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The New version of the German torque calibration standard DIN 51309:2005-12 a comparative overview

D. Röske

Physikalisch-Technische Bundesanstalt (PTB, Germany) Email: dirk.roeske@ptb.de

Abstract

In December 2005, the new version of the DIN 51309 was issued by DIN, the German Institute for Standardization. This standard takes into account some fundamental ideas about the target application of a torque transducer, for example high-level inter-comparison measurements or measurements in industrial environments. Two cases are considered and two different calibration results are calculated on the basis of a standard calibration procedure. For some inter-comparisons, the hysteresis of the transducer does not have any influence on the result and is therefore excluded. This paper shows, on the one hand, the new version in comparison with other standards (e. g. EA-10/14) and some guidelines of the DKD, the German Calibration Service, and describes, on the other hand, its application to torque reference machines.

Keywords: torque, calibration standard, DIN51309, hysteresis, torque reference machine

1 Introduction

The calibration procedure of a measuring instrument should meet the requirements of the device's future application as accurately as possible, and a suitable calibration result should be calculated on this basis. On the other hand, calibrations should be carried out according to existing standards or guidelines for the calibration. One of the well-established calibration standards for static torque measuring devices is the DIN 51309 [1]. Nevertheless, there had been some weaknesses in the former version of this standard regarding mainly the uncertainty calculations and the conformity to the "Guide to the Expression of Uncertainty in Measurement" (GUM). The revision of this standard in the years 2004 and 2005 offered the possibility for some improvements. These will be explained later on in this paper.

DIN 51309 : 1998-02

In the past, according to the former version of the standard [2], there was only one calibration result:

The calibration result X_r shall be calculated according to equation (1*) as the mean value of the indicated results obtained from the increasing series in the changed rotated mounting positions.

$$X_{\mathrm{r}} = \frac{1}{n} \sum_{j=1}^{n} \left(I_j - I_{0,j} \right) \tag{1*}$$

where

n number of increasing series in different mounting positions.

The results measured in the 0° position in the second series at increasing torques (classes 0.05 to 0.5) are not included in the calculation of X_r .

$I_j - I_{0,j}$ is the zero-reduced indication of the transducer at the given load step in mounting position j.

The hysteresis h, caused among other things by creep in the material of the transducer's elastic body and the strain gauge application, is considered as a random variable as well as the deviation associated with the interpolation (f_a):

The relative uncertainty of measurement is calculated according to equation (C.3) for each calibration stage.

$$u_{\mathrm{MG}}^2 = \frac{1}{12} f_0^2 + \frac{1}{12} b'^2 + \frac{1}{8} b^2 + \frac{1}{24} f_{\mathrm{a}}^2 + \frac{1}{12} \left(\frac{r}{M_{\mathrm{K}}} \right)^2 + \frac{1}{6} h^2 \quad . \tag{C.3*}$$

In (C.3*), the following designations are used:

b - relative repeatability error in different mounting positions

b' - relative repeatability error in unchanged mounting position

f_0 - relative error of the residual zero signal

r - resolution of the indicating device

M_K - the applied calibration torque.

In the case of reduced calibrations for the classes 1, 2 or 5, instead of measuring b', the contribution of b ($\frac{1}{8} b^2$) will be taken into account a second time.

It is known that the hysteresis is a systematic deviation and not a random one, therefore (C.3*) is not correct. The same applies to the deviation from the linear fitting curve. Hence, (1*) is not suitable for applications where increasing and decreasing torque values are measured.

Last but not least, there was no mathematical model given as a basis for an uncertainty calculation in conformance with the GUM.

THE NEW DIN 51309

Calibration results

The new version of the DIN 51309 [1] takes this into account. First of all, the most obvious modification is the calculation of two different results (see figure 1) – one for measurements with increasing torque value only (case I) and one for increasing and decreasing torque amplitudes (case II). In the first case, the result Y given by

$$Y(M_\mathrm{K}) = \frac{1}{n}\sum_{j=1}^{n}\left(I_j\left(M_\mathrm{K}\right) - I_{0,j}\right) \tag{1}$$

is the same as in (1*) before. But the hysteresis is completely ignored and does not contribute to the uncertainty of measurement, thus “improving” the result by reducing the uncertainty. This case is applicable to high-precision measurements, for example in comparisons of torque standard machines with lever-mass-systems and air bearings - but also to measurements with increasing torque only, for example the measurement of the increasing tightening moment of a screw connection.
In the second case, the result Y_h is given by

$$Y_\mathrm{h}(M_\mathrm{K}) = \frac{1}{n}\sum_{j=1}^{n}\left(\frac{I_j\left(M_\mathrm{K}\right) + I'_j\left(M_\mathrm{K}\right)}{2} - I_{0,j}\right), \tag{2}$$

i. e. the mean over the different mounting positions of the mean value of the indications at increasing I_j and decreasing I'_j torques reduced by the zero indication $I_{0,j}$ prior to the measurement series. The subscripted “h” indicates that the hysteresis will be taken into account here (see below).

In conformity with the GUM, the symbol Y is used for the result, thus emphasizing that it is an output quantity of the calibration. The input quantities are now denoted by X.

8 Auswertung / *Analysis*

8.1 Kalibrierergebnis / *Calibration results*

Dreh-moment / *torque* in N·m	Fall I / *case* I — Signal / *signal* in mV/V	Fall I / *case* I — rel. Messunssicherheit / *rel. uncertainty* $k = 2$ — Ausgleichsfunktion / *interpolation* — kubisch / *cubic*, in %	linear, in %	Fall II / *case* II — Signal / *signal* in mV/V	rel. Uns.-intervall/ *rel. uncert. interval* $k = 2$ — linear, in %
Rech					
0	0,000000			-0,000083	
10	0,100011	0,017	0,260	0,100026	0,196
20	0,200048	0,017	0,234	0,200141	0,166
30	0,300117	0,017	0,204	0,300269	0,146
40	0,400224	0,017	0,170	0,400414	0,126
50	0,500375	0,017	0,133	0,500583	0,105
60	0,600576	0,017	0,091	0,600783	0,083
80	0,801152	0,017	0,019	0,801295	0,038
100	1,002000	0,017	0,119	1,002000	0,058
Links					
0	0,000000			0,000083	
-10	-0,100011	0,017	0,260	-0,100026	0,196
-20	-0,200048	0,017	0,234	-0,200141	0,166
-30	-0,300117	0,017	0,204	-0,300269	0,146
-40	-0,400224	0,017	0,170	-0,400414	0,126
-50	-0,500375	0,017	0,133	-0,500583	0,105
-60	-0,600576	0,017	0,091	-0,600783	0,083
-80	-0,801152	0,017	0,019	-0,801295	0,038
-100	-1,002000	0,017	0,119	-1,002000	0,058

Figure 1: Results of a calibration according to DIN 51309 (synthetic data – screenshot from a calibration certificate)

Regressions

The old version of the DIN standard required fitting curves (somewhat improperly called “interpolation functions”) of 1st, 2nd and 3rd degree without absolute term (only 1st degree for classes 1 to 5). A large number of calibration certificates produced at PTB showed that the approximation of the measurement results with a linear and a cubic function is sufficient. There is no need for an additional quadratic regression. Furthermore, from the application’s point of view there is often the possibility to adjust the sensitivity using a linear scaling factor and a linear regression. When a PC is used, the fitting curve can be of any degree, but the cubic function is adequate. Therefore the calculation of a 2nd degree function was omitted. Furthermore, the calculation of the 3rd degree function is now necessary only for case I assuming that a higher precision requires a higher degree of approximation. The result calculated for case II according to (2), thus averaging the hysteresis for increasing and decreasing torque nearly to zero, is very often quite linear. In addition, the non-linearity of the result (2) is normally much smaller than the effect of the hysteresis. Therefore only a linear regression is applied.

9 Interpolationsgleichungen / *Interpolation equations* S in mV/V M in N·m

9.1 Fall I, Kubische Interpolationsgleichung / *Case I, Cubic interpolation equation:*

9.1.1 Rechtsdrehmoment / *clockwise torque:*

$$S_{ai} = 0{,}01 \cdot M_i + 0{,}0000001 \cdot M_i^2 + 0{,}000000001 \cdot M_i^3$$
$$M_{ai} = 100{,}0002 \cdot S_i + -0{,}1011 \cdot S_i^2 + -0{,}0981 \cdot S_i^3$$

9.1.2 Linksdrehmoment / *anticlockwise torque:*

$$S_{ai} = 0{,}01 \cdot M_i + -0{,}0000001 \cdot M_i^2 + 0{,}000000001 \cdot M_i^3$$
$$M_{ai} = 100{,}0002 \cdot S_i + 0{,}1011 \cdot S_i^2 + -0{,}0981 \cdot S_i^3$$

9.2 Fall I, Lineare Interpolationsgleichung / *Case I, Linear interpolation equation*

9.2.1 Rechtsdrehmoment / *clockwise torque:*

$$S_{ai} = 0{,}01001408 \cdot M_i$$
$$M_{ai} = 99{,}8594 \cdot S_i$$

9.2.2 Linksdrehmoment / *anticlockwise torque:*

$$S_{ai} = 0{,}01001408 \cdot M_i$$
$$M_{ai} = 99{,}8594 \cdot S_i$$

9.2.3 Rechts- und Linksdrehmoment / *clockwise and anticlockwise torque:*

$$S_{ai} = 0{,}01001408 \cdot M_i$$
$$M_{ai} = 99{,}8594 \cdot S_i$$

(siehe Fußnote / *see footnote*)

9.3 Fall II, Lineare Interpolationsgleichung / *Case II, Linear interpolation equation*

9.3.1 Rechtsdrehmoment / *clockwise torque:*

$$S_{ai} = 0{,}01001598 \cdot M_i$$
$$M_{ai} = 99{,}8405 \cdot S_i$$

9.3.2 Linksdrehmoment / *anticlockwise torque:*

$$S_{ai} = 0{,}01001598 \cdot M_i$$
$$M_{ai} = 99{,}8405 \cdot S_i$$

9.2.3 Rechts- und Linksdrehmoment / *clockwise and anticlockwise torque:*

$$S_{ai} = 0{,}01001598 \cdot M_i$$
$$M_{ai} = 99{,}8405 \cdot S_i$$

(siehe Fußnote / *see footnote*)

Figure 2: Fitting functions of a calibration according to DIN 51309 (synthetic data - screenshot from a calibration certificate), (Footnote: The linear interpolation equation for clockwise torque and anticlockwise torque cannot be used as a calibration result for alternating torque. It can only be used to adjust the indicator optimally for clockwise torque and anticlockwise torque with a single calibration factor.)

Uncertainties

Another major difference between the two issues of the standard is the definition of the parameters for the uncertainty contribution:

- reproducibility b
- repeatability b'
- residual zero deviation f_0
- hysteresis h
- deviation from fitting curve f_a
- deviation of the indication for transducers with defined scale f_q.

All these parameters are now calculated in absolute terms, i.e. in indicated units and not in %. Their relative values must be calculated for the classification. This means that, in general, there will be different classifications for cases I and II.

Instead of (C.3*) there are now different possibilities to calculate an uncertainty (with the same minor change for transducers of class 1, 2 or 5 as before).

1. Case I, Cubic Regression

In this case the relative expanded (k = 2) **uncertainty** of measurement is calculated according to

$$W(M_{\mathrm{K}}) = 2 \cdot \sqrt{w_{\mathrm{KE}}^2(M_{\mathrm{K}}) + 2 \cdot w_r^2(M_{\mathrm{K}}) + w_b^2(M_{\mathrm{K}}) + w_{b'}^2(M_{\mathrm{K}}) + w_0^2(M_{\mathrm{E}}) + w_{fa}^2(M_{\mathrm{K}})} \qquad (3)$$

with uncertainty contributions from Table 1. The factor 2 near $w_r^2(M_{\mathrm{K}})$ takes into account that a measurement value is calculated as the difference between the reading at calibration torque and the reading at zero, thus containing the influence of the resolution r twice. The residual zero deviation f_0 reflects some influence of the creep (see below), but it can be neglected in most of the cases.

2. Case I, Linear Regression

Due to the systematic nature of the deviation f_{a} from the linear fitting curve, the relative expanded (k = 2) **uncertainty** of measurement is calculated according to

$$W(M_{\mathrm{K}}) = 2 \cdot \sqrt{w_{\mathrm{KE}}^2(M_{\mathrm{K}}) + 2 \cdot w_r^2(M_{\mathrm{K}}) + w_b^2(M_{\mathrm{K}}) + w_{b'}^2(M_{\mathrm{K}}) + w_0^2(M_{\mathrm{E}}) + \left(\frac{f_{\mathrm{a}}(M_{\mathrm{K}})}{Y(M_{\mathrm{K}})} \cdot 100\%\right)^2} \qquad (4)$$

with the uncertainty contributions from Table 1.

3. Case II, linear regression

Due to the systematic nature of the hysteresis h and the deviation f_{a} from the linear fitting curve, an **uncertainty interval** is calculated according to

$$W'(M_{\mathrm{K}}) = \left|\frac{f_{\mathrm{a}}(M_{\mathrm{K}})}{Y_{\mathrm{h}}(M_{\mathrm{K}})}\right| \cdot 100\% + \left|\frac{h(M_{\mathrm{K}})}{2 \cdot Y_{\mathrm{h}}(M_{\mathrm{K}})}\right| \cdot 100\% + 2 \cdot \sqrt{w_{\mathrm{KE}}^2(M_{\mathrm{K}}) + 2 \cdot w_r^2(M_{\mathrm{K}}) + w_b^2(M_{\mathrm{K}}) + w_{b'}^2(M_{\mathrm{K}}) + w_0^2(M_{\mathrm{E}})} \qquad (5)$$

with the uncertainty contributions from Table 1, but now related to $Y_{\mathrm{h}}(M_{\mathrm{K}})$. The deviation from the fitting curve f_{a} is now calculated for a linear function approximating the result $Y_{\mathrm{h}}(M_{\mathrm{K}})$ according to (2).

Creep

The creep is a very important property of a torque (or force) transducer with respect to the hysteresis determined in the calibration, but also for the application of the device. The new version of the DIN 51309 is the first standard requiring an information about the creep, although it is not used in the uncertainty calculation or the classification. The correlation between creep and hysteresis can be investigated knowing the loading regime during the calibration (load-time-diagram), but the application of the device is normally not known to the calibrating laboratory, therefore the creep should be of greater importance to the customer than to the calibrator.

The creep value is calculated on the basis of the short-term creep in a three- minute waiting time interval after the last preloading prior to the measuring series. In the past, a statistical investigation of this creep over three minutes showed that this value, multiplied by 4, is in very good agreement with the result of a normal creep test over 20 minutes [3].

8.3 Kriecheinfluss aus Kurzzeitkriechen / *Creep influence from short-term creep*
Vor der ersten Messreihe jeder Einbaustellung wurde die Signaländerung während einer dreiminütigen Wartepause registriert.
Das arithmetische Mittel der auf den zugehörigen Endwert bezogenen Änderungen ist das Kurzzeitkriechen.
The signal variation during a three-minute waiting interval was recorded before the first series of every mounting position.
The short-term creep is the arithmetic mean of the related to the corresponding full-scale value variations.
Das mit dem Faktor 4 multiplizierte Kurzzeitkriechen ergibt / *the short-term creep multiplied by 4 yields* -0,004 %.

Figure 3: Creep value measured in a calibration according to DIN 51309 (synthetic data - screenshot from a calibration certificate)

Calibration Procedure and Calculations

It is worth noting, that the calibration procedure itself is not affected by the modifications in DIN 51309. The number of steps, series and mounting positions has not altered. Only the estimation and calculation of the calibration results differ. It is, of course, hard work to integrate all additional calculations into the software, to change the layout and the content of the calibration certificate and to do this without any mistakes and errors. For this purpose, PTB's torque working group is offering some test data sets by means of which the correctness of the calculations can be verified. All the formulas and intermediate results are available in Microsoft Excel and can be checked – something that is often impossible with proprietary software.

Problem with Torque Machines of Reference Type

Torque measuring machines of the reference type use a calibrated torque transducer as a reference and their indication contains the information about the applied torque. In the former version of the standard, linear, quadratic and cubic fitting curves were given for clockwise and anti-clockwise directions (the case of a common function for clockwise and anti-clockwise directions is not considered here). Now we have one cubic and two linear (case I and case II) fitting functions and the question arises which of these is the right one.

The answer is: it all depends on the application. If the machine is used with increasing torque values only, then all three functions can be used. Usually the deviation from the cubic function, i.e. the uncertainty, is smaller and yields the best results. Next comes the linear function of case I which will be better suited than that of case II, because the hysteresis is not taken into account. The worst uncertainty is associated with case II. On the other hand, a machine measuring only increasing torque values is not compatible with DIN 51309.

In the case of increasing and decreasing torque values, case II can be applied, but the result will often be not satisfying. The hysteresis being a property of the transducer should not deteriorate the uncertainty of the machine. For high-precision applications, case I should be adopted, if possible with cubic fitting function, which is not a problem for increasing torque values. But a second cubic function must be determined from the calibration data for decreasing torque values. This function will have an absolute term due to the residual zero signal and a common point with the function for increasing torque values at maximum calibration torque. (PTB's torque working group offers an annex to the calibration certificate containing these functions and their inverses.) In the application, depending on the direction of the torque change, the one or the other fitting function must be taken to determine the calibration torque. The problem remains, of course, if the reference transducer is not used in the full range. The function for increasing torque values can be used as before, but a new function must be calculated for the decreasing torque values. This problem will be the subject of another publication.

Comparison with other Standards

The EA-10/14 [4] issued in July 2000 (now under revision as new EURAMET Guide) can be considered as a model for a part of the new DIN. Its scope is the "static calibration of torque measuring systems using supported beams or the comparison method with reference transducer". The uncertainty calculation [4, (11a)] is the same as in (3), except for the omitted contribution $w_0^2(M_\mathrm{E})$ of the residual zero deviation f_0.

Hysteresis ("reversibility") is only considered for classification (Annex C) if increasing and decreasing torque is applied. There is no uncertainty calculation given in which the reversibility is included. Furthermore, in EA-10/14, there is neither a calibration result for increasing and decreasing torque and corresponding fitting curves mentioned, nor creep.

The DKD-R 3-7 [5] is a German standard for higher precision indicating torque wrenches. Such wrenches can be used as transfer wrenches for the calibration of torque wrench calibration devices. The calibration result is calculated from the increasing torque only and, instead of the deviation from a fitting curve, the deviation of the indication is determined. The reversibility is treated as a random variable like in the old DIN version. In some cases the influence of a changed lever arm length is dominant and the reversibility does not play a major role.

The DKD-R 3-5 [6] is a German standard for alternating torque, i.e. the application and measurement of clockwise and anti-clockwise torque in one set-up. It is remarkable that as a rule, the maximum reversibility in the case of alternating torque is observed near the zero signal. This effect is called "mechanical remanence". Graphically it is visualized by a big loop having the shape of a lense, and very often it covers some other effects, such as non-linearity and dependence on the mounting position. The main problem is that the user of a calibrated torque transducer normally has no information about the current working point on the loop, therefore the uncertainty is at least twice the reversibility and its influence on the measurement is especially strong in the lower range of torque amplitudes. The reduction of this influence using, for example, fitting curves, brings about the same problem as described above – for the full range it is possible, but in partial ranges different functions must be defined. The result of a DKD-R 3-5 calibration is calculated as the mean value between increasing and decreasing series and only a linear regression is used. This corresponds to case II of the new DIN 51309, although the clockwise and anti-clockwise results are independent in the DIN in contrast to the DKD-R 3-5.

CONCLUSION

The calibration procedure of a measuring instrument should always meet the requirements of the device's future application. The new version of the DIN 51309 takes this into account. Besides some improvements with respect to the GUM it offers now more possibilities for the customer. Depending on the measurement problem, different calibration results and corresponding uncertainties can be used in order to reduce the uncertainty in the target application. Important for the customer is to have the background knowledge about these calibration results.

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(translated: DKD-R 3-5, Issue: 1998-12, Calibration of torque measuring devices for static alternating torques)

Table 1: Parameters, distributions and corresponding relative standard uncertainties

parameter	distribution	relative standard uncertainty w in %
resolution r	type B rectangular	$w_r = \dfrac{\left(\dfrac{r}{2}\right)}{\sqrt{3}} \cdot \dfrac{100}{M_\mathrm{K}}$
reproducibility b	type B rectangular	$w_b = \dfrac{\left(\dfrac{b(M_\mathrm{K})}{2}\right)}{\sqrt{3}} \cdot \dfrac{100}{Y(M_\mathrm{K})}$
repeatability b'	type B rectangular	$w_{b'} = \dfrac{\left(\dfrac{b'(M_\mathrm{K})}{2}\right)}{\sqrt{3}} \cdot \dfrac{100}{Y(M_\mathrm{K})}$
residual zero deviation f_0	type B rectangular	$w_0 = \dfrac{\left(\dfrac{f_0}{2}\right)}{\sqrt{3}} \cdot \dfrac{100}{Y(M_\mathrm{E})}$
deviation from fitting curve f_a	type B triangular	$w_{f\mathrm{a}} = \dfrac{\left(\dfrac{f_\mathrm{a}(M_\mathrm{K})}{2}\right)}{\sqrt{6}} \cdot \dfrac{100}{Y(M_\mathrm{K})}$