

MEASUREMENT UNCERTAINTY OF TORQUE MEASUREMENTS WITH ROTATING TORQUE TRANSDUCERS IN POWER TEST STANDS

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ABSTRACT

The objective of the presented study is to introduce a method for estimating the measurement uncertainty of torque measurements. Unlike the well-known approaches, the uncertainty shall take into account the effects acting during torque measurement in industrial applications like power test stands. These effects include the effects also known from laboratory calibration like hysteresis, linearity or interpolation deviation, repeatability, reproducibility. But special emphasis is put on an estimation of their impact under the conditions in the power test stand. Additionally, further effects are included in the consideration, like temperature effects, the influences of parasitic loads and of rotational speed. The mathematical method for an estimation of the uncertainty is presented, the input quantities are discussed and suggestions are made how the uncertainty can be reduced for given applications.

1. INTRODUCTION

Often users of torque transducers ask for the accuracy of the torque measurement. A thorough answer to this question requires the estimation of the measurement uncertainty. This approach is common-ground in the scientific world of metrologists and calibration laboratories, but in the field of industrial applications of torque measurement the concept of measurement uncertainty still has to be established. Before discussing the details of uncertainty estimation it is however imperative, that the fundamental prerequisites for proper functioning of the measuring equipment are met such as proper conditions concerning EMC, chemicals and humidity and loading within the admissible range.

The procedure for estimating the measurement uncertainties requires knowledge of the technical data of the transducers and amplifiers on the one side and of the conditions in the application on the other side. Furthermore, a proper understanding is required of how to combine this information in order to estimate the effects under application conditions. An additional difficulty is the fact that only in very rare cases a complete calibration according to standards like DIN 51309 [1] or EA-10/14 [2] is performed for transducers for industrial use. But even if a complete calibration is planned, an estimation is often required before the components are available in hardware, during the quotation phase or the design phase. For such cases methods are required that allow rough estimations based on the technical specifications the manufacturers give in the data sheets.

2. MATHEMATICAL PRINCIPLE OF THE UNCERTAINTY ESTIMATION

First, one has to decide which effects will take influence on the measurement uncertainty in the given application. For each of these effects there needs to be quantitative information from two sides. First, the properties of the torque transducer regarding this effect and second, the description of the conditions acting in the application. The next step is the calculation of individual uncertainty contributions from the different effects. The principle of the calculation procedure is shown in the schematic, figure 1.

Unlike in the context of calibration, for this consideration all individual uncertainties are expressed as expanded uncertainties. This is a practical approach allowing a consistent

treatment of effects the influence of which is determined by calibration and effects the influence of which is described by technical specifications of the manufacturers. In the case of values determined from a calibration, the individual uncertainty contribution usually needs to be multiplied by the appropriate coverage factor (usually $k=2$) to obtain the expanded uncertainty. In the case of values specified by manufacturer's specifications, the values are usually upper bounds with a high level of confidence, so no additional coverage factor needs to be included.

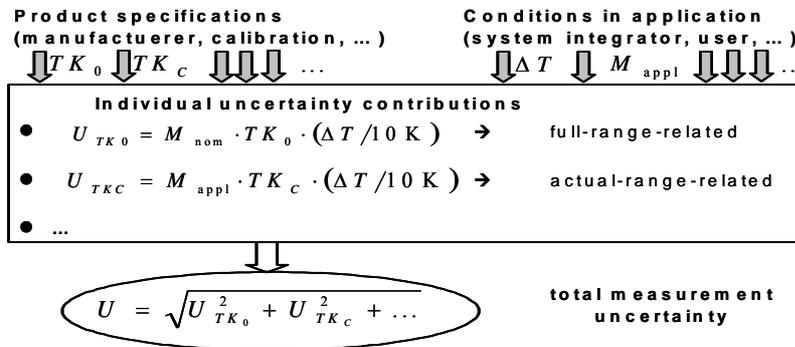


Figure 1: Calculation principle

All uncertainty values are expressed in torque units [N·m]. They apply to the entire range of the torque in the application. This meets the practical demands in test stands. To assign individual uncertainties to individual torque steps would be difficult because such a definition would also depend on the type of load cycle and this cannot be pre-defined because the variety is too big. Yet it is important to note that the range of torque in the application is not necessarily identical with the full range that a transducer model would allow.

The superposition of uncertainties is done according to the equation valid for superposition of standard deviations of statistically uncorrelated effects which follow a normal distribution. The influence of different distribution types (e.g. rectangular or triangular distribution) is not taken into account. This simplification always results in a safe-side estimation.

3. UNCERTAINTY CONTRIBUTIONS FROM THE INDIVIDUAL INFLUENCE EFFECTS

The most important effects are listed in Table 1, together with the sources where to obtain quantitative values describing these effects. The table answers the question whether the influence of the respective effect on the uncertainty is relative to the actual torque, the maximum torque of the calibration or to the maximum torque of the transducer. Also, it lists the source providing the values describing the effect quantitatively: the technical specifications provided by the manufacturer in the data sheets or a calibration.

When deriving equations for the uncertainty contribution of the individual effects it has to be considered that in this case the transducer with its properties (like hysteresis, reproducibility, etc.) is not the specimen, but the reference for the measurements under consideration. Therefore the influence certain properties take on the measurement uncertainty may differ from the influence they have in the calibration of a torque transducer. Also this influence depends on the information on the transducer that is available. In practice, this is the information used to set up the measuring amplifier. From a theoretical point of view, it is part of the method of transferring a reference torque from a higher level of rank (e.g. calibration laboratory) to this application.

Table 1: Properties of torque transducers influencing the measurement uncertainty

Property / Quantity (symbol)	Effect acting on ...			Available from ...			
	full range of transducer M_{nom}	full range of calibr. M_E	max. torque in application M_{appl}	data sheets	test protocol	calibration	experience
temperature effect on the zero signal (TK_0)	X) ¹			X			
temperature effect on the sensitivity (TK_C)			X	X			
hysteresis / reversibility (h / d_{hys})		X		X	X	X	
linearity deviation / interpolation error ($dlin / f_a$)	X		X) ²	X	X	X	
linearity incl. hysteresis (d_{lh})		X		X	X		
repeatability (b' / σ_{rel})				X		X	
reproducibility (b)						X	
uncertainty of calibration / of sensitivity (u_{KE} / d_C)	X		X) ²			X	
mechanical remanence (f_{rem})			X			X) ³	
influence of parasitic loads (d_{para})	X) ¹			X		X) ³	
influence of speed of rotation (d_{speed})	X) ¹						X
influence of adaptation parts	X) ¹						X

)¹ The effects are not determined by torque, but by other (ambient) influences. However the relation with the full range of the transducer (nominal or rated torque) is the accepted way of communicating these effects.

)² Usually, the values specified in data sheets by the manufacturers are related to the full range of the transducer (nominal or rated torque). In a proper calibration however, the values will be given relative to the respective torque step.

)³ Requires special non-standard calibration procedures.

The equations for the individual uncertainty contributions given in table 2 are for two alternative scenarios: The first scenario is for the case that the transducer's properties have been determined by a full calibration according to standards like DIN 51309 or EA-10/14. This is however quite seldom the case in industrial measurement. The second scenario is that the data has to be taken from manufacturer's data sheets. This is the scenario that holds in particular, when a first estimation of the uncertainty has to be made before the system (e.g. test stand) has been built. Of course, the values obtained from calibration are usually better for the uncertainty estimation. Yet there are values which a calibration does not provide, such as the temperature effects. These have to be taken from data sheets in any case. Finally, there are effects neither specified in data sheets nor determined during a normal calibration. For these effects, pragmatical values have to be based upon experiences. Leading manufacturers can often provide support concerning their products.

Of course such a list can never be complete, there are more influences that potentially should be taken in account under certain conditions. It must also be noted, that this only includes the effects which are connected with properties of the torque transducers. But there are also effects which are entirely determined by properties of the rest of the system and yet influence the measurement uncertainty. The most important example for such an effect is friction of bearings or even air. This generates a torque which acts as a difference between the torque indicated by the measuring device and the torque the user is interested in (e.g. the torque generated by a motor or engine). Another example is the torque required for accelerating shaft components due to their inertia.

Table 2: Determination of the uncertainty contributions from individual transducer properties

Property / Quantity (symbol)	requires calibration		Expanded uncertainty from individual effect [in torque units]
	yes	no	
temperature effect on the zero signal (TK_0)		X	$U_{TK0} = M_{nom} \cdot TK_0 \cdot \frac{\Delta T}{10K}$
temperature effect on the sensitivity (TK_C)		X	$U_{TKC} = M_{appl} \cdot TK_C \cdot \frac{\Delta T}{10K}$
hysteresis: reversibility (h)	X		$U_{hys} = k \cdot \max_{M=0 \dots M_{appl}} [h(M)]$
hysteresis: hysteresis error ($d_{hys,max}$)		X	$U_{hys} = M_{nom} \cdot d_{hys,max}$
linearity deviation / interpolation error (f_a)	X		$U_{lin} = \max_{M=0 \dots M_{appl}} [f_a(M)]$
linearity deviation / interpolation error (d_{lin})		X	$U_{lin} = M_{nom} \cdot d_{lin}$
linearity incl. hysteresis (d_{lh})		X	$U_{lh} = M_{nom} \cdot d_{lh}$
repeatability (b')	X		$U_{b'} = k \cdot \frac{1}{2} \cdot \max_{M=0 \dots M_{appl}} [b'(M)] \cdot)^*$
repeatability (σ_{rel})		X	$U_{b'} = k \cdot \frac{M_{appl}}{\Delta M_{ref}} \cdot \Delta M_{ref} \cdot \sigma_{rel}$
reproducibility (b)	X		$U_b = k \cdot \frac{1}{2} \cdot \max_{M=0 \dots M_{appl}} [b(M)] \cdot)^*$
uncertainty of calibration / of sensitivity (u_{KE})	X		$U_K = k \cdot \max_{M=0 \dots M_{appl}} [u_{KE}(M)]$
uncertainty of calibration / of sensitivity (d_C)		X	$U_K = M_{nom} \cdot d_C$
mechanical remanence (f_{rem})			$U_{rem} = \frac{M_{appl,max+} - M_{appl,min-}}{2 M_E} \cdot f_{rem}(M)$
influence of parasitic loads (d_{para})	X		$U_{para} = M_{nom} \cdot d_{para} \cdot \frac{L_{para}}{L_{para,ref}}$
influence of speed of rotation (d_{speed})	X		$U_{speed} = \left(\frac{n_{appl}}{n_{nom}} \right)^2 \cdot d_{speed} \cdot M_{nom}$
influence of adaptation parts			no general form for equation

)* In these cases, the maximum effect is only half the span determined by the calibration. This is because the amplifier adjustment can be based on the average between these limits.

Thus, the equation equation for a total uncertainty including all the effects listed, is

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

In this equation, the uncertainty contribution U_{lh} is not contained, because the effects linearity deviation and hysteresis are already taken into account by the individual contributions U_{lin} , and U_{hys} .

4 - QUANTITATIVE DETERMINATION OF THE CONDITIONS

The above discussion of the mathematical treatment has shown that the exact knowledge of the conditions in the application is of utmost importance for a reliable estimation of the measurement uncertainty of measurements in an application. However this is a lot more complex than one might expect. Only a few examples will be given to illustrate this.

The maximum and minimum torque in the application need to be known in order to determine the influence of all those quantities the effects of which depends on actual torque or the maximum torque in the application. Examples are the temperature effect on the sensitivity and hysteresis. Also, a good knowledge of the maximum torque may allow to choose a transducer with a smaller nominal range and thus better accuracy properties. The problem with determining the maximum torque is, that often only an average torque is known, as the torque signal obtained with a low pass filter or the averaged signal over a certain number of engine revolutions. But it is the dynamic processes which determine the real maximum loads. For example the peaks occurring in the instances of the combustion in a combustion engine.

The relevant temperature for the calculation of the effects of the TK_0 and TK_C is the temperature of the transducer, not the ambient temperature. This temperature depends on the ambient temperature, the heat generated by the machines in the system (e.g. combustion engines, electric dynamometers or motors) and the heat conduction in the system. Heat conduction is partly the conduction in the metal parts and partly the cooling effect from the surrounding air to rotating machine parts. To determine this temperature, either measurements of the temperature have to be done on single components of the rotating shafts or a complex mathematical estimation is necessary.

Parasitic loads are maybe the most complex quantity to estimate. They depend on the prestresses from misalignment and geometric eccentricity. In order to obtain this effect quantitatively one needs the tolerances for these geometric errors and the stiffness coefficients (in particular bending stiffness) of the shaft components and the influence of bearings. In addition, this situation is also subject to thermal deformation on the geometry. So the parasitic loads may change under operation conditions. The second general source for parasitic loads are the dynamic forces generated by unbalance. They depend of the residual unbalance, the stiffness and bearing situation and speed. Again a mathematical estimation requires quite complex mathematical models. Even if vibration measurements are possible, they will usually give vibration deflections, velocities, accelerations or local stresses in certain measuring points. So even in this case, some complex mechanical modelling is necessary for determining the parasitic loads in the form required here.

5. METHODS FOR REDUCING THE MEASUREMENT UNCERTAINTY FOR AN APPLICATION

There are several different approaches for improving the measurement uncertainty in a given application. Of course, the best result is obtained, when all of them are combined.

The first approach is the one that usually considered first: Use a transducer with improved specifications. But there are other possibilities that can often be equally or even more effective.

The second approach is a more accurate determination of the transducer properties. This is done very effectively by a calibration according to high standards. A further optimization of information can be achieved, when the calibration range is adapted to the range the transducer

will be used in. Even in the worst case, when an individual transducer is not better than specified by the manufacturer, this will lead to better results in the estimation. For example the effect of repeatability is reduced, when the characteristic line is based on the average of several measurements of the same torque.

The third approach is: Improve the physical conditions in the application, examples for such measures are: Temperature isolation may reduce heat flux from driving machine or retarding machine (e.g. electric machines or combustion engines) to the transducer. Thus temperature conditions for the transducer may become better. Parasitic loads too can be reduced by designing the test stand appropriately. Adaptation parts may be designed equivalent to those used during calibration, alternatively calibration can be performed with the original adaptation parts (like for example in on-site calibration). Details on this question have been shown by Andrae in [3].

The fourth approach is: Improve the metrological processes and concepts in the application. For example it is often quite easy to eliminate the effect of the temperature effect on the zero signal. This can be done by performing a zero adjustment of the measurement amplifier only after the system has reached its stable working temperature. As can be seen in the study of Roeske and Peschel [4], the effect of the remanence can be halved when a zero point adjustment takes this effect into account. This can be done if the effect is known and a defined preloading sequence is performed before the zero adjustment of the amplifier. Further examples can be found. Another group of measures that belong the category of improving metrological processes deals with the effects that are not directly connected with properties of the torque measuring device. Examples are test-runs with disconnected shaft train, i.e. without any test object (e.g. transmission). The data acquired in such a test run is taken as the reference, and only the difference between this reference data and the data acquired in a real test run is considered the measuring result. By this method many effects of bearing friction, air friction and inertia can be compensated.

In particular the third and fourth approach offer a wide field for improvements, that engineers responsible for test stand concepts are usually not sufficiently aware of. Only a few hints could be given in this publication, a quantitative study of would be of great interest.

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