Deliverable D2 within 19ENG08

- Report describing the requirements of tachometers such as the evaluation of existing tachometer measuring principles and their capabilities, and the procedure developed to calibrate tachometers with an uncertainty of 0.01 % -

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The views expressed in this report are those of the authors and of the EMPIR 19ENG08 WindEFCY project team.

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Authorship

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Content

1 Introduction

This report was generated in work package 2 (WP2) of the EMPIR project 19ENG08 “Traceable mechanical and electrical power measurement for efficiency determination of wind turbines” short WindEFCY. The aim of the report is to define the requirements of tachometers used on nacelle test benches (NTBs) and to evaluate the principles and the capabilities of existing tachometers, as well as to develop the calibration procedure with a measurement uncertainty of 0.01 %. The outcome is a rotational speed transfer standard, which is an important part of the mechanical power determination and contributes to WP2 and further work packages of the project. The tachometer transfer standard – together with the torque transfer standard (TTS) – will be used to calibrate the mechanical power measurement in NTBs.

For getting an overview of encoders used in nacelle, motor and generator test benches, a questionnaire amongst the project’s stakeholders has been conducted. Five stakeholders from different backgrounds such as manufacturers of measurement devices as well as test bench manufacturers and operators have participated in the survey. As a result from the questionnaire, encoders in most test benches are not calibrated but rather rely on the manufacturer specification regarding accuracy. Moreover, the results from the questionnaire are used to specify a requirements list on encoders for rotational speed measurement up to 1600 min^{-1} in nacelle test benches.

To improve the measurement uncertainty (MU) of encoders in test benches, a transfer standard for rotational speed measurement is developed. Based on an overview list of commercially available tachometers, an appropriate measurement device for rotational speed is selected. The challenge of developing a transfer standard for rotational speed measurement in NTBs is the lack of a stator at the rotor hub of the nacelle under test, where both torque and rotational speed are to be measured. This lack is due to the enormous height at the rotor hub and missing rigid structures. A stator-less rotational speed measurement is realised by an inclinometer that measures the rotational angle of the drive train over time. The inclinometer is to be combined with the 5 MN m TTS and implemented on the low-speed shaft (LSS) of NTBs. Therefore, the range of rotational speed measurement for the LSS does not go beyond 25 min^{-1}.

The selected inclinometer is calibrated in the length and angle laboratory of PTB and is proved to have an expended MU ($k = 2$) of 0.014° and a repeatability of 0.005° in static condition. The MU contributions of the time measurement and dynamic effect are to be determined at a later point.

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2 Tachometers: rotational speed measurement

One aim of WP2 is to use a tachometer to measure the shaft rotational speed of NTBs in the range from 3 min^{-1} to 20 min^{-1} with an MU of 0.01 %. In this section, the principles of different tachometers are explained and compared for evaluation. Finally, an inclinometer is selected as the proper sensor type for the project regarding its capabilities of stator-less angular measurement.

2.1 Measuring principles of tachometers

Based on the measurement principles of rotational speed, tachometers can be divided into two types:

- The first type of tachometer measures the transient angular speed of a rotating shaft. For example, by placing an accelerometer on the shaft with a radius of *r*, the radial acceleration due to the centrifugal force can be measured to calculate the shaft rotational speed as in (1).

$$n = \frac{60}{2\pi} \cdot \sqrt{\frac{a}{r}} \tag{1}$$

  Another example of this tachometer type are gyroscopes. There are various types of gyroscopes available on the market, including mechanical, optical, ring laser and micro-electromechanical system (MEMS) gyroscopes [1]. One of the major advantages of this tachometer type is its high sampling rate, which is, however, not required for power measurement and efficiency determination. On the contrary, fulfilling the 0.01 % uncertainty goal is difficult for this tachometer type. Because at 3 min^{-1}, the sensors are required to have an uncertainty as low as 0.0018 °/s. Due to restrictions such as scale-factor stability and bias stability, this specific requirement is difficult to achieve with neither accelerometers nor gyroscopes. Fulfilling the MU target with this tachometer type increases the cost and complexity of the system.
- The other type of tachometers measures the rotational speed n as an averaged speed by measuring the covered angle $\Delta\phi$ over a certain length of time Δt, as in (2) and (3).

$$\Delta\phi = \phi_2 - \phi_1 \tag{2}$$

$$n = \frac{\Delta\phi}{\Delta t} \cdot \frac{60}{360°} \tag{3}$$

  In equation (2), ϕ_1 is the start angular position and ϕ_2 is the end angular position of the time interval. The standard uncertainty σ_n of the rotational speed measurement is calculated based on two uncertainty contributions: the angle measurement σ_Φ and the time measurement σ_t:

$$\sigma_\mathrm{n}{}^2 = \left(\frac{\partial n}{\partial \phi_1} \cdot \sigma_\Phi\right)^2 + \left(\frac{\partial n}{\partial \phi_2} \cdot \sigma_\Phi\right)^2 + \left(\frac{\partial n}{\partial \Delta t} \cdot \sigma_\mathrm{t}\right)^2, \tag{4}$$

$$\sigma_\mathrm{n} = \frac{60}{360°} \cdot \sqrt{2\left(\frac{\sigma_\Phi}{\Delta t}\right)^2 + \left(\frac{\phi_2 - \phi_1}{\Delta t^2} \cdot \sigma_\mathrm{t}\right)^2}. \tag{5}$$

  In (5), σ_Φ and σ_t are fixed values depending on the sensor specifications. The standard uncertainty σ_n measured with the same sensor specifications is inversely proportional to the time interval Δt [2]. This means the MU of the rotational speed can be greatly reduced if the time interval Δt is measured for multiple shaft revolutions comparing to for several degrees, in which a more tolerant requirement can be applied on the angular sensors, as shown in Figure 1. Therefore, the major advantage of this tachometer type is that the high uncertainty requirement of the rotational speed measurement can be achieved using more affordable, less accurate angular sensors [3].

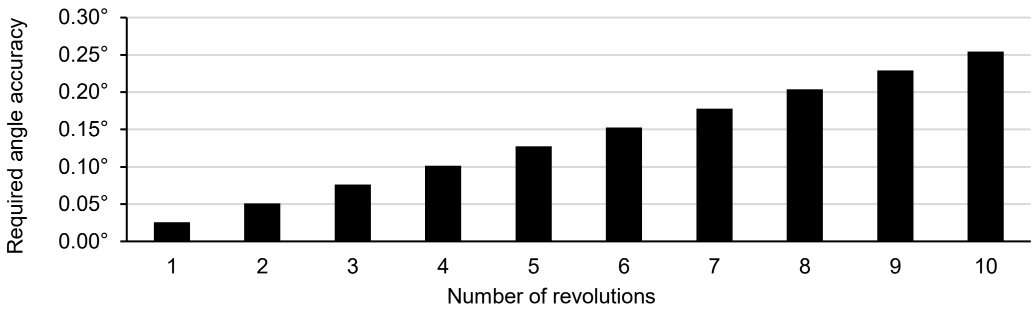

Figure 1: Accuracy requirement on the angular sensor depending on the measurement period [3].

2.2 Rotary encoders

Rotary encoders are frequently used in NTBs as rotational speed transducers. They can be divided into two types:

- The absolute encoder measures the angular position of the shaft using the binary code marked on its disk.
- The incremental encoder induces a square or sinusoidal signal the frequency of which is proportional to the measured rotational speed. It measures the relative angular movement $\Delta\phi$ in (3) by counting the number of periods. The absolute angular position can be determined regarding a reference point as well. Alternatively, the rotational speed can be determined directly by measuring the length of each signal period.

The coding of both absolute and incremental encoders can be succeeded using optical, capacitive, inductive or magnetic methods [4]. Figure 2 shows an optical incremental encoder and an optical absolute encoder disk.

Figure 2: Optical incremental encoder (Left) [5] and optical absolute encoder disk (right) [6].

Furthermore, both absolute and incremental encoders do not directly measure the transient rotational speed, but the averaged speed value for a certain time interval as in (3). Normally, this time interval is measured between every two slots to ensure the widest measurement bandwidth, because a fast update rate is essential for dynamic control purposes. In terms of mechanical power determination, the method described in section 2.1 can be implemented to improve the accuracy, in which the averaging time interval is prolonged to multiple shaft revolutions.

To have an overview of encoders used for rotational speed measurements in NTBs, a questionnaire has been sent to project partners and stakeholders. The provided information is presented in Table 1. The accuracy of absolute encoders is usually defined by periods per revolution, which also defines the resolution of the binary code. For incremental encoders, the term "poles per revolution" defines the number of the signal period for one shaft revolution, which determines the measurement update rate, while the accuracy of incremental encoders is often not available from the manufacturers' side and

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therefore remains unknown. The encoders currently used by the project partners and stakeholders are not calibrated and thus lack traceability to national standards [3].

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[1]	Absolute	16384	0.02 °	Digital	No	No
	Incremental	131072	n/a	Square wave	No	Yes
CWD[2]	Incremental	1024	n/a	Sine wave	No	No
A[3]	Incremental	8192	n/a	Sine/square wave	No	n/a
B[3]	Absolute	n/a	0.18 °	Square wave	No	Yes
C[3]	Incremental	16384	n/a	Sine wave	No	Yes

Furthermore, in some of the NTBs, the rotational speed is not measured at the same point as the torque. This could result in additional uncertainty in the mechanical power measurement under torque ripples due to shaft inertia. Therefore, the rotational speed should be measured together with the torque directly at the nacelle input to minimise the systematic error in the mechanical power determination [3].

Although rotary encoders are widely used in NTBs for rotational speed measurement, they are not the optimal choice for the project because of their rotor-stator interaction structure. To prepare the calibration measurement using transfer standards at each NTB, brackets for the encoder stator need to be individually constructed to hold the stator near the shaft while the shaft rotates. In most NTBs, this construction can be challenging for external measurement devices mounted at the nacelle input, because the shaft is located several meters above the ground with a tilt angle of several degrees. Consequently, the construction is time-consuming and the stator bracket would need to be very long and is therefore not robust enough against vibrations to ensure the demanded precise air gap between rotor and stator [3]. For this reason, it is optimal to use a stator-less angular sensor, which can be mounted inside the TTS. In this way, the TTS and the tachometer are integrated as a unified body and can be hence independent of the construction environment of different NTBs.

Requirements list for encoders in NTBs

[1] Dynamic Nacelle Testing Laboratory (DyNaLab) at Fraunhofer Institute for Wind Energy System

[2] Center for Wind Power Drives (CWD) at RWTH Aachen University

[3] Anonymous stakeholders

Table 2 represents a generic requirements list on the metrological characteristics for measuring the rotational speed n in an NTB in order to determine the mechanical power P_{mech}:

$$P_{\mathrm{mech}} = 2 \cdot \Pi \cdot M \cdot n. \tag{6}$$

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Table 2: Requirements list on the metrological characteristics for measuring the rotational speed n in an NTB.

Requirement	Unit	Value / Priority
Independent rotational speed measurement		Requirement
Timewise synchronisation of torque and rot. speed measurement		Requirement
Location of rot. speed measurement		As close as possible to the torque measurement
MU	[%]	0.01
Resolution	[°]	0.1
Accuracy $x(n_{\min})$	[°/s]	0.0018
Measurement range	[min^{-1}]	0-20
Measurement in both rotational directions		Requirement
Measurement during rotation		Requirement

The required accuracy $x(n_{\min})$ for the angular speed measurement is calculated by:

$$x(n_{\min}) = n_{\min} \cdot 0.01\% = \ 3 \cdot 10^{-4}\text{min}^{-1} \text{ or } 0.0018°/\text{s}, \tag{7}$$

with $n_{\min} = 3 \text{ min}^{-1}$.

Table 3 expresses the requirements on the electrical characteristics for measuring the rotational speed n in an NTB.

Table 3: Requirements list on the electrical characteristics for measuring the rotational speed n in an NTB.

Type	Unit	Value
☐ Absolute		
☒ Incremental		
Electrical signal		
Analogue		
☐ Square wave		
☒ Sine / cosine wave		
☒ TTL		
☒ HTL		
Digital		
☒ CAN bus		
Electrical supply voltage	[V]	≤ 24
Same telemetry system as torque transducer	Optional	

Table 4 depicts the mechanical requirements on a tachometer to measure rotational speed n in an NTB. Some information about the 5 MN m torque transducer manufactured by HBK is confidential and therefore not shown here.

Table 4: Requirements list on the mechanical characteristics for measuring the rotational speed n in an NTB.

Requirement	Unit	Value / Priority
Dimensions 5 MN·m torque transducer (rotor)		
Flange diameter	[mm]	Confidential
Hollow-shaft diameter	[mm]	Confidential
Stator		Not available
Mechanical interface		Non-intrusive, wear-free
Easy to mount		Requirement

Table 5 lists the requirements on the operational conditions to measure the rotational speed n NTBs. The requirements correspond to operational conditions in NTBs.

Table 5: Requirements list on the operational conditions for measuring the rotational speed n in an NTB.

Requirement	Unit	Value / Priority
Operating temperature	[°C]	10 – 60
Operating relative humidity	[% rH]	5 – 50
Resistant to alternating ambient conditions		Requirement
Resistant to vibrations		Requirement

2.3 Commercially available tachometers

Based on the requirements lists for encoders in NTBs, four commercially available encoders were reviewed regarding their measuring principle and their suitability for the application in test benches. All encoders introduced in the following work well for an application in test benches. The challenge in establishing a transfer standard for rotational speed measurement in NTBs is the missing stator at the rotor hub, where the rotational speed is to be measured. All commercially available encoders represented in the following are reliant on a stator.

2.3.1 Baumer

The Baumer HDmag flex MIR 3000F is an incremental encoder specially designed for shafts with a diameter between ø 300 mm and 3183 mm. The encoder consists of a sensing head and a magnetic band with a resolution of up to 131072 pulses per revolution, which is an accuracy of 2.75 x 10^{-3} ° (9.90 ʻʼ) per pulse. The sensor head in combination with the long magnetic band can be deployed for rotational speed measurements ≤ 150 min^{-1}. [7] This robust and wear-free, fully encapsuled sensor with large mounting tolerances is used to measure the rotational speed in the DyNaLab at Fraunhofer IWES. It can be exposed to temperatures between -40 °C and 85 °C.

2.3.2 SIKO

The SIKO incremental magnetic sensor LE100/1 [8] works linearly with the magnetic band MB100/1 [9] and rotationally with the magnetic tape ring MBR100 [10]. The repeated accuracy of the sensor amounts to max. ± 1 µm and the reading distance between the sensor head and the magnetic band is ≤ 0.4 mm. Over a band length of 100 m, the linearity deviation is up to ± 8 µm. This encoder can be installed in harsh conditions with temperatures ranging from -10 °C up to 70 °C and a relative humidity of 100 %.

2.3.3 Renishaw

The optical incremental encoder system TONiC with either a RTL linear, a RKL partial arc or a RES or REX rotary scale is manufactured by Renishaw and designed for highly-dynamic precision motion systems. It has a sinusoidal output and a very high accuracy. The resolution of the RKL narrow stainless steel partial arc tape for rotary measurements is 7.2 x 10^{-3} ° with an accuracy of 1.8 x 10^{-3} ° for a scale of 20 µm. For the scale of 40 µm, the resolution is 1.44 x 10^{-2} ° and the accuracy amounts to 1.8 x 10^{-3} ° as well. The robust stainless steel encoder tape scale can be wrapped around a shaft. The supplied tape length is up to 20 m [11], [12].

Moreover, Renishaw supplies an optical absolute encoder system RKLA-S to measure rotary movements with a very high accuracy of 1.8 x 10^{-3} and a resolution of 1.08 x 10^{-2} for the 30 µm scale. The supplied tape length is up to 21 m [13].

The systems can also work under harsh conditions with temperatures between -20 °C and 70 °C and a relative humidity of 95 %. They are resistant to vibrations of maximum 100 m/s^2 at 65 Hz to 2000 Hz for all three axes.

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2.3.4 Heidenhain

Heidenhain supplies modular absolute and incremental angle encoders with optical or magnetic scanning principle. Despite their sufficient accuracy, Heidenhain does not offer a suitable encoder matching the mechanical requirements – especially not the diameter which is less than ø 560 mm [14].

2.3.5 Hübner

The manufacturer Johannes Hübner Giessen offers magnetic rotary encoders for incremental bearing-less speed measurement. The applications are made for hollow shafts up to approx. ø 1500 mm and a contactless scanning with up to 100 000 pulses. The pulse wheel can be mounted directly onto the shaft and can measure high speeds. The encoders can be exposed to harsh conditions with temperatures between -40 °C and 100 °C. More information on resolution and accuracy is missing [15], [16].

2.4 Stator-less measurement of rotational speed via the inclinometer

To overcome the challenge of setting up a rigid structure at a great height as a stator for the rotational speed measurement, a stator-less measurement approach via an inclinometer is chosen.

2.4.1 Measurement principle

MEMS inclinometers are angular sensors measuring the gravity vector with the reference to the sensor coordinate system. Inside, two accelerometers are placed perpendicularly to measure the gravity components in the two axes and the inclination angle ϕ of the system is determined with respect to the gravity vector. MEMS inclinometers are widely used for navigation and robot control, because of their small size, high reliability and low costs. In addition, inclinometers are implemented for tilt angle measurement of rotational shafts in [17] and [18]. For its capabilities of stator-less angular measurement, an inclinometer is selected as the proper sensor type for the project. In this way, the torque transducer and tachometers are integrated as a unified body and can be hence independent of the construction environment of different NTBs.

In DyNaLab, an inclinometer manufactured by GEMAC sensors (IS1BP360-U-CL) with analog output is currently in use for rotational speed measurement and system monitoring. For a higher accuracy [19] and robust signal transmission, the CAN bus version (IS1BP360-C-CL) of the GEMAC inclinometer is selected as the tachometer for the project.

The measurement axis z of the inclinometer and the shaft rotary axis z' are aligned together, as shown in Figure 3. Ideally, these two axes are aligned to the horizontal axis z_0 as well. Two accelerometers A_x and A_y are perpendicularly placed inside the measurement plane x-y and the gravity components a_x and a_y are measured in both axes. The rotary angle ϕ is calculate as:

$$\phi = \gamma = \arctan\frac{a_y}{a_x}. \tag{8}$$

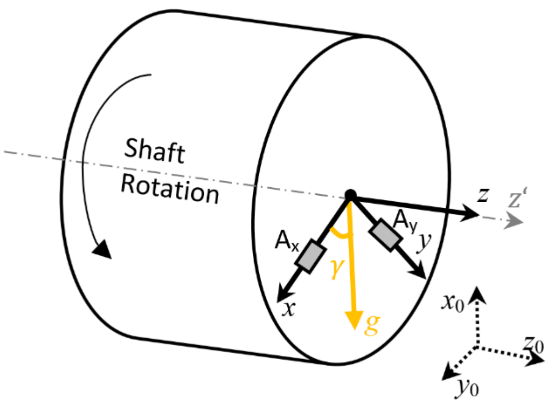

Figure 3: Rotary angle measurement model using an inclinometer in ideal conditions.

2.4.2 Installation of the inclinometer and deviation analysis

To integrate the inclinometer in the TTS, it is mounted on the centering part inside the transducer cover, as shown in Figure 4.

Figure 4 also demonstrates the potentially deviated measurement conditions in practice in NTBs that differ from the ideal conditions in Figure 3. Three parameters are used to describe the potential deviations:

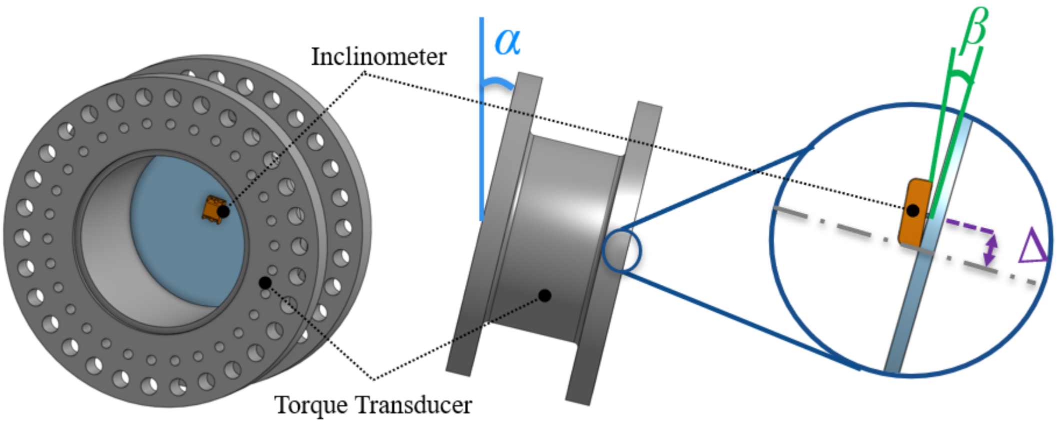

Figure 4: Integration of the inclinometer in the torque transducer [3].

1. ***Shaft tilt angle*** α
The rotary axis z' of NTBs is normally not horizontally oriented. To simulate the field condition, the shaft is often turned by a tilt angle α out of the horizontal axis z_0, as shown in Figure 5 (a). Under this condition, the gravity vector $\vec{g}$ is not inside the inclinometer measurement plane *x-y* anymore, which leads to the result that the measurement angle γ now indicates the orientation of the gravity projection $\overrightarrow{g'}$ to the measurement plane *x-y*. [3]

2. ***Installation misalignment angle*** β
The measurement axis z of the inclinometer will have a misalignment angle β relative to the shaft rotary axis z' due to the misalignment during the installation, as presented in Figure 5 (b). In this case, the measurement plane *x-y* is no longer parallel to the shaft cross-section, and hence the angle γ again indicates the direction of the gravity projection $\overrightarrow{g'}$, instead of the true gravity vector $\vec{g}$. [3]

3. ***Installation centering offset*** Δ
Another possible misalignment due to the installation is that the inclinometer is not centered correctly within the shaft cross-section. As a result, the centrifugal acceleration $\overrightarrow{a_c}$, which points away from the rotary axis and towards the circumference in the radial direction, will be measured by the accelerometers as well. Consequently, the vector sum $\overrightarrow{g'}$ including the gravity $\vec{g}$ and the centrifugal acceleration $\overrightarrow{a_c}$ are measured together by the two accelerometers A_x and A_y, as shown in Figure 5 (c). [3]

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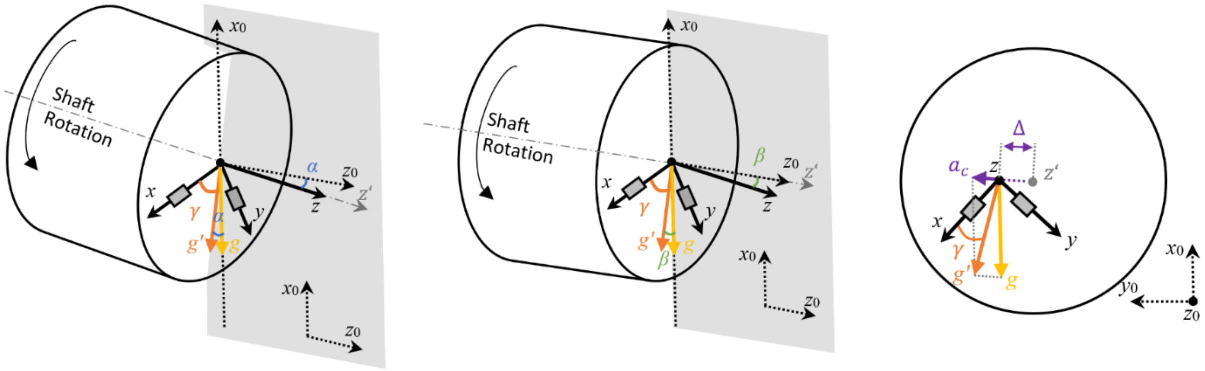

(a) (b) (c)

Figure 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 z'; (d) centering offset Δ [3].

Under the conditions shown in Figure 5 (a), (b) and (c), the angle γ is not measured in reference to the true gravity vector as in the ideal case in Figure 3. Therefore, the measurement angle γ is not necessarily equal to the shaft rotary angle ϕ. For a better understanding of the deviations, a multibody model is built in MATLAB/Simulink, which uses quaternions to describe the relative movement of the inclinometer coordinate system under rotation, considering different parameter conditions of α, β, and Δ. The quaternion q is a four-part hyper-complex number, which describes the object orientation in a 3-dimensional coordinate system:

$$q = a + bi + cj + dk. \tag{9}$$

The quaternion of the model output defines the relative orientation of the inclinometer coordinates and the earth coordinates. Therefore, the unit vectors $\vec{n}_\mathrm{x}$, $\vec{n}_\mathrm{y}$ and $\vec{n}_\mathrm{z}$ of the inclinometer coordinate axes can be calculated from the earth coordinate unit vectors $\vec{n}_{\mathrm{x}0}$, $\vec{n}_{\mathrm{y}0}$ and $\vec{n}_{\mathrm{z}0}$:

$$\begin{pmatrix} 0, \vec{n}_\mathrm{x} \\ 0, \vec{n}_\mathrm{y} \\ 0, \vec{n}_\mathrm{z} \end{pmatrix} = q \cdot \begin{pmatrix} 0, \vec{n}_{\mathrm{x}_0} \\ 0, \vec{n}_{\mathrm{y}_0} \\ 0, \vec{n}_{\mathrm{z}_0} \end{pmatrix} \cdot q^*. \tag{10}$$

The gravity vector $\vec{g}$ is first superposed with the centrifugal acceleration $\vec{a}_\mathrm{c}$ and then projected in the measurement plane *x*-*y* in (11).

$$\overrightarrow{g'} = (\vec{g} + \vec{a}_\mathrm{c}) - \vec{n}_\mathrm{z} \cdot (\vec{g} + \vec{a}_\mathrm{c}) \cdot \vec{n}_\mathrm{z} \tag{11}$$

Lastly, the measurement angle γ of the gravity projection $\overrightarrow{g'}$ is calculated and compared with the shaft rotational angle ϕ. The difference between these two angles indicates the measurement deviation under the simulated condition:

$$dev = \phi - \gamma = \phi - \cos^{-1}\left(\frac{\overrightarrow{g'} \cdot \vec{n}_\mathrm{x}}{|\overrightarrow{g'}| \cdot |\vec{n}_\mathrm{x}|}\right). \tag{12}$$

The simulation results of the deviation at 20 min^{-1} are presented in Figure 6. Firstly, the misalignment parameters β or Δ alone can result in sinusoidal deviations in the measurement, but with different frequencies. Secondly, the shaft tilt angle α has no independent influence on the measurement. That means it does not influence the measurement when the measurement axis is perfectly aligned ($\beta = 0°$). On the contrary, a deformed sinusoidal deviation distribution can be induced by the shaft tilt angle α when $\beta \neq 0°$. Considering all above, it is shown that for every shaft revolution, all types of deviations of an inclinometer are periodic. Therefore, by measuring the start angle ϕ_1 and the end angle ϕ_2 at the same angular position, the deviations in both measurements are identical. Therefore, the angle difference $\Delta\phi$ for the rotational speed measurement will not be coupled with the investigated deviation. With this method, the periodic deviations are compensated, and the measurement results can hence be considered as valid as measured in the ideal conditions as in Figure 3. In addition, the above-mentioned deviations are measured experimentally as well to validate the simulation [3]. The experimental setup will be elaborated in section 4 in detail.

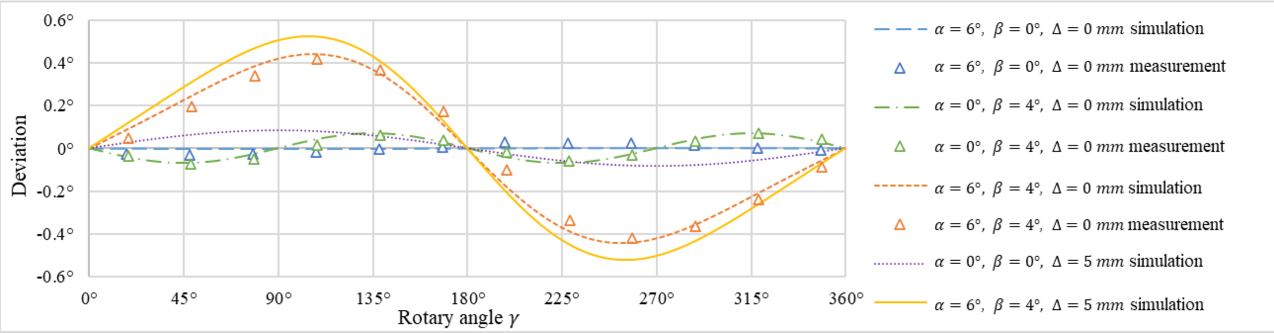

Figure 6: Rotary angle deviations resulting from the shaft tilt angle α, the misalignment angle β and the centering offset Δ at 20 min^{-1} [3].

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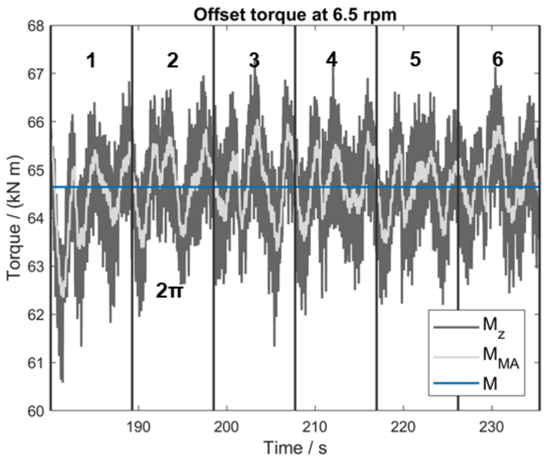
3 Averaging period and synchronisation

Since the torque and rotational speed of a rotating shaft are not constant in NTBs, the mechanical power is measured as an averaged value. For an accurate mechanical power determination, both rotational speed and torque should be measured synchronously within the same averaging period.

In Figure 7, the measured torque signal in an NTB is presented as an example, in which periodically recurrent ripples are coupled in the torque signal. The oscillation is similar in every revolution. Thus, to improve the accuracy, torque should always be averaged over an integer number of revolutions (min. two revolutions), and the averaging period T_{m} should vary with the rotational speed [20].



- M_z (dark grey) is the raw torque signal measured by the TTS installed in the NTB.
- M_{MA} (light grey) is the moving average of the raw signal with a window size of 50 data points.
- M (blue) is the mean torque value averaged over 6 full revolutions.
- M_{rev} are the mean torque values for each revolution

$M_{\mathrm{rev}=1} = 64.314\ kN\ m$ $M_{\mathrm{rev}=4} = 64.702\ kN\ m$

$M_{\mathrm{rev}=2} = 64.723\ kN\ m$ $M_{\mathrm{rev}=5} = 64.583\ kN\ m$

$M_{\mathrm{rev}=3} = 64.744\ kN\ m$ $M_{\mathrm{rev}=6} = 64.793\ kN\ m$

Figure 7: Measured torque signal in an NTB at 6.5 rpm [20].

The same measurement time period T_{m} for the torque measurement can be applied to the covered angle $\Delta\phi$ for the rotational speed measurement in (3) to realise a synchronised rotational speed measurement.

3.1 Determination error using an averaging period

The standard method of mechanical power determination of a rotating shaft is expressed as:

$$P_{\mathrm{m1}} = \frac{1}{T_{\mathrm{m}}} \cdot \int_0^{T_{\mathrm{m}}} M(t) \cdot n(t) \mathrm{d}t, \qquad \textbf{(13)}$$

where the transient value of torque $M(t)$ and rotational speed $n(t)$ are multiplied and then averaged over the desired time period T_{m} [2]. The determined mechanical power is named as P_{m1}. As the rotational speed and the torque can be measured more accurately by measuring separately over multiple revolutions, the method used in this project is expressed as:

$$P_{\mathrm{m2}} = \frac{1}{T_{\mathrm{m}}} \cdot \int_0^{T_{\mathrm{m}}} M(t) \mathrm{d}t \cdot \int_0^{T_{\mathrm{m}}} n(t) \mathrm{d}t. \qquad \textbf{(14)}$$

Compared to the standard method in (13), this re-expression in (14) is mathematically valid for constant torque and rotational speed. In practice, torque and speed are not constant. So, the applicability of (14) is analysed by estimating its determination error $e_{\mathrm{P_m}\%}$ comparing to (13) in practice:

$$e_{\mathrm{P_m}\%} = \frac{P_{\mathrm{m2}} - P_{\mathrm{m1}}}{P_{\mathrm{m1}}}. \qquad \textbf{(15)}$$

This analysis was carried out in the work of [2]. The results of the work show that the corresponding determination error $e_{\mathrm{P_m}\%}$ is generally small and negligible for mechanical power determination. However, the error is tightly related to the ratio of the torque ripples and thus should be carefully considered in case of high torque ripples. Therefore, in this project, the curves of torque and rotational speed will be recorded in order to be able to analyse the determination error $e_{\mathrm{P_m}\%}$.

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3.2 Synchronisation

The synchronisation of the torque and the rotational speed measurement is realised by the data acquisition (DAQ) systems. The DAQ module QuantumX MX840b is used to communicate with the inclinometer with CAN bus and receives the external IRIG-B synchronisation signal. Another two QuantumX modules MX238b and MX430b are connected to the torque measurement bridges of the TTS, and work as slaves to the master module MX840b. The synchronisation between the DAQ modules is established via IEEE1394b FireWire.

The subject of the synchronisation is to garantie that the rotational speed and the torque mean value are measured at the same time. According to the work in Deliverable 1 [20], the synchronisation accuracy using FireWire is smaller than 1 µs. Thus, the major factors influencing the timewise alignment of the averaging periods of torque and rotational speed are their update frequencies as well as the internal delay of the inclinometer. The update frequency is 150 Hz for the TTS and 50 Hz for the inclinometer. In the worst-case scenario, the true timewise misalignment of two signals measured at the same time stamp can be around 10 ms. As the delay within the inclinometer is not accessible, it is not further considered in the evaluation. Finally, the accuracy of the synchronisation is rated by the ratio k between time wise misalignment a_s and the length of the averaging interval.

$$k = \frac{a_s}{T_\mathrm{m}} = \frac{10\mathrm{ms} + 1\mathrm{\mu s}}{T_\mathrm{m}} \tag{16}$$

If the signals are averaged over 6 revolutions under 10 min^{-1}, the ratio k is around 0.03 %. It is safe to conclude that the designed synchronisation mechanisms are able to offer a high data alignment accuracy in a timewise manner for mechanical power determination.

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4 Calibration procedure for transfer tachometers

In this section, the selected inclinometer is calibrated in order to be used as a rotational speed transfer standard. To ensure that the calibration results are valid for the measurement in NTBs as well, the inclinometer is mounted on the TTS centering part via an aluminum adapter plate. The three parts are then used as a unified body for both calibration and practical measurement, as shown in Figure 8.

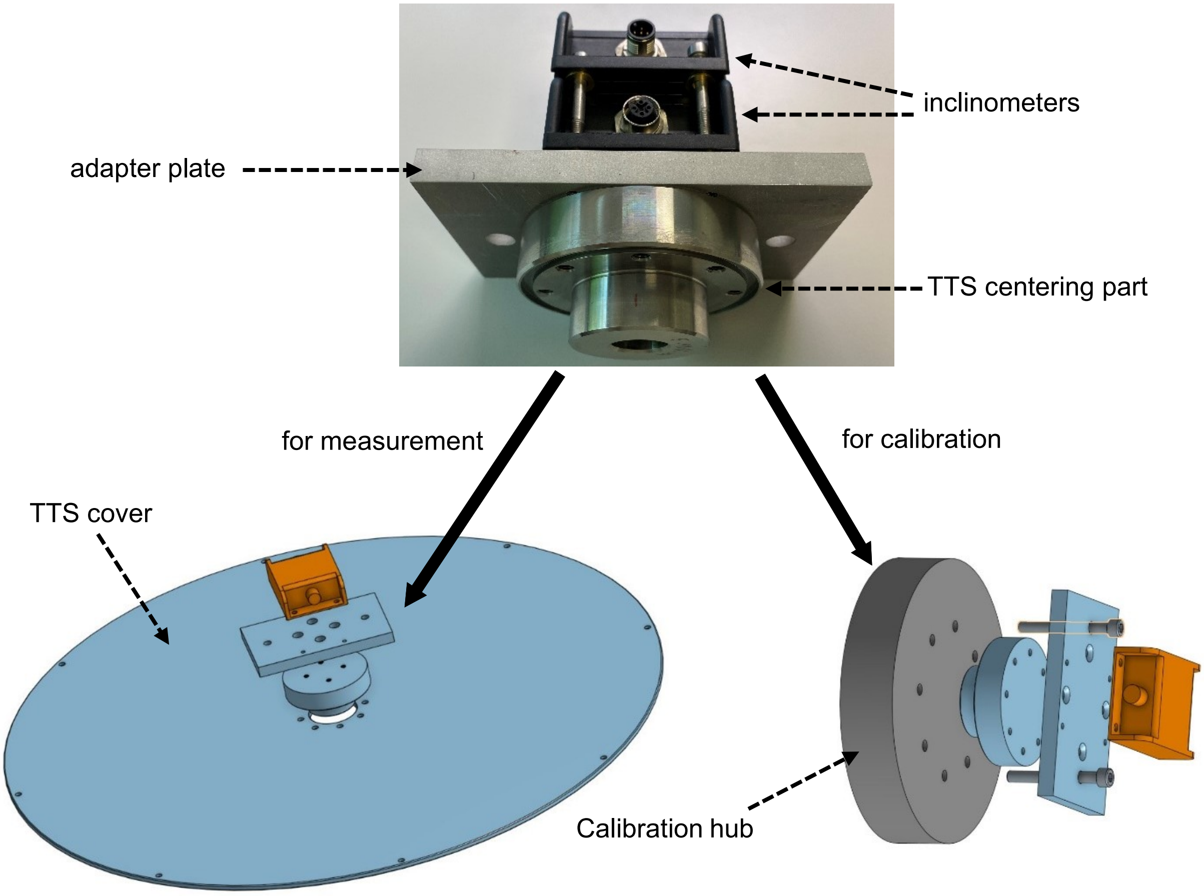

Figure 8: Implementation of the inclinometer for measurement and calibration using the same adaption.

In addition, a second inclinometer (GEMAC IS2BP090-C-CL) is placed on top of the measurement inclinometer. The second inclinometer can measure the angular position of the other two coordinate axes. This will help to identify the shaft tilt angle α in NTBs and the misalignment angle β due to installation.

4.1 Static calibration set-up

Static calibration of the inclinometer was carried out in the length and angle laboratory at PTB. An optical dividing head, as shown in Figure 9, is used as the calibration reference. The hub of the calibration machine can be freely rotated around the x and y axes, and the absolute angular position can be read through the optical scope with a resolution of 1”. The deviation of the reference machine was forehead calibrated and used for the correction of the reading.

Firstly, the rotational axis y of the hub is placed horizontally for standard calibration. By rotating the hub around the y axis from 0° to 360° in steps of 30°, the measurement signal of the inclinometer is read by the DAQ module MX840b using a 0.22 Hz Bessel filter and a 50 Hz sampling rate. For a better result, the calibration is repeated 5 times at different mounting positions, and the measured inclination angles are compared with the reference angles in Table 6.

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Table 6: Comparison of measured incination angles with reference angles.

Set angle of the reference in °	Inclinometer reading in °	Measurement deviation in °
0	347.970	0.074
30	317.935	0.056
60	287.920	0.024
90	257.860	-0.036
120	227.863	0.077
150	197.808	-0.089
180	167.798	-0.099
210	137.825	-0.071
240	107.868	-0.029
270	77.913	0.016
300	47.955	0.059
330	17.975	0.079

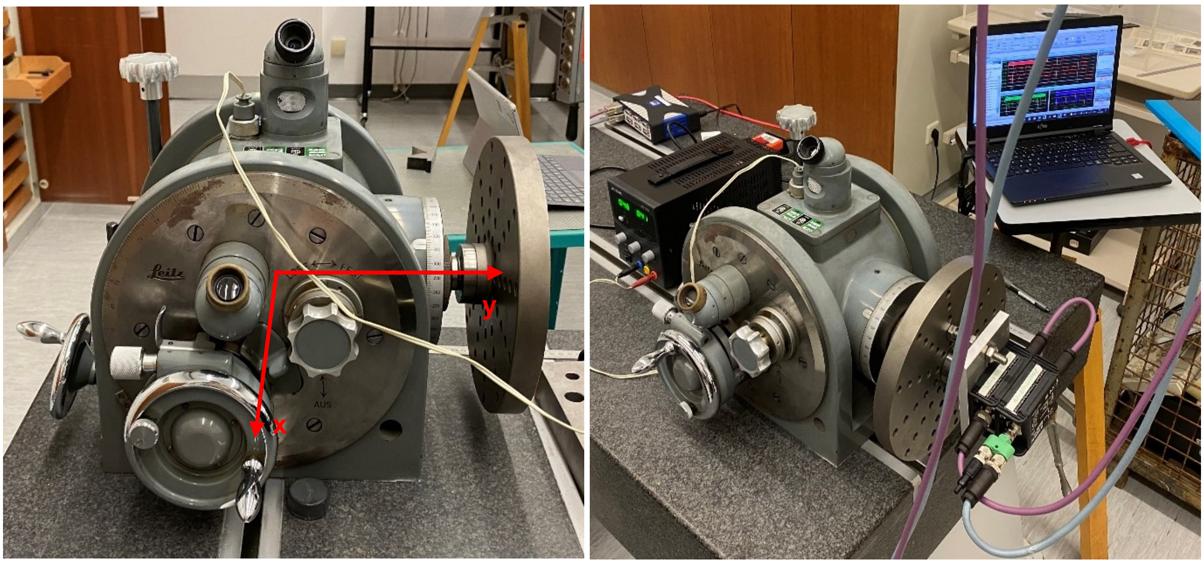

Figure 9: The calibration machine used as reference (left) and the mounting of the inclinometer on the hub via adaption (right).

Overall, the static calibration of the inclinometer shows an expended MU ($k = 2$) of 0.014° and a repeatability of 0.005°.

Secondly, the hub (axis y) was rotated around the x axis by 6° to simulate the tilt angle α in NTBs described in section 2.4.2. Similarly, the installation misalignment angle β can be set by the two screws connecting the adaption plate on the calibration hub. The measurement inclinometer is tested under these parameters to verify the simulation results in Figure 6. The presented simulation and experiment data show a good match in Figure 6.

4.2 Set-up of rotational speed transfer standard

The calibrated inclinometer fixed on the centering part is installed inside the TTS cover in order to be centered in the rotating center. The measurement CAN bus cables are connected to the DAQ systems

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through the outlet, as presented in Figure 10. Furthermore, a temperature and humidity sensor is fixed beside to record the temperature changes along the measurement campaign.

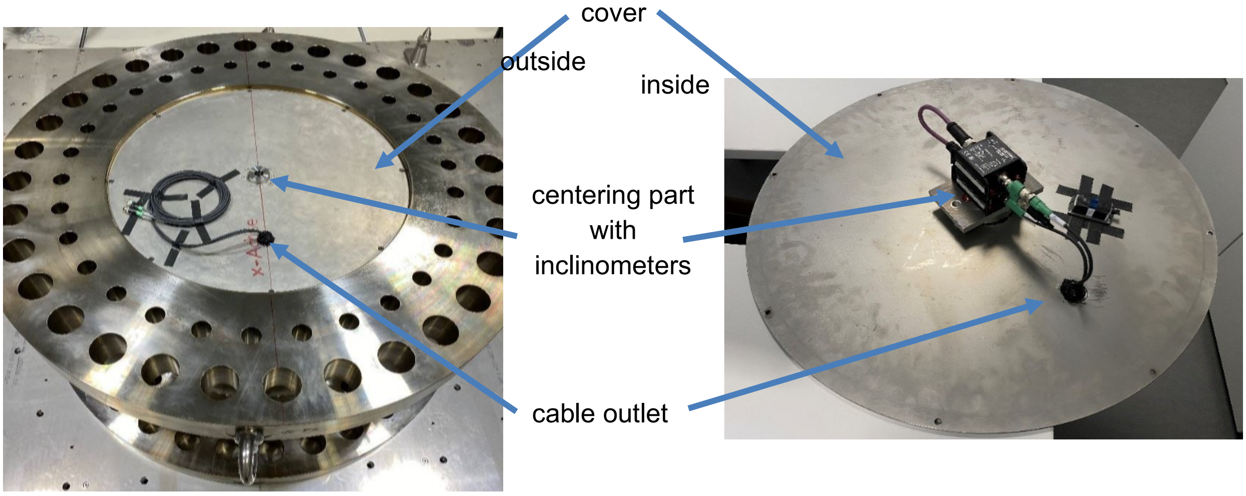

Figure 10: Installation of the inclinometer in the TTS.

4.3 Measurement uncertainty of the rotational speed transfer standard

The constructed rotational speed transfer standard together with the TTS builds up PTB's mechanical power transfer standard and will be implemented in NTBs for mechanical power calibration and efficiency determination. Compared to the static calibration, rotational speed measurement in NTBs can be influenced by additional dynamic effects: The inclinometer cannot be centered perfectly in the shaft cross-section, the centrifugal acceleration pointing away from the rotary axis towards the circumference in the radial direction will affect the measurement; the rotational speed of NTBs is not perfectly constant and coupled with alternating components; the vibrations in NTBs, etc. By evaluating the measurement results, the traceability chain of rotational speed measurement will be investigated.

Besides the dynamic effects, the measurement results are also impacted by the mounting and environmental conditions as well as the process of data evaluation. By considering the above-mentioned additional effects and their estimated MU contributions, the traceability chain can be established. According to the project requirement, the goal is to measure the rotational speed with less than 0.01 % MU.

4.4 Implementation and test of the rotational speed transfer standard

Within the frame of the project, PTB's mechanical power transfer standard will be implemented in the NTB of Fraunhofer IWES for mechanical power calibration and efficiency determination. The topology of the measurement system is demonstrated in Figure 11. For the measurement, three QuantumX modules are used to measure the different strain gauge signals of the TTS and communicate with the inclinometer via CAN bus. Meanwhile, the external IRIG-B synchronisation signal is received by the master module MX840b and the other two modules work as slaves to the master clock. The synchronisation between the DAQ modules is established via IEEE1394b FireWire. As the DAQ modules should be placed inside the rotating shaft to be connected with the sensors, the required DC power supply and the IRIG-B signal are connected through slip rings. The DAQ modules are connected to an Ethernet switch in the rotating shaft and the signal transmission to the measurement PC is through the slip ring as well.

Since torque and rotational speed are recorded for a mechanical power determination in a post processing, no live results can be seen in real time during the measurement. To have a better overview during the measurement, the output function of channel 1 of MX430b is used to convert the measured

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torque into a voltage output signal. The voltage signal is transmitted to the power analyser for a live monitoring but not for data evaluation.

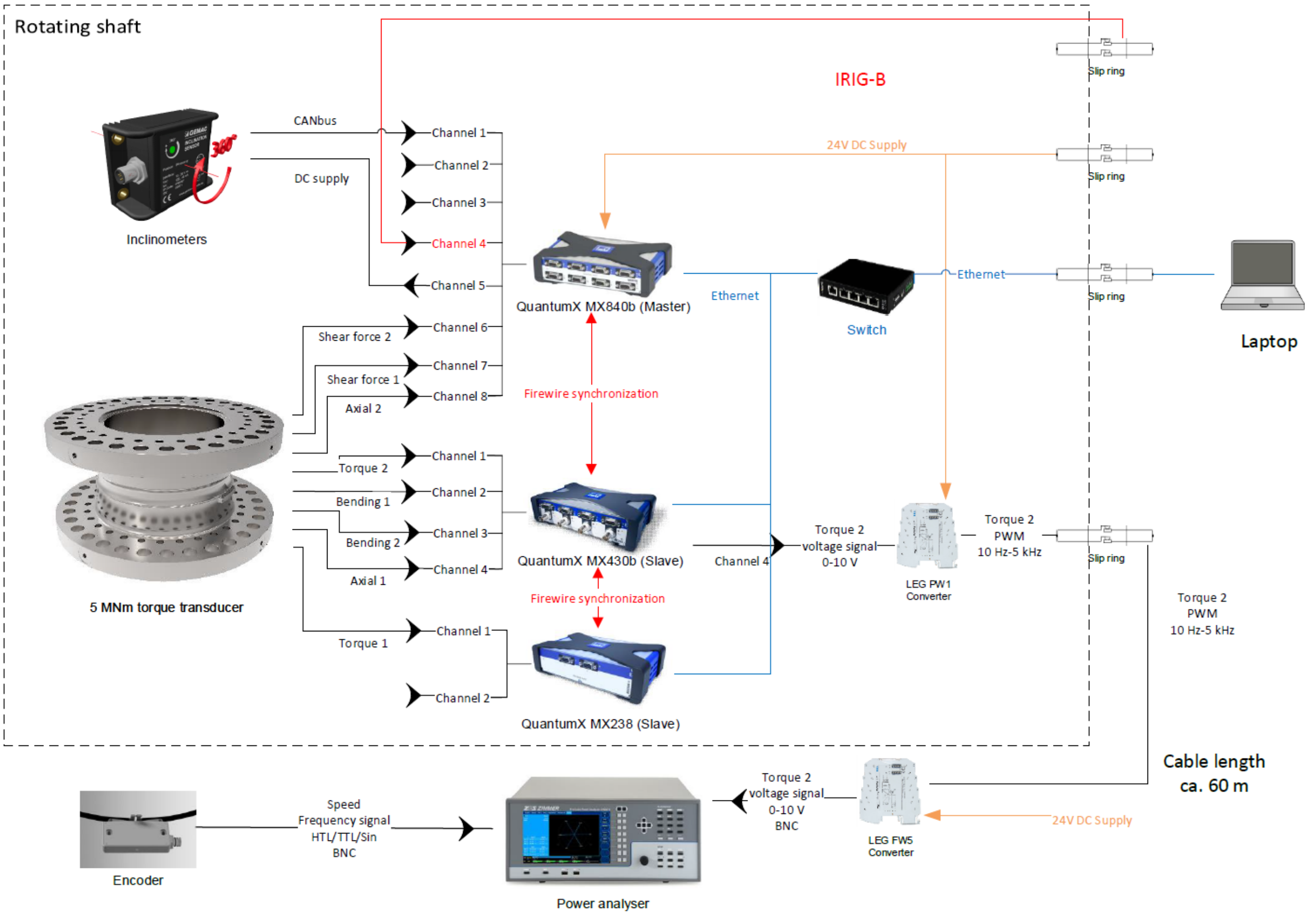

Figure 11: Topology of the transfer standard measurement system at Fraunhofer IWES.

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5 Conclusion and future work

After reviewing the up-to-date tachometer technologies and listing the requirements of tachometers used in NTBs, a MEMS inclinometer is selected as a proper sensor type for the project because of its capabilities of stator-less angular measurement. Based on the selected inclinometer, a rotational speed transfer standard is built and integrated into the existing TTS, which is an important part of the mechanical power and efficiency determination. The angular calibration and the deviation analysis of the inclinometer help to develop the calibration procedure of the rotational speed transfer standard. The inclinometer is to be combined with the 5 MN m torque transfer standard and implemented on the LSS of NTBs. Therefore, the range of rotational speed measurement does not go beyond 25 min^{-1}.

Within the frame of the project, PTB's mechanical power transfer standard will be implemented in the NTB of Fraunhofer IWES for mechanical power calibration and efficiency determination. During the smeasurement, the inclinometer will measure under rotation for the first time. Besides the static angular MU, the uncertainty contributions of time measurement and dynamic effects are to be determined based on the measurement data.

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VII Acronyms

CWD	Center for Wind Power Drives
DAQ	data acquisition
DyNaLab	dynamic nacelle testing laboratory
EMPIR	European Metrology Programme for Innovation and Research
EU	European Union
FhG IWES	Fraunhofer Gesellschaft - Institut für Windenergiesysteme
IRIG-B	inter range instrumentation group timecode B
LSS	low-speed shaft
MEMS	micro-electromechanical system
MU	measurement uncertainty
NTB	nacelle system test bench
PTB	Physikalisch-Technische Bundesanstalt
RWTH	Rheinisch-Westfälische Technische Hochschule Aachen
VTT	Technical Research Centre of Finland Ltd.
WindEFCY	Wind efficiency
WP2	Work Package 2

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