Metrological characterisation of rotational speed measurement using an inclinometer in a nacelle test bench

Zihang Song[1], Paula Weidinger[1], Hongkun Zhang[2], Marcel. Heller[2], Rafael Soares Oliveira[3] and Rolf Kumme[1]

[1] Physikalisch-Technische Bundesanstalt Braunschweig, Germany, zihang.song@ptb.de
[2] Fraunhofer IWES, Bremerhaven, Germany, marcel.heller@iwes.fraunhofer.de
[3] Instituto Nacional de Metrologia, Qualidade e Tecnologia, RJ, Brazil, rsoliveira@inmetro.gov.br

Abstract

The measurement of mechanical power in nacelle test benches is an essential part of determining the efficiency of wind turbines. For this purpose, the selected inclinometer is integrated into the torque transfer standard to build a transfer standard for mechanical power measurement. The metrological characteristics of rotational speed measurement using the inclinometer are investigated by considering the static calibration, the uncertainty contributions due to mounting misalignments, eccentricity, dynamic effects, and the process of data evaluation. Finally, the traceability chain of the rotational speed measurement is established.

1 Introduction

Wind energy is considered one of the most important renewable energy sources for electrical power generation. Accurately measuring the efficiency of wind turbines on a nacelle test bench (NTB) plays an essential role in the development and validation phases, as even a small amount of measurement uncertainty (MU) represents an enormous amount of potential energy.

To provide traceability to national standards, the project titled “Traceable mechanical and electrical power measurement for efficiency determination of wind turbines (WindEFCY)” was started within the frame of the European Metrology Programme for Innovation and Research (EMPIR). As part of this project, a mechanical power transfer standard for NTBs was developed in [1]. It uses a torque transducer and an inclinometer for torque and rotational speed measurements. In this paper, the calibration and measurement of the selected inclinometer will be executed to establish a traceability chain of rotational speed measurement on the NTB.

2 Mechanical power transfer standard for NTBs

The mechanical power transmitted by the rotating shaft in NTBs is considered to be the power input to the device under test (DUT) and hence essential for efficiency determination. In order to perform accurate mechanical power measurement traceable to the national standard, a 5 MN·m torque transducer is used as the torque transfer standard (TTS), and an inclinometer is used as the transfer standard for the rotational speed.

2.1 The 5 MN·m torque transducer

In previous work described in [2, 3], the characteristics of the 5 MN·m torque transducer were investigated at the Physikalisch-Technische Bundesanstalt (PTB), and the transducer was implemented as the TTS in the NTB at the Center for Wind Power Drives (CWD) in Aachen using a freshly developed calibration procedure for torque under constant rotational speed. The TTS, as shown in **Figure 1**, is equipped with strain gauges for measuring torque, bending moment, shearing, and axial force.

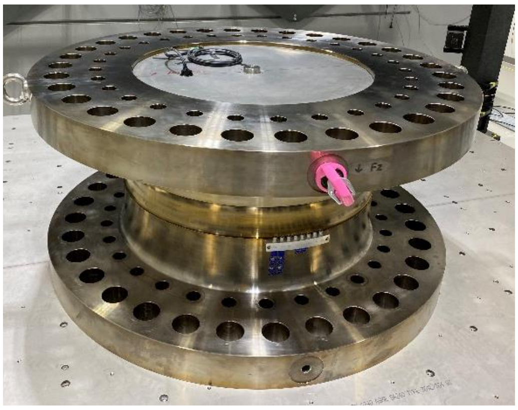

Figure 1 The 5 MN·m torque transducer used as TTS

2.2 Inclinometer integration for rotational speed measurement

The rotational speed should be measured at the same time and at the same shaft position as the torque signal in order to minimize systematic errors when determining the mechanical power. Due to the great height of the drive train in NTBs, an inclinometer is selected in preference to conventional rotary encoders based on stator-rotor-interaction. The inclinometer can determine the rotational speed by measuring the rotational angle of the drive train over time. Taking advantage of its stator-less feature, the inclinometer is installed on the inner side of the TTS cover plate on the centring part, as shown in **Figure 2**. In addition, a second inclinometer for the other two measurement axes is stacked on top of the first one to monitor the tilt angle of the drive train.

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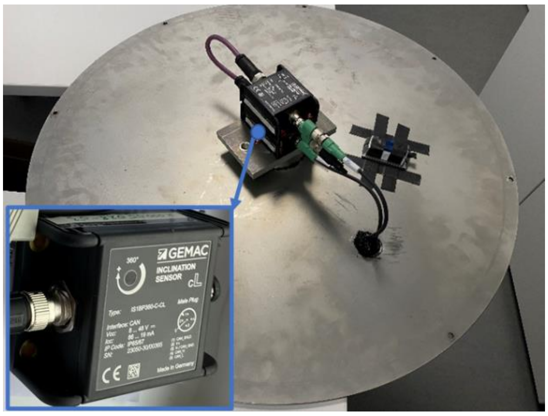

Figure 2 The inclinometer stack centred on the inner side of the TTS cover plate

In contrast to rotary encoders, the stator-less inclinometers are mounted directly inside the torque transducer and are hence independent of the construction environment of the NTB [4].

3 Dynamic Nacelle Testing Laboratory of Fraunhofer IWES

The Dynamic Nacelle Testing Laboratory (DyNaLab) of Fraunhofer IWES is an NTB located in Bremerhaven, Germany. As presented in **Figure 3**, the NTB includes motor drives on the left side, a non-torque load application system in the middle, the generator (DUT) on the right side, and a grid simulator. The drive train can deliver power up to 10 MW in total.

Figure 3 DyNaLab NTB at Fraunhofer IWES [5]

3.1 Measurement setup

PTB’s mechanical power transfer standard is mounted directly in front of the DUT (**Figure 4**) to perform the mechanical power calibration and the efficiency determination. The data acquisition (DAQ) system is placed inside the rotor shaft and rotates together with the drive train during operation.

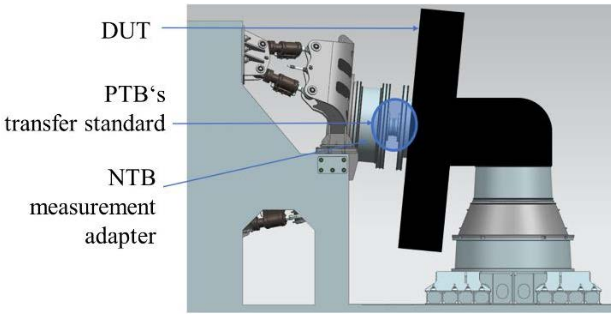

Figure 4 PTB’s mechanical power transfer standard mounted in the DyNaLab NTB

3.2 Performed measurement curves

The measurement curves performed in the NTB are designed based on the calibration procedure for torque under constant rotational speed in [2]. In the characteristic curve presented in **Figure 5**, the DUT is loaded with stepwise increasing and decreasing torque (0%-60% with 10% load steps, plus step 80% and step 100% of 5 MN·m) and repeated for five different rotational speeds (4.5 min^{-1}, 5 min^{-1}, 6 min^{-1}, 7 min^{-1} and 8 min^{-1}).

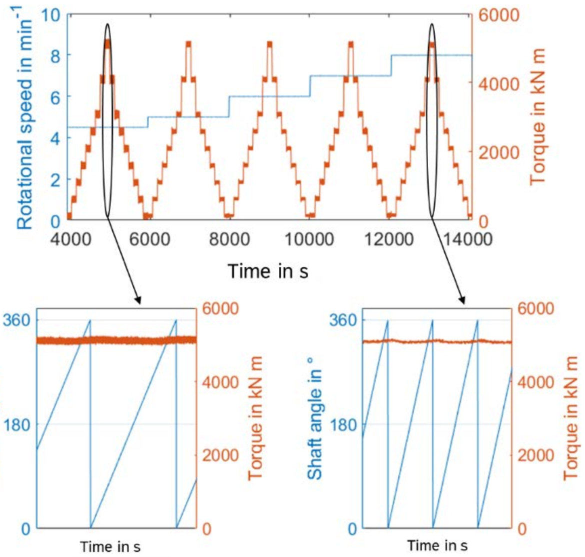

Figure 5 Characteristic curve with stepwise increasing and decreasing torque for five different speeds

4 Metrological characterisation of the selected inclinometer

The selected inclinometer is a microelectromechanical system (MEMS). It includes two perpendicularly placed accelerometers for inclination measurement with reference to gravity. By placing the inclinometer at the centre of the drive train, the angle position ϕ of the rotating shaft is determined with respect to gravity. The average rotational speed n is calculated based on the travelled angle $\Delta\phi = \phi_2 - \phi_1$ and the consumed time Δt:

$$n = \frac{\Delta\phi}{\Delta t} \cdot \frac{60}{360°}. \qquad (1)$$

The standard uncertainties of the angle measurement σ_ϕ and the time measurement σ_t contribute to the total standard uncertainty σ_n of the rotational speed measurement:

$$\sigma_n{}^2 = \left(\frac{\partial n}{\partial \phi_1}\cdot\sigma_\phi\right)^2 + \left(\frac{\partial n}{\partial \phi_2}\cdot\sigma_\phi\right)^2 + \left(\frac{\partial n}{\partial \Delta t}\cdot\sigma_t\right)^2, \quad (2)$$

$$\sigma_n = \frac{60}{360°}\cdot\sqrt{2\left(\frac{\sigma_\phi}{\Delta t}\right)^2 + \left(\frac{\phi_2-\phi_1}{\Delta t^2}\cdot\sigma_t\right)^2}. \quad (3)$$

It can be observed that σ_n is inversely proportional to the consumed time Δt. Therefore, measuring the rotational speed for a longer time can significantly reduce the uncertainty [4]. In this paper, the rotational speed was measured for six shaft revolutions. The measurement results were then evaluated to investigate the traceability chain of rotational speed measurement.

4.1 Static calibration

Static calibration of the inclinometer was carried out in the length and angle laboratory at PTB. The selected inclinometer showed an expended MU (k=2) of 0.014° under static measurement with a 0.22 Hz Bessel lowpass (LP) filter [4]. The standard uncertainty of angle measurement verified in the static calibration can be expressed as

$$\sigma_{\phi\_s} = 0.007°. \quad (4)$$

4.2 Uncertainty analysis of angle measurement

Compared to the static calibration, rotational speed measurement with the inclinometer can be influenced by additional effects.

4.2.1 Installation angle misalignment

Angle misalignment β describes the inconsistency of the inclinometer measurement axis and the shaft rotating axis due to installation offset. It results in a systematic deviation between the measured angle and the actual angular position of the rotating shaft. This deviation can be further increased by the tilting angle α of the drive train. Using the second inclinometer, the tilting angle α was measured to be around 4° in the NTB and the angle misalignment β was determined to be smaller than 1°. Based on the measured angle values, the systematic deviation was calculated applying the model proposed in [1]. The outcome shows a slightly deformed sinusoidal deviation with an amplitude of 0.07° whose frequency matches the frequency of shaft rotation. Since the start and end angle position ϕ_1 and ϕ_2 are measured over an interval of six shaft revolutions, the deviation is, theoretically speaking, removed in the angle difference $\Delta\phi$. In practice, the limited sampling rate (40 Hz) means that the difference between the angle positions of ϕ_1 and ϕ_2 may be as much as 1.2° at 8 min^{-1}. Applying this value in the sinusoidal deviation curve, the maximum deviation resulting from installation angle misalignment may amount to 0.0015°.

$$\sigma_{\phi\_m} = 0.0015° \quad (5)$$

4.2.2 Eccentricity

The inclinometer cannot be centred perfectly in the shaft cross-section. Consequently, the measurement will be affected by the centrifugal acceleration pointing away from the rotary axis towards the circumference in the radial direction. Given the size of the sensor body, a 10 mm offset between the rotating centre and the inclinometer measurement axis is taken into account and contributes to the uncertainty σ_{ϕ_e} due to centrifugal acceleration. Superposing the maximum centrifugal acceleration at 8 min^{-1} to the gravity vector, the measured angle can be changed by up to 0.0008°:

$$\sigma_{\phi\_e} = 0.0008°. \quad (6)$$

4.3 Data evaluation

In the data evaluation process (**Figure 6**), the angle position measured between 0° and 360° is accumulated to a continuously increasing travelled angle. A particular type of error was identified within the increasing angle data. When this type of error occurs, the signal transmission is paused for the next data sample, causing the continuously increasing angle to remain constant within the next sampling interval. Since the error occurs about every two minutes and is not related to the rotational speed of the drive train, it is thought to be a self-correction process in the MEMS internal clock during data transmission via CAN bus that takes place when the accumulated offset reaches the sampling interval. In the process that follows, the error is manually removed and considered to be the uncertainty contribution of the time measurement.

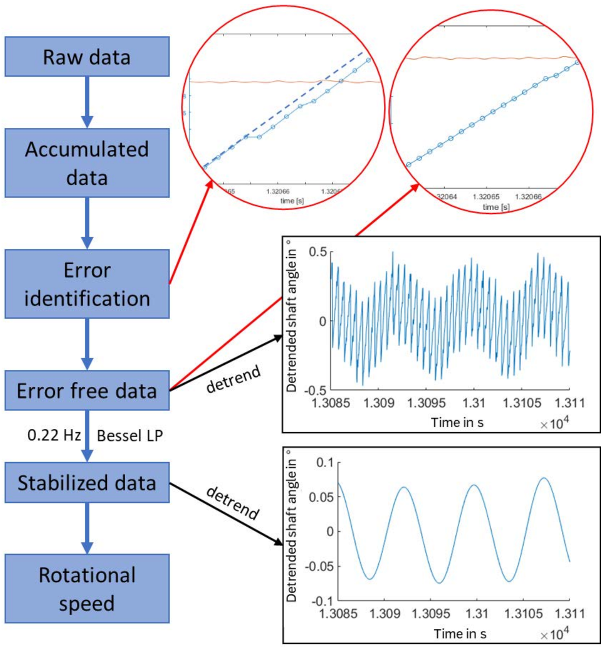

Figure 6 Inclinometer data evaluation flow chart

The uncertainty of the time measurement is therefore deemed to have a rectangular distribution with the width of the sampling interval (25 ms). The corresponding standard uncertainty σ_t is expressed as

$$\sigma_\mathrm{t} = \frac{25\ \mathrm{ms}}{2\sqrt{3}} = 7.22\ \mathrm{ms}. \qquad (7)$$

Afterwards, the 0.22 Hz Bessel LP filter is adapted to the inclinometer data to reduce the noise and retain the data processing condition during the static calibration process. As the noise and oscillation are difficult to observe in the curves of the continuously increasing angle, the data before and after the LP filter are detrended and presented as in **Figure 6**.

As demonstrated in **Figure 7**, the filtered shaft angle of the NTB is not perfectly constant and is coupled with alternating components due to torque ripples.

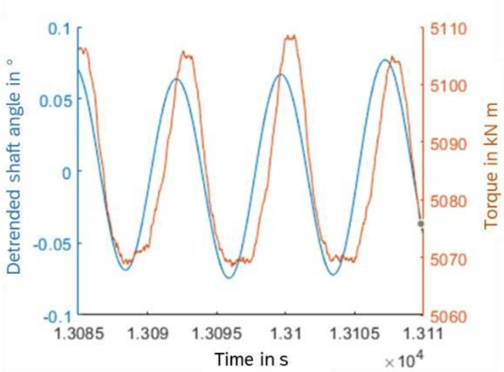

Figure 7 The detrended shaft angle position and the oscillating torque

The corresponding uncertainty contribution σ_{ϕ_d} due to dynamic behaviour can be determined similarly to the method used in subsection 4.2.1:

$$\sigma_{\phi\_\mathrm{d}} = 0.0015° \qquad (8)$$

4.4 Summary of the measurement uncertainty budget

The total standard uncertainty of the shaft angle measurement is calculated as

$$\sigma_\phi = \sqrt{{\sigma_{\phi\_\mathrm{s}}}^2 + {\sigma_{\phi\_\mathrm{m}}}^2 + {\sigma_{\phi\_\mathrm{e}}}^2 + {\sigma_{\phi\_\mathrm{d}}}^2}. \qquad (9)$$

In summary, all uncertainty contributions are listed in **Table 1** and the estimated total expanded MU (k=2) of rotational speed measurement with the inclinometer in the NTB is presented in **Table 2** using equation (3).

Table 1 Summary of uncertainty contributions

Contribution	Standard uncertainty	Contribution	Standard uncertainty
σ_{ϕ_s}	0.007°	σ_{ϕ_d}	0.0015°
σ_{ϕ_m}	0.0015°	σ_ϕ	0.0074°
σ_{ϕ_e}	0.0008°	σ_t	7.22 ms

Table 2 Total MU (k=2) of rotational speed measurement

Rotational speed min^{-1}	Absolute MU min^{-1}	Relative MU %
4.5	$8.1\cdot10^{-4}$	0.018 %
5	$1\cdot10^{-3}$	0.020 %
6	$1.4\cdot10^{-3}$	0.024 %
7	$2\cdot10^{-3}$	0.028 %
8	$2.6\cdot10^{-3}$	0.032 %

5 Conclusion

This paper investigated the metrological characteristics of rotational speed measurement using an inclinometer in an NTB. Besides the static calibration, the MU contributions due to mounting misalignments, eccentricity, dynamic effects, and the process of data evaluation were estimated. Based on the above-mentioned MU contributions, the traceability chain of the rotational speed measurement was established. In future work, the rotational speed will be expanded with further measurement techniques, such as the vibrometer, for comparison and validation.

6 Acknowledgement

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7 Literature

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