Development of a torque calibration procedure under rotation for nacelle test benches

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Abstract. Precise torque measurement in multi-MW nacelle test benches (NTBs) is crucial for the efficiency determination of wind turbines. However, because the torque transducers of NTBs are not yet traceable to national standards, their accuracy is not yet known. To rectify this, a calibration procedure was developed for torque under rotation using a torque transfer standard. The results of measurements performed on an NTB are presented for a validation and adjustment of the method planned. Different influences on the calibration measurements are discussed, such as static and rotational zero point determination, rotational speed $n$, and ambient conditions.

1. Introduction

Within its policy framework, whose targets for climate and energy are to be achieved by 2030, the European Union (EU) has set itself the objective – amongst other environmental targets – of increasing renewables to at least 27% of the overall energy consumed in the EU [1]. To date, wind energy has made the greatest contribution to the amount of renewable energy produced. As the power ratings of modern wind turbines can reach the multi-MW range, wind energy is the form of technology that has the greatest potential for augmenting the renewable energy output. The percentage of wind energy among all forms of renewable energy is highly affected by the efficiency $\eta$ of wind turbines: the increase in energy production is proportional to the increase in efficiency. Hence, the enhancement of nacelle efficiency is a primary goal in nacelle development [2]. As is true of all mechanical systems, the efficiency $\eta$ of an entire nacelle is defined as the ratio of electrical output power to the mechanical input power:

$$\eta = \frac{P_{el}}{M \cdot n \cdot 2\pi}. \quad (1)$$

For this direct efficiency measurement method, the mechanical input can be determined by rotational speed $n$ and torque $M$, while the electrical power $P_{el}$ can be calculated by the product of current $I$ and voltage $U$. To measure these quantities, and to test the overall system even during the development process of nacelles, nacelle test benches (NTBs) have been put into operation over the past several years. In NTBs (example in Figure 1), the torque $M$ can often be measured by an internal torque transducer. A precise torque measurement is crucial for the efficiency determination; however, because these torque transducers are not yet traceable
to national standards, their accuracy is not yet known. Moreover, most torque transducers in
NTBs do not measure torque directly at the nacelle’s rotor hub, as would be required for a
reliable efficiency determination, but between the load application system (LAS) and the engine
[3]. As a consequence, significant losses evoked, for example, by intermediary components are
not considered. To rectify this, a 5 MN m torque transducer was acquired by the Physikalisch-
Technische Bundesanstalt (PTB) and characterised [4] to allow it to be used as a torque transfer
standard (TTS) that could calibrate NTBs directly at the nacelle’s rotor hub.

Within the project "Torque measurement in the MN m range", which is funded by the European
Metrology Programme for Innovation and Research (EMPIR), a torque calibration method under
rotation was developed and tested. The first recommendations for this special calibration
procedure for torque measurements under rotation in NTBs were given in [3]. This paper focusses
on the development of such a torque calibration procedure under rotation based on a static torque
calibration in torque standard machines, which will be explained in the following sections. It
also describes the measurements performed, which are evaluated and investigated in order to
validate and adjust the theoretically developed calibration procedure. For comparison purposes,
the setup for a static torque calibration is outlined first.

2. Static torque calibration

Standard calibration procedures are used to trace transducers to national standard units, thereby
evaluating their performance and deviation from the national standard in a static manner. Static
is defined as a rigid state without any rotation and with a pure torque load. A well-known,
international torque calibration procedure is described in EURAMET cg-14 [5]. For the execution
of such a calibration, special boundary conditions are required:

- The ambient conditions during calibration should be stable to ±1 K in the range of 18 °C to
  28 °C, but preferably between 20 °C and 22 °C, and are to be recorded.
- Before using the transducer, temperature stabilisation is required; this can be achieved by
  storing the transducer with an applied supply voltage under calibration conditions.
- The zero signal is to be taken in a vertical position prior to the installation of the transducer.

Figure 1. 5 MN m torque transfer standard of the Physikalisch-Technische Bundesanstalt
installed at the rotor hub of a nacelle on the nacelle test bench at the Center for Wind Power
Drives, RWTH Aachen.
in the calibration machine.
- An overload test by exceeding the nominal torque by 8% to 12% is to be performed for 1.5 min to rule out the possibility of an unexpected failure of the transducer or the couplings. This should be done prior to the calibration measurements.

The calibration procedure itself consists of torque applied clockwise and anti-clockwise in a static manner without any lateral or longitudinal forces or bending moments. According to the calibration procedure, the transducer is to be loaded with at least five discrete and approximately equally spaced torque steps within 20% to 100% of the calibration range. Here, the time interval between the successive calibration steps should be similar. To analyse the hysteresis of a transducer, increasing (inc) and decreasing (dec) load cycles (Figure 2) are implemented. Before measuring the load cycles, the transducer is to be pre-loaded with the maximum calibration torque. The influence of misalignments and gravity is minimised by measuring the transducer in different mounting positions separated by 120°. An additional incremental load series in one mounting position is required for the determination of the repeatability, while the measurements in different mounting positions give an indication of the reproducibility of the transducer. Furthermore, it is important that the signal be recorded only after the stabilisation of the indication.

For any further processing, and in order to evaluate the readings, the values recorded are to be tared using the zero value obtained before the respective load sequence. The result of a calibration can either be a classification of the transducer to be calibrated or a relative expanded measurement uncertainty. Based on the calibration readings, a transfer function is calculated that converts the transducer signals in mV/V into torque in the corresponding unit. This regression curve of either first or third degree can then be used to translate any signal of the transducer into the concurrent applied torque.

3. Realisation of the measurements

In order to allow the torque calibration procedure developed to be tested under rotation, a specific setup was needed consisting of an established NTB, a suitable TTS equipped with a fitting data acquisition system (DAQ) and a telemetry system, and a timewise synchronisation of the two DAQs deployed.

3.1. Nacelle test bench to be calibrated

The 4MW NTB chosen (Figure 1), which is located at the Center for Wind Power Drives (CWD) of RWTH Aachen, used a direct mover to drive the nacelle, which is the device under
test [8]. Here, the applied torque $M$ is measured directly by a torque transducer with a nominal range of $M_{nom} = 2.7 \text{ MN m}$. As with most transducers, this torque transducer does not tolerate additional mechanical loads; for this reason, it is mounted between the two parts of a curved-tooth coupling, which compensates mechanical loads caused by the LAS and squint angle in the alignment of the drive train in order to allow pure torque to be transmitted.

The nacelle is a research nacelle owned by Forschungsgemeinschaft Antriebstechnik e.V. (FVA) and equipped with a high-speed generator and a main gearbox. It has a rated power of 2.75 MW, a maximum torque of approx. $M_{\text{max}} \approx 1.6 \text{ MN m}$, and a nominal rotational speed of $n_{\text{max}} = 17.5 \text{ rpm}$ (consistent $n_{\text{min}} = 6.5 \text{ rpm}$) on the low speed shaft (LSS) [6]. These boundary conditions (Table 1) limit the torque range as a function of the rotational speed to be calibrated.

During the calibration procedure, $n_{\text{LSS}}$ was controlled by the prime mover control system, while $M$ was operated by the control system of the generator converter system. Moreover, a DAQ with a sampling frequency of $f_{\text{sample}} = 1200 \text{ Hz}$ and a $f_{\text{filter}} = 180 \text{ Hz}$ Bessel Filter was employed to record $n$, which was measured by an incremental encoder, and the torque $M$, which was measured by the torque transducer. The DAQ was realised permanently without any triggers in order to allow the torque and rotational speed acceleration ramps between the different load steps to be monitored.

| Symbol   | Designation                             | Value   | Unit     |
|----------|-----------------------------------------|---------|----------|
| $M_{\text{min}}$ | Min. applicable torque under rotation | 0       | MN m     |
| $M_{\text{max}}$ | Max. applicable torque under rotation | $\approx 1.6$ | MN m     |
| $n_{\text{min}}(M)$ | Min. rotational speed under torque load on LSS | 6.5 | rpm      |
| $n_{\text{max}}(M)$ | Max. rotational speed under torque load on LSS | 17.5 | rpm      |
| $n_{\text{min}}(M = 0)$ | Min. rotational speed without torque on LSS | 0       | rpm      |
| $n_{\text{max}}(M = 0)$ | Max. rotational speed without torque on LSS | 25.0 | rpm      |

3.2. 5 MNm torque transfer standard

Calibrating the torque measurement in an NTB means comparing the internally measured torque to a TTS that measures torque directly at the place where this mechanical input is to be determined; for the efficiency determination of nacelles, this is directly at the nacelle’s rotor hub. To this end, a 5 MN m TTS, which is traced to the national torque standard up to 1.1 MN m statically and without rotation [4], was installed in this place (Figure 1). The 5 MN m TTS is a multi-component transducer whose main objective is to measure torque via a hollow-shaft spring body that experiences linear-elastic deformation evoked by the applied torque. This deformation is converted into an electrical signal by strain gauges. The coherence between the exactly applied torque $M_i$ in kN m and the electrical output signal $S_i$ in mV/V was defined in the calibration, and amounts to:

$$M_i = 3851.5 \frac{\text{kN m}}{\text{mV/V}} \cdot S_i.$$  (2)

This linear regression curve was determined for a clockwise torque load applied in increasing and decreasing steps, which is a perfect fit for the intended use of the calibration procedure in the NTB. Because of the very good linearity of the TTS, a linear regression curve is sufficient. A calibration beyond 1.1 MN m is not yet feasible [4]; however, because of the good linearity of the
TTS, the regression curve can be extrapolated linearly. A redundant measurement is performed by two torque measuring bridges in the TTS.

For a rotating application of the TTS, self-sufficient DAQ with a wireless data transmission was developed. The DAQ consists of a very precise amplifier (Quantum MX238B) that has a 225 Hz carrier frequency for the torque bridges and two additional amplifiers (Quantum MX430B) that have a 600 Hz carrier frequency for the additional bridges and a battery that functions as an independent power supply while under rotation. It is very important that the data gathered be accessible within a narrow time frame while the measurements are being performed. This was ensured by means of two wireless access points and a computer communicating via WLAN. To avoid imbalances and force/torque shunt, the components of the DAQ are symmetrically distributed around the TTS’s flange (Figure 3). To gain a resolution of 1° for a maximum rotational speed of 25 rpm, the sampling frequency must be $f_{\text{sample}} = 150$ Hz. In addition, a Bessel filter with a frequency of $f_{\text{filter}} = 50$ Hz was used for the TTS.

3.3. Timewise synchronisation
The two separate DAQs were synchronised in a timewise manner by means of an ideal, digitally generated square-wave signal with an amplitude of ±5 V and a frequency of $f = 0.2$ Hz, which was recorded by both DAQs. Based on this square-wave signal, the temporal shift between the two data sets was corrected. The rough adjustment of the two data sets is based on distinctive signal changes as shown in Figure 4 on the left side, while the fine synchronisation relies on the square-wave signal and on the temporal shift between the two curves gathered by the different DAQs. The advantage of this synchronising method for two data sets is its easy applicability to different NTBs with all kinds of DAQs.

4. Analysis of the torque calibration procedure under rotation
Common torque standards such as EURAMET cg-14 [5] provide methods only for static torque calibration as described in Section 2. However, both nacelles and NTBs operate under rotation. Therefore, neither the available standards nor the current standards are applicable for the certification of NTBs.

As the calibration of a direct torque measurement using a TTS is similar to that of a torque reference machine - wherein a calibrated TTS and a transducer to be calibrated are compared to each other - the general effects as found in [7] were considered. These general effects are: instable ambient conditions such as temperature/temperature gradients and humidity; the measurement uncertainty of the TTS including its calibration curve; the characteristics of the electrical components such as amplifiers; and the electromagnetic compatibility (EMC) of the TTS and its DAQ. Besides misalignments of the experimental setup, which are considered in the measurement uncertainty as being part of the calibration setup, torque inversion can appear.
Figure 4. Timewise synchronisation of the two data sets using a square-wave signal recorded by both data acquisition systems in order to achieve a precise alignment.

Torque inversion is induced by emergency brakes and should be avoided during the calibration procedure. [3]

However, the most significant distinction between the well-known static torque calibration defined in [5] and torque calibration in an NTB is the rotation, whose influence is investigated by combining the two input variables $M$ and $n$. Furthermore, to date, even for the torque calibration under rotation, neither dynamic effects nor additional/parasitic loadings evoked by the LAS have been observed. While the influence of additional/parasitic loadings should be estimated (since non-stationary loadings are normal operation conditions for wind turbines) and tested in hardware-in-the-loop (HIL) simulations, dynamic torque calibration is very difficult and should therefore be avoided. The following focusses on the NTB-specific influences on the measurement result. [3]

4.1. Ambient conditions

To minimise the effects caused by ambient conditions, calibration was carried out at a temperature range between 23°C and 29.5°C. Prior to all calibration measurements, both transducers were stored with the supply power applied in the calibration environment in order to acclimatise it, as defined in common calibration guides [5]. Moreover, the temperature and humidity that affect strain gauges of the TTS were recorded as close to the strain gauges as possible, with a sufficient sampling frequency of $f_{\text{sample}} = 0.05$ Hz. In this specific case, the influence of the ambient conditions is negligibly small. For calibrating the torque measurement of an NTB in a wider temperature range, the temperature is to be varied within this range during the calibration measurements.

4.2. Emergency brakes

An abrupt stop of the drive train can induce torque inversion. This reversal of applied torque again leads to a small torque alteration caused by the hysteresis of the transducer. To avoid this influence in case of a sudden emergency brake, the maximum possible torque in the driving direction should be applied afterwards and is to be held for about 5 min. Before the next
measurement, a new zero point is to be taken for the signal taring, thus minimising the hysteresis effect. It is also advisable to pursue quality management to ensure that the transducers employed are handled adequately after an emergency brake, thereby reducing the factors that have an unintended influence on the measurement.

4.3. Zero point determination
A crucial parameter for any calibration is the zero point determination, which is of great importance for the taring of all measurement signals. Since both transducers rotate during operation, taking a static zero signal in only one position is not sufficient: either a static zero point determination averaged over several horizontal positions or a rotational zero point determination should be taken into account. Here, both versions have been tested.

For the static zero point determination, the zero-torque signal was measured over incrementally rotating positions relative to the measuring axis. During post-processing, the torque signal was averaged over \( t_{\text{meas.}} = 30 \, \text{s} \) with a prior dwell time of \( t_{\text{dwell}} = 20 \, \text{s} \) for each position. Subsequently, the averaged torque signals per position were averaged again to get an overall zero point. In order to consider the influence of the transducers’ dead weight, distinct relative positions (e.g. \( 12\cdot30^\circ \), \( 6\cdot60^\circ \), and \( 4\cdot90^\circ \)) were tested and the same order of magnitude found for the torque signal of both transducers; this is a good indication that the same additional influences, such as system oscillations and noise, exist on both transducers.

For the rotational zero point determination under permanent rotation, the NTB was operated with a low rotational speed of \( n_{\text{min}} = 6.5 \, \text{rpm} \), and the torque signal was averaged over 6 full rotations using \( n \) and the measuring time to calculate full rotations. Prior to the averaging, the dwell time was observed. The procedure can also be incorporated into the general test routine of a new nacelle implementation to get a reliable zero point.

The most suitable solution found was to proceed similarly to the zero point determination defined in EURAMET cg-14 and to determine a rotational zero point with \( n_{\text{min}} = 6.5 \, \text{rpm} \).

![Rotational zero point determination](image1)

**Figure 5.** Example of a stepwise increase and decrease of the torque load at 6.5rpm with the rotational zero point determination before and after each load cycle with generator and, therefore, frequency converter switched off and on.
before and after every load cycle when \( M = 0 \) kN m. Due to the fact that the nacelle torque control system starts when the nacelle frequency converter (FC) is switched on (with FC), thereby changing the torque signal (Figure 5), the generator was switched on for the zero point determination. This zero signal was used to tare the rest of the torque signals in post processing. A similar procedure is recommended for other test benches as well. During and after calibration, it is of great importance that the taring of the NTB transducer not be manipulated (in case such a possibility exists). An additional static torque calibration once a week makes it easier to assess the stress state of the transducers and the drive train, and could reveal additional, unanticipated influences on the system.

4.4. Characteristic maps

To investigate the relation between the rotational speed and the applied torque, so-called characteristic maps were developed. These maps are designed in such a way that they can cover the entire operating range of the NTB for rotational speed and torque load from \( n_{\text{min}} \) to \( n_{\text{max}} \) and from \( M_{\text{min}} \) to \( M_{\text{max}} \) depending on the boundary conditions of the nacelle installed; the points of resonance were deliberately not considered. In order to analyse the influence of rotational speed on the applied torque (and vice versa), different combinations of constant torque and increasing and decreasing rotational speed (and vice versa) were performed. The characteristic maps employed are schematically depicted in Figure 6. All four examples cover the same range, but in a different order so that the effects of different control scenarios can be analysed.

![Figure 6](image-url) 

**Figure 6.** Different characteristic maps used to analyse the coherence between both the input parameters of torque \( M \) and the rotational speed \( n \).

After the two data sets have been synchronised, the sequences to be analysed for each measurement are defined. Within these sequences, which follow a dwell time of \( t_{\text{dwell}} = 20 \) s after reaching a stable torque signal, the torque signal is averaged over 6 full rotations. This procedure is based on empirical values given in [10]. As an example, the data processed for a characteristic map of type CM1a is presented in Figure 7. The torque signals \( M_{\text{NTB}} \) and \( M_{\text{TTS}} \) acquired for the NTB transducer and the TTS are plotted over time. While these signals refer to the ordinate on the left, the ordinate on the right is for the rotational speed \( n \). Moreover, the mean signal values for all three variables are plotted in the averaging sequences to ensure that the dwell time observed was sufficient for reaching a stationary state for the signal averaging. The visual distance between the torque signals is due to the raw data not being tared.

To assess the performance of the NTB torque transducer, an evaluation process based on DIN 7500-1 [9] was developed. The result is the indication deviation of the NTB transducer from the TTS relative to the value of the TTS that represents the applied torque load. Table 2 depicts these results in the form of a matrix that describes the interrelation between the torque
Averaging results

Figure 7. Measurement data of CM1a characteristic map, including averaged signals and marked analysing sequences.

and the rotational speed, including all appearing influences. The torque signal measured by the NTB transducer can then be corrected by the indication deviation, depending on the torque and rotational speed combination.

Table 2. Relative indication deviation between the torque transducer in the nacelle test bench and the torque transfer standard for different torque loads and rotational speeds.

| Torque (kN m) | 375 kN m | 750 kN m | 1150 kN m | 1500 kN m |
|--------------|----------|----------|-----------|-----------|
| 6.5 rpm      | 4.153 %  | 4.189 %  | 4.158 %   | 4.124 %   |
| 9.8 rpm      | 4.178 %  | 4.194 %  | 4.166 %   | 4.128 %   |
| 14.2 rpm     | 4.267 %  | 4.245 %  | 4.194 %   | 4.156 %   |
| 17.5 rpm     | 4.216 %  | 4.226 %  | 4.181 %   | 4.148 %   |

Under high rotational speed, the behaviour of a torque transducer can differ from the behaviour in a static calibration due to rotation-induced centripetal force. This can lead to alterations both in the zero signal and in the sensitivity of the transducer. In [11], it was found that the relative deviation of the torque signal under rotation of \( n = 100 \text{ rpm} \) is less than \( 6 \cdot 10^{-4} \). Based on this outcome, the influence of the rotational speed at maximum \( n_{\text{max}} = 17.5 \text{ rpm} \) on the TTS is imperceptible. However, in the relative indication deviation of an NTB, coherence between the rotational speed and the torque, especially for small torque ranges, can be identified. It is to be assumed that these effects are not caused by the rotational speed directly, but by the control system of the NTB and by friction arising in the LAS, which is influenced by a changing rotational speed. It is for this reason that, with increasing rotational speed, the relative indication deviation rises (Table 2). Furthermore, the relative indication deviation is smaller for larger torque loads where the signal to resolution ratio improves and the friction decreases.
5. Conclusion and outlook
Using the torque calibration method under rotation presented in this work, including the sampling frequency and filter settings tested and the zero point determination proposed, torque transducers in NTBs can be traced to national standards. Without special tests for development reasons, the calibration procedure can be performed within a reasonable time frame. By correcting the torque signal measured while considering the relative indication deviation of approx. 4%, the accuracy of torque measurement in the NTB can be improved; a measurement uncertainty will be established later in the EMPIR project.

Furthermore, the application of the 5 MN m TTS, including the DAQ and the telemetry system, was successful. A torque calibration above 1.1 MN m without extrapolation is not yet possible, but will be once the 5 MN m torque standard machine at PTB is realised [12]. Since neither nacelles nor NTBs work under pure torque loading conditions, small variations of parasitic loads such as single components and components in various combinations should be considered in order to expand the scope of the procedure proposed.

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