IMEKO 23rd TC3, 13th TC5 and 4th TC22 International Conference
30 May to 1 June, 2017, Helsinki, Finland

# INVESTIGATION OF THE CALIBRATION CAPABILITIES OF A 1 KN·M AND 10 KN·M REFERENCE CALIBRATION MACHINE

*F. Crößmann*

Hottinger Baldwin Messtechnik GmbH, Darmstadt, Germany, felix.croessmann@hbm.com

**Abstract** – To expand the capacity of its calibration laboratory, Hottinger Baldwin Messtechnik GmbH is planning to use two new reference calibration machines in the range up to 1 kN·m and 10 kN·m respectively. In addition to the theoretical consideration of the individual elements contributing to measurement uncertainty, measurement data is also compared using the $E_n$ value as a demonstration of the target measurement uncertainty of 0,02% ($k$ = 2).

**Keywords:** torque, calibration machine, measurement uncertainty

## 1. INTRODUCTION

As in most national metrology institutes, in the calibration laboratory of Hottinger Baldwin Messtechnik GmbH (HBM), dead weight machines are used to calibrate torque transducers. They offer the advantage of the lowest possible measurement uncertainty. Thus the minimum achievable measurement uncertainty of the according to ISO 17025 DAkkS-accredited HBM calibration laboratory for the torque range from 100 N·m to 10 kN·m considered in this article is $8 \cdot 10^{-5}$ (25-kN·m Torque Reference Standard Machine). The constantly rising demand for calibration certificates, especially for industrial applications, driven for example by the requirements of ISO 9001 certification, has led in the past to an enormous increase in the utilization of existing calibration machines. In addition to extensive calibrations to DIN 51309 or EURAMET cg-14 [3, 5], calibrations with reduced scope, for example to VDI/VDE 2646 [12], are also becoming more important. These circumstances have led to a growing use of high-precision dead weight machines for calibrating industrial sensors with lower accuracy requirements, such as the HBM transducer type T40B or T10F. To meet this rising demand now and in the future, HBM is planning to expand its fleet of systems, beginning with two independently developed calibration machines based on the reference principle in the range up to 1 kN·m and 10 kN·m respectively. The use of reference calibration machines not only allows for freely selectable calibration stages over the entire load range, but also makes it possible to record measured values while continuously adding or removing the load.

In this article the individual uncertainties relevant in determining overall uncertainty are named and quantified on the basis of tests performed, then the expanded measurement uncertainty is calculated using the 1 kN·m calibration machine as an example. In addition to this theoretical description of the machine measurement uncertainty, the measurement performance of both machines will be examined by means of $E_n$ comparison in terms of meeting the target expanded measurement uncertainty of $2 \cdot 10^{-4}$.

## 2. DESCRIPTION OF THE REFERENCE CALIBRATION MACHINE AND ITS MAIN COMPONENTS

The calibration machine is divided into three modules: system 1 (up to 1 kN·m), system 2 (up to 10 kN·m) and the mounting space between them. The mounting space makes it possible to mount the adapter outside of the calibration machine so that the transducer being tested can then be inserted into the relevant machine by means of carriers. This reduces mounting time within the machine to a minimum. The two reference calibration machines are nearly identical in structure, differing only in the nominal torque of the installed measuring references. Both machines are structured according to the 3-column principle as it is used for example in the calibration machine presented by Wozniak et al. at the Central Office of Measures (GUM, Poland) [13]. The measuring line is aligned vertically, which minimizes the space required as well as reducing the effect of parasitic bending torques due to the intrinsic weight of the torque transducer being tested and the effect of the adaptation required for installation.

The connection between the adapter of the sensor being tested and the calibration machine was implemented based on DIN ISO 12667 [4] with staggered teeth. This makes it possible to measure in the three installation positions required for DIN 51309 and in contrast to the intermeshing described in the standard, due to its symmetrical structure it ensures uniform transfer of torque [1] with fast and easy assembly. To reduce the effect of shape and mounting tolerances on the calibration machine, pliable couplings are installed above the reference transducer and below the device being calibrated.

TB2 reference torque transducers from HBM with a maximum capacity of 1 kN·m and 10 kN·m respectively are used as a measurement reference. HBM MGCplus data acquisition systems with ML38B measuring amplifier modules for the reference transducer and calibrated device with mV/V signal are used as measuring amplifiers. If the device being calibrated has a frequency output, a measuring amplifier type ML60B is used. The calibration machine is controlled by a control program developed by HBM which makes it possible to perform the calibration completely automatic, including recording of measurement data. To reduce machine complexity, the current machine layout has no provision for active control in holding the load stage, with the result that the signal change shown in figure 4 represents the creep of the machine and of the transducer. However, overlapping these two effects does require mechanical separation of the calibrated device by opening the load line for the short-term creep to be determined as part of DIN 51309.

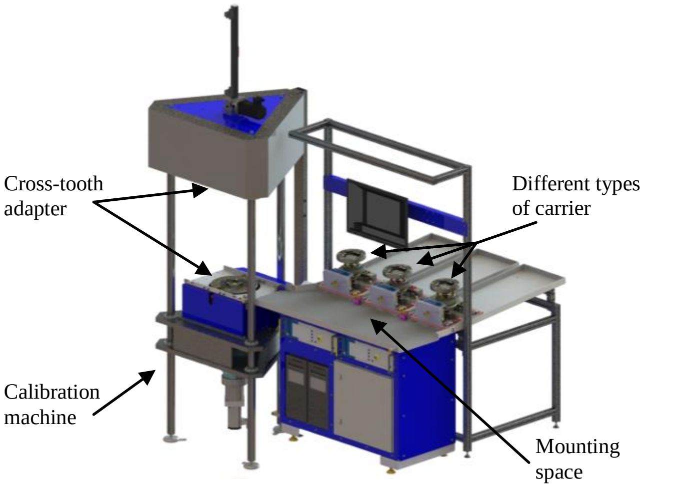


Fig. 1: CAD picture of the calibration machine with its mounting space

## 3. CALCULATION OF THE MEASUREMENT UNCERTAINTY

The process for determining the connected measurement uncertainty is explained below based on the example of a 1 kN·m system. Unless explicitly noted otherwise, statements made here also apply to the 10 kN·m system. Figure 2 shows the individual groups contributing to the overall measurement uncertainty. The individual elements contributing to the overall measurement uncertainty are explained in detail in sections 3.1 through 3.5. The expanded measurement uncertainty of the calibration machines can then be calculated in section 3.6 based on the model equation (4) that is set up.

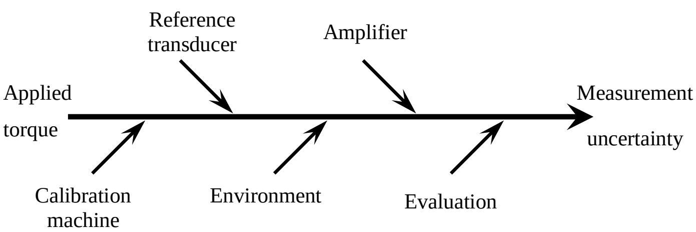


Fig. 2: Ishikawa diagram

### 3.1 Reference Transducer

$\boldsymbol{w}_{\mathbf{Rt}}$ – The reference transducer used, HBM type TB2, was calibrated with its adaptation in the HBM DAkkS-accredited calibration laboratory to DIN 51309. The uncertainty component of the 1 kN·m reference transducer is $w_{Rt} = 1 \cdot 10^{-4}$ ($k = 2$) and $w_{Rt} = 8 \cdot 10^{-5}$ ($k = 2$) of the 10 kN·m reference transducer with use of the cubic interpolation function.

$\boldsymbol{w}_{\mathbf{St}}$ – It is assumed for the long-term stability of the reference transducer that a value of $w_{St} \leq 2 \cdot 10^{-5}$ annually (rectangular distribution) is not exceeded. This limit value is based on the stability analysis of transfer measurement devices of the same type, which have been in use in the HBM calibration laboratory for several years. As Röske [9] notes in his paper, a stronger systematic change in the characteristic value is expected at the beginning of the strain gauge's service life in measuring devices and this change becomes continually smaller over time. Because of this, the validity of the assumptions made here will be verified in the future by regular internal $E_n$ comparisons (section 4.2).

$\boldsymbol{w}_{\mathbf{Cr}}$ – Since the creep of the reference transducer cannot be separated from the creep of the calibration machine, the creep of the reference transducer is part of uncertainty component $w_{Sp.}$

### 3.2 Calibration Machine

$\boldsymbol{w}_{\mathbf{Sp}}$ – Röske [9] cites tolerances in shape and position and changes in the installation position of the reference transducer after removal and mounting as quantities that may affect the measurement result. The effect due to the creep of the calibration machine must also be taken into account. Since the individual influencing factors are very difficult to quantify separately, Röske proposes using the reproducibility $b\,(M_{cal})$ and repeatability $b'\,(M_{cal})$ errors of the measurement signals as a parameter to estimate the effect of these disturbance variables. Parameter $w_{Sp}$ corresponds to the maximum difference between the measurement signals as the test object rotates about the measuring axis (0°, 120°, 240°) and is assumed to be distributed normally. The mean value of all mounting positions for each load stage serves as a reference value, since according to Brüge et al. [2] it can be considered to be free of the effects of fastening.

Numerous calibration with HBM transducers of type TN and TB2 were carried out to determine the uncertainty value $w_{Sp}$ defined by equation (1) [10]. The selected transducers are used for years as transfer measurement devices in the HBM calibration laboratory to trace back the direct load machines to the German National Metrology Institute (PTB) (table 1 and 2). The reason for the choice of these two transducer types was, beside their high accuracy, the different design - TN transducer shaft-type, TB2 transducer flange-type. The values of the reproducibility $b\,(M_{cal})$ defined to DIN 51309 were calculated to quantify the uncertainty component $w_{Sp}$. In addition to the system behavior of the reference calibrating machine, the calculated $b$-values include the reproducibility of the transducer.

$$w_{\mathrm{Sp}}\left(M_{\mathrm{Cal}}\right)=\frac{\left|b\left(M_{\mathrm{cal}}\right)\right|}{2\cdot\sqrt{3}\cdot Y\left(M_{\mathrm{cal}}\right)} \quad (1)$$

To get a better estimation of the investigated system behavior, the *b*-values of the PTB calibration are additionally shown in figure 3. A comparison of the *b*-values indicate that the reproducibility of the reference calibration machine differs from PTBs direct load machines only in the range of small torques, what can be explained by the decreasing signal value of the measurement and control reference.

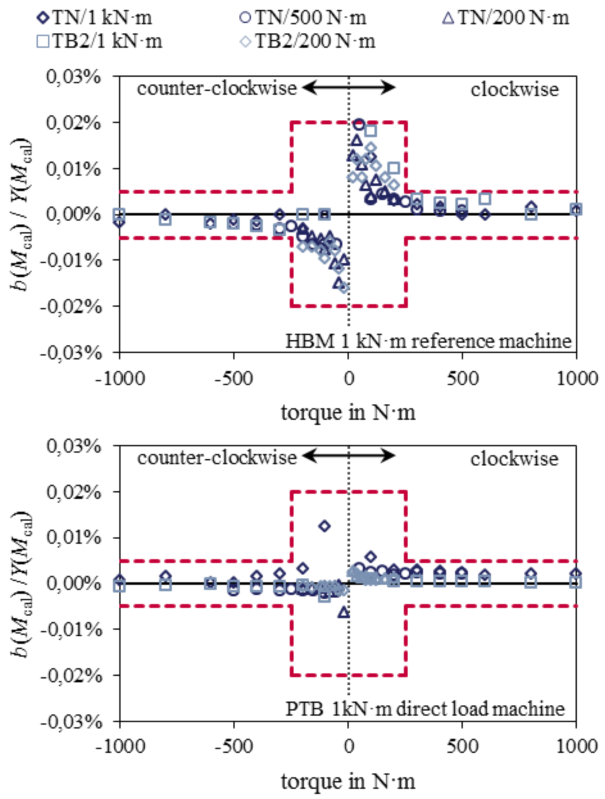


Fig. 3: Reproducibility $b(M_{\mathrm{cal}})$ of TN and TB2 transfer devices at the HBM 1 kN·m reference calibration machine (above) and the PTB calibration machine

Out of the shown calibration results at the 1 kN·m reference calibration machine, following limits of the *b*-value was defined: for $|M_{\mathrm{cal}}| \leq 200$ N·m $b = 0{,}02\%$ and $|M_{\mathrm{cal}}| > 200$ N·m $b = 0{,}005\%$. This limits leads to an uncertainty component of $w_{\mathrm{Sp}} = 5{,}8\cdot10^{-5}$ for $|M_{\mathrm{cal}}| \leq 200$ N·m respectively $w_{\mathrm{Sp}} = 1{,}4\cdot10^{-5}$ for $|M_{\mathrm{cal}}| > 200$ N·m. The values of $w_{\mathrm{Sp}}$ closely match the results of Brüge et al. [2] with the use of elastic couplings.

$\boldsymbol{w_{\mathrm{Al}}}$, $\boldsymbol{w_{\mathrm{Bm}}}$ – The effect of possible additional unknown axial loads and bending moments on the measurement result was also examined separately. For this study, measurements with an additional load (~ 9 kg) on the upper or lower teeth adapter were done. The weights were arranged symmetrically and asymmetrically on the adapter to generate also a bending moment. The results of these tests indicate that their effect may be ignored and any possible effect is described with sufficient accuracy by the uncertainty component $w_{\mathrm{Sp}}$.

### 3.3 Amplifier

$\boldsymbol{w_{\mathrm{Am}}}$ – Since the reference transducer with its permanently assigned measurement module was calibrated as a measurement chain, only its long-term stability is taken into account as an uncertainty component. Based on known measuring amplifiers of the same type (MGCplus with ML38B), a rectangular distributed value of $w_{\mathrm{Am}} \leq 8{,}0\cdot10^{-6}$ (per year) is applied as the uncertainty component contributed by a measuring amplifier. In case of using amplifiers of type HBM DMP40, DMP41 or ML60B the value of the long-term stability is much smaller, so that for a conservative uncertainty calculation the value of the ML38B is also be used. The validity of the assumption made here will be verified in the future by regular recalibration of the measuring amplifier.

$\boldsymbol{w_{\mathrm{Ca}}}$ – The reference transducer is connected by a specially shielded 6-wire cable (HBM-Greenline [7]). The available infrastructure of the calibration laboratory is also used to prevent electromagnetic interference. Consequently the effect of the cable and possible electromagnetic interference is neglected, $w_{\mathrm{Ca}} = 0$.

$\boldsymbol{w_{\mathrm{Sy}}}$ – A frequently overlooked factor contributing to measurement uncertainty is the result of non-synchronous acquisition of measured values by the reference and device being calibrated. The cause of non-synchronous data acquisition in the MGCplus data acquisition system that is used is the differing structure of the ML38B and ML60B measuring amplifiers. To quantify the measurement acquisition time offset, the group run time $\tau_{\mathrm{gt}}$ of the relevant amplifier was determined with a signal generator. It was determined in this manner that the time offset between the two ML38Bs for the same filter settings is less than 500 ms. For devices being calibrated with frequency output, however, the group runtime of the measuring amplifier used (ML60B) differs from the reference amplifier (ML38B), with a low-pass filter of 0,1 Hz Bessel by approximately $\Delta\tau_{\mathrm{gt}} = 3{,}3$ s. In connection with the signal curve shown in figure 4 for holding a load stage, the uncertainty amount determined with equation (2) is in this example $w_{\mathrm{Sy}} \leq 2{,}7\cdot10^{-5}$.

$$w_{\mathrm{Sy}}\left(M_{\mathrm{Cal}}\right)=\left|\frac{X\left(M_{\mathrm{Cal}},\tau\right)-X\left(M_{\mathrm{Cal}},\tau+\Delta\tau_{\mathrm{gt}}\right)}{\sqrt{3}\cdot X\left(M_{\mathrm{Cal}},\tau\right)}\right| \quad (2)$$

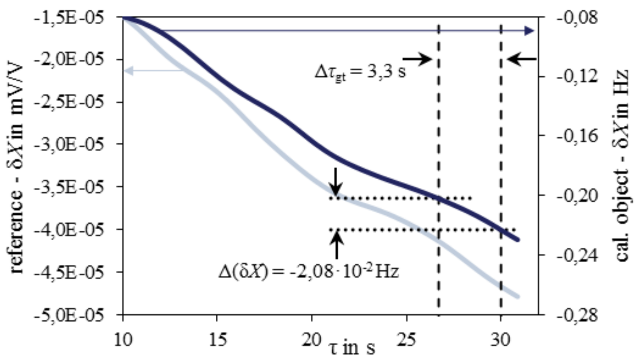


Fig. 4: Signal change while holding the load stage during calibration due to machine and transducer creep

As outlined in the introduction to this article, plans call for the two calibration machines to be used mainly for calibrating industrial sensors such as the T40B or T10F from HBM. The measurement signal of these sensors usually has Hz as the unit of measurement. This necessarily requires the time adjustment of the two measuring signals during the calibration. In order to meet this requirement, the existing data acquisition software has been successfully expanded.

Despite this correction of the systematic effect of non-synchronous data acquisition, the uncertainty component $w_{\mathrm{Sy}}$ must be taken into consideration. On the basis of extensive tests and taking into account the sample rate and filter settings, the uncertainty resulting from non-synchronous data acquisition can be specified according to equation (2) with $w_{\mathrm{Sy}} \leq 3{,}2\cdot 10^{-5}$ ($\Delta\tau_{\mathrm{gt}} = 0{,}8$ s). This specification of $w_{\mathrm{Sy}}$ corresponds to a worst case estimation, since for calibration with HBM own amplifiers, the time offset is known and therefore the uncertainty of the remaining time offset (after correction) is less than the assumed value of 0,8 s.

### 3.4 Environment

$\boldsymbol{w_{\mathrm{TC0}}}$, $\boldsymbol{w_{\mathrm{TCs}}}$ – Since a change in the temperature results in a change in the zero point (parallel offset of the characteristic curve, $TC_0$) as well as a change in the characteristic value (change in the slope of the characteristic curve, $TC_s$) [11], the two rectangularly distributed uncertainty components $w_{\mathrm{TC0}}$ and $w_{\mathrm{TCs}}$ must be considered. To minimize the $TC_0$ value, the reference transducers were specially adjusted during the manufacturing process so that a value of $3{,}4\cdot 10^{-5}$.per 2 K can be assumed to calculate the uncertainty component $w_{\mathrm{TC0}}$. The $TC_0$-value is specified in this manner because of a requirement of the calibration laboratory according to which the maximum fluctuation in the room temperature over the course of the calibration must not exceed the range of 22,0 ± 1°C. To calculate the uncertainty component $w_{\mathrm{TCS}}$ the data sheet value of 0,006% per 2 K is used [8].

$\boldsymbol{w_{\mathrm{rH}}}$ – The effect of relative humidity can be ignored in the planned operating range of the calibration machine (45 ± 10) % due to the hermetically encapsulated structure of the reference transducer.

### 3.5 Evaluation

$\boldsymbol{w_{\mathrm{In}}}$ – Since an enormous amount of control effort is required to approach load stages exactly, a deviation of ±1% of the load stage is permitted. Because the values of the even load stage are specified on the calibration certificate, this value is calculated by linear interpolation. This makes it necessary to consider the uncertainty component $w_{\mathrm{In}}$ as defined by equation (3) in the amount of $w_{\mathrm{In}} \leq 2{,}0\cdot 10^{-6}$.

$$w_{\mathrm{In}}(M_{\mathrm{Cal}}) = \left| \frac{Y(M_{\mathrm{Cal\text{-}1\%}}) + \frac{X_{\mathrm{sens}}}{M_{\mathrm{max}}}\cdot(M_{\mathrm{Cal}} - M_{\mathrm{Cal\text{-}1\%}}) - Y(M_{\mathrm{Cal}})}{Y(M_{\mathrm{Cal}})} \right| \quad (3)$$

$\boldsymbol{w_{\mathrm{Hy}}}$ – If a measurement is performed in the calibration subrange of the reference transducer, the uncertainty component $w_{\mathrm{Hy}}$ will be applied for the unknown hysteresis of the reference transducer. A program developed by HBM is used for this purpose. It simulates the values for continuously removing load in subrange and saves the results in the measurement data analysis. In order to determine the remaining uncertainty due to hysteresis, the deviation between the simulated values and the measured values of a subrange calibration is calculated. As shown in Figure 6, the maximum deviation (based on the rated output) is 0,0008%.

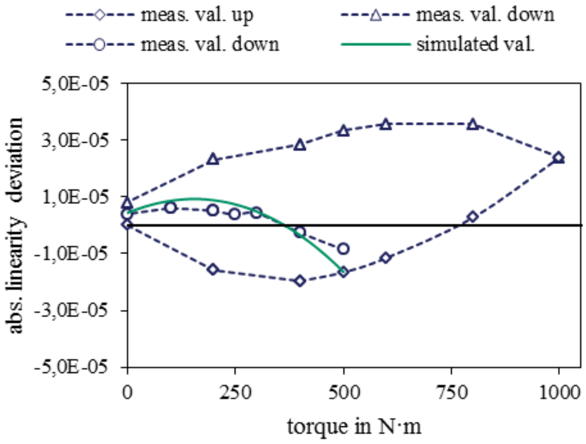

Fig. 5: Absolute linearity deviation of a full and subrange calibration as well as the deviation of the simulated data

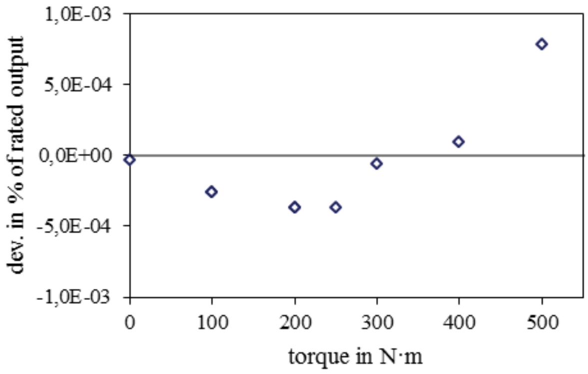

Fig. 6: Deviation of the measured values to the simulated values relative to the rated output

The described way to determine the rectangularly distributed uncertainty component $w_{\mathrm{Hy}}$ was already successfully verified during the DAkkS-accreditation of the HBM 400 kN·m reference calibration machine [6]. For the measurement uncertainty budget, a maximum deviation of 0,003% was assumed, that results in an uncertainty component of $w_{\mathrm{Hy}} = 1{,}95\cdot 10^{-5}$.

### 3.6 Expanded Measurement Uncertainty

The expanded measurement uncertainty (expansion factor $k = 2$) is determined on the basis of the uncertainty components discussed in the previous sections and shown in figure 7, using equation (4).

$$W = 2\cdot\sqrt{w_{\mathrm{Rt}}^2 + w_{\mathrm{St}}^2 + w_{\mathrm{Sp}}^2 + w_{\mathrm{Am}}^2 + w_{\mathrm{Sy}}^2 + w_{\mathrm{TC_0}}^2 + \ldots + w_{\mathrm{TC_s}}^2 + w_{\mathrm{In}}^2 + w_{\mathrm{Hy}}^2} \quad (4)$$

The maximum measurement uncertainty calculated with the expansion factor $k = 2$ is $W_{1\,\mathrm{kN \cdot m}} = 1{,}63 \cdot 10^{-4}$ for the 1 kN·m and $W_{10\,\mathrm{kN \cdot m}} = 1{,}73 \cdot 10^{-4}$ for the 10 kN·m reference calibration machine. If the calibration machines are used in a subrange, the expanded measurement uncertainty is increased due to the consideration of $w_{\mathrm{Hy}}$ to $W_{1\,\mathrm{kN \cdot m}} = 1{,}68 \cdot 10^{-4}$ and $W_{10\,\mathrm{kN \cdot m}} = 1{,}77 \cdot 10^{-4}$. The presented results of the theoretical measurement uncertainty analysis confirm that both calibration machines meet the target measurement uncertainty of $2{,}0 \cdot 10^{-4}$.

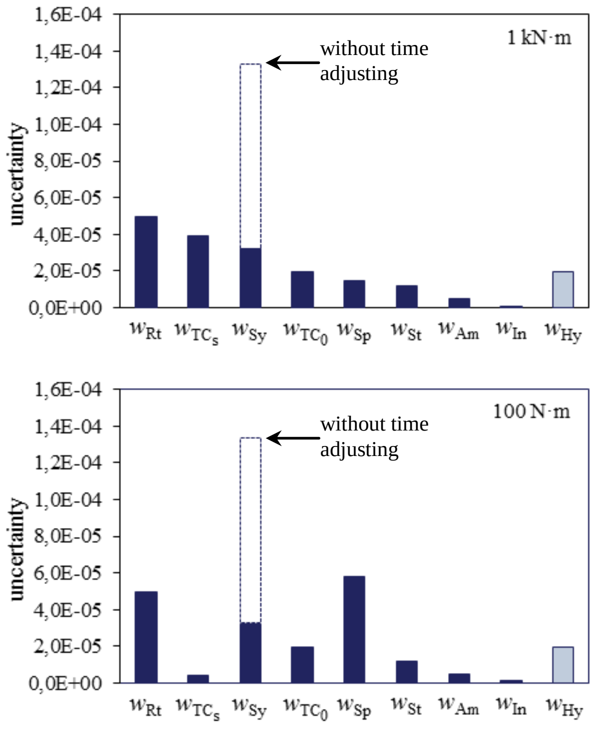


Fig. 7: Uncertainty components taken into consideration for calculating the expanded uncertainty $W_{1\,\mathrm{kN \cdot m}}$ of the 1 kN·m reference calibration machine

## 4. COMPARISON OF RESULTS

In addition to the theoretical consideration of measurement uncertainty covered in section 3, the two calibration machines will now also be examined in terms of measurement performance. To do this the transfer measurement devices listed in table 1 and 2 were first calibrated on direct loading machines in the calibration laboratory to DIN 51309. This was followed by measurements on the reference calibration machines, also to DIN 51309. The $E_{\mathrm{n}}$ value defined by equation (4) is used to compare the measured values. Since both the reference transducers and the transfer measurement devices were calibrated on the same direct loading machines (section 4.2), their results are correlated. Therefore the $E_{\mathrm{n}}$ value is defined according to Wöger [14] by equation (5). The index *Ref* identifies the values of the reference machine and *Lab* corresponds to the comparison values of the direct load machine.

$$E_n = \frac{X_{\mathrm{Lab}}(M_{\mathrm{K}}) - X_{\mathrm{Ref}}(M_{\mathrm{K}})}{\sqrt{U_{\mathrm{Lab}}^2(M_{\mathrm{K}}) + U_{\mathrm{Ref}}^2(M_{\mathrm{K}})}} \qquad (5)$$

### 4.1 $E_{\mathrm{n}}$ comparison to PTB calibration machine

Figure 8 shows the results of the $E_{\mathrm{n}}$ comparison between the PTB 1 kN·m direct load machine and the HBM 1 kN·m reference calibration machine. The results clearly show that the calibration machine meet the criterion $|E_{\mathrm{n}}| \leq 1$ over the whole load range.

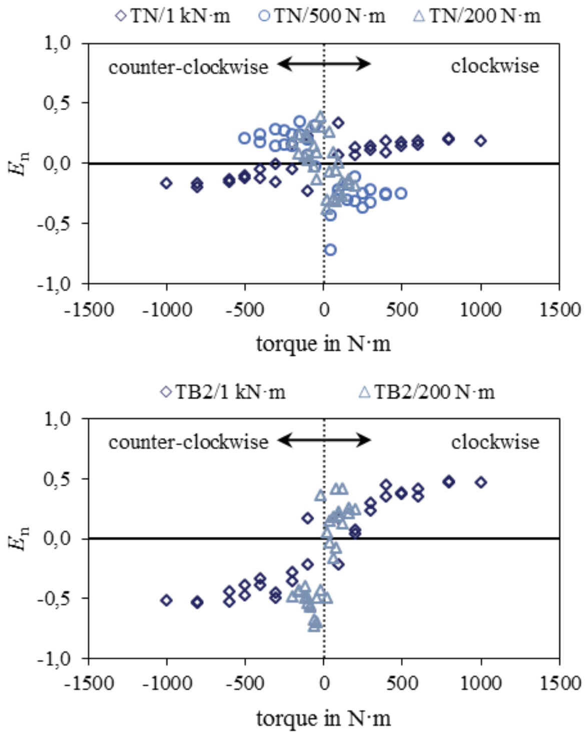


Fig. 8: $E_{\mathrm{n}}$ comparison of PTB calibration with the 1 kN·m reference calibration machine

Table 1: Transfer measurement devices used in the $E_{\mathrm{n}}$ comparison

| Transfer measurement device | Measurement uncertainty $U_{\mathrm{Lab}}$ | $U_{\mathrm{Ref}}$ |
|---|---|---|
| TN / 200 N·m | $2 \cdot 10^{-5}$ | $2 \cdot 10^{-4}$ |
| TN / 500 N·m | $2 \cdot 10^{-5}$ | $2 \cdot 10^{-4}$ |
| TN / 1 kN·m | $2 \cdot 10^{-5}$ | $2 \cdot 10^{-4}$ |
| TB2 / 200 N·m | $2 \cdot 10^{-5}$ | $2 \cdot 10^{-4}$ |
| TB2 / 1000 N·m | $2 \cdot 10^{-5}$ | $2 \cdot 10^{-4}$ |

### 4.2 $E_{\mathrm{n}}$ comparison to HBM calibration machines

In addition to the $E_{\mathrm{n}}$ comparison with the values of the PTB 1 kN·m direct load machine (section 4.1), in figure 9 and 10 the HBM internal $E_{\mathrm{n}}$ comparison with the DAkkS-accredited 1 kN·m and 25 kN·m direct load machines is shown. As before the results of the internal comparison clearly confirm, that both reference machines meet the criterion $|E_{\mathrm{n}}| \leq 1$ over their whole load range.

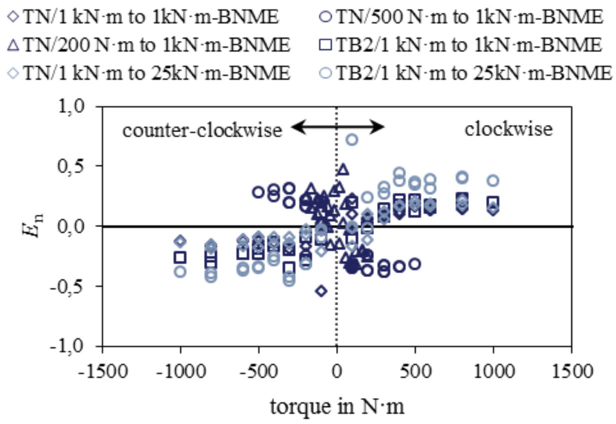


Fig. 9: HBM internal $E_n$ comparison of the 1 kN·m reference calibration machine

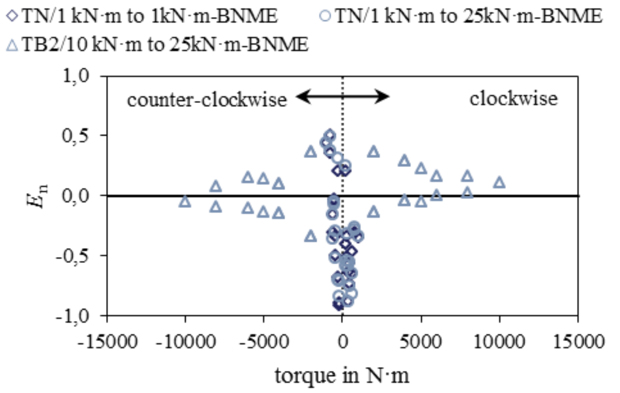


Fig. 10: HBM internal $E_n$ comparison of the 10 kN·m reference calibration machine

Table 2: Transfer measurement devices used in the HBM internal $E_n$ comparison

| Transfer measurement device | HBM measurement uncertainty $U_{Lab}$ 1 kN·m BNME | 25 kN·m BNME |
|---|---|---|
| TN / 200 N·m | $1 \cdot 10^{-4}$ | — |
| TN / 500 N·m | $1 \cdot 10^{-4}$ | — |
| TN / 1 kN·m | $1 \cdot 10^{-4}$ | $8 \cdot 10^{-5}$ |
| TB2 / 1 kN·m | $1 \cdot 10^{-4}$ | $8 \cdot 10^{-5}$ |
| TB2 / 10 kN·m | $1 \cdot 10^{-4}$ | $8 \cdot 10^{-5}$ |

## 5. CONCLUSION

In this paper two new reference calibration machines for expanding the HBM calibration laboratory were presented, covering a load range up to 1 kN·m and 10 kN·m respectively. Using the 1 kN·m machine as an example, the individual uncertainty components were named and quantified. The expanded measurement uncertainty calculated according to equation (4) is $W_{1\ \text{kN·m}} = 1{,}68 \cdot 10^{-4}$ of the 1 kN·m and $W_{10\ \text{kN·m}} = 1{,}77 \cdot 10^{-4}$ of the 10 kN·m reference calibration machine.

In addition to the theoretical description of measurement uncertainty, the measurement performance of both calibration machines was examined. To do this, transfer measurements between PTB respectively HBM direct load calibration machines and the two new reference calibration machines were used to compare the measured values based on the $E_n$ value calculated according to equation (5).

Both the theoretically determined measurement uncertainty as well as the results of all $E_n$ comparison (to the German National Metrology Institute (PTB) and HBM internal) confirm the targeted measurement uncertainty of both reference calibration machines of 0,02% ($k$ = 2).

## 6. REFERENCES


[1] J. Andrae, “Measurement and Calibration Using Reference and Transfer Torque Flanges, XVII IMEKO International conference, Istanbul, Turkey, 2001

[2] A. Brüge. D. Peschel and D. Röske, “The Influence of Misalignment on Torque Transducers”, XVI IMEKO International conference, Vienna, Austria, 2000

[3] DIN 51309:2005-12, Materials Testing Machines – Calibration of Static Measuring Devices, DIN Deutsches Institut für Normung e.V., Beuth Verlag GmbH, Berlin, Germany, 2005

[4] DIN ISO 12667:1993, Commercial Vehicles and Buses – Cross-tooth Propeller Shaft Flanges, Type T; of KV180 Intermeshing, DIN Deutsches Institut für Normung e.V., Beuth Verlag GmbH, Berlin, Germany, 1993

[5] EURAMET cg-14, “Guidelines on the Calibration of Static Torque Measuring Devices”, European Association of National Metrology Institutes, Braunschweig, Germany, 2011

[6] H. J. Fraiss, L. Stenner and D. Röske, “Development of a New 400 kN·m Torque Calibration Machine”, XXI IMEKO International conference, Prague, Czech Republic, 2015

[7] Hottinger Baldwin Messtechnik GmbH, “Greenline Shielding Design”, http://www.hbm.com/fileadmin/mediapool/hbmdoc/technical/i1578.pdf (07.03.2017)

[8] Hottinger Baldwin Messtechnik GmbH, “TB2 Torque reference transducer“, data sheet

[9] D. Röske, „Uncertainty in Torque Measurements with Torque Reference Facilities”, Technisches Messen, vol. 78, no. 2, pp. 77-78, 2011

[10] D. Röske, „276. PTB-Seminar – Messunsicherheiten bei der Darstellung und Messung des Drehmomentes”, Physikalisch-Technische Bundesanstalt, p. 17

[11] R. Schicker and G. Wegener, “Drehmoment richtig messen“, Hottinger Baldwin Messtechnik GmbH, Darmstadt, Germany, 2002

[12] VDI/VDE 2646, Torque Measuring Devices – Minimum Requirements in Calibrations, Fachbereich Fertigungsmesstechnik, VDI/VDE-Gesellschaft Mess- und Automatisierungstechnik, Düsseldorf, Germany, 2006

[13] M. Wozniak and D. Röske, “Investigation of the Calibration and Measurement Capabilities of the New 5 kN·m Torque Calibration Machine at GUM”, XXI IMEKO International conference, Prague, Czech Republic, 2015

[14] M. Wöger, “Remarks on the $E_n$-Criterion Used in Measurement Comparison”, PTB-Mitteilung 109 (1999)