalignment	X		X	X		
Inflow angle measurements	X		X	X		
Wind speed measurements	X	X	X	X	X	
Free wind speed measurements with STF	X	X	X	X	X	X
Turbulence measurements	X	X	X	X	X	X
Shear measurements	X	X	X	X	X	X
Environmental measure-ments and statistics	X		X	X	X	X
Relative power curve measurements	X	X	X	X	X	X(*)
Power curve measurements IEC61400-12-2	X	X	X	X	X	X
Loads measurements IEC61400-13	X	X	X	X	X	X

(*) The STF is applied to the measured wind speeds in order to obtain ΔAEP

6.1 Power performance measurements

Power curve measurements with use of spinner anemometers should today be made according to the IEC61400-12-2 standard [1]. The standard describes how wind speed measurements made on the nacelle or spinner can be related to free wind speed measurements with the use of a nacelle transfer function, NTF. With use of a spinner anemometer we call it a spinner transfer function, STF. A measurement procedure for an NTF is described in [1] annex D, including the use of a site calibration for complex terrain measurements. A measurement procedure for an NTF in flat terrain is described in annex B of [1]. Validity criteria of an NTF is described in annex A of [1].

7. Uncertainty analysis

Regarding the uncertainty analysis of spinner anemometer measurements the IEC standard [1] does not give appropriate descriptions. An approach developed specifically for estimate of

uncertainty on spinner anemometer wind speed measurements has been proposed in [19]. The main descriptions of this approach are summarized in the following.
The uncertainty analysis of spinner anemometer wind speed measurements should follow a procedure specific to this type of instrument. The non-linear transformation algorithm in the spinner anemometer makes the uncertainty analysis difficult to perform according to the GUM uncertainty standard [21], which is used in the IEC standard [1]. Instead, an approximate Monte Carlo method is proposed in [19], that includes a classification method to take the influence of climatology on the generic spinner anemometer characteristics into account. The proposed procedure considers calibration uncertainties, mounting uncertainties, uncertainties related to operation of the spinner anemometer on the turbine in a given climatology, and other uncertainties.

7.1 Calibration uncertainties

Calibration of the spinner anemometer for traceable free wind speed measurements is made in the following order:

1. Sonic sensor zero wind calibration
2. Sonic sensor wind tunnel calibration
3. Spinner anemometer internal calibration
4. Inflow angle calibration (determination of k_α)
5. Wind speed calibration (determination of k_1 determined as part of the STF)
6. Spinner transfer function calibration, STF

The calibration values for sonic sensor zero wind calibration is automatically inserted into the spinner anemometer box. The sonic sensor wind tunnel calibration shall be inserted into the spinner anemometer box manually. Then the spinner anemometer internal calibration is made and inserted automatically. The inflow angle calibration constant k_α is inserted manually. And finally, the wind speed calibration constant k_1 and the STF are inserted manually. When this calibration track with calibrations and insertion of constants into the spinner anemometer box is followed, see Figure 4, then the calibrated path in [19], figure 31, is followed, and the uncertainty components are minimized. Use of the “default” path, see Figure 22, with use of default $k_{1,d}$ and $k_{2,d}$ constants in the box during wind measurements, will result in larger uncertainty components, and is not recommended for wind measurements, but may be sufficient for inflow angle measurements.

7.1.1 Sonic sensor zero wind calibration

The manufacturer of the spinner anemometer makes a zero wind calibration of individual sonic sensors in combination with the specific electronic box so that the measured wind speed at zero wind is output as zero, see the spinner anemometer manual [3].

No uncertainty is associated with a zero wind calibration in this connection as the zero wind calibration only ensures that zero wind speed is correct, and that the default type wind speed algorithm of the sonic sensor can be applied.

7.1.2 Sonic sensor wind tunnel calibration uncertainty

The uncertainty on the calibrated wind speed along the sonic sensor path in the wind tunnel calibration [8] is influenced by the uncertainty of the wind tunnel wind speed and on the measured sonic sensor path angle. The relation is:

$$V_n = V_t \cos\varphi \qquad (22)$$

where V_t is the wind tunnel wind speed. The combined standard uncertainty is:

$$\sigma_c^2(V_n) = \left(\frac{\partial(V_t \cos\varphi)}{\partial V_t}\right)^2 \sigma(V_t)^2 + \left(\frac{\partial(V_t \cos\varphi)}{\partial\varphi}\right)^2 \sigma(\varphi)^2 = \cos^2\varphi \cdot \sigma(V_t)^2 + V_t^2 \sin^2\varphi \cdot \sigma(\varphi)^2 \qquad (23)$$

Or expressed in the uncertainty terms of annex G:

$$u_{N1,i}^2 = \left(\frac{\partial(V_t \cos\varphi)}{\partial V_t}\right)^2 u_t^{\ 2} + \left(\frac{\partial(V_t \cos\varphi)}{\partial\varphi}\right)^2 u_\varphi^{\ 2} = \cos^2\varphi \cdot u_t^{\ 2} + V_t^2 \sin^2\varphi \cdot u_\varphi^{\ 2} \qquad (24)$$

where $\sigma(V_t) = u_t$ is the standard uncertainty on the tunnel wind speed from the calibration certificate

$\sigma(\varphi) = u_\varphi$ is the standard uncertainty on the measured sonic sensor path angle

7.1.3 Spinner anemometer internal calibration uncertainty

The internal calibration is performed with the presumption that the average wind speed measured by the three sonic sensors is constant, so that the internal calibration does not influence on the measurement of average wind speeds. Therefore, no uncertainty is applied to the internal calibration.

7.1.4 Inflow angle calibration uncertainty

The preferred method for calibration of a spinner anemometer for yaw misalignment measurements is by yawing the stopped wind turbine in and out of the wind several times at moderate wind speeds while spinner anemometer wind speed and yaw misalignment is recorded [10]. When k_α is inserted into the spinner anemometer box as the correct ratio between k_2 and k_1 then absolute yaw misalignment measurements can be made, and wind speed measurements can be converted linearly.

The uncertainty on the calibrated k_α value is estimated from the variations of the uncertainty on the wind speed response method on several wind turbines and also variations to other calibration methods. The experienced level of uncertainty is within ±10% of F_α, see [10].

7.1.5 Spinner anemometer wind speed uncertainty

The calibration for wind speed measurements by the spinner anemometer at the rotor centre is a calibration that determines the constant k_1 [11]. However, as is mentioned in the next chapter, the determination of k_1 is made simultaneously with calibration of the STF.

For measurements of wind speed at the rotor centre alone (when not applying the STF), the k_1 constant should be applied the uncertainty from the high and or low wind speeds in the STF from which the k_1 constant was determined.

Apart from the uncertainty on k_1 the uncertainty on the wind speed measurements at the rotor centre shall include calibration uncertainties (excluding the STF), mounting uncertainties and operational uncertainties. These are described in following chapters.

7.1.6 Wind speed STF calibration uncertainty

The calibration for wind speed measurements at the rotor centre is a calibration of k_1 made during operation of the wind turbine, combined with calibration of the STF, [11]. The STF is made directly from measurements with the default k_{1d} value and the calibrated k_α value, so k_1 can be determined with a linear proportionality without transforming measured data to the definition of the measured wind speed with the non-linear inverse and direct transformation algorithms. When applying the k_1 constant, the STF, including determination of the uncertainty, will make a full relation to the free wind speed.

As the uncertainty of the STF is fully determined by the procedure in [11] no uncertainty should be applied to determination of the k_1 constant when considering free wind speed measurements and application of the STF.

The uncertainty of the STF measurement is derived from the method description in [1], annex G, with the free stream wind speed uncertainty component taken from table G.2 in the annex. The uncertainty of the nacelle wind speed components in table G.2 should be substituted with the uncertainty of the spinner anemometer wind measurements at the rotor centre as described in the previous and the following chapters.

7.2 Mounting uncertainties

The positioning and direction of the sonic sensors on the spinner are of high importance with respect to the wind speed measurement uncertainty of the overall spinner anemometer. The positions of the sonic sensors on the spinner shall be clearly defined and described in mounting instructions on beforehand, before mounting of the sensors. The positions of the sonic sensors on the spinner of the wind turbine on which the k_1 constant and the STF are measured, are the reference positions of sonic sensors for measurement of power curves on other wind turbines of the same type. The reference positions shall be used to evaluate the mounting positions on other turbines of the same type, and to validate the transfer of the STF to these turbines, as described in this document in annex A.

The mounting uncertainties include longitudinal position alignment, lateral position alignment, direction alignment, sonic sensor path angle alignment, and accelerometer alignment in sonic sensor.

7.2.1 Sonic sensor longitudinal alignment uncertainty

The air flow over the spinner from the stagnation point in the nose is accelerated over the spinner surface to the edge of the spinner. Due to the accelerated flow, the longitudinal positioning of the sonic sensors on the spinner surface is very sensitive to the exact determination of the k_1 constant during measurement of the STF and for achievement of the same reference k_1 constant when the STF is transferred to another wind turbine of the same type with the same spinner design.

The longitudinal positioning on the spinner surface is close to where the spinner surface has a slope angle to the shaft axis of 35º. The default sonic sensor path angle is tilted upwards with an angle of 35º relative to the mounting foot surface. This means that the sonic sensor path often is parallel with the shaft axis after installation on the spinner. However, there may be deviates from this default position.

An estimate of the influence on the sonic sensor measured wind speed on the longitudinal positioning for the ideal reference mounting can be made with potential theory for a sphere.

The potential flow on a sphere for an incompressible, inviscid, irrotational fluid is determined as:

$$V_r = Ucos\varphi(1 - \left(\frac{r}{R}\right)^3) \quad (25)$$

$$V_t = Usin\varphi(1 + 0.5\left(\frac{r}{R}\right)^3) \quad (26)$$

Where

V_r	is the radial flow speed towards the centre of the sphere
V_t	is the tangential flow speed
U	is the free wind speed
φ	is the position angle on the sphere
r	is the radius to the sonic path centre
R	is the radius of the sphere

The sonic sensor path flow speed is then the projection of V_r and V_t on the sonic sensor path, as shown in Figure 13:

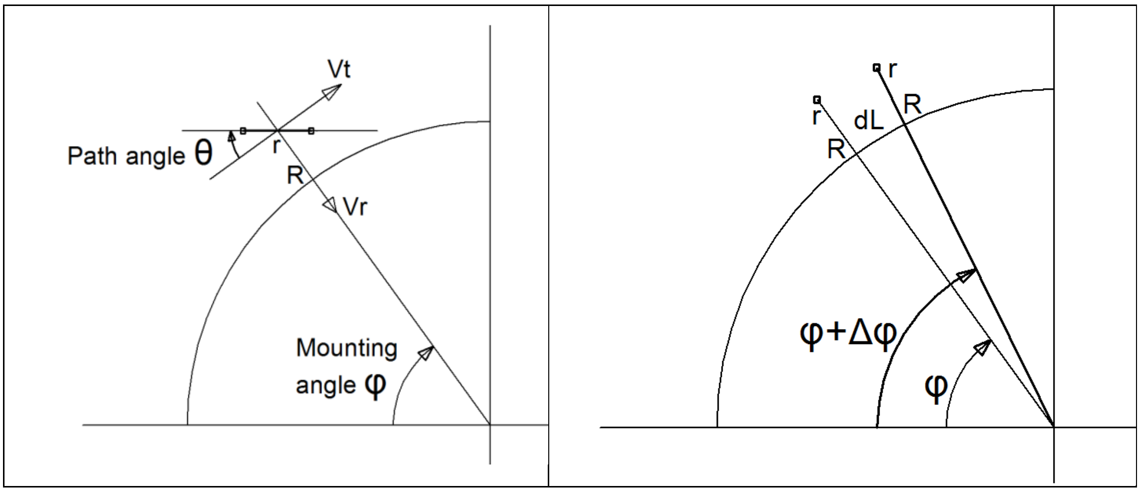

Figure 13 Mounting and path angles for determination of sonic path flow speed for potential flow over sphere (left) and deviation angle for longitudinal deviation (right)

$$V_1 = V_t cos\theta + V_r sin\theta \quad (27)$$

Where

θ is the sonic sensor path angle

The sensitivity of the longitudinal mounting deviation to the sonic sensor flow speed is made by converting the tangential deviation dL to the change in position angle φ, then deriving the radial and tangential flow speeds, and project these on the sensor path and then derive the deviation in wind speed. The sensitivity is shown in Figure 14, where radius is the distance perpendicular from the shaft axis to the mounting position of the sensor (to centre of sonic path). For example, for a radius of 1m radially from the shaft we can estimate a 0.45% difference in sonic sensor output per cm sonic sensor mounting error. The deviation in longitudinal alignment is considered positive for deviations in direction of the nacelle.

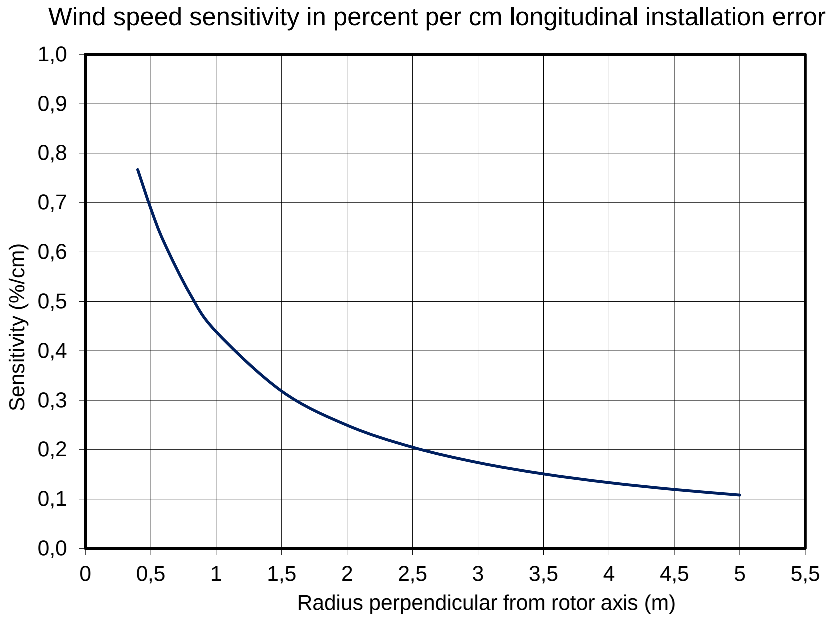

Figure 14 Sketch showing the calculation of sonic sensor path wind speed from potential flow over sphere

7.2.2 Sonic sensor direction alignment uncertainty

The direction alignment of the sonic sensors (angular alignment) is important since the actual inflow angle to the sonic sensor is influenced by lateral flow due to the rotational speed, and this influences on the signal output. The direction alignment sensitivity depends on the radius from the rotor axis to where the sonic sensor is positioned on the spinner. For larger radii the lateral wind speed component is increased and this increases the sensitivity to direction alignment. Figure 15 shows the sensitivity as a function of the lateral inflow angle. The estimated lateral inflow angles and percentage wind speed deviations of three types of wind turbines and two different wind speeds are shown on the curve as well. The percentage wind speed deviation is estimated by calculating the ratio of the cosine to the lateral inflow angle and the cosine to the lateral inflow angle plus one degree.

7.2.3 Sonic sensor path angle uncertainty

From the wind tunnel calibration the path wind speed is calibrated based on the actual measured sonic path tilt angle. This means that the path wind speed is traceable calibrated and measures the correct wind speed at the local position on the spinner. Deviations on the sonic sensor path angle (default 35.0º) occurs and has a significant influence on the measured flow speed because the vertical inflow angle to the sensor path always depends on the cosine to the path angle, see Figure 16, which shows the inflow angle relative to the position on a sphere calculated with potential flow theory. The actual sonic sensor path angle shall be measured during calibration as described in the wind tunnel calibration procedure [8]. A deviation from the default value has the same influence as the lateral angle deviation considered in the previous chapter. Thus, Figure 15 can be used for the sonic sensor path angle sensitivity as well. At the path angle 35º the deviation sensitivity is seen to be 1.25% of the wind speed per degree deviation. The deviation is considered positive for upwards tilting of the path angle.

For practical reasons it is appropriate to normalize the wind tunnel calibrations to the default 35º path angle. When wind tunnel calibrations on all sonic sensors on several wind turbines are normalized to the default angle then the wind tunnel calibrations takes care of the variations of actual sonic sensor path angles, and no uncertainty needs to be applied to the sonic sensor path angle variations. However, an uncertainty must be applied due to spinner surface angle variations at the sonic sensor installation positions.

7.2.4 Sonic sensor lateral alignment uncertainty

If one sonic sensor is not positioned exactly in the middle between two blades then there will not be 120º between the sonic sensors. This will have an influence on the both the sonic path wind speed measurement and on the accelerometer measurement as there will be a phase shift on the output from these sensors. The wind speed measurement will be offset with an angle that corresponds to the lateral alignment deviation, and the deviation in wind speed will correspond to an offset in the sinusoidal variation over a full rotation of the rotor. The accelerometer measurement will be offset with a similar angle and the deviation in acceleration will correspond to an offset in the sinusoidal variation over a full rotation of the rotor. Deviations are considered positive in the rotation direction.

7.2.5 Sonic sensor accelerometer alignment uncertainty

The accelerometer in the foot of each sonic sensor must be correctly aligned in the lateral direction in order to measure the azimuth position correctly. If an accelerometer is not correctly aligned the determination of the azimuth position of the rotor will deviate from the correct position and there will be a phase shift in the signal. The influence of the sonic sensor accelerometer alignment in the sonic sensor foot will correspond to an offset in the sinusoidal variation over a full rotation of the rotor as for the sonic sensor lateral alignment.

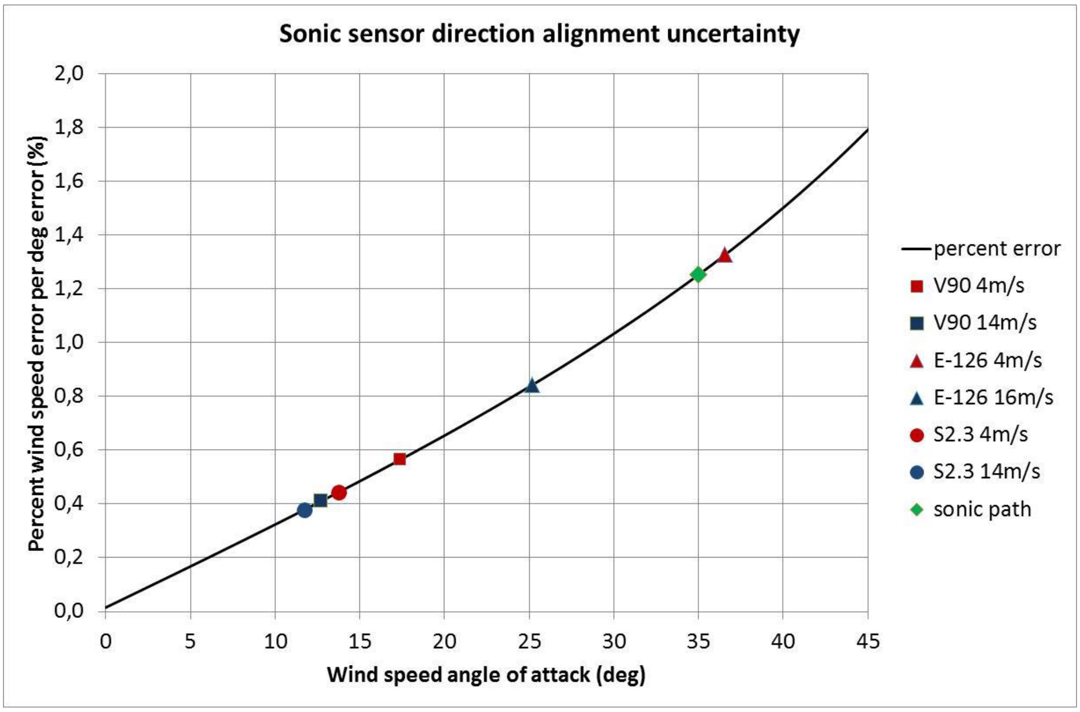

Figure 15 Sensitivity in percent of sonic sensor measured wind speed on the lateral mounting angle deviation of sonic sensors as function of lateral inflow angle to the sonic sensor path. Additionally, the sensitivity of the sonic sensor path uncertainty is shown (green diamond)

7.3 Operational influences

The spinner anemometer measurements are influenced by the climatic conditions and the turbine behaviour during operation of the wind turbine. The climatic conditions are the same influential parameters as for cup and sonic anemometers in the IEC61400-12-1 standard [16]: wind speed, turbulence intensity, average flow inclination angle and temperature. The inflow angle to each sonic sensor depends on rotational speed, yaw misalignment, turbulence, and on shaft tilt bending due to thrust on the rotor.

7.3.1 Vertical inflow angle to sonic sensors

The vertical inflow angle variations in Table I.1 in the IEC61400-12-1 standard [16] for class A vary from -3º to 3º and -15º to 15º for class B.

With a shaft axis tilt angle of, typically 5º, and only considering the class B conditions the variations correspond to rotor inflow angles from -20º to 10º relative to the rotor axis. These inflow angles give rise to inflow angle variations on the individual sonic sensor paths during rotation. The inflow angles may be investigated with potential flow on a sphere with a radius of 1.22m, corresponding to 1m radius at the 55º position on the sphere. The inflow angle on a sonic sensor on the upper side of a sphere at the position 55º, relative to the shaft, is 34.3º, see Figure 16. For -20º inflow angle to the axis, corresponding to 75º position angle on the upper side of the sphere (when inflow angles are considered to be analogue to change of sonic position on the sphere as the stagnation point move accordingly), the inflow angle to the sonic path is 34.7º, and for 10º inflow angle to the axis, corresponding to 45º position angle on the sphere, the inflow angle is 34.0º. For a sonic sensor on the lower side of the sphere, corresponding to 35º position angle on the sphere, the flow angle to the sonic path is 33.5º. The vertical inflow angle to the sonic sensor is thus varying only a few degrees from 35º, the angle at which the sonic sensors are calibrated in wind tunnel. The inflow angle on the sphere does therefore not seem to influence significantly on the vertical inflow angle on the sonic sensor path. For larger radii of sonic sensor positions the inflow angles to the sonic path will be much closer to 35º.

The vertical inflow angle on the sonic sensor path is under these conditions so close to the inflow angle during wind tunnel calibration that the influence is small enough to be neglected for both class A and class B climate conditions.

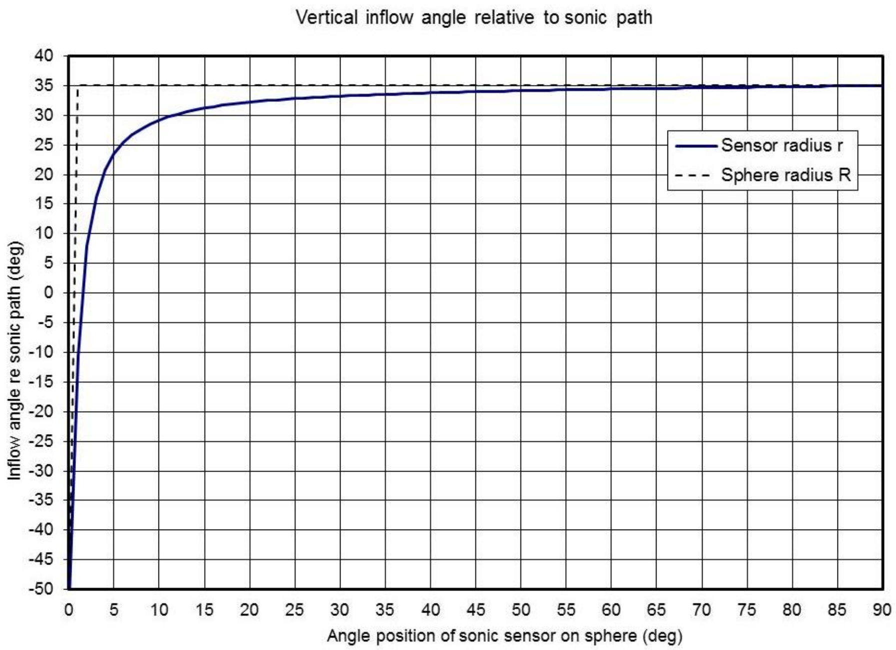

Figure 16 Vertical inflow angle relative to sonic sensor path calculated by potential flow over sphere. Angle position may also be used to consider inflow angle variations to the spinner anemometer

7.3.2 Lateral inflow angles to sonic sensors

The influence from the lateral inflow angle to the sonic sensor path is quite different as the angle varies significantly during operation. With the sonic sensor in a horizontal position the rotor flow inclination angle give rise to a vertical wind speed component that leads to a significant lateral inflow angle to the sonic sensor path. With an inflow angle to the spinner of -20º the vertical upwards component is 36% of the horizontal wind speed. This vertical component must be added to the existing lateral wind speed component due to rotor rotation.

For a V90 turbine at 4m/s the upwards component is 1.44m/s which results in lateral wind speeds of 2.35m/s and -0.54m/s, respectively on either side. This corresponds to lateral inflow angles of 30.4º and -7.7º, respectively. With an inflow angle of +10º to the spinner, the upwards wind speed component is -17.6%, corresponding to -0.70m/s, and lateral wind speeds to the sonic paths of 1.60m/s and 0.20m/s. This corresponds again to lateral inflow angles of 21.8º and 2.8º.

With these significant lateral inflow angle variations during rotation the response of the sonic sensor to lateral inflow angles is rather important. If the lateral inflow angle response is cosine shaped then the influence is zero. Otherwise, there is a systematic deviation that depends on the lateral inflow angle response.

7.3.3 Sonic sensor lateral angular response

There are wind tunnel tests that show directional influence on sonic anemometers due to supporting structure and sonic sensor head distortion. The 35º tilt angle of the sonic sensor path does significantly reduce the basic influence of the sonic sensor head distortion on the flow in the sensor path. However, on the spinner anemometer sonic sensors, the arc tube influences on the sonic sensor flow speed measurements.

The lateral angular response shall be determined and measured in a wind tunnel with the same setup as for wind tunnel calibration [8]. The mounting plate with sonic sensor should be rotated around the supporting tube so that the centre of the sonic sensor path is right above the axis. The flow directions may be set with preset lateral angles to the sonic sensor: , ±0°, ±2°, ±4°, ±6°, ±8°, ±10°, ±15°, ±20°, ±25°, ±30°, ±35°, ±40°, ±45°, ±50°, ±55°, ±60°, ±65°, ±70°. Alternatively, flow directions may be varied with a very slow sweep rate.

The response shall be measured for tunnel wind speeds in the range 4-16m/s, for example for 4, 8, 12 and 16m/s.

The rotation direction of wind turbines is almost always clockwise when the rotor is seen from the front. The inflow to the sonic sensor due to the rotation is thus coming from the left side when viewing the sonic sensor from the sensor foot. This corresponds to negative lateral inflow angles.

A measurement of the lateral angular response were performed with the mounting plate setup from [8], and for 4, 8, 12 and 16m/s wind speeds. Figure 17 shows the setup where the sonic sensor is yawed to negative lateral inflow angles. Figure 18 shows the measured average of the three sensors. The curves for the different wind speeds are seen to fall close and to show a symmetric pattern. The maximum deviation is about 2.5% at about ±50º lateral inflow angles. The fitted curve is expressed by:

$$\Delta c = 0.025 \cdot (abs(\sin(1.9\alpha)))^4 \qquad (28)$$

Where α is the lateral inflow angle in radians

More detailed description of the lateral response measurements are shown in [19].

Figure 17 Setup of spinner anemometer on mounting plate according to [8] in WindGuard GmbH wind tunnel with a high lateral inflow angle

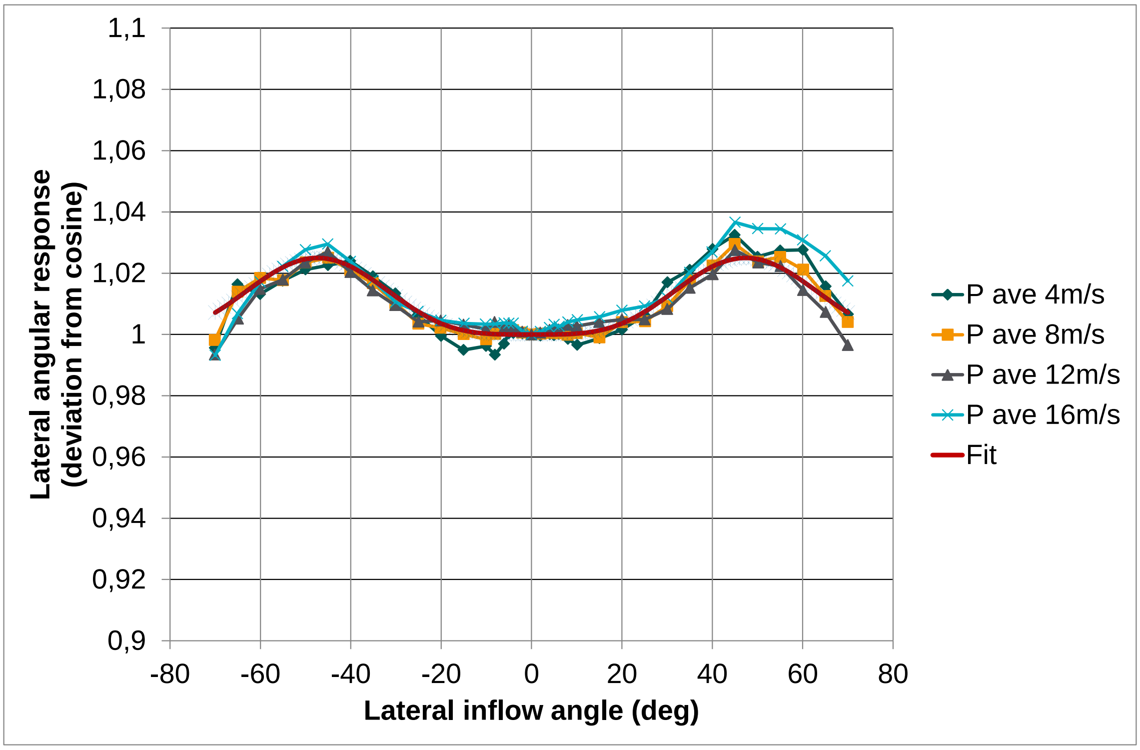

Figure 18 Average lateral angular response of all three sonic sensors at different wind speeds [19]

7.3.4 Turbulence influence on uncertainty

An investigation on a 2D sonic anemometer have not shown influence to turbulence while exposed to sinusoidal wind speed variations in a wind tunnel. This indicates that flow speed variations in the same direction on a sonic sensor do not seem to provide sensitivity to turbulence.

The influence of turbulence on spinner anemometer measurements is only significant through the lateral angular response of the sonic sensors. The atmospheric turbulence will give rise to variations of wind speeds in the sonic sensor paths and to variations in lateral inflow angles to the sonic sensors. The lateral inflow angle variations shall be added to the variations due to rotational speed, yaw misalignment and wind flow inclination angles to the rotor. The turbulence influence is thus complicated as it must be combined with other influences to find the response due to variations of lateral inflow angles during operation.

7.3.5 Determination of lateral inflow angle to sonic sensors

The lateral inflow angles to sonic sensors may be estimated with the sphere analogy. From the turbulent wind input on the rotor we will estimate the lateral inflow angles. The inflow wind speed to the spinner is assumed not to be rotated due to the rotor aerodynamics, and the lateral wind speed components are assumed to be constant over the spinner. With these assumptions it is a question about converting the inflow wind speeds to wind speed components in coordinate systems following each sonic sensor. Coordinate shifts convert the inflow wind speeds to sonic sensors as follows.

From horizontal 10min artificial Mann-wind to sloped wind:

$$u_s = u_i \cos(\beta) - w_i \sin(\beta) \quad (29)$$

$$v_s = v_i \quad (30)$$

$$w_s = u_i \sin(\beta) + w_i \cos(\beta) \quad (31)$$

From sloped wind speed with yaw misalignment to axial directional flow:

$$u_g = u_s \cos(\gamma) - v_s \sin(\gamma) \quad (32)$$

$$v_g = u_s \sin(\gamma) + v_s \cos(\gamma) \quad (33)$$

$$w_g = w_s \quad (34)$$

From axial directional flow to axial aligned flow:

$$u_b = u_g \cos(\delta) - w_g \sin(\delta) \quad (35)$$

$$v_b = v_g \quad (36)$$

$$w_b = u_g \sin(\delta) + w_g \cos(\delta) \quad (37)$$

From axially aligned flow to lateral flow wind speeds at each sonic sensor:

$$w_{s1} = u_b \cos(\theta) - w_b \sin(\theta) \quad (38)$$

$$w_{s1} = u_b \cos(\theta + 2\pi/3) - w_b \sin(\theta + 2\pi/3) \quad (39)$$

$$w_{s3} = u_b \cos(\theta + 4\pi/3) - w_b \sin(\theta + 4\pi/3) \quad (40)$$

Now the lateral inflow angles may be determined by:

$$\alpha_{s1} = atan(\frac{\omega R + w_{s1}}{u_b}) \quad (41)$$

$$\alpha_{s2} = atan(\frac{\omega R + w_{s2}}{u_b}) \quad (42)$$

$$\alpha_{s3} = atan(\frac{\omega R + w_{s3}}{u_b}) \quad (43)$$

More details of determination of the lateral inflow angle are shown in [19].

7.3.6 Influence of vibrations on rotor azimuth position measurement

Rotor azimuth position is derived from signals from the accelerometers mounted in the feet of the sonic sensors. The accelerometers are influenced by gravity, but also by accelerations of the spinner. Rotor rotation acceleration is cancelled out with the rotor azimuth position algorithm using three accelerometers. The nacelle moves along the shaft direction as well as sideways due to softness of the tower in tower bending. Movements in the vertical plane are limited due to stiffness in the vertical direction. Movements along the shaft direction are not influencing the accelerometers as the vibrations are perpendicular to the accelerometers. The most influential movements might therefore be lateral vibrations of the nacelle. However, local vibrations of the spinner surface also influence the accelerometers. As the accelerometers are mounted perpendicular to the spinner surface the up and down vibrations should not be important and merely the transversal vibrations should be important.

An example of a measured accelerometer signals is shown in Figure 19.

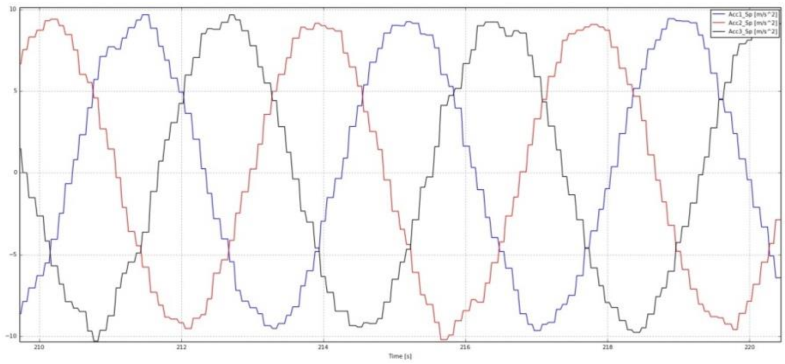

Figure 19 Measured accelerometer signals from three sonic sensors on a spinner anemometer (output frequency of sonic anemometer is 10Hz while sampling frequency is 35Hz)

The rotor azimuth position measurement uncertainty may be simulated by adding a lateral sinusoidal vibration in the accelerometer equations:

$$P_1 = -G \sin\varphi + A_t + A_v \cos(\varphi)\sin(\omega_v t) \quad (44)$$

$$P_2 = -G \sin(\varphi + 2\pi/3) + A_t + A_v \cos(\varphi + 2\pi/3)\sin(\omega_v t) \quad (45)$$

$$P_3 = -G \sin(\varphi + 4\pi/3) + A_t + A_v \cos(\varphi + 4\pi/3)\sin(\omega_v t) \quad (46)$$

The influence of vibrations may be evaluated by using these equations in calculation of the spinner anemometer response. A simulation with a vibration frequency of 9Hz and an amplitude of 0.4m/s^2 is shown in Figure 20. The variations are seen to be significantly smaller than in Figure 19. However, the measurements in Figure 19 were made with 35Hz scanning on a 10Hz spinner anemometer output, which give the staircase type of signal which is not seen in Figure 20.

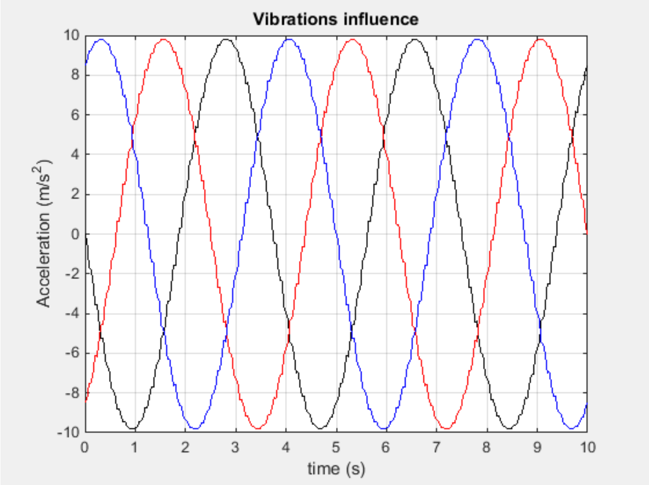

Figure 20 Simulated accelerometer signals from three sonic sensors with vibrations

7.4 Other uncertainty components

7.4.1 Data acquisition system

The data acquisition system of spinner anemometer data is digital. No transmission losses are relevant for the measurements. The sonic sensor wind speed measurements are based on a 14bit analog to digital converter with a resolution of about 0.02m/s. The uncertainty on the horizontal 10min wind speed measurement is approximated as $u_{dNi} = 0.001/\sqrt{3}\, m/s$.

7.4.2 Spinner geometry uncertainty

The geometry of the spinner is the basis for the air flow over the spinner and for the spinner anemometer to work as intended. Ideal rotational symmetric spinners with precisely positioned sonic sensors will provide the most accurate wind speed measurements when transferring nacelle transfer functions from one turbine to another. The spinner on the turbine where the STF is measured will be the reference for other wind speed measurements on the same type of wind turbine. The precision of the geometry on the spinner is therefore important for the transfer of the STF to another wind turbine. Deviations in spinner geometry should therefore be investigated in detail when an STF is transferred to another turbine. The IEC61400-12-2 standard [1] is setting requirements for acceptable geometry variations in annex C. The mentioned geometry requirements within 100mm in deviations of the nacelle should be lowered significantly for geometry deviations of a spinner, see annex A. The deviations in geometry from the reference spinner should be assessed by photographic techniques where pictures of spinners with sonic sensors on the two turbines (the reference and the transfer turbine) are compared by laying transparent photos over each other, see [19]. The same photographic techniques should be used to assess sonic sensor mounting deviations.

7.4.3 Rotor induction change

The measurement of the STF is valid for the reference turbine. Criteria for the validity of the STF are mentioned in [1]. One criteria is if the wind turbine control is different so that the induction in the rotor centre is different then the STF may not be valid. The same can be said if the blades are different, for example by applied vortex generators on the inboard part of the blades. For each transfer of an STF, one should look out for such induction changes that could reduce the validity of the STF.

7.4.4 Limitations of conversion algorithm

The transformation algorithm is a theoretical simplification for the relations between measured sonic sensor wind speeds and the overall horizontal wind speed and inflow angles. The theoretical assumptions seem to work quite well as documented by wind tunnel tests [20]. However, the wind tunnel measurements showed a sonic sensor flow distortion effect, which was evident in a dip in the sinusoidal wind speed curves. This flow distortion effect in the prototype sonic sensor was in later designs eliminated by increasing the sonic sensor path angles to 35º. The transformation algorithm assumption may be valid for normal operational inflow angles while for larger inflow angles the aerodynamic flow over the spinner will deviate significantly because of the spinner geometry, and the flow will separate when the sonic sensors come into the wake of the spinner. This may be important for the conditions during calibration of the k_α constant where the wind turbine in yawed in and out of the wind, but not for calibration of the k_1 constant where the wind turbine is pointing into the wind. A small uncertainty may be considered for the measurement uncertainty of U_{hor} due to limitations of the conversion algorithm.

7.4.5 Seasonal variability

The standard [1] requires an uncertainty due to seasonal variability being added to the NTF uncertainty budget ($u_{M2,i}$). The seasonal variability is an uncertainty component that is not part of the measurement uncertainty. It is an uncertainty component that is added when the measured NTF is extrapolated to be representative for a whole year. The uncertainty is proposed set to 2% in [1]. However, the 2% uncertainty may vary significantly from case to case. As the STF is a relation between two measurements at the same height on the mast and at the spinner anemometer, the influence due to atmospheric variations may be somewhat lower if the measurement is made in very flat terrain, Experience on seasonal variability of STF's can be gained from successive STF measurements during all seasons of the year with the spinner anemometer. When an STF is transferred to power curve measurements at another season, the seasonal variability has to be taken into account.

In [1] the measurement of a power curve, NPC, is also required to add a seasonal variability ($u_{M5,i}$). In this case the seasonal variability is considered for a generic power curve, while for a site specific power curve the uncertainty is questionable. For a measurement campaign lasting a few months the variability over a whole year is not known. Only in the case where a measurement campaign of a power curve of a few months needs to be made representative to a whole year or the whole life time of a wind turbine, this uncertainty on extrapolation of measured data should be added. Indeed, the uncertainty on seasonal variability in [1] is put on the power in the power curve since it represents the variability in power due to vertical shear and veer and is not due to the point wind speed measurement made by the spinner anemometer. This, of course, depends on how the power curve is defined with a hub height point wind speed measurement or an equivalent wind speed measurement taking care of vertical wind speed shear and veer.

The IEC standard [1] additionally mentions two more uncertainty components on the NPC, the variation to rotor inflow, $u_{M6,i}$ (2%), and the turbulence effect on averaging and binning, $u_{M7,i}$ (1%). These uncertainties are again mentioned for generic power curves, while for site specific power curves the uncertainties are questionable, and should not be included unless being specifically required.

7.4.6 Flow distortion due to terrain

The standard [1] requires an uncertainty component due to influence of the terrain on the nacelle (upflow, turbulence, shear), to account for its effect on the correlation between nacelle wind speed and free wind speed measured during the STF and the NPC. This uncertainty is connected with the sensitivity of the nacelle anemometer due to upflow, turbulence and shear. However, at the spinner, there are no such flow distortions due to upflow, turbulence and shear due to the nacelle. This term is therefore not relevant for spinner anemometers.

7.5 Summary on uncertainty components

The uncertainty components are all summarized in Table 1, where nomenclature of each component follows IEC61400-12-2 [1] as much as possible. Table 1 also lists the measurement parameter in the transformation algorithm on which the uncertainty component has an influence.

The uncertainty from the wind tunnel calibrations ($u_{N1,V1,i}, u_{N1,V2,i}, u_{N1,V3,i}$) are assumed fully correlated if they are all calibrated in the same batch. All mounting uncertainties are considered uncorrelated because the mounting of sensors is an individual process. All other measurement uncertainties are considered uncorrelated.

Table 1 Uncertainty components related to spinner anemometer measurements according to IEC61400-12-2

Uncertainty component	Designation*	Influence on parameter	Correlation coefficient
1. Calibrations			
• Wind tunnel calibration [m/s]	$u_{N1,V1,i}$, $u_{N1,V2,i}, u_{N1,V3,i}$	V_1, V_2, V_3	1, 1, 1
• Angular calibration k_α [%]	u_{N41i}	k_α	0
• Wind speed calibration k_1 [%]	u_{N42i}	k_1	0
2. Operational characteristics, class	u_{N2i}		0
• Inflow angle to rotor [º]	u_{N21i}	U_{hor}	
• Turbulence [%]	u_{N22i}	U_{hor}	
• Yaw misalignment [º]	u_{N23i}	U_{hor}	
• Accelerometer vibrations [m/s²]	u_{N24i}	P_1, P_2, P_3	
• Shaft tilt angle increase [º]	u_{N25i}	δ->U_{hor}	
3. Sonic sensor mounting	u_{N3i}		
• Longitudinal position [m]	u_{N31i}	V_1, V_2, V_3	0
• Directional uncertainty [º]	u_{N32i}	V_1, V_2, V_3	0
• Sonic path angle [º]	u_{N33i}	V_1, V_2, V_3	0
• Lateral position [m]	u_{N34i}	$V_1, V_2, V_3, P_1, P_2, P_3$	0
• Accelerometer alignment [º]	u_{N35i}	$P_1, P_2, P_3,$	0
4. Other uncertainty components			
• Data acquisition system [m/s]	u_{dNi}	U_{hor}	0
• Use of default k constants [%]	u_{N5i}	U_{hor}	0
• Spinner geometry (PC2)** [%]	u_{N6i}	U_{hor}	0
• Rotor induction change** [%]	u_{N7i}	U_{hor}	0
• Limitations on algorithm [%]	u_{N8i}	U_{hor}	0

* Index i relates to wind speed bin and numbers refer to IEC61400-12-2 uncertainty designations where possible

** PC2 relates to transfer of STF to another wind turbine

7.6 Modelling the measurand – combination of uncertainties

The basis for determination of measurement uncertainties starts with the Guide to the Uncertainty in Measurements [21]. The measurand, or the output quantity of the spinner anemometer, is the horizontal wind speed U_{hor}. The input quantity measurements are the sonic sensor wind speeds and the accelerometer measurements. A range of uncertainty components relates to these input quantities. However, other uncertainty components relates to the horizontal wind speed U_{hor}. The relationship between the sensor uncertainties and the horizontal wind speed uncertainties is through the spinner anemometer transformation algorithm. This relationship is the basis for modelling the measurand according to GUM.

7.7 Combination of uncertainties according to GUM

In order to calculate the uncertainty in U_{hor}, which is a function of the measured variables V_1, V_2, V_3, k_1, k_α , δ, P_1, P_2, and P_3, the uncertainty sources of the nine variables are modelled as additive variables (x_1, …, x_j , …, x_N) of zero average and a given standard deviation, where $N = \sum_{i=1}^{9} n_j$ and n_j are the number of uncertainty components in the j^{th} measured variable (V_1, V_2, V_3, k_1, k_α , δ, P_1, P_2, or P_3). Then we can express U_{hor} as a function of the nine variables as follows:

$$U_{hor} = F(V_1, V_2, V_3, k_1, k_\alpha, \delta, P_1, P_2, P_3) = f(x_1, \ldots, x_j, \ldots, x_N) \tag{47}$$

Using GUM [22] the combined uncertainty in the horizontal wind speed can in general be calculated by:

$$u^2(U_{hor}) = \sum_{i=1}^{N} \sum_{j=1}^{N} \left(\frac{\partial f}{\partial x_i}\right) \left(\frac{\partial f}{\partial x_j}\right) u(x_i) u(x_j) r(x_i, x_j) \tag{48}$$

where x_i and x_j are the standard uncertainties of the variables modelling the i^{th} and j^{th} uncertainty sources, and $r(x_i, x_j)$ is the correlation coefficient of those two variables. The factors $c_j = \left(\frac{\partial f}{\partial x_j}\right)$ are the sensitivity coefficients, and all the uncertainty sources associated to the same measured variable have the same sensitivity coefficient. For example, for all x_j associated with V_1, $c_j = \left(\frac{\partial f}{\partial x_j}\right) = \left(\frac{\partial F}{\partial V_1}\right)$.

It is, however, extremely difficult to use the ordinary GUM method because the derivatives vary significantly during rotation of the rotor. It would be extremely difficult to determine sensitivities for each uncertainty component for all the relevant varying operational conditions. Sources of uncertainty may affect several variables simultaneously, and thus affect uncertainty on U_{hor} in a very complex way. The ordinary GUM approach is thus not a viable method for combination of the uncertainties.

7.8 "Simplified" Monte Carlo simulation approach

Another approach for the uncertainty analysis of the spinner anemometer is proposed. This approach includes a simplified Monte Carlo simulation [22] of 10min operation of the spinner anemometer in the wind and includes all influential conditions during operation, and includes all necessary dependencies. For each uncertainty component, the propagation of an error equal to one standard deviation is simulated, and the output of a full 10min operation simulation of the horizontal wind speed is derived. The influence of each uncertainty component is calculated separately while all other uncertainty components are kept constant or equal to zero. By simulation of the influence of all influential parameters directly to represent the uncertainty on the horizontal wind speed, the sensitivity factors are all set equal to one when the uncertainty components are combined.

7.8.1 Classification requirements for a spinner anemometer

The lateral angular response is a built-in characteristic of the sonic sensors and has an influence with a systematic deviation of the sonic sensor measurements. The vibrations of the spinner and the tilting increase of the rotor shaft at higher wind speeds also have systematic influences on all measurements. The lateral angular response, vibration of the spinner and the tilt increase are therefore included in all simulations. The influence of these uncertainty components due to environmental operational conditions during the k_1/STF calibration and during wind speed and power performance measurement campaigns are determined in a classification approach similar to classification of cup anemometers in IEC61400-12-1, using class A, B and S environmental conditions. For the environmental calibration conditions during calibration of k_1/STF a class S for the operational conditions during the calibration are used. For all other measurement campaigns a class A, B or S may be used.

The operational conditions of the spinner anemometer for the classification are derived from Table I.1 in [16], and are shown in Table 2.

Table 2 Operational conditions for spinner anemometer uncertainty classification calculations, derived from [16]

	Class A Terrain meets requirements in [6]	**Class B** Terrain does not meet requirements in [6]	**Class C** Terrain meets requirements in [6]	**Class D** Terrain does not meet requirements in [6]	**Class S** Special class with user defined ranges
	Range	Range	Range	Range	Range
Wind speed V[m/s]	4 to 16	4 to 16	4 to 16	4 to 16	4 to 16
Turbulence intensity	0,03 to 0,12 + 0,48/V	0,03 to 0,12 + 0,96/V	0,03 to 0,12 + 0,48/V	0,03 to 0,12 + 0,96/V	User defined
Turbulence structure $\sigma_u/\sigma_v/\sigma_w$	1/0,8/0,5*	1/0,8/0,5*	1/0,8/0,5*	1/0,8/0,5*	User defined or 1/0,8/0,5*
Average flow inclination angle (°)	−3 to 3	−15 to 15	−3 to 3	−15 to 15	User defined
Yaw misalignment (°)	-5 to 5	-10 to 10	-5 to 5	-10 to 10	User defined
Rotational speed (rpm)	As a function of wind speed	As a function of wind speed	As a function of wind speed	As a function of wind speed	As a function of wind speed
Tilt and tilt angle increase (°)	As a function of wind speed	As a function of wind speed	As a function of wind speed	As a function of wind speed	As a function of wind speed
Spinner vibrations	User defined	User defined	User defined	User defined	User defined
Air Temperature (°C)	0 to 40	-10 to 40	-20 to 40	-20 to 40	User defined
Lateral angular response	Wind tunnel measurement	Wind tunnel measurement	Wind tunnel measurement	Wind tunnel measurement	Wind tunnel measurement

The operational conditions: wind speed, turbulence, flow inclination angle, yaw misalignment and rotational speed are measured during the measurement campaign, and the parameter ranges are determined. The combinations of the operating condition in Table 2 are simulated using an artificial wind generation model to model 10min 3D time traces. The artificial wind input may be generated by the Mann code [23], also used in cup anemometer classification [16]. Following the procedure in [16] on determination of systematic deviations the class index is found from:

$$k = 100 \cdot max|\epsilon_i / w_i| \qquad (49)$$

where

k	is the class number;
w_i	is a weighting function in m/s that defines the deviation envelope, see below
ε_i	is the deviation in m/s for influence parameter combination i;

The weighting function w_i averages the influence of absolute and relative deviations:

$$w_i = 0.5\frac{m}{s} + 0.5 \cdot U_i \quad (50)$$

where

U_i is the wind speed in m/s for influence parameter combination i

7.8.2 Spinner anemometer uncertainty simulation model

The simulation model for application and propagation of uncertainties of the spinner anemometer are shown in Figure 22 Flow chart of calculation code for propagation of uncertainties. First, from left, the artificial wind input is generated for a certain wind speed and turbulence intensity. The slope is then added to the wind file and then a yaw misalignment is added. The reference wind conditions, U_{hor}, γ and β, are then calculated from the wind file and the 10min average values, $U_{hor0ave}$, γ_{0ave} and β_{0ave} are derived. The reference wind conditions are input conditions to the calibrated path. Individual deviations due to uncertainties on the calibrations, $k_1 + \Delta k_1$ and $k_\alpha + \Delta k_\alpha$, deviation on tilt angle $\delta + \Delta\delta$, and the individual azimuthal deviations on sonic sensors $\varphi + \Delta\varphi$, are then added. These conditions are now the conditions that the spinner anemometer “see”. The inverse transformation algorithm is then used to find the local sonic sensor flow speeds that they “see”. Uncertainties in sonic sensor wind speeds due to mounting uncertainties of the sonic sensors and wind tunnel calibration are then added to the sonic sensor wind speeds and the accelerometer angle deviation is added to the accelerometer measurements. These “measured V and P values” are then used to derive the “measured wind conditions”, U_{hor}, γ and β with the direct transformation, and the 10min average values U_{horave}, γ_{ave} and β_{ave} are calculated. The differences to the reference wind conditions $U_{hor0ave}$, γ_{0ave} and β_{0ave} are finally derived.

7.8.3 Spinner anemometer classification index

The lateral angular response, vibration of the spinner and the tilt increase, are as mentioned before, included in all simulations. In order to find the deviations due to the environmental operating conditions alone, without calibration and mounting uncertainties being applied, all combinations of operating conditions from the parameter ranges in Table 2 are used to calculate systematic deviations ε_i. The maximum deviation is used to find the class index k according to equation 49.

Assuming a rectangular frequency distribution of the errors due to different operational conditions, the resulting standard uncertainty due to operational characteristics (the classification) is expressed as:

$$u_{N2i} = \frac{1}{\sqrt{3}}\frac{k}{100}\left(5m/s + 0.5U_{hor,i}\right) \quad (52)$$

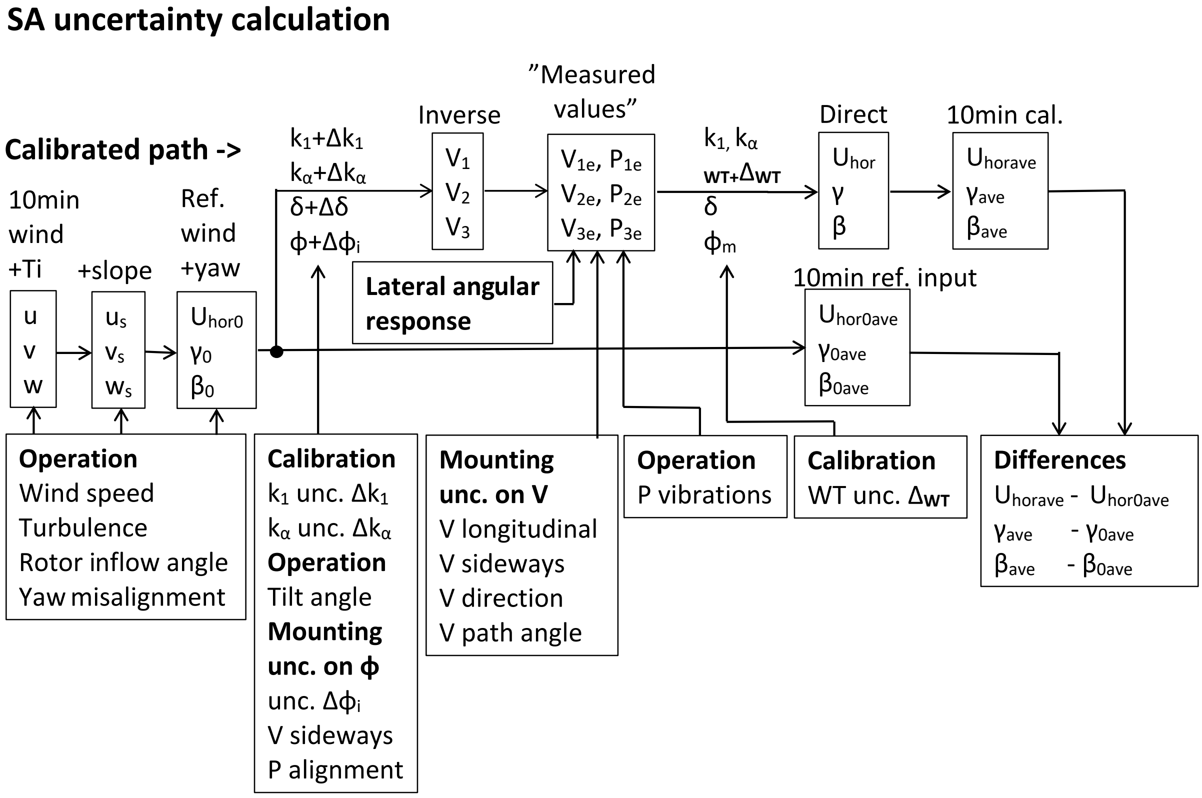

Figure 21 Flow chart of calculation code for propagation of uncertainties

7.8.4 Derivation of individual calibration and mounting uncertainties

The average operational conditions under which the calibration of k_1/STF is made, are considered reference conditions for derivation of individual uncertainties. Deviations in U_{hor} by model calculations of the spinner anemometer characteristics for these reference calibration conditions are reference values for the calculation of the influence of individual uncertainty components.

The deviations due to calibration and mounting uncertainties are determined individually by applying them to the simulations. The deviations from the reference simulations are then extracted, and each component is in this way expressed as an uncertainty in U_{hor}.

The operational conditions for measurement campaigns of wind or power curves are not in the same way referred to the reference calibration conditions as the reference condition is just one of the conditions considered. For wind or power curve measurements the operational conditions for these measurement campaigns shall be used.

Determination of the uncertainties and combination of uncertainties is made according to Figure 22. The deviations in U_{hor} for each wind speed due the operating conditions are determined for each block. The “1 reference” is the uncertainty with operational conditions experienced during the wind speed calibration measurement campaign. The “4 operational” is the operational conditions for the relevant wind or power curve measurement campaign using class A, B or S.

“2 Calibrations” and “3 Mounting” are calculation of the individual uncertainties with use of the reference operational conditions during the k_1/STF calibration measurement campaign.

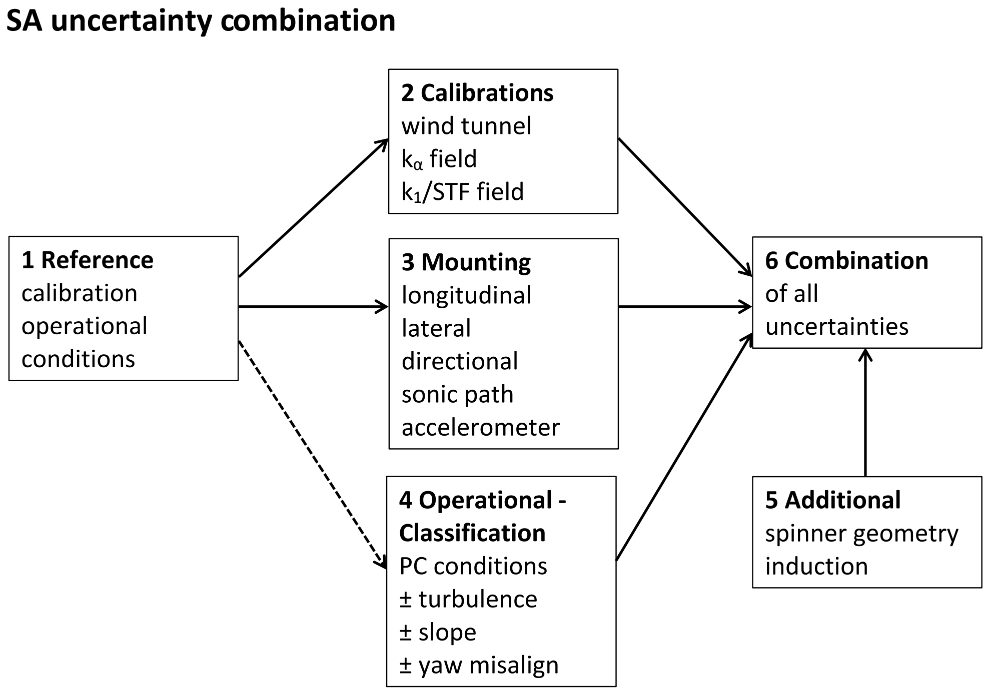

Figure 22 Calculation and combination of all uncertainty components.

7.8.5 Combination of uncertainties

All uncertainty components are now expressed as uncertainties in U_{hor}. Combination of the uncertainty components are made with sensitivity factors equal to one and correlation coefficients equal to 1 or 0 according to Table 1:

$$u^2(U_{hor}) = \sum_{i=1}^{N}\sum_{j=1}^{N} u(x_i)u(x_j)r(x_i, x_j) \tag{53}$$

The final combination of uncertainties is reduced to:

$$u_{Uhor} = \sqrt{\begin{matrix}(u_{U11i} + u_{U12i} + u_{U12i})^2 + u_{U41i}^2 + u_{U42i}^2 + u_{U2i}^2 + 3u_{U31i}^2 \\ +3u_{U32i}^2 + 3u_{U33i}^2 + 3u_{U34i}^2 + 3u_{U35i}^2 + u_{dNi}^2 + u_{U5i}^2 + u_{U6i}^2 + u_{U7i}^2 + u_{U8i}^2\end{matrix}} \tag{54}$$

7.8.6 Summary of procedure for the simplified Monte Carlo simulation approach

The uncertainty calculations with the simulation model of spinner anemometer wind speed measurements is summarized as follows:

1) For the reference case “1 Reference”, the calibration campaign of k_1/STF, with the average operating conditions (turbulence, inflow angle, yaw misalignment and shaft tilt angle plus its increase with wind speed), the deviations in U_{hor} is calculated for each wind speed bin in the range 4-16m/s. Lateral angular response, tilt increase and vibrations of spinner are included in all calculations. These reference deviations are extracted from the deviations calculated from the uncertainties due to calibration and mounting.

2) For “2 Calibrations”, the deviations in U_{hor}, due to individual calibration uncertainties ($u_{N1,V1,i}, u_{N1,V2,i}, u_{N1,V3,i}$, u_{N41i}, u_{N42i}) and for the same “1 Reference” average operating conditions, are calculated. For each calibration uncertainty the deviation in U_{hor} is subtracted the deviation in U_{hor} from the case “1 Reference” to find the corresponding uncertainty ($u_{U11i}, u_{U12i}, u_{U13i}$, u_{U41i}, u_{U42i}).
3) For “3 Mounting”, the deviations in U_{hor} due to individual mounting uncertainties (u_{N31i}, u_{N32i}, u_{N33i}, u_{N34i}, u_{N35i}) and for the same “1 Reference” average operating conditions, are calculated. For each mounting uncertainty the deviation in U_{hor} is subtracted the deviation in U_{hor} from the case “1 Reference” to find the corresponding uncertainty (u_{U31i}, u_{U32i}, u_{U33i}, u_{U34i}, u_{U35i}).
4) For “4 Operational – Classification” deviations in U_{hor} according to the class A, B or S operating conditions (turbulence, inflow angle, yaw misalignment and shaft tilt angle plus its increase with wind speed) for the specific wind or power curve measurement campaign, are calculated. The resulting envelope of deviations from the simulations for each wind speed, expressed with the class k index number, then determines the uncertainty due to operational characteristics (u_{U2i}) with the assumption of a rectangular uncertainty distribution.
5) The uncertainties derived from step 2) to step 4) are now combined with the additional uncertainties, spinner geometry and induction uncertainties, according to equation 54 to get the spinner anemometer wind speed uncertainty, $u_{Uhor,i}$.

7.9 Uncertainty of free wind speed measurements

The reference wind speed for a nacelle power curve (NPC) is the free wind speed, calculated from the application of the spinner transfer function (STF) to the spinner anemometer wind speed. According to IEC61400-12-2 [1], the uncertainty of this calculated free wind speed, u_{Vi}, is the combination of the uncertainty of the nacelle transfer function, $u_{V6,i}$, and the uncertainty of the spinner anemometer wind speed, $u_{Uhor,i}$.

$$u_{V,i} = \sqrt{u_{Uhor,i}^2 + u_{V6,i}^2} \tag{55}$$

Uncertainty of the spinner transfer function, STF, $u_{V6,i}$ is the combination of the following uncertainty components:

$$u_{V6i} = \sqrt{u_{FS,i}^2 + u_{N,i}^2 + \ u_{M,i}^2 + s_{NTF,i}^2} \tag{56}$$

where
$u_{FS,i}$ is the uncertainty of the measured free wind speed by the mast cup anemometer, U_{FS}
$u_{N,i}$ is the uncertainty of the spinner anemometer wind speed, $U_{hor,i}$
$u_{M,i}$ is the uncertainty due to seasonal variations (method); set equal to 0%, as the STF calibration campaign was the same as the wind speed measurement campaign
$s_{NTF,i}$ is the statistical uncertainty of the nacelle transfer function wind speed ratio

The above formulas are valid for the general case where STF and NPC uncertainties are uncorrelated (e.g. the wind turbine – as well as met mast anemometer and spinner anemometer – and wind conditions for which the STF were obtained are different from those where the NPC is measured).

8. Reporting format

The wind measurements shall be reported in such detail that every significant procedural step and test condition can be reviewed, and, if necessary, repeated. This document differentiates between documentation and reporting. The measurement party shall maintain all documentation for future reference, even in the event that the documentation is not reported. The documents should be retained for a prescribed period of time, typically ten years per ISO 17025. The following are the minimum reporting requirements.

The test report shall contain, at a minimum, the following information:

a) An identification and description of the specific wind turbine configuration under test, in such detail as to be able to assess transfer function validity (see annex A), including:
    1) turbine make, type, serial number, production year, spinner description (e.g. drawings, measurements, photos).
    2) rotor diameter and a description of the verification method used or reference to rotor diameter documentation;
    3) rotor speed range;
    4) rated power and rated wind speed;
    5) blade data: make, type, serial numbers, number of blades, fixed or variable pitch, zero pitch offset, and normal pitch angle(s);
    6) tower type, tower height and hub height;
    7) description of the control system (device and software version) including but not limited to documentation of status signals being used for data reduction; turbine control parameters, as far as relevant to the transfer function test (e.g., pitch, yaw, nacelle wind speed and wind direction, rotational speed and power), by agreement between involved parties;
    8) drawings and photographs of the spinner anemometer and sonic sensor mountings (position and direction), data acquisition method, data acquisition averaging time (if multiple instruments a clear identifier of the primary measurements shall be reported).

b) A description of the test site (see 6.2), including:
    1) photographs of all measurement sectors preferably taken from the wind turbine at hub height;
    2) a test site map with such scale as to detail the surrounding area covering a radial distance of at least 20 times the wind turbine rotor diameter and indicating the topography, location of the wind turbine under test, meteorological masts (if applicable), significant obstacles, other wind turbines, vegetation type and height, and measurement sector;
    4) if a site calibration is undertaken to establish the nacelle transfer function, the limits of the final measurement sector(s) shall also be reported;
    5) terrain description including estimates of the slope angle for various directions;
    6) nominal site specific air density;

c) A description of the test equipment, inclusive of the site calibration, nacelle transfer function:

1) identification of the sensors and data acquisition system(s) for each measurement parameter, including documentation of calibrations for the sensors, transmission lines, and data acquisition system;

d) A description of the measurement procedure:
   1) reporting of the procedural steps, test conditions, sampling rate, averaging time, measurement period;
   2) documentation of the data filtering, including exact filter criteria limit values, filtering order and the total number of data points removed;
   3) documentation of all corrections applied to the data;
   4) a summary of the test log book that records all important events during the spinner anemometer wind measurements; including a listing of all maintenance activities on the wind turbine that occurred during the test and a listing of any special actions (such as blade washing) that were completed to ensure good performance;
   5) identification of any data rejection criteria;
   6) in case more than one measurement system was used, a statement regarding the synchronisation of all systems shall be included. The maximum time difference registered between these systems shall be documented and a graph or table showing the time corrections made during the measurement campaign on each measurement system shall be shown.

e) Data from each selected data set shall be presented in both tabular and graphical formats, providing statistics of wind speed and other important meteorological parameters including (refer to 8.4 to 8.8):
   1) scatter plot of mean wind speed as a function of wind direction;
   2) scatter plot of turbulence intensity as function of wind speed
   3) scatter plot of turbulence intensity as function of wind direction;
   4) scatter plot of yaw misalignment as function of wind speed
   5) scatter plot of yaw misalignment as function of wind direction
   6) scatter plot of flow inclination angle as function of wind speed
   7) scatter plot of flow inclination angle as function of wind direction
   8) special databases consisting of data collected under special operational or atmospheric conditions;
   9) if measured, rotational speed and pitch angle should be presented with a scatter plot including binned values versus wind speed and a table with the binned values;
   10) definition of status signals, and plots of status signals during the measurement period.

f) Presentation of results establishing the nacelle transfer function (see Annex A):
   The spinner transfer function shall be reported as per Annex B.

g) Uncertainty of measurement (see chapter 7):
   Uncertainty assumptions on all uncertainty components shall be provided as well as assumptions regarding contribution of uncertainties and correlated / uncorrelated uncertainties, as described in chapter 7.

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Annex A
(proposed normative)
Spinner wind speed transfer function validity procedure

The transfer function can be affected by turbine hardware and control. This Annex describes the criteria that need to be checked to assess if a transfer function measured at one turbine can be applied to another, and is derived from [1] annex C. The criteria in this Annex refer to a comparison of a measurement of an STF on one turbine and the application of the STF on another turbine (or the same turbine at a later date). The following shall be checked that they are identical within limits given before the test is started:

A.1 Measurement procedure:

The averaging time the data points are based on to calculate the transfer function shall be the same as the averaging time the data points are based on to calculate the nacelle power curve.

A.2 Terrain class and slope:

The terrain class assessment, as described in [1] chapter 6, shall not be applied for spinner anemometry. Spinner anemometry is positioned in front of the rotor and is not influenced by blade roots and nacelle in the same way as nacelle anemometry, and spinner anemometry measures inflow angles and yaw misalignment angles, which can be used to characterize the flow due to the terrain.

A.3 Measurement hardware:

1. spinner geometry;
2. sonic sensor mounting positions and sensor path orientations

A.4 Other turbine hardware:

3. the blade type, including aerodynamic devices mounted on the blade;
4. blade root shape, within 50 millimetres;

A.5 Turbine controls:

5. the control software and version to the extent that the changes significantly affect the power performance or the rotor thrust (which influences on induction at the rotor centre) of the turbine as estimated by the manufacturer;
6. all (changes to) parameters related to control of pitch, yaw, rotational speed, power and any other parameters to the extent that (changes to) these parameters significantly affect the power performance or the rotor thrust of the turbine as estimated by the manufacturer; this is to be checked by comparing specific parameters and their related values.
7. operational modes (e.g., noise reduced operation, power curtailment).

If any of these validity criteria are not met, another transfer function shall be used. The validity check shall be reported in such detail that each of the 7 checks in this Annex is supported by evidence.

Annex B
(proposed normative)
Spinner wind speed transfer function measurement procedure

B.1 General

The key result of the spinner wind speed transfer function measurement is a table or a fitted function of flow correction factors for all measured wind speeds. Another result is an estimate of the uncertainty of these correction factors.

The spinner wind speed transfer function, STF, shall be established by a measurement that is almost identical to an IEC 61400-12-2 measurement [1]. All requirements of the standard shall be adhered to, unless this procedure explicitly deviates from the standard.

The spinner wind speed transfer function should be measured on a turbine in flat terrain according to the requirements for flat terrain in IEC61400-12-1 [7] annex B. In case the STF is measured in a terrain that do not meet these requirements, then a site calibration is required. The procedure for a site calibration in IEC61400-12-1 [7] annex C should be used.

The spinner wind speed transfer function shall be measured for a valid sector according to the requirements in IEC61400-12-1 [7] annex A in order to avoid the wakes of other wind turbines and significant obstacles. This test procedure may also provide information that justifies a change to the valid measurement sector.

The spinner wind speed transfer function measurement procedure is designed to assess the effect of the wind turbine rotor on the spinner wind speed and to quantify the relationship of free stream wind speed to spinner wind speed.

B.2 Test setup and equipment

The signals that shall be measured according to IEC61400-12-1 are:

- wind speed on the meteorological mast; (including primary and control anemometer)
- wind direction on the meteorological mast;
- wind turbine power;
- air temperature;
- air pressure;
- turbine generator grid connection status signal.

The data acquisition system may be external, it may be the turbine controller data system, or it may be a combination of both.

If multiple data acquisition systems are used, it shall be verified throughout the measurement that the synchronisation between any of the measurement systems does not deviate more than 1% of the averaging time. Any deviations and/or corrections shall be reported.

In case the turbine controller data system (e.g., SCADA system) is used, the calibration and accuracy of the data system chain (transmission, signal conditioning and data recording) shall be verified by injecting known signals at the transducer ends and comparing these inputs against the recorded readings. This shall be done using instrumentation that is calibrated traceable to national standards. As a guideline, the uncertainty of the data acquisition system should be negligible compared with the uncertainty of the sensors. Furthermore, all calibrations, offsets and corrections applied by the turbine controller data system shall be reported in such detail that these calibrations, offsets and corrections can be undone when post processing the data.

Additional to the requirements of the IEC 61400-12-1, the following signals shall be measured:

- spinner anemometer wind speed;
- spinner anemometer yaw misalignment;
- spinner anemometer inflow angle
- spinner anemometer air temperature
- nacelle yaw position.

The following signals may be captured, to establish validity of the measured transfer function for future use:

- rotor speed;
- pitch angle(s).

Instead of measuring these signals, the software version, relevant parameters and their values may be documented for future validity check.

The nacelle wind direction signal shall be verified in-situ to determine correct operation and establish a specific relation to the nacelle’s longitudinal axis. The nacelle yaw position shall be verified to determine correct operation and establish True North.

B.3 Measurement procedure

A database shall be established as described in the IEC 61400-12-1, with the following change:

- data shall be filtered using the ‘turbine online’ instead of the ’turbine available’ status signal.

The database shall be considered complete when it has met the following criteria:

The selected data sets shall be sorted using the ‘method of bins’ procedure using 0,5m/s bins centred on multiples of 0.5 m/s and by calculating the mean values. The selected data sets shall at least cover a wind speed range extending from cut-in to 1.5 times the wind speed at 85% of the rated power of the wind turbine.

The database shall be considered complete when it has met the following criteria:

- each bin includes a minimum of 30 minutes of sampled data;
- the database includes a minimum of 180 hours of sampled data.

Should a single incomplete bin be preventing completion of the test, then that bin value can be estimated by linear interpolation from the two adjacent complete bins.

The met-mast data shall be binned against the spinner wind speed, with the met-mast wind speed on the X-axis. Then a linear interpolation can be made to interpolate between bins. Using the data in the database, V_{free} shall be calculated using the following formula:

$$v_{free} = \frac{v_{free,i+1} - v_{free,i}}{v_{nacelle,i+1} - v_{nacelle,i}} \cdot \left(v_{nacelle} - v_{nacelle,i}\right) + v_{free,i} \qquad \text{(D.1)}$$

where

$v_{nacelle,i}$ and $v_{nacelle,i+1}$ are bin averages of the spinner wind speed in bin i and $i+1$
$v_{met,i}$ and $v_{met,i+1}$ are bin averages of the met-mast wind speed in bin i and $i+1$, flow correction factors shall be applied from the site calibration measurement, if appropriate
$v_{nacelle}$ is the measured value of the spinner anemometer for which we want to estimate the free stream wind speed
v_{free} is the free stream wind speed estimated using the measured nacelle and met mast wind speed ($v_{nacelle}$ *and* v_{free}, respectively)

The spinner transfer function, STF, is defined as v_{free} as a function of $v_{nacelle}$ per bin. The NSF is only valid from the lowest wind speed bin to the highest wind speed bin and extrapolation of the STF is never allowed.

Alternatively, the function of v_{free} on y-axis and $v_{nacelle}$ on x-axis (binned on $v_{nacelle}$) may be fitted with a mathematical function. A weighted fit may be considered, for instance to adequately account for outliers. It shall be reported how the fit has been made and what weighting function has been used, as well as what the uncertainty contribution of the fitted result is.

B.4 Data quality check

A data quality check shall be performed as described in IEC61400-12-2 [1] Clause 8.5.

Additionally, create and review scatter plots of relevant signals to verify that the provided met mast instrumentation and test site layout description are correct. For example:

> Plot the 10-minute average primary and control anemometer ratio (as defined in IEC 61400-12-1) versus wind direction. Compare the location (degrees with respect to True North or other reference) of the mounting structure (single hub-height anemometer mounting option) or the location of the primary/control anemometer wakes (double hub-height anemometer mounting option) inferred by these plots to the documented instrumentation arrangement. These plots can

also be used to verify the documented turbine to meteorological tower bearing by comparing the inferred turbine wake centre with the expected value.

Discrepancies found shall be investigated and corrected for in the analysis, if possible. Unresolved discrepancies shall be reported in the measurement report.

B.5 Derived results

The derived results are:

1. A spinner transfer function (STF) for wind speed describing V_{free} as a binned result or a mathematical function of bin averaged $V_{nacelle}$
2. Uncertainty analysis on all of the derived results, per chapter 7
3. Report on the nacelle transfer function, as per chapter 9.

B.6 Direction stability check

A measured transfer function may show larger variation in certain wind directions. This can be caused by the local terrain but also because the wind direction may fluctuate a lot if the wind is not from the predominant wind direction. It is recommended to analyse the variance of the transfer function with wind direction in the following way:

The data set that the transfer function is based on shall be binned into 10° wind direction bins, centred on integer multiples of 10°. Where a site calibration has been previously performed, it is recommended to use the same direction bins in order to reflect the directional effect of the site calibration on the transfer function. $V_{free}/V_{nacelle}$ shall be averaged for each bin, and the standard deviation of $V_{free}/V_{nacelle}$ shall be calculated for each direction. The wind speed range for which this is done shall be selected such that it excludes significant pitch activity with adequate margin to allow for the 10 minute averaging. It is also recommended to compare residuals as part of the stability check.

The average and standard deviation shall be plotted against the wind direction average of each bin. This plot will show if the transfer function is sensitive to wind direction. If a clear effect of wind direction can be seen, the measurement sector may be reduced to include only those directions that show a consistent result.

In those cases where a sector has been reduced, the self-consistency check described in D.8 in [1] shall show evidence of the improvement of the new STF.

B.7 Uncertainty

The uncertainty of the nacelle transfer function(s) shall be calculated according to chapter 7.

B.8 Reporting requirements

The following requirements shall be fulfilled:

- the exact positions of the spinner anemometer sonic sensor mountings on the spinner shall be reported, with 5 mm accuracy. The reference to which all distances are measured shall be clearly defined.

- photos from the sonic sensor mountings shall be made, to allow accurate repetition of the measurement setup and to verify the uncertainties on the mounting of sensors
- the spinner anemometer serial number and calibration shall be reported
- the exact filtering used to create the spinner transfer function,
- type of transfer function (e.g. polynomial, binned) and the weighing function used (if applicable)
- presentation of measured data
  - scatter plot of mean free stream velocity as a function of spinner wind speed.
  - table of binned values of the free stream wind speed and the corresponding spinner wind speed (or relevant interpolating function) and the estimated uncertainty.
  - description of transfer function formula including method for fitting and fitted constants
  - The correlation between V_{free} *and* $V_{nacelle}$ shall be reported in the form of the coefficient of determination

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