Extending the Torque Calibration Range – Necessity and Outline of a Mathematical Approach

Paula Weidinger, Gisa Foyer, Christian Schlegel, Rolf Kumme

Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38118 Braunschweig, Germany
Phone: +49 531 592-1231, Fax: +49 531 592-69 1231, Email: Paula.Weidinger@ptb.de

The current torque calibration range up to 1.1 MN·m is not any longer sufficient. The fast growing wind energy sector raised the demand for traceability of torque in the MN·m range over the last few years. To this end, a 5 MN·m torque transducer was acquired to extend the torque calibration range. Since the measuring device cannot be calibrated over its full measurement range, mathematical methods to forecast the behaviour of the torque transducer above 1.1 MN·m and their further development are presented.

1. Introduction

Wind energy is so far the biggest contributor to the produced amount of renewable energy and it is the most promising for an augmentation of the renewable energy share. To improve the energy efficiency of wind energy systems, initially the energy efficiency η of nacelles needs to be determined by measuring the input and output power. Whilst the output power is measured as electrical output P_{el} of the nacelle, the input power is quantified as mechanical power in nacelle test benches (NTBs) by recording the torque M at the nacelle's rotor hub:

$$\eta = \frac{P_{\mathrm{el}}}{\boldsymbol{M} \cdot n \cdot 2\pi} \qquad (1)$$

where n is the rate of rotation. This strongly increases the demand for the traceability of torque determination in NTBs. With modern wind turbines having scaled up to multi-megawatt power ratings, the occurring torques rise up to several MN·m. In order to calibrate an NTB as depicted in Figure 1, the National Metrology Institute of Germany (PTB) acquired a 5 MN·m torque transducer (TT) using strain gauges (SGs) to convert torque into an electrical signal [1]. Before this TT can be deployed as a transfer standard to calibrate NTBs, the TT itself is to be calibrated. Owing to the fact that the world's biggest torque standard machine (TSM), which is located at the PTB, has only a capacity of 1.1 MN·m and a certain precision [2], the 5 MN·m TT can only be calibrated within its partial measurement range of 22 %. Aiming to characterise the TT over its full range, the torque calibration range is to be extended. Without designing a new machine, this can only be achieved by developing an extrapolation method based on the available partial range calibration data [3–5].

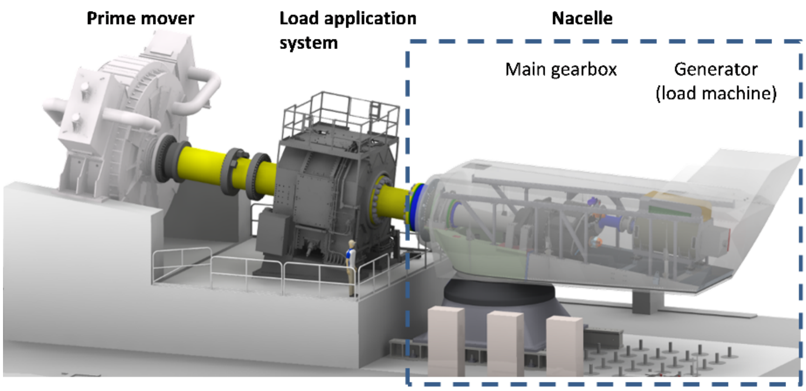

Figure 1: Scheme of the nacelle test bench (NTB)) at Aachen University including a Prime Mover, a load application system to simulate wind loads, and the nacelle under test (Source: CWD).

2. Measuring Device 5 MN·m Torque Transducer

In general, mechanical TTs utilise SGs applied with glue to the deformation body for indirectly converting the applied torque into an electrical signal. The applied torque deforms the spring body of the transducer (cf. Figure 2) linear-elastically and evokes a strain. This strain is transferred through the glue into the conductive lines of the SGs where this current-carrying conductor is strained. Thus, a variation in length and, as a consequence, in profile occurs leading to a change in the electrical resistance of the conductive lines. Since these relative resistance alterations are rather small, they are to be amplified by interconnecting four SGs most commonly in a Wheatstone full-bridge configuration. Thereby the torque dependent output signal is represented in mV/V.

The advantages of SGs are good linearity and reproducibility, high precision, and small hysteresis. Moreover, due to the negligible mass of foil strain gauges, the transducers can be used for rotating applications as the calibration of a NTB and the applied torque can be measured direction-dependent.

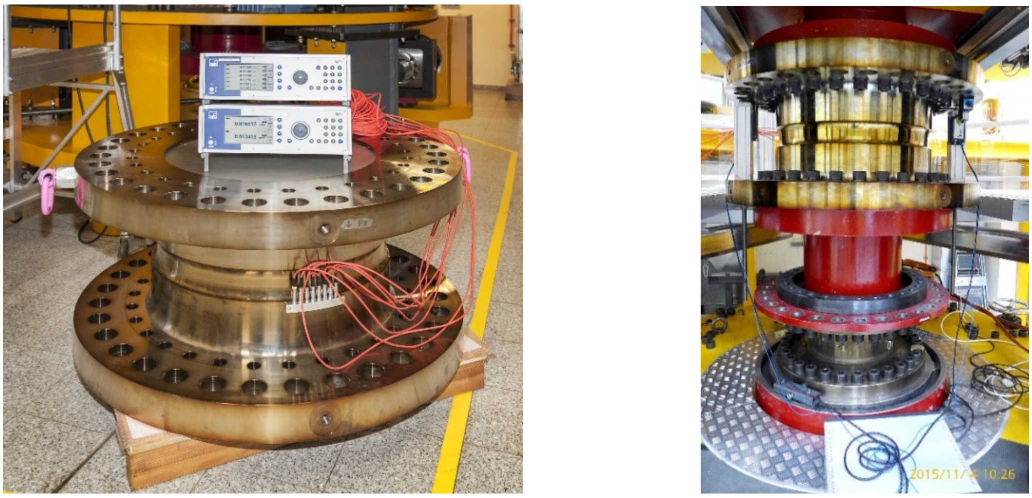

Figure 2: The 5 MN·m torque transducer (TT) (left) and the TT being mounted in PTB's 1.1 MN·m torque standard machine (TSM) to be calibrated (right).

3. Torque Calibration up to 1.1 MN·m

Theoretically the relation between the applied torque and the output signal is linear within the linear-elastic range. From long calibrating experience it is known that small nonlinearities appear even within the linear-elastic range. These can be evoked by the strain transmission through the different adhesive layers and the plastic backing foil of the SG due to their viscoelastic behaviour. Moreover, the material characteristics of the deformation body are not entirely linear. Additionally, a poor bonding quality can induce nonlinearities. These nonlinearities are distinctive for each and every TT. Because of visualisation reasons, the absolute linearity deviations d_{lin} rather than the tared output signals – which seem to be linear – are plotted against the applied torque. The linearity deviation for each load step i is calculated by subtracting a linear regression curve m_{linear} from the tared signal value of each step $S_{\mathrm{meas}}(i)$:

$$d_{\mathrm{lin}}(i) = S_{\mathrm{meas}}(i) - (m_{\mathrm{linear}} \cdot M(i)), \qquad (2)$$

with M being the actual applied torque. Figure 3 depicts a typical linearity deviation curve of a well-known TT (blue) and, in comparison, the partial range calibration results of the 5 MN·m TT up to 1.1 MN·m (red). The torque is applied clockwise and anti-clockwise, as shown in Figure 3, and in increasing and decreasing defined steps as symbolised by solid and dashed lines respectively. In order to minimise setup errors, e.g. eccentricity, non-planarity, and other errors evoked by misalignments, the transducer is rotated around its measuring axis and calibrated three times. The diverse nonlinearities for the different mounting positions are reflected as varying curves per load cycle in the plot. By analysing the deviations of the curves for the different mounting positions a statement about the reproducibility of the TT can be made. In addition, the plot visualises not only the nonlinearities but also the hysteresis and the zero point deviation of the analysed TT [6].

For the future employment of the TT as a calibrated measuring instrument, a cubic regression curve for the signal output considering the nonlinearities is used to determine the applied torque. This enables the interpolation between the calibrated steps with a smallest possible interpolation deviation and, thus, measure any applied torque that lies within the calibrated measurement range. However, this cannot be done for torque loads beyond the calibrated measuring range.

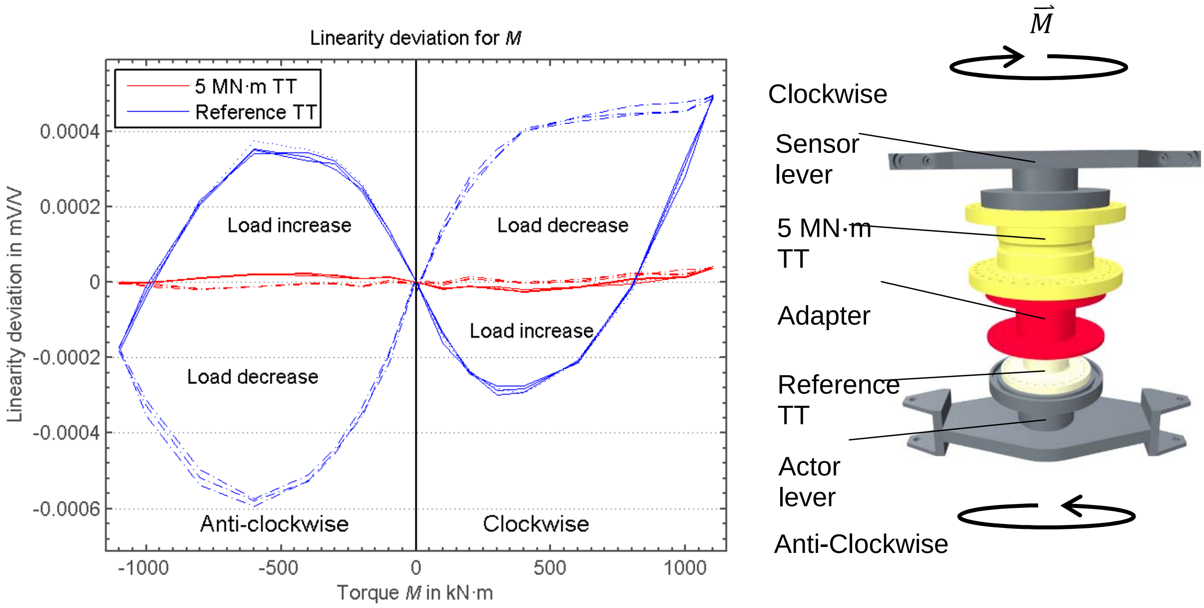

Figure 3: Absolute linearity deviations from the linear best fit depicted for clockwise and anti-clockwise applied increasing (solid lines) and decreasing (dashed lines) torque steps. The blue curve represents a TT with a capacity of 1.1 MN·m while the red curve is of the 5 MN·m TT.

4. Extrapolation of the Calibration Data

Extrapolation is basically estimating signal values outside the observed range. To endorse the necessity of developing a mathematical approach for an extrapolation method based on measurements performed using a well-known TT in a calibrateable range, various approaches for signal extrapolation and their impact on the expected nonlinear behaviour are introduced in Figure 4.

All extrapolations were executed on the 9-point tared calibration signals up to 1.1 MN·m which accounts to 22 % of the maximum measurement range of the 5 MN·m TT. In order to demonstrate the influences on the linearity deviation d_{lin}, this is plotted against the applied torque. For calculating d_{lin}, the linear regression curve for the calculated 22 % range is used as aforementioned. Since d_{lin} varies for the different mounting positions, the extrapolation approaches are implemented for each mounting position separately. For reasons of clarity and comprehensibility, the linearity deviations of the different mounting positions are arithmetically averaged. In addition, the standard deviation for the averaging is calculated and plotted in Figure 4 to emphasise the variation spectrum. All extrapolations are done exemplarily for the clockwise, increasing load.

A rather simple approach based on all increasing clockwise signals is the linear signal extrapolation of which d_{lin} is depicted as a red curve (Linear fit (all signals)). A better representation of normal TT characteristics is a linear extrapolation through the last two calibration signals due to the better measurement uncertainty of the higher signal values. The results are illustrated by the black dotted curve. Besides, a second degree polynomial fit through all calibration signals was extrapolated. The linearity deviation for the quadratic extrapolation is represented by the blue dashed line. As shown in the zoom of Figure 4, the extrapolation curve of a quadratic fit tends to follow the linearity deviation of the original calibration data.

Fitting a polynomial of higher degree to the calibration signals, e.g. a cubic regression curve as done in different torque calibration standards in order to use the calibrated transducer as a measuring device, led to rather big standard deviations. Hence, it is not part of the plot below. One matter for that is the unsteady signal of the TT in this comparatively small calibration range of only 22 %. In such a small range the influences of resolution and noise on the small measurement signal are relatively big and can entail a quite divergent signal. From this, it can be concluded that a wider calibration range is a better base for an extrapolation approach of calibration data. Furthermore, from the standard deviation, which increases with the load steps, it can be summarised that the single measurement values should be weighted before being extrapolated. By this, the noise and resolution influences of the smaller measurement signals on the extrapolation result could be reduced.

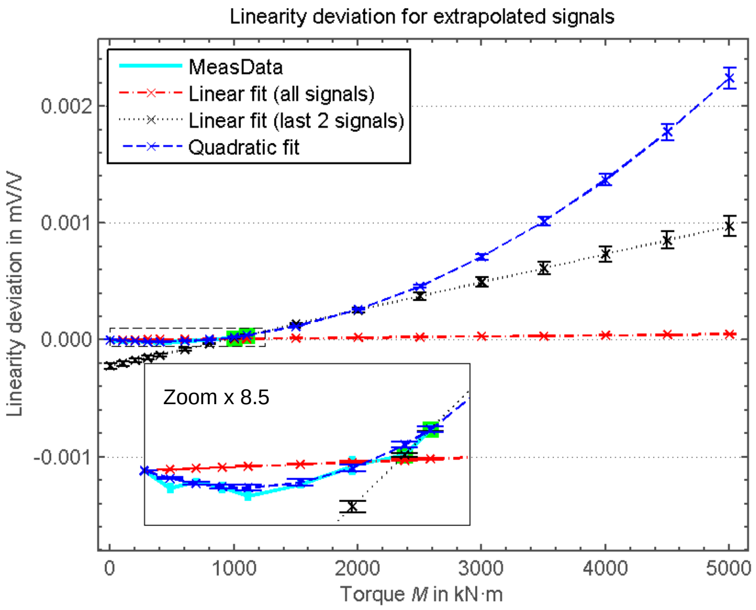

Figure 4: Linearity deviations from the linear best fit obtained for each extrapolated data set. The basic data is up to 1.1 MN·m which is extrapolated up to 5 MN·m using various extrapolation methods.

5. Conclusion and Outlook

As described in the beginning, there is an enormous need for precise torque measurement in the MN·m range coming from the wind energy sector. Since a torque calibration within the demanded range is not feasible so far, differing extrapolation methods of the measurement signals and the associated expected nonlinearities are presented. The extrapolation is a prerequisite for the 5 MN·m torque transfer standard to be deployed for a traceable calibration of NTBs. Therefore, the future goal is it to develop an extrapolation method based on reliable data sets of well-known TTs and the findings of this investigation.

References

[1] Rainer Schicker, Georg Wegener, "Measuring Torque Correctly", Bentrup Druckdienste KG, Bielefeld, 2002.

[2] Diedert Peschel, Dietmar Mauersberger, Daniel Schwind, Ulrich Kolwinski, "The new 1.1MN·m torque standard machine of the PTB Braunschweig/ Germany", Conference on Force, Mass and Torque, 19th IMEKO TC3, Cairo, Egypt, Feb., 2005.

[3] Christian Schlegel, Holger Kahmann, Rolf Kumme, (None), "MN·m Torque Calibraiton for Nacelle Test Benches using Transfer Standards", ACTA IMEKO, Vol. 5, No. 4, pp. 12–18, 2016.

[4] Andreas Brüge, "Mathematical representation of reference torque transducers in partial-range regimes", Conference on Force, Mass and Torque, 20th IMEKO TC3, Merida, Mexico, Nov., 2007.

[5] LaVar Clegg, "Extending Transducer Calibration Range by Extrapolation", Scottsdale, Arizona, USA.

[6] DIN51309:2013-09, "Material testing machines - Calibration of static torque measuring devices", No. 51309, Technical Commitee Drehmoment of Deutscher Kalibrierdienst, 2013

Acknowledgements

The authors would like to acknowledge the funding of the Joint Research Project “14IND14 MN·m Torque - Torque measurement in the MN·m range. This project has received funding from the EMPIR programme con-financed by the European Union’s Horizon 2020 research and innovation programme and EMPIR Participating States.

The lead author gratefully acknowledges support by the Braunschweig International Graduate School of Metrology B-IGSM.