Investigations towards extrapolation approaches for torque transducer characteristics

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Investigations towards extrapolation approaches for torque transducer characteristics

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Abstract. For torque transducers above 1.1 MNm, no traceable measurement has been possible to date. Therefore, an extrapolation method deploying measurement data from partial ranges is to be developed. Both partial and full range measurements up to 20 kNm are performed to gather data for implementing an extrapolation approach. The extrapolated data is evaluated, and the results are compared to the full range results.

1. Introduction
To date, traceable torque measurement has only been possible up to 1.1 MNm [1]. However, certain industries, e.g. the wind power industry, now have a need for precise torque measurement above the current limit driven by the up-scaling of wind turbines to multi-megawatt power ratings. The demand of a traceable torque measurement up to 5 MNm is 4.5 times the available capability worldwide.

This problem is not unique to torque measurement, but also familiar in the sector of force calibration, where most material testing machines work in a range above a traceable force measurement range. In this particular field, extrapolation methods are applied to characterise force transducers above the calibration range [2, 3]. For torque measurements, a mathematical representation employed in partial ranges [4, 5, 6] exists, but there is no extrapolation method including a measurement uncertainty considering the extrapolation method itself. For that reason, an extrapolation method for torque measurement is to be developed. To validate the extrapolation method, a data set using a well-known torque transducer was gathered. Since the metrological properties differ depending not only on the applied torque load but also on the torque at maximum load, partial and full-range measurements performed on different torque standard machines (TSMs) are analysed.

2. Experimental setup
To generate a considerable data set for investigating the dependency of metrological properties on torque load and employed TSMs, a well-known 20 kNm torque transducer was chosen.

The selected torque transducer is a Raute Precision Oy TT1 based on the strain gauge measuring principle. This shaft type transducer was chosen because of its well-known history and its very stable characteristics, e.g. small creep and hysteresis. For the data acquisition, high precision carrier frequency amplifiers DMP 40 and DMP 41 were used. With its shaft interfaces suitable for common hydraulic couplings, the TT1 fits into both considered TSMs.
At the Physikalisch-Technische Bundesanstalt (PTB), the tests were carried out on a dead-weight TSM with a horizontal measuring axis and a measurement range from 100 N·m to 20 kN·m (figure 1). The torque is generated by precisely determined dead-weight stacks in a known gravitational field of the Earth acting as a force at an offset relative to the fixed fulcrum. Due to its special design, the expanded relative uncertainty \( k = 2 \) amounts to \( 2 \times 10^{-5} \).

The reference TSM used at VTT, the Technical Research Center Finland, has a capacity from 200 N·m up to 20 kN·m and is less accurate than the dead-weight TSM at PTB. VTT’s reference TSM has an expanded relative uncertainty of \( 5 \times 10^{-4} \) depending on the reference transducer’s uncertainty and any possibly appearing misalignments. Here, the measuring axis is vertical and both the reference transducer and the transducer to be calibrated are mounted in line (figure 2). As it is a reference TSM, the torque is generated by a multiphase motor and a serially connected high ratio gearbox to ensure a more precise triggering. During the calibration process, both transducers are recorded and compared in a post-processing phase. [7]

Besides the full-range measurements of \( M_{100\%} = 20 \text{ kN·m} \), measurements in partial ranges of 20\%, 50\%, and 80\% of the full range were performed, to analyse the different transducer characteristics for different maximum torque loads. The creep evolved by full load was minimised by starting the measurements at 20\% and it increasing afterwards up to the full range. The loading procedures were performed according to DIN 51309 [8] which means stepwise for clockwise and anti-clockwise torque in separate load cycles with separate pre-loadings and for three mounting positions (0°, 120°, and 240°). Moreover, increasing and decreasing load steps allow a hysteresis analysis as well as the determination of a zero point deviation.

### 3. Evaluation results

The evaluation of both full and partial ranges follows DIN 51309 [8] where a separate taring for every mounting position is used. Moreover, a separate analysis is performed for clockwise and anti-clockwise torque loads. In order to be able to extrapolate measurement data, it is of great importance to analyse the deviations between the different load ranges.

The sensitivity of a torque transducer is the coherence between the signal \( S \) and the applied torque \( M_{\text{nom}} \), whereas the slope \( m \) is calculated by a linear regression curve through the origin (0/0) and the increasing signals, which are averaged over all mounting positions separately for clockwise and anti-clockwise torque. It was found, that the sensitivity varies for different partial loads up to 0.01\% relative to the sensitivity determined for the full range when using a dead-weight TSM, and even more when using a reference TSM. Theoretically the relation between the applied torque and the output signal is linear within the linear-elastic range, however, small
nonlinearities appear in the recorded data. The linearity deviation $d_{\text{lin}}$ for each load step $i$ is calculated by subtracting the linear regression curve with the slope $m_{\text{linear}}$ from the tared measurement signal $S_{\text{meas}}$.

For both data sets, the nonlinearities are very small. The results from VTT (figure 4) do not look as smooth as the PTB’s results (figure 3). There are several reasons which might have caused this. The creep analysis reveals a small short-term creep of the deployed transducer. Furthermore, the continuous data recording of VTT’s TSM, its higher sampling rate, the larger filter parameters and the nonlinearities of the reference transducer might be a reason for the nonlinearities of the calibrated transducer. The zero return or zero point deviation which is the zero signal recorded after each decreasing series seems to be very load dependent. However, for the data gathered on the reference TSM, a relation is not recognisable.

4. Extrapolation approach

Extrapolating a partial range calibration result can be done in many ways. Two main approaches are (i) the extrapolation of the tared measurement data for each measurement and (ii) the extrapolation of the calibration result. In the following, the first approach is used. The zeroed measurement data for the increasing load cycles in all three mounting positions gathered on the dead-weight TSM is extrapolated. Based on the behaviour of torque measurement curves, linear and cubic fitting parameters are calculated and used for the extrapolation. This extrapolated data is then analysed separately for clockwise and anti-clockwise torque according to DIN 51309 case I, which means only the increasing load steps are considered.

By comparing the extrapolated data to the full range measurement data (figure 5), for the 20% range, a high distribution and a large deviation of $2 \cdot 10^{-3}$ relative to the full range signals is ascertained. Therefore, the 20% partial range is not taken into account for an extrapolation up to the full range and the subsequent determination of the calibration result. For an extrapolated measurement range, a growth in the expanded relative uncertainty is expected. This is proven for the extrapolation of the 50% and 80% partial ranges up to the full range for a cubic extrapolation and a case I cubic and separate evaluation (figure 6) of the extrapolated data.

Investigations of torque transducer characteristics in different partial ranges and the full range depending on the utilised TSM are introduced. Based on the emerging nonlinearities of the calibrated transfer function, it was decided on a separate extrapolation of the measurement
--20--10 0 10 20

Torque / (kN m)

Figure 5. Deviation of the extrapolated data based on different partial ranges from the measured full range.

--20--10 0 10 20

Torque / (kN m)

Figure 6. Expanded relative measurement uncertainty for the extrapolated ranges 50% and 80% and the full range.

curves linearly and cubically. As expected, the expanded relative uncertainty increases for the extrapolated ranges. Moreover, by evaluating the differently extrapolated data sets, the extrapolation approach is part of the expanded relative uncertainty.

5. Conclusion and outlook

Only case I of DIN 51309 was investigated which means the reversibility of the transducer is not considered but it is a crucial parameter and should be examined in the future. As an alternative to the presented approach, the calibrated transfer function could be extrapolated, and the uncertainty could be calculated using a Monte Carlo simulation.

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