An innovative method to calibrate a spinner anemometer without use of yaw position sensor

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Abstract. A spinner anemometer can be used to measure the yaw misalignment and flow inclination experienced by a wind turbine. Previous calibration methods used to calibrate a spinner anemometer for flow angle measurements were based on measurements of a spinner anemometer with default settings and a reference yaw misalignment signal measured measured with a yaw position sensor. The yaw position sensor is normally present in wind turbines for control purposes, however, such
5   a signal is not always available for a spinner anemometer calibration. Therefore, an additional yaw position sensor has been installed prior to the spinner anemometer calibration. An innovative method to calibrate the spinner anemometer without a yaw positions sensor was then developed. It was noted that a non calibrated spinner anemometer that overestimate (underestimate) the inflow angle will also overestimate (underestimate) the wind speed when there is a yaw misalignment. The new method leverage on the non linearity of the spinner anemometer algorithm to find the calibration factor F_α by an optimization process
10   that minimizes the dependency of the wind speed to the yaw misalignment. The new calibration method was found to be rather robust with F_α values within $\pm 2.7\%$ of the mean value for four successive tests at the same rotor position.

1 Introduction

Two methods, based on measurements proposed in Pedersen (2014) to calibrate a spinner anemometer for flow angle measurements consist in yawing the wind turbine of $\pm\ 60°$ several times under manual control (as indicated by the turbine yaw position
15   sensor, with respect to the mean wind direction). During this test, the output parameters of the spinner anemometer (U_{hor}, γ, β) are recorded at high sampling frequency (10 Hz). The analysis of the measurements provide the correction factor F_α that multiplied by the default k_α gives the correct k_α calibration value.

$$k_\alpha = k_{\alpha,d} \cdot F_\alpha \tag{1}$$

The methods are based on the assumption that the wind direction is constant during the test. Due to this requirement, Pedersen
20   (2014) recommended to do the test at wind speeds above 6 m/s. Both methods need the yaw position to be measured in order to calculate the reference yaw misalignment γ_{ref}, defined as the mean wind direction minus the instantaneous yaw position during test (see Pedersen (2014) for details). In the first method (abbreviated as GGref) F_α was calculated by calibrating the measurements iteratively, until the linear fit of γ as a function of γ_{ref} was giving a line of slope equal to 1.

In the second method (abbreviated as TanTan), only one linear fitting was made to $\tan(\gamma)$ as a function of $\tan(\gamma_{ref})$. In this case, the slope coefficient of the fit was exactly F_α. The two calibration methods were found to be sensitive to the width of the yawing span. In fact, different F_α values were obtained sub-setting the data-set to a variable span of γ_{ref}.

A new method to find the F_α value, that does not require a yaw position measurement, and use the non linearity of the

5   spinner anemometer conversion algorithm is proposed.

2   The wind speed response method

The method (abbreviated WSR) is based on the assumption that the wind speed is constant during the test. The turbulence of the real wind will add some scatter in the measurements. Yawing several times the wind turbine allows to average the wind speed fluctuations. The spinner anemometer is able to measure inflow angles (yaw misalignment γ and flow inclination β) and

10 wind speed U at the same time. A wrong k_α value will result in a wrong value of the angle γ, which will turn into a wrong value of the horizontal wind speed U_{hor}. In other words, a wrong k_α makes the wind speed measurement dependent on the yaw misalignment. This property of the spinner anemometer model was verified with an artificial data-set with constant wind speed and yaw misalignment going from -60 ° to 60 ° in steps of 10 °. For simplicity, the tilt angle and the flow inclination were set to zero so that the yaw misalignment γ equals the inflow angle α.

15   In the model, the correct calibration value is $k_\alpha = 1$. If the model is set with $k_\alpha = 0.5$ we obtain an overestimation of wind speed and angle (blue curve), while with $k_\alpha = 2$ we obtain an underestimation (red curve).
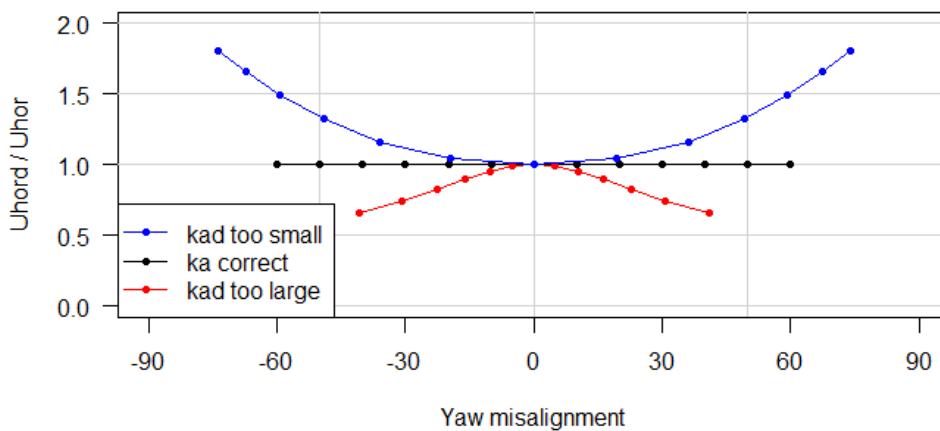
Figure 1. Effect of three k_α values on yaw misalignment and wind speed measurements. Black line shows data where the k_α is correct (equal to one for our theoretical spinner model). Blue curve shows k_α set to 0.5. To correct the blue curve to the black curve, the correction should be made with $F_\alpha > 1$ ($F_\alpha = 2$ in this case). Red line shows k_α set to twice the correct value, therefore we need $F_\alpha < 1$ to correct the measurements to the black line.

Note how the yaw misalignment is underestimated if $k_{\alpha,d}$ is set larger than the correct value k_α (red curve), and how the yaw misalignment and the wind speed is overestimated if k_α is set lower than the correct value. From experience of calibration on several turbines, the default settings of $k_{\alpha,d} = 1$ is too small. Therefore the wind speed response looks like a happy smile and an $F_\alpha > 1$ is required to correct the default calibration value. Note that the wind speed is still measured correctly for small inflow angles.

The method to optimize F_α consist in minimizing the RMSE (root mean square error) of a horizontal linear fit made to the measurements of $U_{hor,d}$ as a function of γ for varying F_α:

$$RMSE = \sqrt{\frac{1}{n}\sum_{1}^{n}(\overline{U_{hor}} - U_{hor})^2}. \qquad (2)$$

The function was optimized to its minimum using a combination of golden section search and successive parabolic interpolation.

3 Application of the method

The measurements were acquired in February 2016 on a Neg-Micon 2 MW wind turbine installed in Danmark. The wind turbine was yawed in and out of the wind several times with the rotor stopped with one blade pointing downwards. Figures 2 and 3 show the 10 Hz data recorded during the calibration procedure. Figure 2A, B and C show non calibrated measurements, while Fig. 3A, B and C show calibrated measurements. In both figures 2 and 3, sub-figure A shows the time series of the yaw misalignment and yaw misalignment reference (measured with a yaw position sensor). Sub-Figure B shows the time series of the wind speed. Sub-Figure C shows the wind speed response as a function of yaw misalignment.

Figure 2D shows the value of F_α calculated with the three different methods (GGref and TanTan from Pedersen (2014) and the present method, WSR), for varying range of yawing the wind turbine out of the wind (data were filtered according to γ_{ref} in steps of $5°$ span per side).
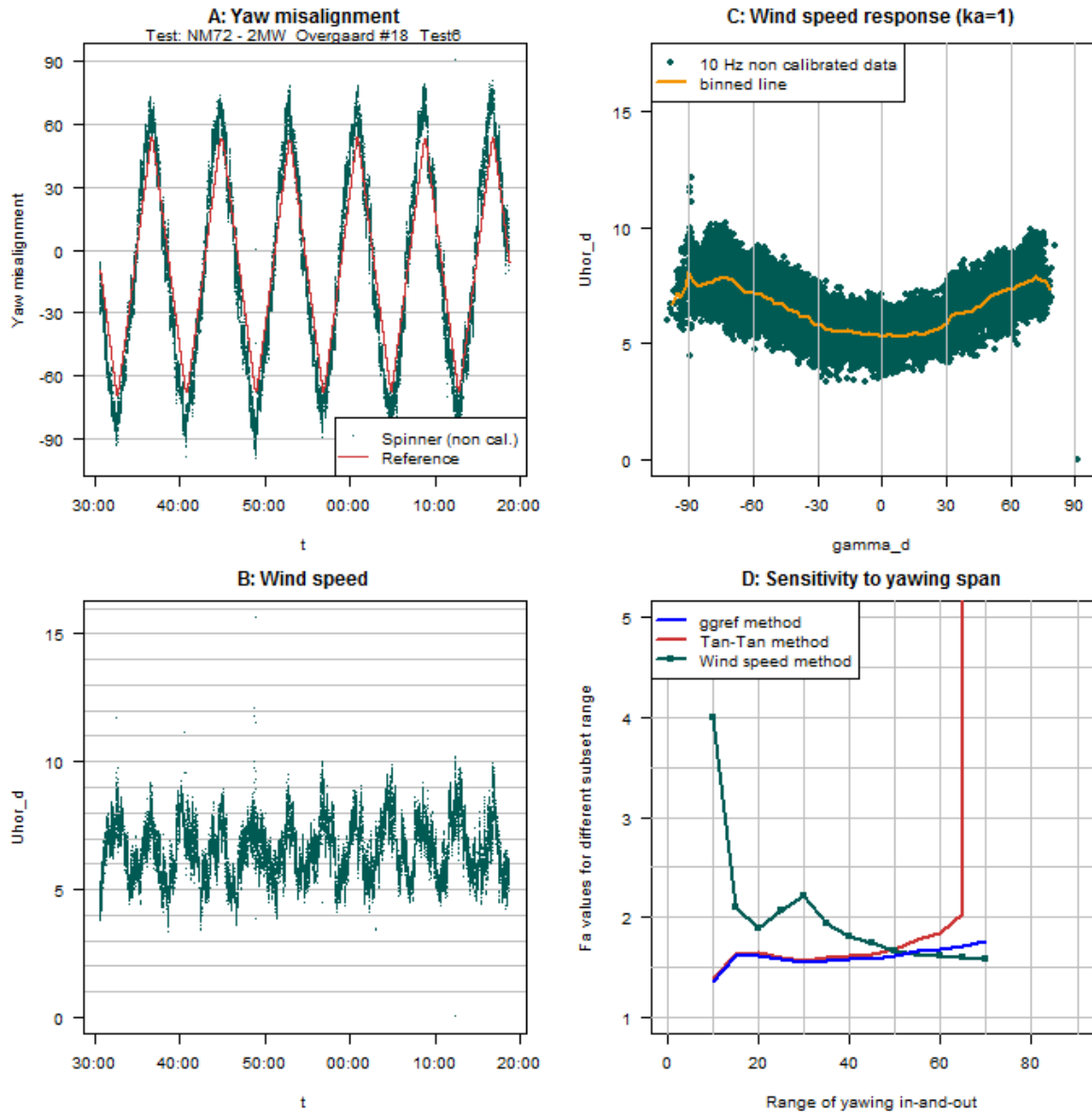
Figure 2. Before calibration, test 6. A: Time series of yaw misalignment as measured by the spinner anemometer and by the yaw position sensor. B: wind speed time series as measured by the spinner anemometer before F1 calibration. C: Wind speed as a function of yaw misalignment both measured by spinner anemometer. D: Calibration correction factor F_α calculated in three different methods, as a function of yawing span ranging from $\pm10°$ to $\pm90°$ in steps of $\pm5°$.
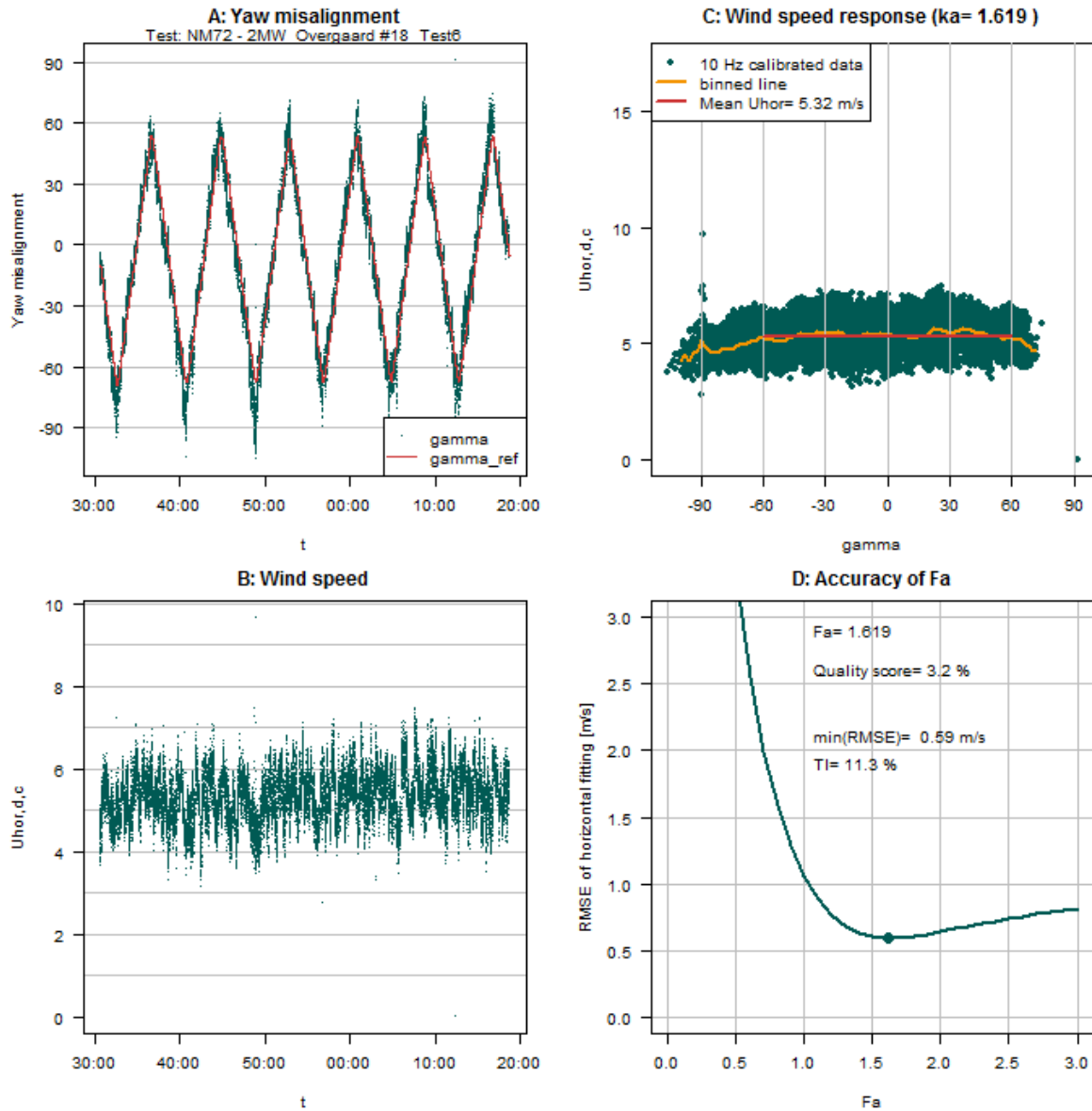
Figure 3. After calibration, test 6. A: Time series of yaw misalignment as measured by the spinner anemometer and by the yaw position sensor. B: wind speed time series as measured by the spinner anemometer before F1 calibration, after F_α calibration. C: Wind speed as a function of yaw misalignment both measured by spinner anemometer and calibrated with F_α. D: Root mean square error of the horizontal fit (red line in sub-figure C) as a function of F_α.

4   Discussion

As seen also in tests performed on other wind turbine models, the GGref and TanTan methods tend to give a higher F_α for increasing yawing span than the WSR method. This is especially true for the TanTan method, because of the tangent function properties, that tend to increase rapidly when approaching 90° angle.

5   As seen in Fig. 2D, the value of F_α is dependent on the chosen width of yawing the turbine in and out of the wind. For the TanTan and GGref methods, Pedersen (2014) suggested to limit the span to ±45°. The value of F_α calculated with the WSR method tends to stabilize and be comparable with the previous two methods for a yawing span within 50° and 70°.

Above a certain large inflow angle (depending on the spinner shape) the air flow would separate from the spinner surface with the consequence of the downwind sensor measuring in a separated flow. In this condition the spinner anemometer cannot
10   measure correctly, since the relation between the sensor path velocities does not follow the spinner anemometer mathematical model.

The F_α value calculated for yawing span of ±60° was 1.619. This value was used to calibrate the measurements, which are show in Fig. 3A, B and C. In Fig. 3C, the red line shows the mean wind speed for the measurements where γ_{ref} is in the range ±60°. Figure 3D shows how the RMSE varies as a function of F_α, and the optimum F_α with a dot at the minimum RMSE.

15   ## 5   Sensitivity analysis

The calibration test was performed several times on the exact same turbine. The rotor was stopped with one blade pointing downwards (so called bunny position) and the nacelle was yawed 6 times for each test, of ±90° (test 7 to 10) or ±60° (test 1 to 6) by operating manually from the turbine control panel. The yaw moves with a speed of about 0.5°/s, therefore one test of 6 sweeps takes approximately one hour. Tests 7 to 10 were made in the same day one after the other for the exact same rotor
20   position. The WSR method was used to calculate F_α (Table 1) for each test and a yawing span of ± 60°.

Table 1. F_α values for eight calibration tests made on the same wind turbine. Tests 7 to 10 were made with exact same rotor position.

Test	1	2	4	6	7	8	9	10
Fa value	1.63	1.72	1.73	1.62	1.46	1.53	1.48	1.53

Regarding the ability of the method to give reproducible results, the variation of F_α for tests 7 to 10 are within ±2.7% of the mean value 1.52. Since the rotor position is the same for the four tests, the only ascribable responsible for the variations is the wind turbulence. The 8 results are within ± 8.5% of the mean value 1.59.
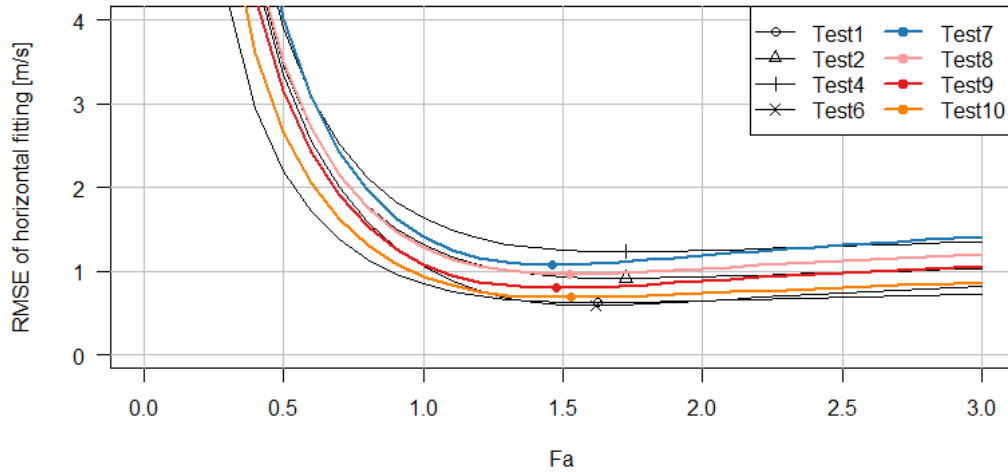
Figure 4. Root mean square error as a function of F_α. Markers locate the minimum value of RMSE and the corresponding F_α value. Colour bold lines are tests performed for the exact same rotor position.
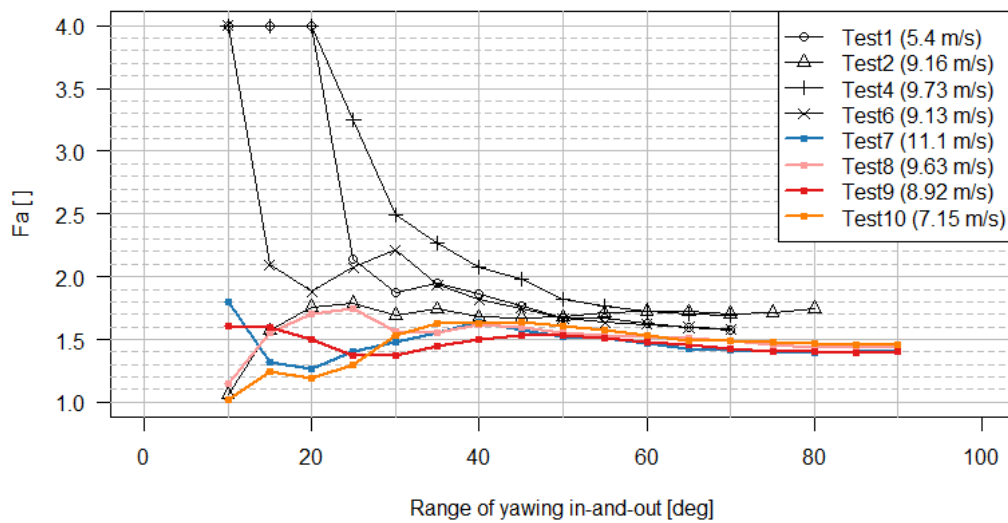
Figure 5. Sensitivity of the F_α to the yawing span. Colour bold lines are tests performed for the exact same rotor position. For test 2 the wind turbine was yawed of $\pm60°$ but an initial offset of the turbine with respect to the wind direction and a wind direction change during the test determined measurements up to $80°$.

6 Goodness of a calibration and benchmark on 17 wind turbine models

The variations encountered in the estimation of F_α call for the definition of a variable to express the quality of the calibration. One indicator could be related to the shape of the curves of Fig. 4. The more flat and shallow minimum, the larger uncertainty on F_α. The indicator was named quality score (QSC, see equation 3), calculated as the slope to the left of the minimum point.

5   Figure 6 shows QSC as a function of the span of yawing.

$$QSC = \frac{RMSE(F_\alpha - 0.1) - RMSE(F_\alpha)}{0.1} \tag{3}$$

What minimum quality score should a test have to give meaningful F_α? To answer this question, the wind speed response method was applied to a database of yawing tests consisting of 29 calibration tests made on 17 turbine models. Results are show in Fig. 7 and Fig. 8.
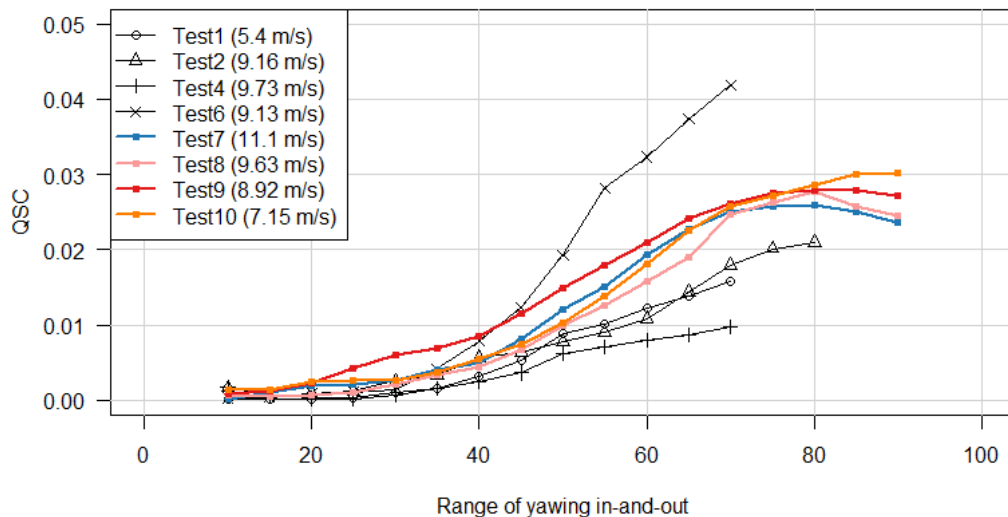
Figure 6. The quality score (QSC) is a measure of how much the RMSE as a function of Fa peaks at the minimum. A wide yawing span gives a more clear peak.

10   Figure 7 can help to identify which conditions of wind speed and turbulence leads to a more precise estimate of F_α, which means a more steep RMSE(F_α) curve, or in other words a high QSC. Average wind speed and turbulence intensity were calculated from the measurements calibrated with F_α, for a range of yaw misalignments included in the interval -30° to 30°. This is to ensure that there is not flow separation from the spinner surface and therefore ensure the spinner anemometer model validity. Figure 7 shows an inverse relation between the quality score and the turbulence intensity of the wind speed as measured

15   by the spinner anemometer during the yawing test. Figure 7 shows that the QSC increase with the wind speed.
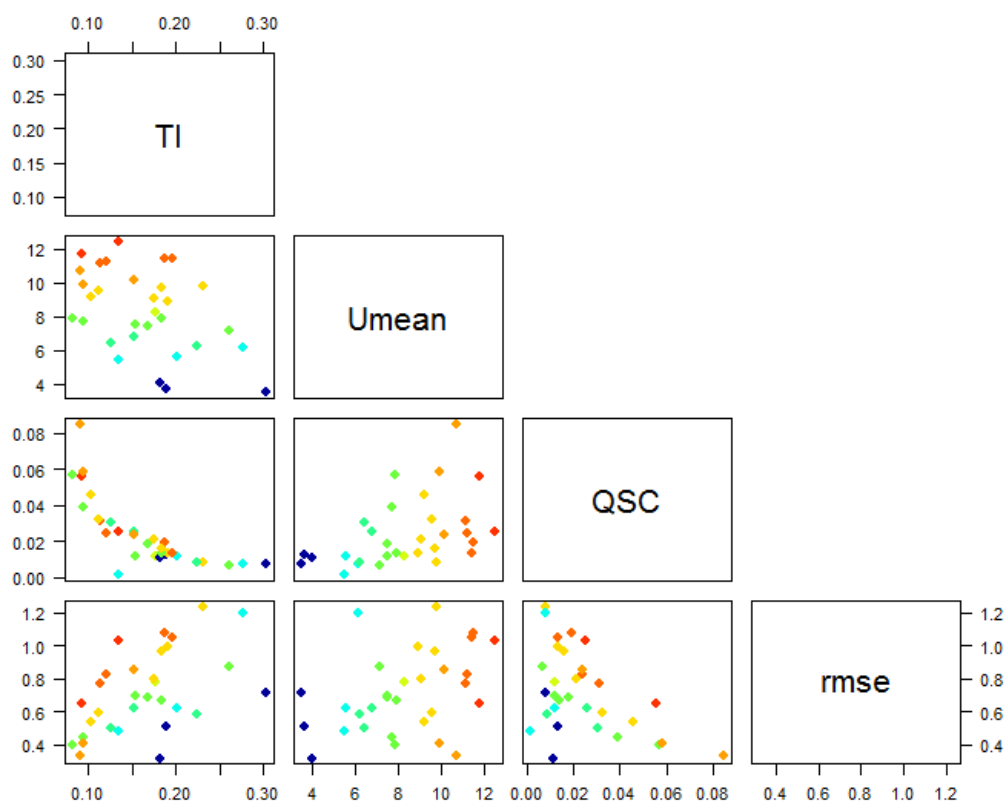
Figure 7. Application of the method to a large database of wind turbines. Colour coded with the mean wind speed.

7 Comparison with previous methods

The F_α was calculated with the three methods: GGref, TanTan, and WSR. The range of yawing (γ_{ref}) was $\pm45°$, $\pm45°$ and $\pm60°$, respectively. Figure 8 shows a certain level of agreement between the three methods.
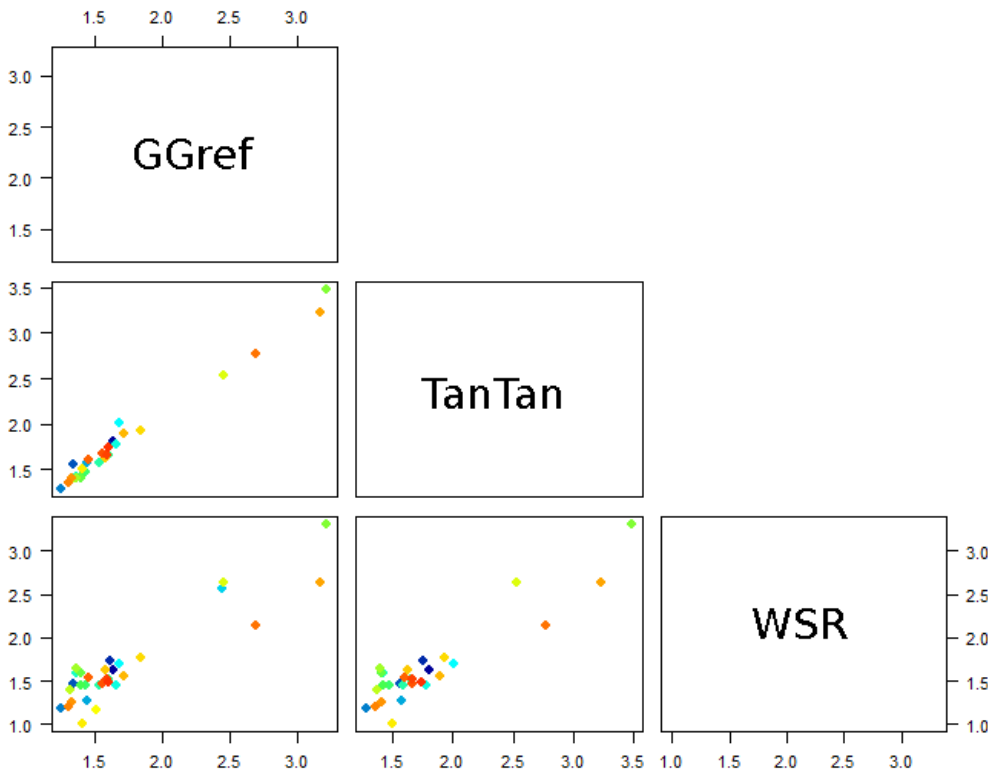
Figure 8. F_α calculated with three methods over a large database of wind turbines. Colour coded with the mean wind speed.

8 Conclusions

5   The article presented a new method to calibrate spinner anemometer flow angle measurements (yaw misalignment). The advantage of the method is that it does not need the yaw position of the nacelle to be measured.

   The robustness of the method was investigated by repeating the calibration test on the same turbine several times, with the rotor locked in the exact same rotor position to avoid sensor mounting deviations to play a role. The F_α values found for 4 tests for the exact same rotor position were within $\pm2.7\%$ of the mean value.

10   The quality score parameter (QSC) was introduced to quantify goodness of the Fa estimate. The QSC was found inversely dependent on the turbulence intensity. To have a sharp estimate of F_α it is therefore better to perform the test in low turbulence

wind conditions. The relation found between the QSC and the width of yawing suggests to yaw the turbine further than $\pm 60°$, up to $\pm 80°$ (this values might be different for other spinner shapes). Another issue to consider is that the test could start with an offset, and end up being -90° to 70° instead of -80° to 80°. This is easily avoidable yawing the wind turbine a bit further than the desired yawing span.

5 The sensitivity of the method to the width of yawing the turbine in and out of the wind was investigated by applying the calibration method to a subset of the original database. The subset was obtained filtering for $\gamma_{ref} \in [-s, s]$, where s was the span ranging from 10° to 90° in steps of 5°. Significant variations of the F_α value were found for yawing span s below approximately 60°.

 The F_α calculated with the wind speed response method was compared with the F_α calculated with previous methods

10 (GGref, TanTan) using 29 calibration tests performed by Romo Wind A/S on 17 wind turbine models. The sensitivity to span of yawing showed that the WSR method tends to stabilize to same values as GGref for yawing span larger than approximately 50°. Both the GGref and TanTan methods gave similar values up to $\pm 40°$, then the TanTan method gave higher F_α and diverged for a yawing span larger than 70°.

 A recommended yawing span to use to calculate F_α seems to be $\pm 60°$ for the WSR method and $\pm 40°$ for the TanTan and

15 GGref methods. It is recommended to verify the variation of F_α as a function of span of yawing (calibrated yaw misalignment when the yaw sensor is not available), since substantially different spinner shapes might give a stable F_α at different yawing span.

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References

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