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Study of a 2 kN·m Torque Transducer Tested at GUM and PTB, Including Creep Behaviour

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Abstract: This article presents a study carried out on a 2 kN·m torque transducer at the Central Office of Measures (GUM) and the Physikalisch-Technische Bundesanstalt (PTB). The weighted least squares method was used to generate the linear regression equations for this torque transducer. The Monte Carlo method and the law of uncertainty propagation were used to calculate the expanded uncertainty. In addition, a creep study was carried out at eight measurement points ranging from 200 N·m to 2000 N·m. The investigations showed that the highest readings of the torque transducer, expressed in electrical units as mV/V, occur within the initial few seconds of the test after the removal of the maximum reference torque.

Keywords: Creep, torque transducer, uncertainty, calibration, wind energy.

1. INTRODUCTION

The increasing demand for wind energy as a renewable and sustainable source of electricity has led to advances in technology and research in this field [1], [2], [3]. The shift away from fossil fuels, driven by environmental policies and strategies, has further emphasized the importance of developing efficient and reliable wind power systems [4], [5].

A key component in wind power generation is the use of torque transducers, which play a crucial role in monitoring the behaviour of wind turbines [6], [7]. These transducers provide important data on the torque generated by the rotor blades as they rotate, so that adjustments can be made to optimize performance based on changing wind conditions. However, it is important to consider the effect of creep behaviour on the accuracy and reliability of these torque transducers.

Creep behaviour, which is characterised by the gradual deformation of a material under constant load over time, can affect the performance of torque transducers in the wind turbine sector. The effects of creep on torque transducers can affect their precision and longevity, ultimately impacting the overall efficiency of wind power systems. Addressing and mitigating the effects of creep on these transducers is critical to ensuring the continued reliability and effectiveness of wind energy technologies.

To assess the suitability of a torque transducer for dynamic or high-precision tasks, such as in the wind energy sector, its creep behaviour must be known. For this reason, DIN 51309 [8] stipulates that during the calibration of torque transducers, corresponding creep measurements must be carried out [9], [10], [11], [12]. This article is an extended version of our earlier article [13], in which we described a metrological characterisation of a 2 kN·m torque transducer carried out at Central Office of Measures (GUM) and Physikalisch-Technische Bundesanstalt (PTB) and the investigation of the creep behaviour of this transducer carried out at GUM.

2. SUBJECT & METHODS

The Hottinger Bruel and Kjear (HBK) special torque transducer (type MPZ1512005b, serial number 210940007) with a lifting capacity of 2000 N·m and a sensitivity of 1.0 mV/V is designed to measure clockwise and anti-clockwise torque (Fig. 1). It is worth to note the mechanical similarities between the present torque transducer and the 5 MN·m torque transducer [14].

It was calibrated up to 2 kN·m on the reference Torque Standard Machine (TSM) working up to 5 kN·m at the GUM (TSM-GUM) with an expanded relative measurement uncertainty of $U_r = 0.04\%$ $(k = 2)$, which is shown in Fig. 2.

It was also calibrated on the reference TSM at PTB (TSM-PTB) up to 1 kN·m with $U_r = 0.003\%$ $(k = 2)$ (Fig. 3). The deformation of the torque transducer was measured electrically in mV/V units using the MGCplus/ML38B/DMP41 measuring amplifier (with a 0.5 Hz Bessel digital filter), which is characterised by the best accuracy class and a resolution of 1 ppm in the ±2.5 mV/V measuring range. The tests were carried out at ambient temperatures.

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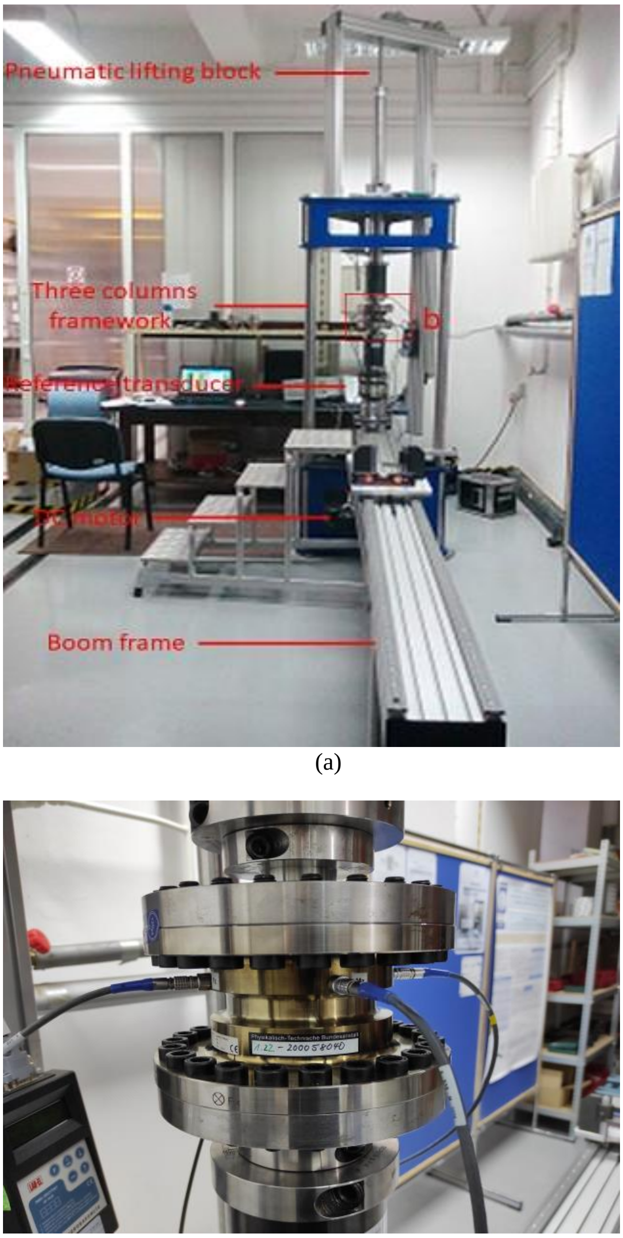
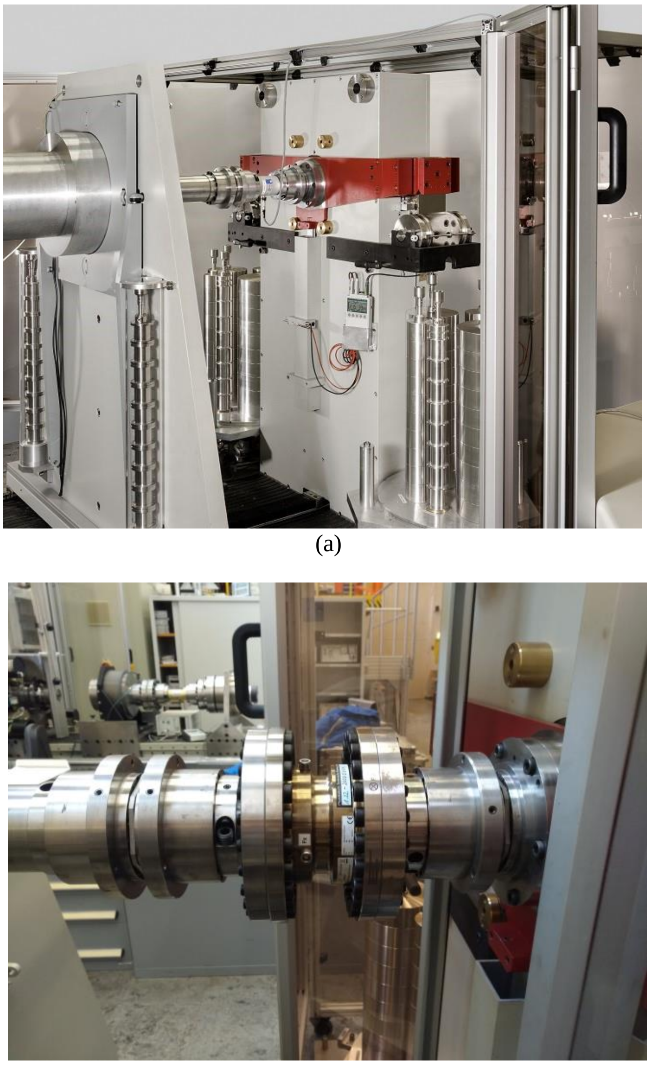
Fig. 1. The HBK special torque transducer with a lifting capacity of 2000 N·m and a sensitivity of 1.0 mV/V designed to measure clockwise and anti-clockwise torque.



(a)

(b)

Fig. 2. The (a) reference TSM up to 5 kN·m at GUM (TSM-GUM) with an expanded relative measurement uncertainty of $U_r = 0.04\%$ $(k = 2)$ and (b) 2 kN·m torque transducer installed in TSM-GUM between two adapters.



(a)

(b)

Fig. 3. The (a) reference TSM at PTB (TSM-PTB) up to 1 kN·m with $U_r = 0.003\%$ $(k = 2)$; (b) 2 kN·m torque transducer installed in the TSM-PTB between two adapters.

Calibration was performed at 8 measurement points: ±200 N·m, ±400 N·m, ±600 N·m, ±800 N·m, ±1000 N·m, ±1200 N·m, ±1600 N·m and ±2000 N·m. This procedure complied with the guidelines of the "Calibration of torque measuring devices and torque transducers", which are based on the DIN 51309:2022 standard [8]. The creep tests were performed with the 2 kN·m torque transducer in both clockwise and anti-clockwise directions, following the ISO 376:2011 standard [15]. It should be noted that due to the significant similarities of the creep tests according to the ISO 367:2011 and DIN 51309:2005-12 standards, the results should be very similar.

3. CALIBRATION OF THE TORQUE TRANSDUCERS TO THE ELECTRIC SIGNAL

When calibrating the transducers, the measured values of torque and the electrical signal of the transducer are performed on the measuring site for each selected individual measuring point.

The uncertainty budget [16] takes into account the uncertainties resulting from signal errors caused by various components. These components include uncertainties related to the results of reference transducers for cubic fitting, short-term creep of reference transducers, long-term drift of reference transducers, misalignment of the device, related to the resolution and stability of the indicating device, use of reference transducers in partial ranges, stability of torque transmission to shafts, influence of temperature variation and also for type B uncertainty due to: the resolution error of indicator (2 times), the reproducibility error, the repeatability error, the zero indication error and the interpolation error.

As a result, the values of the measured signal y_i and the torque x_i, are obtained together with the expanded relative uncertainties of the signals at each measurement point with an expanded factor $k = 2$. These values and uncertainties are included in Table 1.

The measurements were performed at points with coordinates x_i and y_i, where $i = 1,...,n$ and the standard uncertainties refer only to the torque measurement signal and $u(y_i) = \frac{U_r(y_i)y_i}{100k}$ and $k = 2$. The linear equation $y = ax+b$ coefficients a and b and the standard uncertainties of the ratios: u_a and u_b and the correlation coefficient are expressed by the following equations:

$$a = \frac{\Delta_a}{\Delta},\ \ b = \frac{\Delta_b}{\Delta},\ \ u_a = \sqrt{S/\Delta},\ \ u_b = \sqrt{S_{xx}/\Delta},$$

$$\rho_{ab} u_a u_b = -\frac{S_x}{\Delta},$$

where

$$\Delta = \mathrm{S} \cdot S_{xx} - S_x^2$$

$$\Delta_a = \mathrm{S} \cdot S_{xy} - S_x \cdot S_y$$

$$\Delta_b = S_y \cdot S_{xx} - S_x \cdot S_{xy} \tag{1}$$

and the auxiliary parameters are given by:

$$S = \sum_{i=1}^{n} \frac{1}{u^2(y_i)},\ S_x = \sum_{i=1}^{n} \frac{x_i}{u^2(y_i)},\ S_{xx} = \sum_{i=1}^{n} \frac{x_i^2}{u^2(y_i)}$$

$$S_{xy} = \sum_{i=1}^{n} \frac{x_i y_i}{u^2(y_i)},\ S_y = \sum_{i=1}^{n} \frac{y_i}{u^2(y_i)} \tag{2}$$

Table 1. Input data for straight line regression - results of measurements for TSM-PTB and TSM-GUM.

	TSM-PTB (up 1 kN·m)		TSM-GUM (up 2 kN·m)	
Torque x_i [N·m]	Signal y_i [mV/V]	Measure of relative expanded uncertainty of signal $U_r(y_i)$ [%], $k=2$	Signal y_i [mV/V]	Measure of relative expanded uncertainty of signal $U_r(y_i)$ [%], $k=2$
Clockwise Torque				
100	0.053390	0.023	-	-
200	0.106783	0.017	0.106689	0.06
300	0.160177	0.014	-	-
400	0.213574	0.010	0.213401	0.06
500	0.266973	0.006	-	-
600	0.320371	0.004	0.320118	0.05
800	0.427171	0.003	0.426844	0.05
1000	0.533973	0.006	0.533574	0.05
1200	-	-	0.640302	0.05
1600	-	-	0.853731	0.05
2000	-	-	1.067136	0.07
Anti-clockwise Torque				
-2000	-	-	-1.067420	0.07
-1600	-	-	-0.853676	0.07
-1200	-	-	-0.640245	0.06
-1000	-0.533984	0.006	-0.533537	0.06
-800	-0.427178	0.004	-0.426823	0.06
-600	-0.320377	0.005	-0.320105	0.06
-500	-0.266977	0.007	-	-
-400	-0.213578	0.010	-0.213393	0.06
-300	-0.160181	0.013	-	-
-200	-0.106784	0.018	-0.106684	0.07
-100	-0.053391	0.024	-	-

For a linear regression defined by the uncertainty equation, the standard uncertainty for a regression line along the OY axis is given by (1) and (2):

$$u_y^2 = x^2 u_a^2 + 2|x| u_a u_b \rho_{ab} + u_b^2 \tag{3}$$

according to the Law of Propagation of Uncertainty (LPU) as the sum of the distributions in generally correlated variables: ax with a standard uncertainty $|x|u_a$ and the distribution of the variable b with a standard uncertainty u_b, where ρ_{ab} is the correlation coefficient between these random variables. The expanded uncertainty for a linear regression is increased by the coverage factor, which is determined by the inverse distribution function from the Student's t-distribution with $n-2$ degrees of freedom for the coverage factor with the coverage probability 0.95 ($\alpha = 0.05$), i.e. $U_y = t_{n-2,1-\alpha/2}\, u_y$. The uncertainty range of the regression line is described by $ax + b \pm U_y$. In the Monte Carlo Method (MCM), the random variables corresponding to the x-coordinates of the measurement points are generated as random samples (10^7 samples were taken) from Gaussian distributions $N(\mu,\sigma^2)$ with expected values $\mu = y_i$ and variances $\sigma^2 = u^2(y_i)$ with $i = 1,...,n$. The values of the coverage area are intervals for a 0.95 probability for the selected x and are determined as the sum of the distributions $ax+b$, using the formulas to define the parameters slope a and intercept b described above.

4. RESULTS AND DISCUSSION

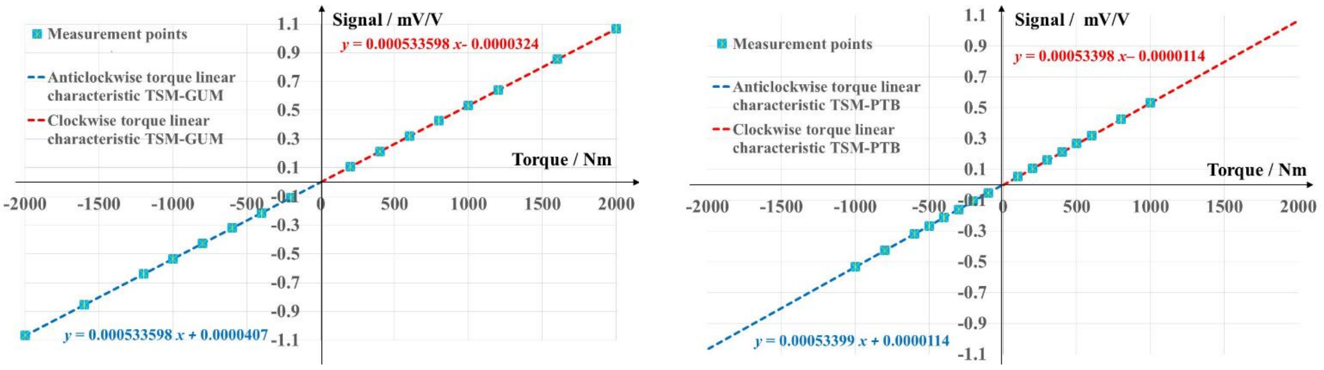
Calibration of the 2 kN·m torque transducer on the TSM-GUM in the measuring range from 200 N·m to 2000 N·m in clockwise and anti-clockwise direction confirmed its class 0.2 for both creep and hysteresis [17]. It is worth noting that the results obtained meet the requirements of class 0.1. However, due to the uncertainty of GUM's torque reference standard of 0.04%, the calibration class of the transducer had to be lowered. The calibration of the above torque transducer on the TSM-PTB was carried out in the range up to 1 kN·m. The calibration results are described in the calibration certificate [18]. The calibration of the torque transducer on the TSM-PTB was limited to the range up to 1 kN·m due to the technical limitations of the calibration setup in the PTB facility. This limitation refers to the maximum torque value that could be accurately measured and calibrated with the equipment and procedures available there. As a result, it was necessary to extrapolate the calibration data in order to cover the extended range from 200 N·m to 2000 N·m. Extrapolation involves predicting the behaviour of the transducer beyond the calibrated range based on the assumption of linearity of its response. However, it is crucial to acknowledge that extrapolation introduces potential inaccuracies, especially when considering factors such as nonlinearity, drift and hysteresis in the transducer's characteristics. Despite these challenges, extrapolation is often used when direct calibration within the entire measurement range is not feasible. To mitigate potential errors associated with extrapolation, a thorough analysis of the transducer's characteristics in the lower range and consideration of influencing factors are required. It is also important to limit extrapolation to regions where linearity can reasonably be assumed. Overall, while extrapolation enables the use of the transducer across the entire measurement range, it requires careful consideration and risk assessment to ensure reliable results. The basic tool for fitting a nonlinear relationship to measurement points is the least squares method. In the general approach, it is the Weighted Total Least Squares method (WTLS) method that takes into account all the generally different uncertainties of the coordinates of the points and the different correlations between the coordinates of the measurement points.

A. *Linear regression*

The linear regression equation for a 2 kN·m torque transducer tested on the TSM-GUM and TSM-PTB with WLS is shown in Table 2 and Fig. 4(a).

Table 2. Equations of the linear regression determined by WLS for the 2 kN·m torque transducer tested on TSM-GUM and TSM-PTB input data from Table 1 and using formulas from (3).

Calibration site	Linear regression equation determined by WLS	
	Clockwise direction	Anti-clockwise direction
TSM-GUM	$y = 0.000533598 \cdot x - 0.0000324$ $u_a = 8.06E-08$ $u_b = 3.98E-05$ ρ_{ab}=-0.776	$y = 0.000533598 \cdot x + 0.0000407$ $u_a = 9.62E-08$ u_b=4.63E-05 ρ_{ab}=-0.785
TSM-PTB	$y = 0.00053398 \cdot x - 0.0000114$ u_a=1.06E-08 u_b=5.63E-06 ρ_{ab}=-0.863	$y = 0.00053399 \cdot x + 0.0000114$ u_a=1.19E-08 u_b=5.92E-06 ρ_{ab}=-0.841



(a) (b)

Fig. 4. Straight-line fitting of the relationship of the transducer's normalised signal as a function of torque using the least squares method: (a) TSM-GUM; (b) TSM-PTB.

B. *The absolute and relative uncertainties of LPU and MCM methods across the entire calibration range*

The relative uncertainties for the transducer signal in the measuring ranges above 500 N·m were less than 0.005% for both clockwise and anti-clockwise measurements at TSM-PTB, while at TSM-GUM the relative uncertainties for the same range were approximately 0.02% to 0.04% for anti-clockwise torque and almost 0.02% to 0.03% for clockwise torque. However, the relative expanded uncertainty values obtained for decreasing torque values measured below 500 N·m in both directions increased significantly and are therefore not included in Fig. 5. This is because the relative expanded uncertainty decreases for torque values closer to zero. The comparison of the absolute uncertainties determined using LPU and MCM for the calibration at TSM-PTB and TSM-GUM in the range from -2000 N·m to 2000 N·m is shown in Fig. 6. In all cases, the estimate of the expanded uncertainties determined with MCM is at a lower level than the values calculated with LPU. The linear regression equations determined by WLS for the 2 k N·m torque transducer, tested on TSM-GUM and TSM-PTB yielded expanded uncertainties, with the uncertainties obtained from the more accurate MCM estimated to be lower than those from LPU.

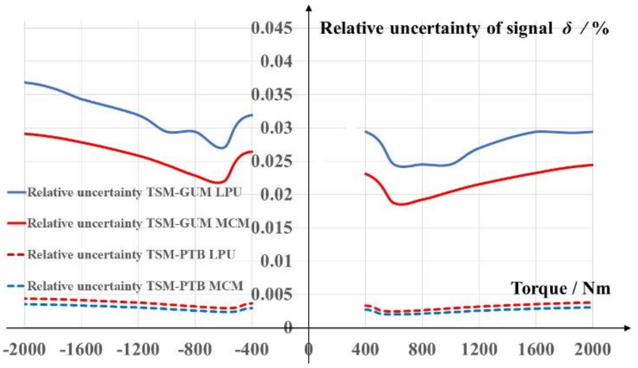


Fig. 5. Comparison of the expanded relative uncertainties determined via LPU and MCM for the calibration on TSM-PTB and TSM-GUM in the range from -2000 N·m to -500 N·m and from 500 N·m to 2000 N·m.

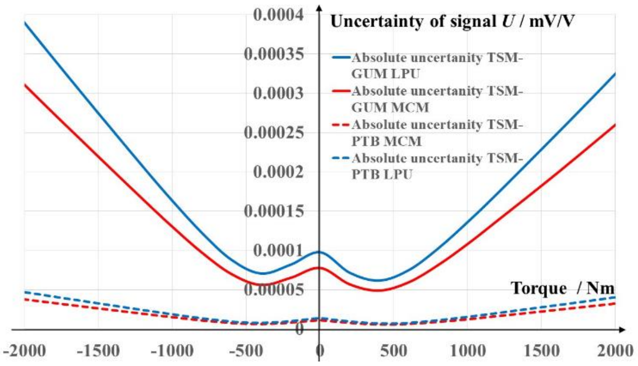


Fig. 6. Comparison of the expanded absolute uncertainties determined via LPU and MCM for the calibration on TSM-PTB and TSM-GUM in the range from -2000 N·m to 2000 N·m.

C. *Creep study*

A creep study was performed with the 2 kN·m torque transducer in both clockwise and anti-clockwise directions using GUM's 5 kN·m reference TSM. The tests were performed in accordance with the ISO 376:2011 standard [15]. A diagram illustrating the creep test is shown in Fig. 7. The tests were carried out at eight measurement points from 200 N·m to 2000 N·m. The creep behaviour of the 2 kN·m PTB torque transducer for measurements taken after applying the reference torques of 200 N·m, 1.6 kN·m and 2 kN·m and for measurements taken after removing these reference torques are shown in Fig. 8. The mV/V reading was measured after 5 s and then every 2 s for the first 30 s after applying and releasing the desired torque.

After applying and removing the reference torque of 200 N·m, an increasing trend in creep behaviour can be observed (Fig. 8(a)). When a reference torque of 1.6 kN·m is applied, the trend in creep behaviour changes to a decreasing trend (Fig. 8(b)), while a plateau can be observed when the maximum reference torque of 2 kN·m is applied (Fig. 8(c), upper inset). Only when the maximum reference torque is removed (after applying M_{max} for 35 s) can an increase in creep be observed in the first few seconds (Fig. 8(c), lower inset).

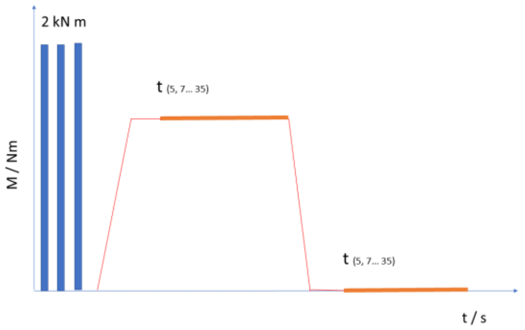
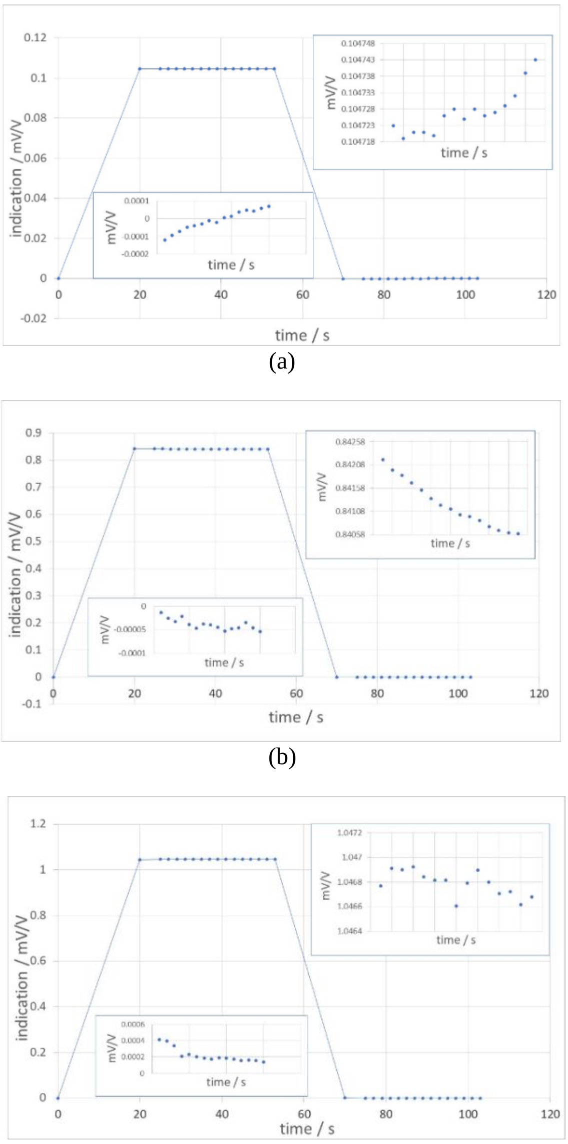


Fig. 7. A diagram illustrating the creep study of the 2 kN·m torque transducer in accordance with the ISO 376:2011 standard [15].



(a)

(b)

(c)

Fig. 8. Graph of 2 kN·m torque transducer indication given in electrical units [mV/V] versus time [s] for measurements carried out after applying (a) 200 N·m torque, (b) 1600 N·m torque and (c) the maximum reference torque (at 2 kN·m, ~1.04 mV/V) and for measurements carried out after removing the applied reference torque. The insets represent the creep in the first 30 s of the measurement after the load application. For clarity, there are no error bars.

5. DISCUSSION

The linear regression equations determined by WLS for the 2 kN·m torque transducer tested on TSM-GUM and TSM-PTB yielded expanded uncertainties, with the uncertainties determined by the more accurate MCM estimated to be lower than those determined by the LPU. In addition, a creep study was performed for 8 measurement points from 200 N·m to 2000 N·m. The findings show that creep was barely detectable after applying the maximum reference torque of 2 kN·m. However, creep increases in the first few seconds after the maximum reference torque is removed.

6. CONCLUSIONS

The HBK special torque transducer, which is designed for clockwise and anti-clockwise torque measurement with a lifting capacity of 2 kN·m, was calibrated up to 2 kN·m on the reference Torque Standard Machine at GUM and up to 1 kN·m on the reference TSM at PTB. The linear regression equation s determined by WLS for the 2 kN·m torque transducer, which were tested on the TSM-GUM and the TSM-PTB, resulted in expanded uncertainties, with those determined by the more accurate MCM estimated lower than those determined by the LPU. A creep study was performed for the 2 kN·m torque transducer, which included eight measurement points in the range of 200 N·m to 2000 N·m. The results showed that creep was minimal after applying the maximum reference torque of 2 kN·m. However, after removing the maximum reference torque, an increase in creep was observed in the first few seconds. Algorithmic approaches to analyse the creep behaviour of this torque transducer were proposed in a recent study [19].

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