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MEASUREMENT UNCERTAINTY OF ROTATING TORQUE TRANSDUCERS WHEN USED IN PARTIAL LOAD RANGES

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Abstract: The present contribution examines how metrological specifications can be derived for a given type of torque transducer when specifications for use in the full nominal measuring range are known, but the specifications for use in a partial load range are required.

Keywords: rotating torque transducers, uncertainty of measurement, partial load range.

1. INTRODUCTION

The contribution shows results required for the estimation of the uncertainty of measurement of rotating torque transducers in industrial applications. Since the estimation has to be made in the design phase of an application (e.g. a test stand for automobile engines) full calibration results are usually not available. The estimation has to be based on specifications given by manufacturers. The method was presented in a previous publication of the authors [1].

The specifications are usually based only on tests and calibrations for the nominal measuring range of the torque transducers. If an engine test stand is designed and the required maximum torque (including safety factors) is 700 N·m, a typical choice would be a torque transducer with a nominal torque of 1 kN·m. The specifications (e.g. temperature effects, hysteresis) the manufacturers give are related to the nominal torque. However for the estimation of the measurement uncertainty in the test stand it is required to know specifications for use of the transducer in the measuring range up to 700 N·m (partial load range). Some of the metrological parameters needed for the uncertainty budget could be acquired by simply adding torque steps in the very low range to a usual calibration cycle (i.e. a calibration in which the maximum calibration torque is the nominal torque of the transducer). A certain number of metrological properties however, do not only depend on the respective torque step, but also on the maximum torque of the calibration cycle. Therefore, from a strict point of view a separate calibration is required in the partial load range. But in practice, this cannot be done for all possible partial load ranges. Therefore the task of this study is to find out, how metrological properties of a transducer in a partial load range can be estimated from data taken from specifications or calibrations in the nominal load range.

When describing the uncertainty contributions in physical units (N·m), the method will be an algorithm for downscaling. When describing the uncertainty contributions as percentages of the actual range, the most optimistic prognosis would be that the values remain unchanged. In general it is however expected that upscaling is necessary. A method can only be derived from empirical measurements.

2. EFFECTS AND PARAMETERS TO BE CONSIDERED

2.1. Background

The general background is shown in figure 1: When a transducer is used in a partial load range, the behavior may be considerably different depending on the load range in which the transducer is used. This question is more complex than simply asking for individual parameters for a certain load step (e.g. reversibility at 40% of the nominal torque), because these parameters usually also depend on the range in which the transducer is used

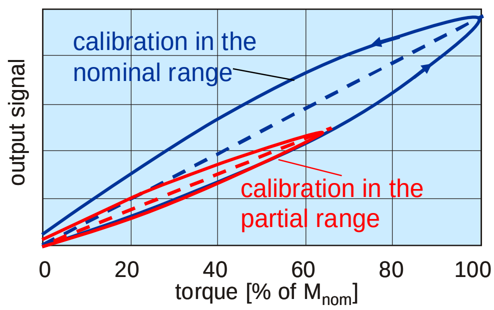

Fig. 1. Background

2.2. Contribution to the measurement uncertainty

In [1], two of the authors of the present study have presented an approach for estimating the total uncertainty for torque measurements in the application. According to their study, the total uncertainty can be obtained from the equation:

$$U = \sqrt{\begin{matrix} U_{TK0}^2 + U_{TKC}^2 + U_{\text{hys}}^2 + U_{\text{lin}}^2 + U_{b'}^2 + U_b^2 \\ + U_{\text{C}}^2 + U_{\text{rem}}^2 + U_{\text{para}}^2 + U_{\text{speed}}^2 + U_{\text{ada}}^2 \end{matrix}} \quad (1)$$

The individual uncertainty contributions in this equation are from (given in the same order as in the equation above):

- temperature effects on the zero signal (TK_0)
- temperature effect on the sensitivity (TK_C)
- hysteresis
- linearity deviation
- repeatability
- reproducibility
- determination of sensitivity
- mechanical remanence (hysteresis of the zero signal)
- parasitic loads
- rotational speed
- adaptation parts

2.3. Parameters to be considered

For some parameters the behavior for the partial load range can easily be predicted from physics: Temperature effect on the zero value has always the same influence (in units of N·m), regardless of the measuring range in which the transducer is used. Temperature effect on the sensitivity should always be proportional with the actual value of torque, regardless of the range. Therefore these two groups of parameters will not be considered in the further investigation.

The important effects to be examined are

- hysteresis
  (described by the parameter reversibility)
- linearity
  (described by the parameter linearity deviation / interpolation error)
- zero signal return
- mechanical remanence
  (also called hysteresis of the zero signal)

2.4. Sensitivity

In practical applications, the characteristic line of a transducer is described only in terms of a linear relation. The sensitivity is the parameter defining the slope of this characteristic line.

Sensitivity itself is not to be considered a parameter describing metrological quality. In the context of the present study however, it is of importance, how big the difference is between the sensitivities determined for different measuring ranges. The sketch in figure 1 shows the principle. Even if it should turn out that there is a relevant difference in sensitivities, the metrological properties in the partial load ranges may still be as good as in the nominal load range (when expressed as percentage of the respective range). But it would mean that for use in the partial load range the adapted sensitivity would have to be determined. In other words: in such a case a separate calibration for the partial load range should be considered.

3. CONCEPT OF THE EXPERIMENTAL INVESTIGATIONS

3.1. Specimens

Specimens for the investigation were three rotating torque transducers, with a nominal torque (rated torque) M_{nom} of 1 kN·m. The special design features of this type are

- measuring body based on axial shear elements
- high stiffness against torsion and parasitic loads
- strain gages positioned inside the hollow measuring body which is hermetically sealed
- measuring body design identical with a proven torque transfer standard

Fig. 2. 1 kN·m torque measurement flange (rotor) (HBM, type T10FS)

Figure 2 shows such a transducer. The picture shows that mounting is done via flanges as common in industrial practice. The flange on the right hand side in the foto bears an additional outer ring containing the antenna for the non-contacting power supply and signal transmission between the rotor and the stator.

Design and technology of this transducer type provide the highest accuracy available with rotating transducers for industrial applications.

3.2 Test procedure

The measurement procedure was adapted to the specific aspects of the study. Therefore the procedure did not completely obey any of the standardized calibration standards or guidelines. The procedure included the following:

- Increasing and decreasing torque.
- Steps of 10% of the respective calibration range.
- Measurements with clockwise and anti-clockwise torque (separate cycles with separate preload cycles)

- For each of the specimens, the complete procedure was performed for three different calibration ranges: 100 %, 50 % and 20 % of the nominal load range. In one case, a testing in 10 % of the nominal load has been performed instead of the 20 % range.
- In order to isolate the effects under consideration from the effects dismounting and mounting, the mounting position was not changed during all the different tests of one specimen.

3.3. Test facility

The tests are carried out on a reference standard torque calibration machine with a nominal range of 1 kN·m, which is accredited within the DKD (German Calibration Service) according to ISO/IEC 17025. The machine uncertainty is specified with 0.01 % of the actual torque for torque steps from 5 N·m up to 1 000 N·m.

Fig. 3. 1 kN·m torque reference standard machine in the HBM calibration laboratory

To achieve such a high accuracy, the machine is equipped with air bearings for supporting the lever arm minimizing the bearing friction. The fine spacing of torque steps is achieved by using binary weight stacks. Each weight can be controlled individually. A unique feature of this machine is the pedestal which is made from hard stone instead of the usual steel. This ensures an excellent dimensional stability.

The graphs in the following section show that the effects under discussion are partly smaller than the uncertainty of the calibration machine. However it has to be considered, that the accredited best uncertainty of the machine must take into account the traceability to the national standard. But in the current study the task are comparisons of measurements taken with the same machine under almost unchanged conditions. For such comparisons, the excellent consistency and reproducibility allows reliable statements even for effects which are an order of magnitude smaller than the accredited uncertainty of the machine.

4. RESULTS OF THE EXPERIMENTAL INVESTIGATION

4.1. Sensitivity and linearity deviation

A good impression of linearity deviation and hysteresis can be obtained from figure 4 which shows the respective output signals plotted versus the torque steps. The graph includes three separate calibration ranges for the same specimen. The respective values of maximum calibration torque M_E were 100 %, 50 % and 20 % of the full nominal torque M_{nom}. Results are shown for both torque directions, clockwise and counter-clockwise. Separate zero correction values (determined after the preloadings) have been used, so both cycles appear to have their starting point at exactly the origin of the coordinate system.

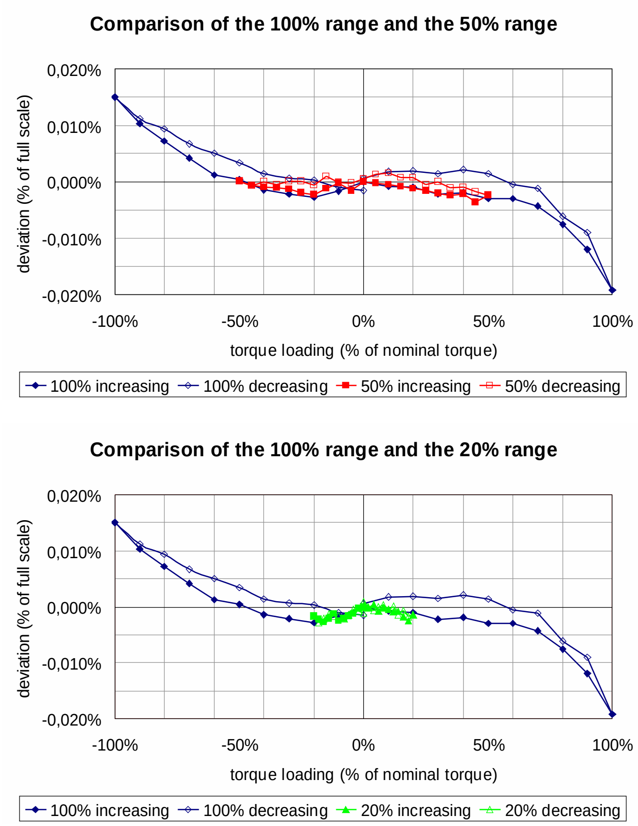

Fig. 4. Deviation from the linear best fit line for different calibration ranges (specimen no. 1)

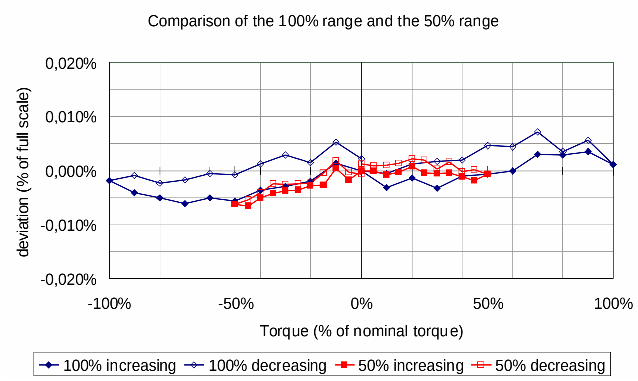

Fig. 5. Deviation from the linear best fit line for the 100% and 50% calibration ranges (specimen no. 2)

For scaling reasons, the output signals are shown in terms of the deviation from a straight line characteristic which was obtained from a least square fit for clockwise and counter-clockwise torque in the 100 % calibration range.

Figure 4 is for specimen no. 1, which shows the biggest influence of linearity deviation among all specimens examined. The graph shows, that for this specimen straight line characteristic curves for the partial ranges (20 % range, 50 % range) will give different results than for the full nominal range (100 % range).

Figure 5 shows the deviations for specimen no. 2, which has a much smaller nonlinearity effect. In this case, hysteresis is more severe than nonlinearity.

For the quantitative discussion of sensitivity and linearity, some considerations about the application should be made first:

In the typical application of rotating torque transducers, measurements cannot be restricted to a load situation of increasing load only. Therefore the optimized characteristic line should be chosen as a best fit for the entire load cycle including increasing and decreasing torque. However, many users of rotating torque transducers use a so-called two point adjustment: the amplifier is adjusted by defining a zero point and the point full nominal torque and the associated output signal. This kind of adjustment always results in bigger linearity deviations than a best fit including the complete calibration cycle. However it is usually closer to the latter version than a best fit which is based on data from the increasing branch of the calibration cycle only.

An interpolation by a higher polynomial is not common in the considered applications. Furthermore, in many cases hysteresis is the more severe effect in comparison to nonlinearity. Therefore a higher polynomial description of the characteristic line does not make sense when both the increasing and decreasing branch of the load cycle are to be included.

Since this study aims to describe the effects affecting the measurement uncertainty in the applications, the considerations of sensitivity and linearity deviation are based on the most common method, which is the two point adjustment.

The individual sensitivities given in table 1 are determined according to a two-point adjustment procedure for the respective calibration range. There are separate sensitivities for clockwise and anti-clockwise torque. To make the comparison more comfortable, the different sensitivities for each specimen are expressed in terms of the deviation from a standardized reference sensitivity. The deviation is defined such that a positive deviation means:

- in case of a sensitivity for clockwise torque: the slope of the characteristic line is bigger than the slope of the reference line
- in case of a sensitivity for counter-clockwise torque: the slope of the characteristic line is smaller than the slope of the reference line

The reference line is the same as for the graphical representations above (the best fit sensitivity determined for clockwise and counter-clockwise torque in the 100 % calibration range). For this reason even the sensitivities for the 100 % calibration range usually show some deviation from the best fit sensitivity.

In table 1 the associated reference sensitivity is given in absolute physical units. Since the output of this type of rotating torque transducer is an FM modulated frequency signal, the unit is Hz. The common representation is to give the signal (zero-compensated) for the full nominal torque instead of signal per N·m.

Linearity deviation in table 1 is given as a percentage of the respective calibration range.

Table 1. Deviation of the sensitivities for the different calibration ranges from the best fit line for the 100 % calibration range

Speci-men no.	Cal. range	Reference sensitivity [Hz / M_{nom}]	sensitivity deviation		linearity deviation	
			clockw.	counter-clockw.	clockw.	counter-clockw.
1	100%	4926.43	-0.019%	-0.015%	0.0122%	-0.0078%
	50%		-0.005%	0.000%	0.0041%	-0.0045%
	20%		0.000%	-0.007%	-0.0065%	-0.0086%
2	100%	5002.89	0.001%	0.002%	0.0063%	0.0053%
	50%		-0.001%	0.013%	0.0050%	0.0062%
	10%		-0.026%	-0.012%	0.0132%	-0.0258%
3	100%	5013.77	0.003%	0.002%	0.0075%	-0.0065%
	50%		-0.009%	0.015%	0.0087%	-0.0063%
	20%		-0.019%	0.015%	-0.0130%	-0.0063%

The comparison of sensitivities between the different calibration ranges shows a maximum deviation of 0.027 % if the 10 % range is taken into account and a maximum of 0.019 % if only the 50 % and 20 % ranges are taken into account. These deviations are clearly within the specifications of the transducer type. But they show that in some cases the use of an adapted sensitivity can improve the accuracy of measurements in partial load ranges. A typical case of a transducer with such properties is the one in figure 4. The figure illustrates that the nonlinearity effects are much bigger than the hysteresis effects in this case. Therefore, there is not much difference between the two possibilities for gaining such an adapted sensitivity value:

- from the values associated with the small range, but acquired in a calibration for the full nominal torque
- from a separate calibration in the partial load range

The comparison of the linearity deviations shows that the nonlinearity effects in relation to the respective calibration ranges are similar for all calibration ranges. In some cases they are even better in the partial load ranges.

4.2. Hysteresis

The graphs in section 4.1 show clearly, that the hysteresis for identical torque steps is considerably smaller for load cycles in a partial load range. This result was expected. For the quantitative discussion, table 2 gives the hysteresis in terms of the reversibility. The table shows the maximum found in the absolute values of reversibility for clockwise and counter-clockwise torque. All values are given

- as percentages of the full nominal torque M_{nom} and
- as percentages of the respective calibration ranges

Table 2. Comparison of hysteresis (max. reversibility found in the respective calibration range, including clockwise and counter-clockwise torque)

Calibration range		Specimen 1	Specimen 2	Specimen 3
100%	% of M_{nom}	0.0044 %	0.0058 %	0.0072 %
	% of M_E	0.0044 %	0.0058 %	0.0072 %
50 %	% of M_{nom}	0.0022 %	0.0024 %	0.0028 %
	% of M_E	0.0043 %	0.0048 %	0.0056 %
20 %	% of M_{nom}	0.0011 %	---	0.0014 %
	% of M_E	0.0053 %	---	0.0070 %
10 %	% of M_{nom}	---	0.0022 %	---
	% of M_E	---	0.0224 %	---

A comparison of the values shows that for specimens 1 and 3 the hysteresis (when expressed as a percentage of the respective calibration range) remains almost unchanged between the different calibration ranges. The same holds for the 50 % range of specimen 2. Only the 10 % range shows a bigger hysteresis. The hysteresis (as a percentage of the full nominal range) for this calibration range is even bigger than it would be expected for a 20 % calibration range. So probably there is a mixture of two effects:

- a specimen which shows weaker properties than the others
- the fact that the 10 % calibration range is more critical than partial calibration ranges of 50 % and 20 % of M_{nom}

4.3. Zero return

Zero return may highly depend on the maximum load applied in the respective load cycle, therefore it is of interest in this study. The values for different calibration of the specimens are given in table 3. For each calibration range, the table shows the maximum of the absolute values from clockwise and counter-clockwise calibration.

Table 3. Comparison of zero return for the different calibration ranges (maximum of clockwise and counter-clockwise)

Calibration range		Specimen 1	Specimen 2	Specimen 3
100%	% of M_{nom}	0.0015 %	0.0022 %	0.0019 %
	% of M_E	0.0015 %	0.0022 %	0.0019 %
50 %	% of M_{nom}	0.0006 %	0.0012 %	0.0018 %
	% of M_E	0.0011 %	0.0024 %	0,0036 %
20 %	% of M_{nom}	0.0011 %	---	0.0016 %
	% of M_E	0.0056 %	---	0.0081 %
10 %	% of M_{nom}	---	0.0018 %	---
	% of M_E	---	0.0089 %	---

A comparison of the zero return values shows that they are almost independent from the different calibration ranges (when expressed as a percentage of the full nominal torque M_{nom}). In other words, the range-related effect has to be upscaled, when a torque transducer is to be used in a partial load range.

4.4. Mechanical remanence

The mechanical remanence is an effect, which is of crucial importance when torque transducers are to be used for measuring alternating torque. Since this effect describes the shift of the zero signal occurring after a change of the loading direction. This effect is considered important because of the typical time histories of torque in the application under discussion. In test stands for automotive components it is typical that the direction of torque changes, even though the direction of revolution may be constant. The most evident example are uphill and downhill driving phases.

In order to define a clear quantitative definition of the mechanical remanence (at least) one full preload sequence is performed in one load direction, the zero signal is acquired, (at least) one full load cycle in the opposite load direction is performed and the zero signal is acquired again. The mechanical remanence is the difference between the two zero signals, expressed in torque units or as a percentage of the calibration range.

The same effect is also known as the hysteresis of the zero point, or toggle effect. The terminology and definition used in the present study are taken from a work of Röske and Peschel [2]. The same terminology has meanwhile also been implemented in the German DIN standard for torque calibration DIN 51309 [3].Their work has also shown the high importance of this parameter for alternating torque applications. The first aspect is, that the mechanical remanence is usually considerably bigger than all other effects which are classically included in the uncertainty budgets for torque measurements. Secondly, their study brought another important result: Knowing the mechanical remanence as defined above, plus the results from separate calibration for the two possible torque directions allows a very good approximation of a calibration for alternate torque.

From the definition it is very probable, that the mechanical remanence depends of the maximum torque for the load cycles. However, there are no published experimental studies on this dependency. To the knowledge of the authors, the present study is the first one to show this dependency, however only for one specific type of torque transducer. Furthermore, this type was designed to have an extremely small mechanical remanence.

The determination in the course of the presented study was based on a comparison of the zero signals at the following two specific moments of the test measurements:

1. after a complete measurement with clockwise torque, consisting of 3 preload cycles and one measurement cycle
2. after the complete measurement with counter-clockwise torque, consisting of 3 preload cycles and one measurement cycle

The results obtained for the mechanical remanence are shown in table 4.

Table 4. Comparison of mechanical remanence values

Calibration range		Specimen 1	Specimen 2	Specimen 3
100%	% of M_{nom}	-0.018 %	-0.024 %	-0.019 %
	% of M_E	-0.018 %	-0.024 %	-0.019 %
50 %	% of M_{nom}	-0.009%	-0.009%	-0.006 %
	% of M_E	-0.018 %	-0.018 %	-0.011 %
20 %	% of M_{nom}	-0.002 %	---	-0.002 %
	% of M_E	-0.010 %	---	-0.008 %
10 %	% of M_{nom}	---	-0.002%	---
	% of M_E	---	-0.013 %	---

A comparison of the remanence values shows that the values are smaller for the partial range calibrations than for the full range calibrations, even when expressed as percentages of the respective calibration ranges. This means, that for this parameter the downscaling for partial load operation could be chosen even stronger than linear.

5. CONCLUSION

5.1. General Tendency of the results

The aim of the study was to find out, how certain metrological parameters will change, when a torque transducer is to be used in a partial load range. It was found, that most parameters can be downscaled by a linear approach proportional with the downscaling of the operating range. For example, the parameter reversibility would have the same value (when expressed as a percentage of the actual operation range) for operation ranges smaller than 100 % of the nominal torque. The results are summarized in table 5.

Table 5. Summary of results
Resulting downscaling of metrological parameters when the calibration range is smaller than the nominal torque range

effect / parameter	downscaling
linearity deviation	linear (plus safety factor)
hysteresis / reversibility	linear (plus safety factor) for partial ranges down to 20%
zero return	not permissible
mechanical remanence	stronger than linear (plus safety factor)

The deviations of the sensitivities were found to be small too. Nevertheless, for transducers with a bigger nonlinearity, it makes sense to derive an adapted sensitivity for operation in the partial load range. Nevertheless, this will usually not require an extra calibration in the partial load range, if data from a full calibration are available with calibration points within the partial load range.

5.2. Additional Remarks

These results have been found by examining a relatively small number of specimens of one specific type and nominal torque. Nevertheless the authors are convinced that they may be generalized at least for a certain group of transducers:

- identical transducer type or types with comparable geometry of the measuring body
- transducer types made from the same material under reproducible production processes (e.g. heat treatment)
- transducer types with the same procedures and reproducible production processes for strain gage production and bonding

Of course, a reasonable safety factor must be used, when the results of this study are to be used for prognosis for other individuals than the tested specimens.

Furthermore, it has to be noted, that such results have been possible only by using an excellent calibration machine. In particular the presence of friction or bending moments would have harmful influence on the results.

The purpose and background of the study was, to derive a method for estimating the measurement uncertainty of torque transducers in a typical and difficult industrial application (power test stands). But it seems justifiable to generalize the results for a more general view of partial range calibrations.

The presented investigation was limited to one particular type of transducer of one particular manufacturer. It has revealed the excellent properties of this type, yet for comparison, it would be of interest to investigate other torque transducer types of other manufacturers.

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