Metrological evaluation of torque measurement up to 5 MN m under rotation in a 10 MW nacelle test bench

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Abstract

The torque input to nacelles is of great importance for the efficiency determination of these nacelles. For a reliable and traceable torque measurement in nacelle test benches, a torque transfer standard is installed in the drive train directly at the rotor hub of the nacelle and certain combinations of torque and rotational speed, so-called characterisation maps, are applied and measured. In doing so, the torque measurement in the 10 MW nacelle test bench DyNaLab at Fraunhofer IWES is characterised metrologically up to 5 MN m in form of a relative indication deviation including the corresponding expanded measurement uncertainty.

1 Introduction

In nacelle test benches (NTBs), the input torque is a crucial parameter – not only for the efficiency determination of the device under test (DUT) but also for Hardware-in-the-Loop (HiL) tests and the validation of simulations [1]. To ensure a reliable and accurate torque measurement, it needs to be traced to national standards in form of a calibration or metrological characterisation. With the growth in capacity of multi-megawatt wind turbines, the torque in wind turbines as well as in NTBs increases too **(Figure 1)**.

To trace the torque measurement in the Dynamic Nacelle Testing Laboratory (DyNaLab) of Fraunhofer IWES in Bremerhaven, Germany, a measurement campaign within the project “Traceable mechanical and electrical power measurement for efficiency determination of wind turbines”, short WindEFCY, was performed using a torque transfer standard (TTS). In this paper, first results of this metrological characterisation of the torque measurement in the DyNaLab NTB are given.

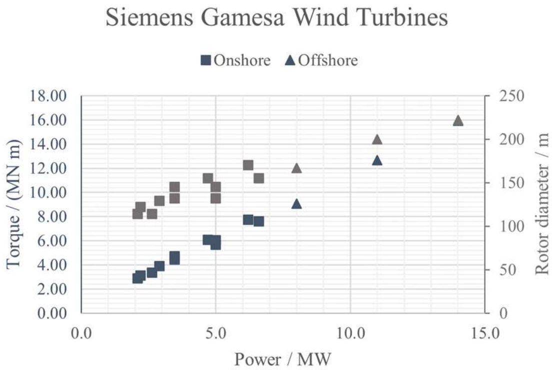

Figure 1 Nominal wind turbine capacity vs. appearing nominal torque (left) calculated for wind turbines of the Siemens Gamesa Renewable Energies (SGRE) portfolio based on information taken from SGRE’s website [2]

2 Measuring set-up

To characterise the torque measurement in an NTB and to trace it to national standards, a TTS **(Figure 2)** is additionally installed as part of the low-speed shaft (LSS) of the NTB. The position of torque measurement directly at the rotor hub of the DUT is particularly important for the efficiency determination whereas the mechanical power is measured as input to the DUT. This set-up of using a transfer standard in order to calibrate another measurement device is comparable to a reference calibration machine. Thus, the same influences as in reference torque standard machines affect the TTS and, therefore, the metrological characterisation of the torque measurement in the NTB.

The TTS used here has a measuring capacity of 5 MN m. It is calibrated merely up to 1.1 MN m due to the lack of suitable torque calibration possibilities [3]. Above that, its behaviour is assumed using the linear calibration curve for clockwise torque:

$$M_{\mathrm{TTS}} = 3850\ \mathrm{kN\ m} \cdot \left(\frac{\mathrm{mV}}{\mathrm{V}}\right)^{-1} \cdot S_{\mathrm{TTS}}, \quad \textbf{(1)}$$

where S_{TTS} is the TTS’s output signal in mV/V and M_{TTS} is the corresponding calibrated torque output in kN m combined for increasing (inc) and decreasing (dec) torque. The measurement uncertainty above 1.1 MN m is predicted by extrapolating the calibration results [4] gathered in different partial ranges. The predicted expanded $(k = 2)$ relative measurement uncertainty for 5 MN m amounts to $10.03 \cdot 10^{-4}$.

In this paper, the metrological characterisation of the torque measurement in the DyNaLab of Fraunhofer IWES is described. The DyNaLab, with a testing capacity of 10 MW, features a nominal torque of 8.6 MN m (overload 13 MN m) [1]. Thus, by using the 5 MN m TTS only a partial range metrological characterisation is feasible. The NTB is driven by two tandem motors coupled by an intermediate shaft. In the NTB, the torque is measured using eight strain gauge (SG) full bridges glued to the hollow-shaft of the adapter connecting the NTB to the DUT **(Figure 4)**. The SGs are homogeneously distributed

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around the hollow shaft that has a constant thickness. Moreover, with additional SGs on this adapter not only the deflection due to torque load can be detected at the rotor hub, but also wind loads (such as dynamic blade forces simulated as rotational radial loads and dynamic wind loads emulated by rotating yawing forces) simulated by the hexapod or non-torque loading (NTL) system can be observed. As the adapter is designed for the maximum possible additional mechanical loads, the expected bridge sensitivity for the torque measurement is comparatively low, which means that parasitic influences have a relatively great effect on the torque measurement signal. For the present measurements, the NTL system was blocked, and its self-weight was compensated, because the TTS would not withstand the simulated wind loads.

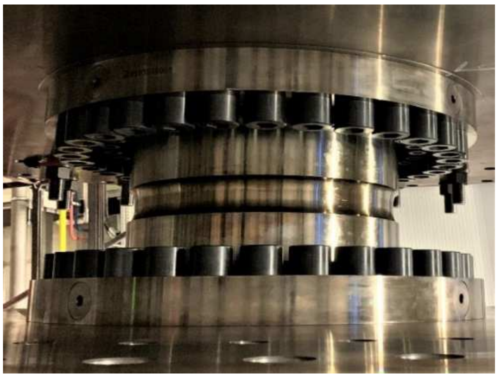

Figure 2 TTS installed in NTB between two adapters

For the data recording of the two different measurement devices (the TTS and the NTB's measurement adapter), two separate data acquisition (DAQ) systems are instrumented which are synchronised via an IRIG-B signal resulting in the same time stamp. Both DAQ systems are installed inside the drive train of the NTB. Data transfer, control communication and power supply for the rotating systems are realised via a slip ring and a WLAN connection. The DAQ systems instrumented for the data recording are synchronised via an IRIG-B signal resulting in the same time stamp. The time stamp source comes from a global positioning antenna.

3 Characterisation procedure

The applied characterisation procedure was specially developed for torque calibration under quasi-static rotation as basically explained in [5] and [6].

3.1 Characterisation load cycles

To characterise the torque measurement in the NTB, different combinations of torque M and rotational speed n_{NTB}, so-called characterisation maps **(Figure 3)**, are applied and measured by the TTS and the NTB's torque measurement adapter. The characterisation maps are analysed per load step M_{C} and n_{NTB}. To this end, the torque signals $\bar{I}_j$ are averaged over six full drive train revolutions ($l = 6$):

$$\bar{I}_j(M_{\mathrm{C}}, n_{\mathrm{NTB}}) = m^{-1} \cdot \sum_{i=1}^{m} I_{\mathrm{meas},i}, \tag{2}$$

with $m = l \cdot (n_{\mathrm{NTB}} \cdot 1\ \mathrm{min} \cdot (60\ \mathrm{s})^{-1})^{-1} \cdot f_{\mathrm{sample}}$,
and $l \in \mathbb{Z}_{>0}$,

where the number of single signals averaged over depends on the rotational speed and the sampling frequency f_{sample}.

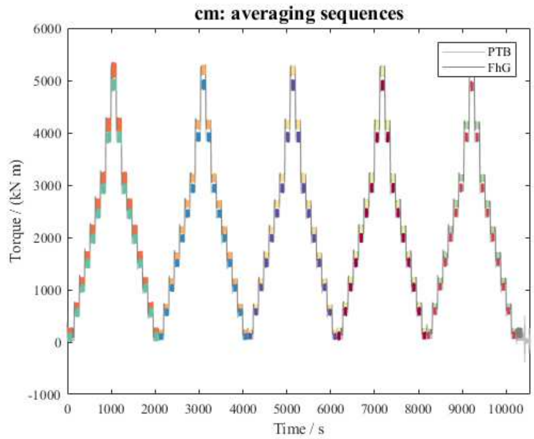

Figure 3 Application of different combinations of torque M at rotational speeds of $n_{\mathrm{NTB}} = 4.5, 5, 6, 7,$ and $8\ \mathrm{min}^{-1}$ to characterise the NTB torque measurement metrologically

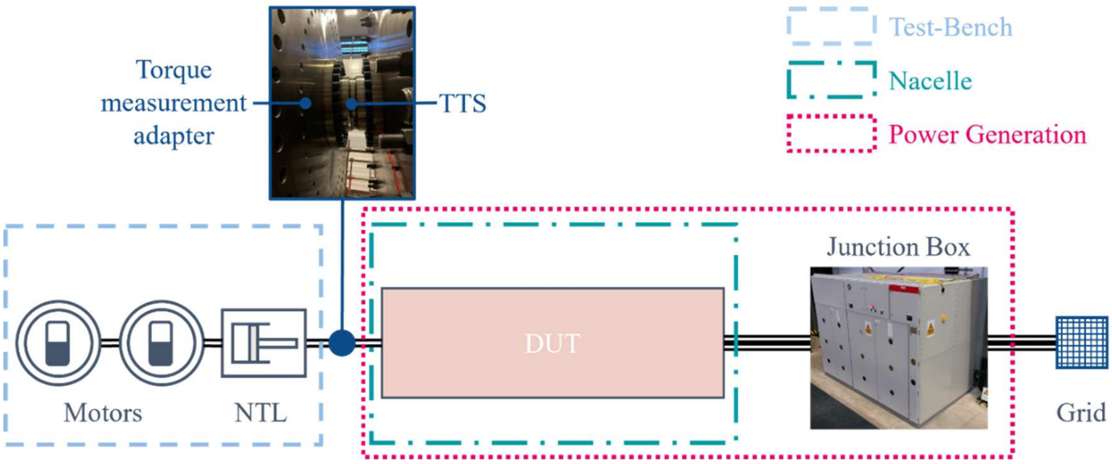

Figure 4 Schematic overview of the set-up to calibrate the torque measurement of the DyNaLab of Fraunhofer IWES up to 5 MN m via a TTS installed on the LSS

The number of revolutions averaged over is a compromise between a good characterisation result and a decent measurement time; both the linearity deviation and the measurement uncertainty are getting better with increasing number of revolutions.

3.2 Static zero signal determination

The static zero signal $I_{0,\text{stat}}$ is averaged over different positions p incrementally rotated over one full rotation of the drive train. Other than the load signals, the zero signals per revolution step p $\bar{I}_{0,j}$ are averaged over a measurement time of $t_{\text{meas}} = 10\,s$ after a settling time of $t_{\text{settle}} = 30\,s$:

$$I_{0,\text{stat}} = p^{-1} \cdot \sum_{j=1}^{p} \bar{I}_{0,j}, \tag{3}$$

with $$\bar{I}_{0,j} = m^{-1} \cdot \sum_{i=1}^{m} \bar{I}_{0,i},$$

and $$m = t_{\text{meas}} \cdot f_{\text{sample}}$$

In this measurement campaign, the drive train including the TTS and the torque measurement adapter was rotated in steps of 30° over one full rotation ($p = 12$).

3.3 Characterisation method

Before the characterisation result can be calculated, the output signals of the TTS must be corrected for systematic errors:

(i) The TTS was calibrated using an MGC plus DAQ system with an ML38 amplifier module. For the measurement campaign in the NTB, however, an MX238B amplifier was deployed to read out the TTS signals. The amplifier switching is corrected for by subtracting the calibration coefficient of the ML38 (C_{ML38}) and adding up the calibration coefficient of the MX238B (C_{238B}):

$$I_{\text{P-amp},j}(M_{\text{C}}) = I_{\text{M},j}(M_{\text{C}}) - C_{\text{ML38}}(M_{\text{C}}) + C_{\text{238B}}(M_{\text{C}}). \tag{4}$$

(ii) The TTS manifests a small drift over time that needs to be corrected for by the drift coefficient C_{drift}:

$$I_{\text{P-drift},j}(M_{\text{C}}) = I_{\text{P-amp},j}(M_{\text{C}}) \cdot C_{\text{drift}}. \tag{5}$$

(iii) Moreover, the TTS signal is corrected for altered environmental conditions using the relative humidity coefficient C_{rH} and the relative temperature coefficient C_{T} and taking into account the deviation in relative humidity and temperature in the NTB from the ideal environmental conditions in the calibration laboratory ($T = 22\,°\text{C}, rH = 41.5\,\%$):

$$I_{\text{P-envir},j}(M_{\text{C}}) = I_{\text{P-drift},j}(M_{\text{C}}) - C_{\text{rH}} \cdot \Delta rH - C_{\text{T}} \cdot \Delta T \tag{6}$$

All the corrections are fraught with uncertainties that are to be considered in the overall measurement uncertainty of the torque characterisation in the NTB.

The result of the metrological characterisation is the relative indication deviation $\bar{q}$ per load step M_{C} and n_{NTB}. The approach is based on DIN 7500-1 [7]. Before the overall relative indication deviation is calculated, the relative indication deviation for each repeated load cycle j is calculated in %:

$$q_j(M_{\text{C}}) = \frac{I_j(M_{\text{C}}) - I_{\text{M},j}(M_{\text{C}})}{I_{\text{M},j}(M_{\text{C}})} \cdot 100\,\%, \tag{7}$$

where $I_j(M_{\text{C}})$ is the torque load indicated by the torque measurement adapter in the NTB and $I_{\text{M},j}(M_{\text{C}})$ is the torque load indicated by the TTS per load step M_{C} per repeated load cycle j. Here, the measurements were repeated twice ($j = 1 \dots 2$).

The overall relative indication deviation $\bar{q}$ per load step M_{C} is the arithmetic mean of the relative indication deviation over all four repetitions ($n = 4$):

$$\bar{q}(M_{\text{C}}) = n^{-1} \cdot \sum_{j=1}^{n} q_j(M_{\text{C}}). \tag{8}$$

The measurement uncertainty budget is based on DIN 7500-1 as well. It consists of the three main uncertainty contributions: (a) the resolution, (b) the repeatability, and (c) the TTS.

(a) The uncertainty contribution of the relative resolution of the NTB's torque measurement adapter u_{res} for each examined load step is the square root of the sum of two components squared: (i) the uncertainty component under load a_{M} and (ii) the uncertainty component after load release a_{Z}. The uncertainty contribution of the relative resolution is calculated as follows:

$$u_{\text{res}}(M_{\text{C}}) = \sqrt{\left(\frac{a_{\text{M}}(M_{\text{C}})}{2\sqrt{3}}\right)^2 + \left(\frac{a_{\text{Z}}(M_{\text{C}})}{2\sqrt{3}}\right)^2}. \tag{9}$$

Both the relative resolution $a_{\text{M}}(M_{\text{C}})$ and the uncertainty contribution of the relative resolution $u_{\text{res}}(M_{\text{C}})$ are expressed in %.

(b) The uncertainty contribution of the relative repeatability u_{rep} is the standard deviation of the best expected value q_j in % and the relative mean indication deviation $\bar{q}$ in %:

$$u_{\text{rep}}(M_{\text{C}}) = \sqrt{\frac{1}{n(n-1)} \sum_{j=1}^{n} \left(q_j(M_{\text{C}}) - \bar{q}(M_{\text{C}})\right)^2}. \tag{10}$$

(c) The uncertainty contribution of the TTS u_{std} consists of the relative calibration uncertainty of the TTS u_{cal} and additional uncertainty contributions due to deviating environmental conditions (A), the sensitivity drift of the TTS over time (B), the deviation because of the amplifier switching of the TTS (C), the synchronisation of the different data sets (D), and the accuracy of the rotational speed measurement (E) [8]:

$$u_{\text{std}}(M_{\text{C}}) = \sqrt{u_{\text{cal}}(M_{\text{C}})^2 + A^2 + B^2 + C^2 + D^2 + E^2} \tag{11}$$

Part of the result of the metrological characterisation is the expanded measurement uncertainty per load step $U(M_{\text{C}})$:

$$U(M_{\text{C}}) = k \cdot u(M_{\text{C}}) \tag{12}$$
$$= k \cdot \sqrt{\left(u_{\text{res}}(M_{\text{C}})\right)^2 + \left(u_{\text{rep}}(M_{\text{C}})\right)^2 + \left(u_{\text{std}}(M_{\text{C}})\right)^2},$$

where k is the coverage factor. It is recommended to use a coverage factor of $k = 2$. In certain cases, k can be calculated based on the number of effective degrees of freedom as stated in the Guide to the expression of uncertainty in measurement (GUM).

4 Metrological characterisation

The output of the metrological characterisation is the traceability of the torque measurement adapter in the NTB to national standards in form of a relative indication deviation **(Figure 5)** including a measurement uncertainty budget for the indication deviation. For the partial range torque measurement up to 5 MN m in the DyNaLab NTB, the relative indication deviation lies between - 2.5 and - 3.9 % for two repetitions.

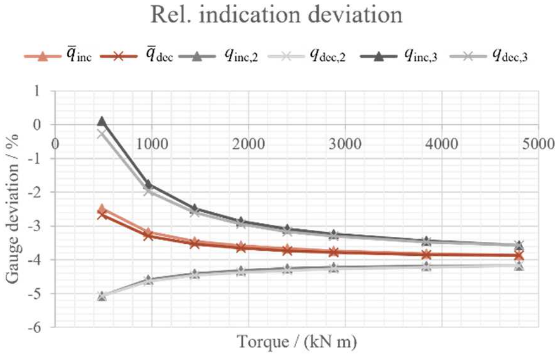

Figure 5 Indication deviation per load step $\bar{q}(M_{C})$ of the torque measurement adapter in the NTB relative to the TTS as result of the torque characterisation

The divergence in the repeatability needs to be further analysed. Major influences might be temperature and relative humidity and the bearing of the hexapod (NTL) during the measurement campaign. The temperature climbed from about 17.3 °C in the beginning up to 23.9 °C while the relative humidity, which has a greater influence on the torque measurement of the NTB torque measurement adapter, varied between 53.4 % and 42.8 %. Moreover, the temperature gradient along the drive train can lead on to tension causing crosstalk effects on the torque measurement.

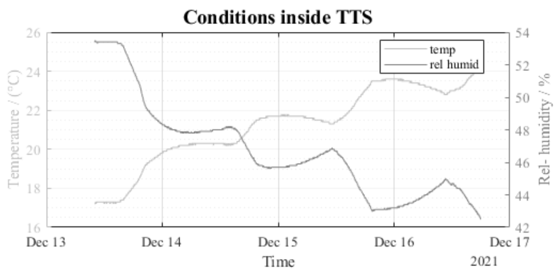

Figure 6 Temperature inside the TTS

The biggest contributors $u_i(M_{\mathrm{C\,max}}, n_{\max})$ (**Table 1**) to the expanded measurement uncertainty at maximum torque and maximum rotational speed $U(M_{\mathrm{C\,max}}, n_{\max})(k=2)$ are the relative repeatability u_{rep} and the extrapolated measurement uncertainty of the TTS u_{std}, which again reinforces the uncertainty of the sensitivity drift B.

Table 1 Uncertainty contributions $u_i(M_{\mathrm{C\,max}}, n_{\max})$ to the expanded meas. uncertainty $U(M_{\mathrm{C\,max}}, n_{\max})(k=2)$

Uncertainty contribution	Symbol	PDF	*u* in %
Rel. repeatability	u_{rep}	normal	0.453
Rel. resolution	u_{res}	rectangular	0.168
TTS	u_{std}	rectangular	0.546
Envir. effect	A	normal	1.90E-05
Sensitivity drift	B	rectangular	0.288
Amp. switching	C	normal	1.35E-04
Synchronisation	D	rectangular	1.00E-03
Rotational speed	E	normal	0.032 [8]

5 Conclusion

The torque measurement adapter in the 10 MW NTB DyNaLab at Fraunhofer IWES is metrologically characterised in form of a relative indication deviation including the corresponding expanded measurement uncertainty per load step. This was done by installing a TTS in the NTB's drive train directly at the rotor hub of the DUT and applying so-called characterisation maps, which are defined combinations of torque and rotational speed (load steps). The relative indication deviation of about – 3.9 % ($U(M_{\max}, n_{\max}) = 1.45$ %) at 5 MN m means, that the NTB's torque measurement adapter indicates less torque than applied, which affects the direct efficiency determination and should, therefore, be corrected for.

6 Acknowledgments

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7 Literature

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