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10 MW mechanical power transfer standard for nacelle test benches using a torque transducer and an inclinometer

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ABSTRACT

Accurately measuring the mechanical power of wind turbines is essential for determining their efficiencies. As there is currently no standardized method available for a traceable mechanical power measurement of wind turbines, we propose a 10 MW mechanical power transfer standard based on a 5 MN·m torque transducer and an inclinometer for rotational speed measurements up to 20 min^{-1}. In particular, the deviation of using an inclinometer is investigated both in simulation and experiments, and a compensation method is proposed. By tracing both the torque and the rotational speed measurements to national standards, it can offer a mechanical power measurement with 0.5 % measurement uncertainty.

1. Introduction

Wind energy is considered as one of the most important renewable energy sources for electrical power generation. To fight the challenge of global warming, the use of wind energy has been increased sharply in the last ten years. At the same time, the power capacity of future wind turbines is being increased to above 10 MW to harvest more wind energy using fewer wind turbines. Accurately measuring the efficiency of wind turbines is thus becoming more important, as even a small amount of measurement deviation represents an enormous amount of potential energy.

The nacelle of a wind turbine is located behind the rotor blades and connected to the tower. It includes the rotor shaft, the gear box (if applicable), the generator and the electronics. The efficiency of this system can be measured on a nacelle test bench (NTB) as in Fig. 1. This is where the prime mover generates the torque and rotates the shaft, and the non-torque loading (NTL) simulates the parasitic loads, such as thrust force, bending and shearing. Ideally, the mechanical input power is measured on the nacelle's rotor hub, while the electrical power output is measured on the input to the power grid. In this way, the nacelle efficiency can be determined. Besides this direct measurement method, there are other efficiency measurement methods, such as the indirect measurement, the calorimetric [1] and the back-to-back methods [2,3]. Measuring the mechanical power is challenging within these methods and avoided in some cases, as it often contributes the biggest share of the efficiency measurement uncertainty (MU). To date, a metrological standard for rotary mechanical power measurement has only been developed on a small scale [4]. Therefore, the project titled "Traceable mechanical and electrical power measurement for efficiency determination of wind turbines (WindEFCY)" started within the frame of the European Metrology Programme for Innovation and Research (EMPIR). A 10 MW mechanical power transfer standard is to be developed, which includes a 5 MN·m torque transducer with 0.5 % MU and a rotational speed sensor up to 20 min^{-1} with 0.01 % MU. In this paper, a mechanical power transfer standard is proposed, which uses the 5 MN·m torque transfer standard (TTS) for torque measurement and an inclinometer for traceable rotational speed measurement.

2. Torque measurement

In a former project, a 5 MN·m torque transducer was established as TTS for NTBs (Fig. 2). In general, the TTS converts the applied torque into electrical signals by measuring the body deformation with strain gauges (SGs). It offers good linearity, high precision, good reproducibility, and small hysteresis at the same time. In addition, because of their negligible mass, SGs can be applied for torque measurement under rotation and can thus measure the torque in a direction-dependent manner [5]. The TTS was calibrated on the 1.1 MN·m torque standard machine at PTB and implemented in the NTB at CWD Aachen, using a newly developed torque calibration procedure under constant rotation. To achieve an accurate measurement, the torque signals are averaged over an integer number of shaft revolutions as the signals are periodically recurrent [6].

3. Rotational speed measurement

Within the frame of the project, the shaft rotational speed is to be measured in the range of 5–20 min^{-1} with a relative MU of less than 0.01 % (100 ppm).

If the rotational speed is measured directly in transient value, i.e. using a gyroscope, the sensor MU must be less than 0.003°/s to meet the accuracy requirement. Although various types of gyroscopes are available on the market, due to the restriction of the scale-factor stability and the bias stability, this specific requirement is difficult to achieve in a measurement campaign. This increases the cost and complexity of the system [7].

Alternatively, the rotational speed n in min^{-1} can be determined as an averaged speed by measuring the covered angle $\Delta\varphi$ over a certain

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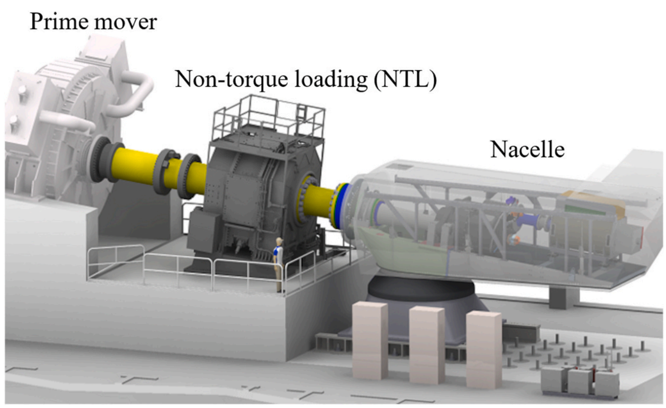

Fig. 1. NTB at Center for Wind Power Drives (CWD) at RWTH Aachen University, consisting of a prime mover, an NTL and the nacelle (Source: CWD).

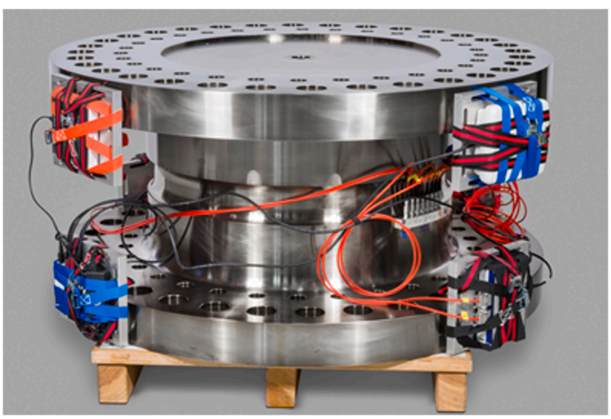

Fig. 2. TTS including data acquisition and telemetry systems [6].

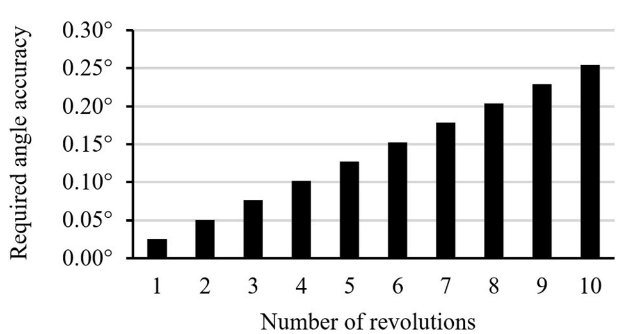

Fig. 3. Accuracy requirement on the angular sensor depending on the measurement period.

length of time Δt:

$$\Delta\varphi = \varphi_2 - \varphi_1, \tag{1}$$

$$n = \frac{\Delta\varphi}{\Delta t} \cdot \frac{60}{360^\circ}, \tag{2}$$

where φ_1 is the angle measured at the beginning and φ_2 is the angle measured at the end of the time interval. Since the MUs of φ_1 and φ_2 are fixed, the relative MU of the rotational speed can be reduced by measuring over a larger angle difference $\Delta\varphi$. As the torque signal is averaged over an integer number of shaft revolutions, in terms of mechanical power determination the same measurement period can be applied to the covered angle $\Delta\varphi$ for the rotational speed measurement. In this way, the rotational speed is measured synchronously to the torque over an integer number of shaft revolutions. At the same time, the high accuracy requirement of the rotational speed measurement can be achieved using more affordable, less accurate angular sensors. This accuracy requirement is depending on the measurement period expressed as the number of shaft revolutions (Fig. 3).

3.1. Rotary encoder

In NTBs, the rotary encoders are the most frequently used rotational speed transducers which can be divided into two types: the (a) absolute encoder measures the angular position of the shaft using the binary code marked on its disk; the (b) incremental encoder induces a frequency signal proportional to the rotational speed. It measures the relative angular movement by counting the number of periods and determines the absolute position regarding the reference point. Alternatively, the rotational speed can be determined directly by measuring the length of each signal period.

To select the appropriate rotational speed sensor, an overview of the rotational speed measurements in NTBs is presented in Table 1, based on the information provided by the project partners and stakeholders.

The accuracy of absolute encoders is usually defined by periods per revolution, which defines the resolution of the binary code. On the other hand, poles per revolution have an influence only on the update rate, and the accuracy of incremental encoders is often not available from the manufacturers' side and therefore remains unknown. The encoders are not calibrated and thus lack traceability to national standards.

Furthermore, in some of the NTBs, the rotational speed is not measured at the same point as the torque, which can result in additional uncertainty in the mechanical power measurement. To rectify this, the rotational speed is supposed to be measured directly at the nacelle input together with the torque to minimize the systematic error in mechanical power determination. Since the encoder measurement is based on the rotor-stator interaction, brackets need to be constructed to hold the stator near the shaft while the shaft rotates. In most NTBs, this construction can be challenging for external transfer standard, because the shaft is located several meters above the ground with a tilt angle of several degrees. Consequently, the stator bracket would need to be very long and is therefore not robust against vibrations. For this reason, it is optimal to use a stator-less rotational speed sensor, such as an inclinometer, which can be mounted inside the TTS and is hence

Table 1
Datasheet of rotary encoders used in NTBs.

NTB	Encoder type	Periods per revolution	Accuracy	Signal output	Calibration	Torque and rotational speed measured at the same point?
DyNaLab[a]	Absolute	16384	0.02°	Digital	No	No
	Incremental	131072	n/a	Square wave	No	Yes
CWD	Incremental	1024	n/a	Sine wave	No	No
A[b]	Incremental	8192	n/a	Sine/square wave	No	n/a
B[b]	Absolute	n/a	0.18°	Square wave	No	Yes
C[2]	Incremental	16384	n/a	Sine wave	No	Yes

[a] Dynamic Nacelle Testing Laboratory (DyNaLab) at Fraunhofer Institute for Wind Energy System.
[b] Anonymous stakeholders.

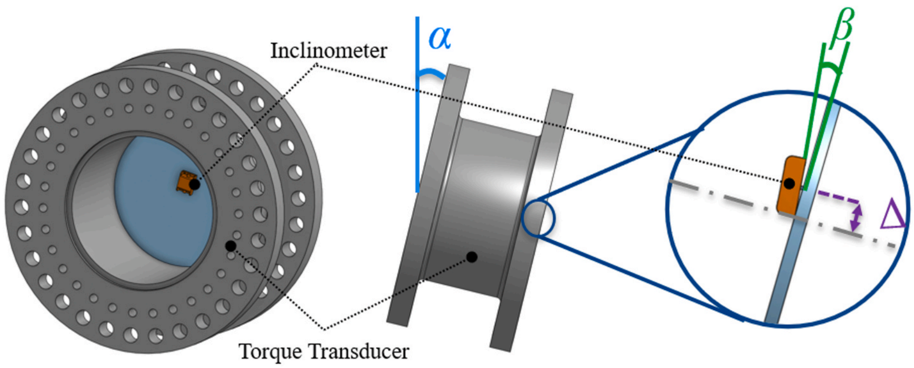

Fig. 4. Integration of the inclinometer in the torque transducer.

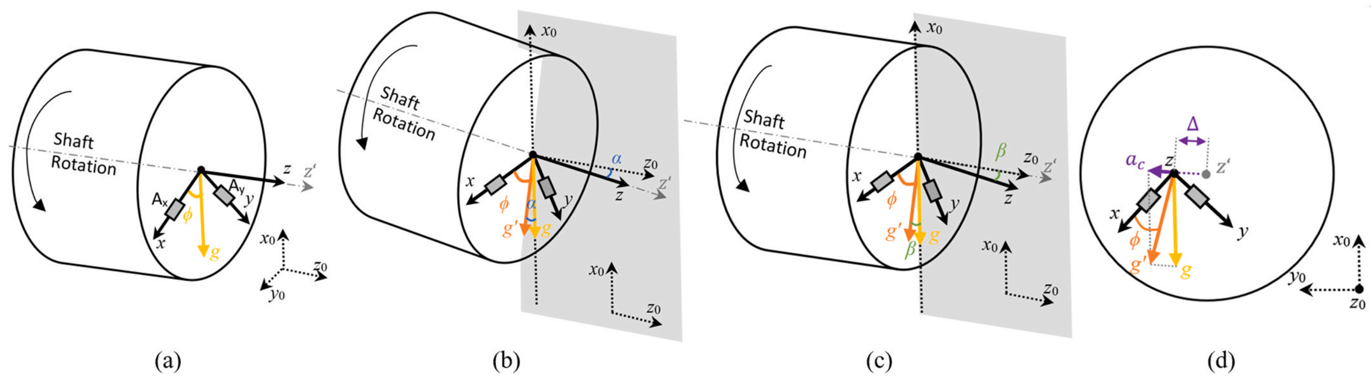

Fig. 5. Rotary angle measurement model using an inclinometer: (a) ideal conditions; (b) NTBs' rotary axis *z*' not horizontal (shaft tilt angle α); (c) misalignment angle β between the inclinometer measurement axis *z* and the shaft rotary axis; (d) centering offset Δ.

independent of the construction environment of the NTB.

3.2. Inclinometer

An inclinometer uses microelectromechanical system (MEMS) accelerometers to measure the orientation of gravity with reference to the inclinometer coordinate system. By this means, the inclination angle φ of the system is determined with respect to gravity. As the MEMS can be manufactured in a small size with low costs and high reliability, inclinometers are widely used for robot control and navigation systems. Furthermore, the authors of [8,9] use inclinometers to measure the tilt angle of rotational shafts.

In this paper, we use a single-axis inclinometer (GEMAC, IS1BP360–C-CL) to measure the shaft rotary angle γ. As shown in Fig. 5 (a), the measurement axis *z* of the inclinometer is aligned with the shaft rotary axis *z*', which also aligns to the horizontal axis z_0 in the ideal case. Inside the measurement plane *x*-*y*, two accelerometers (A_x and A_y) are placed perpendicularly to measure the gravity components in their axes (a_x and a_y). The rotary angle γ can be expressed as:

$$\gamma = \varphi = \arctan\frac{a_y}{a_x}. \tag{3}$$

To integrate the inclinometer in the torque transducer, the inclinometer is centered inside the transducer as shown in. Fig. 4.

As demonstrated in Fig. 4, the measurement conditions on NTBs in practice differ from the ideal conditions in Fig. 5 (a) for the following reasons:

1 *Shaft tilt angle* $\boldsymbol{\alpha}$

The NTBs' rotary axis *z*' is not horizontally oriented but has a tilt angle α to the horizontal axis z_0, as shown in Fig. 5 (b). This leads to the fact that the gravity vector $\vec{g}$ is not inside the inclinometer measurement plane *x*-*y* anymore. Therefore, the measurement angle φ now indicates the orientation of the gravity projection $\vec{g'}$ to the measurement plane *x*-*y*.

2 *Installation misalignment angle* $\boldsymbol{\beta}$

Due to installation misalignment, the inclinometer measurement axis *z* can have a misalignment angle β relative to the shaft rotary axis *z*', as presented in Fig. 5 (c). Because the measurement plane *x*-*y* and the shaft cross section are not parallel to each other in this case, the angle φ again indicates the direction of the gravity projection $\vec{g'}$.

3. Installation centering offset Δ

If the inclinometer is not centered correctly in the shaft cross section, the centrifugal acceleration $\vec{a_c}$ pointing away from the rotary axis towards the circumference in the radial direction will affect the measurement. Consequently, the two accelerometers A_x and A_y measure the vector sum $\vec{g'}$ of the gravity $\vec{g}$ and the centrifugal acceleration $\vec{a_c}$, as shown in Fig. 5 (d).

The three above-mentioned parameters will potentially affect the angle measurement of the inclinometer as the shaft rotates. Thus, the measured angle φ is not necessarily equal to the shaft rotary angle γ. To ensure measurement accuracy, this deviation is further investigated. A multibody model is developed in MATLAB/Simulink using quaternions to describe the rotation of the inclinometer coordinate system for a given rotary angle γ, considering different parameter settings of α, β, and Δ. In a 3-dimensional coordinate system, rotations and orientations can be described by a four-part hyper-complex number named quaternion q:

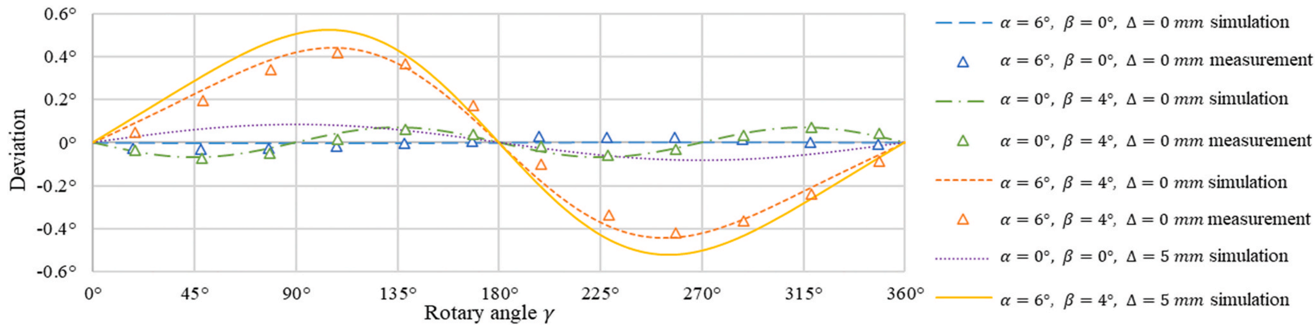

Fig. 6. Rotary angle deviations resulting from the shaft tilt angle α, the misalignment angle β and the centering offset Δ at 20 min^{-1}.

$$q = a + bi + cj + dk. \tag{4}$$

Since the quaternions calculated by the model represent the orientation of the inclinometer coordinates relative to the earth coordinates, the unit for vectors of the inclinometer axes $\vec{n}_x$, $\vec{n}_y$ and $\vec{n}_z$ can be calculated as:

$$\begin{pmatrix} 0, \vec{n}_x \\ 0, \vec{n}_y \\ 0, \vec{n}_z \end{pmatrix} = q \cdot \begin{pmatrix} 0, \vec{n}_{x0} \\ 0, \vec{n}_{y0} \\ 0, \vec{n}_{z0} \end{pmatrix} \cdot q^{*}. \tag{5}$$

Afterwards, the gravity vector $\vec{g}$ is superposed with the centrifugal acceleration a_c and projected in the measurement plane x-y in (6).

$$\vec{g}' = \left(\vec{g} + \vec{a}_c\right) - \vec{n}_z \cdot \left(\vec{g} + \vec{a}_c\right) \cdot \vec{n}_z \tag{6}$$

Finally, the deviation is calculated between the rotary angle γ and the inclinometer measurement angle φ.

$$dev = \gamma - \varphi = \gamma - \cos^{-1}\left(\frac{\vec{g}' \cdot \vec{n}_x}{\left|\vec{g}'\right| \cdot \left|\vec{n}_x\right|}\right) \tag{7}$$

The deviation analysis results at 20 min^{-1} are presented in Fig. 6. Meanwhile, deviations are measured experimentally to validate the simulation. It can be seen that the misalignment parameters β and Δ can both result in sinusoidal deviations in the measurement. Interestingly, the shaft tilt angle α has no independent influence on the measurement. It leads to no deviation when the measurement axis is perfectly aligned ($\beta = 0°$) but causes a deformed sinusoidal deviation distribution when $\beta \neq 0°$. Altogether, the analysis shows that the deviation of the rotary angle measurement using an inclinometer is periodic for every shaft revolution. Therefore, if the angles are measured at the same shaft rotary position, the start angle φ_1 and the end angle φ_2 in (1) are coupled with the same deviation, which does not influence the angle difference $\Delta\varphi$ for the rotational speed measurement. Using this method, the periodic deviations can be compensated. The measurement results are thus the same as the results measured in the ideal conditions as in Fig. 5 (a), in which the rotational speed is measured without this installation related deviation, and the MU is only related to the inclinometer itself. Lastly, a static calibration of the inclinometer shows an expended MU ($k = 2$) of 0.014° and a repeatability of 0.005°. The requirement in Fig. 3 can be achieved with a measurement period of one shaft revolution.

4. Conclusions

In this paper, we explore the possibility of developing a 10 MW mechanical power transfer standard for NTB based on a 5 MN·m torque transducer and an inclinometer for rotational speed measurement up to 20 min^{-1}. We focus on the rotational speed measurement and illustrated the influences of the operating parameters by analyzing the deviation of the inclinometer with the help of a simulation model and experimental measurements. With the compensation method, the proposed transfer standard can measure the rotational speed with 0.01 % MU and the mechanical power with less than 0.5 % MU.

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