IMEKO 22nd TC3, 15th TC5 and 3rd TC 22 International Conferences
3 to 5 February, 2014, Cape Town, Republic of South Africa

OPERATING CONDITIONS FOR TRANSFER CLICK-TORQUE WRENCHES

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Abstract: For different types of click-torque wrenches, measurement uncertainty contributions of typical calibration conditions were investigated. Procedures which differ from those given in ISO 6789 were suggested for transfer measurements at calibration facilities for click-torque wrenches in order to improve their reproducibility. Examinations were carried out for influences like lever length, rise time, temperature and humidity.

Keywords: Torque, click-torque wrench, ISO 6789, transfer

1 Introduction

Click-torque wrenches (CTWs) are to be calibrated according to ISO 6789 [1]. In this standard, conformity limits are required which amount to ±4 % and ±6 % respectively, for the relative deviation of the releasing value. Nevertheless, CTWs intended as transfer standards for the traceability of the calibration facilities concerned should comply with much greater requirements. They should correspond to the best measurement capabilities (bmcs) of laboratories accredited for CTW calibration in the German accreditation body (DAkkS). These bmcs cover the range from 0.2 % to 1 % (fig. 1).

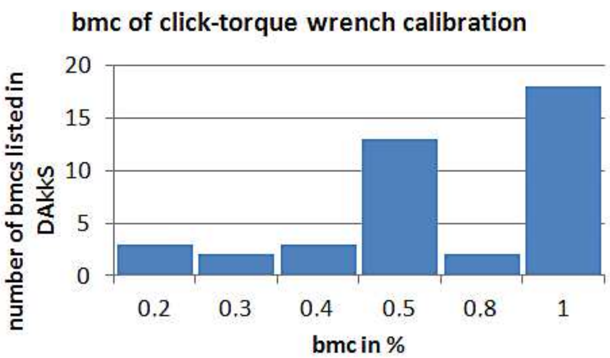

Figure 1: Distribution of listed bmcs in the DAkkS for click-torque wrench calibration according to ISO 6789.

A key comparison of the Deutscher Kalibrierdienst (DKD) based on procedures according to the ISO 6789 using CTWs demonstrated the insufficiency of the combination of the CTWs with these procedures for transfer purposes. Therefore, nowadays only indicating transfer torque wrenches can deliver the traceability of the static torque calibration in the concerning facilities according to the bmc values of calibration laboratories. But specific dynamic requests to the facilities destined for CTW calibration cannot be verified by indicating torque wrenches. Therefore the use of transfer CTWs is necessary particularly during assessments to complement the traceability of laboratories working in the field of ISO 6789.

In order to submit proposals for the selection of suitable types of CTWs and for measurement procedures which help overcome known restrictions of the available types, this work surveys important sources of measurement uncertainty of different types of CTWs.

2 Characterisation of CTWs

2.1 Calibration facility

The measurements for this paper were performed at the 2-kN·m calibration facility of the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig. This facility generates torque loads continuously using an electric motor and a gearbox. The detection of the load was conducted with Raute reference torque transducers of type TT1 and an HBM DMCplus transient recorder. Fitted with a DV55 carrier frequency amplifier module, this recorder is able to detect releasing signals (fig. 2) under the following conditions:

carrier frequency	4.8 kHz
resolution	(24 ... 15) bit
sampling rate	(150 ... 9600) Hz.

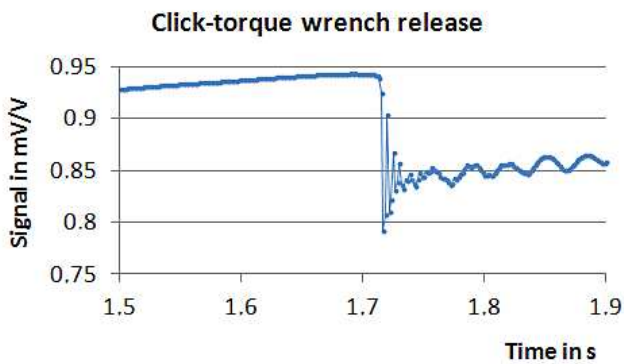

Figure 2: Torque signal of a releasing click-torque wrench over time.

Altogether, the expanded relative contribution of the reference measuring chain results in approximately $8 \cdot 10^{-4}$.

2.2 Measurements

Calibrations of CTWs according to ISO 6789 are mainly meant to achieve the deviation of the actual release torque *K* from the value which is set at the CTW. For this purpose, repeated releases are to be performed five times each at

20 %, 60 % and 100 % of the nominal torque. Hence inherent properties of the CTW, like running-in and repeatability, should be part of the result.

The intention of the measurements in this work is to figure out the CTW's coefficients of disturbing quantities and other contributions to their measurement uncertainty.

Furthermore, procedures are questioned in order to minimize the impact of disturbing quantities and to maximize the reproducibility during a transfer measurement in a calibration laboratory. These procedures are discussed later in this paper.

In the following, brief descriptions are given of the measurement procedures used for determining considerable influences on the calibration of CTWs.

2.3 Release torque *A*:

The calibration facility performs a constantly increasing load until the CTW releases and the measured torque falls sharply. The peak value *A* of the recorded signal of the reference measuring chain is calculated, taking into account the relative noises of the release curve, which is a specific value of the CTWs between $2 \cdot 10^{-5}$ and $2 \cdot 10^{-4}$ and of the reference measurement chain's zero signal (typically $3.5 \cdot 10^{-5}$). Together with the relative uncertainties of the signal recording and of the sensitivity of the reference transducer, plus the influences of the reference transducer creeping and of the zero signal drift, the combined relative uncertainty of the determination of the release torque *A* amounts to about $4 \cdot 10^{-4}$.

2.4 Relative repeatability s_{rpt}:

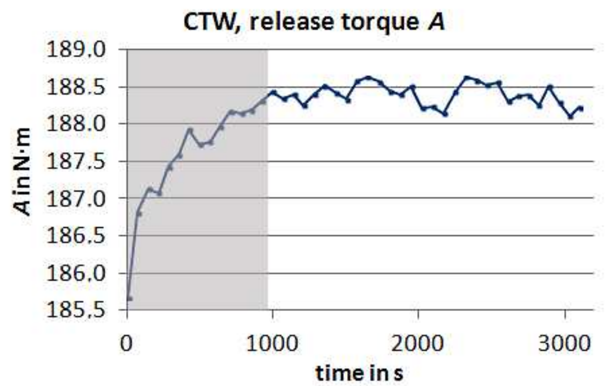

Figure 3: Devolution of the release torque *A* of a CTW during consecutive releases. The running-in reaches to value No. 14 (shaded area) and the relative standard deviation of the rest of the data delivers a relative repeatability s_{rpt} of $7.6 \cdot 10^{-4}$.

With a preliminary series of up to 120 releases, several purposes are to be served. First, the CTWs' lubrication after long idleness should be recovered and, second, the maximum release rate should be achieved. If releases succeed too fast, thermal effects in the release mechanism provoke a drift of the release torque value. Furthermore the relative standard deviation of the values of *A* provides the relative repeatability s_{rpt} (fig. 3).

Due to friction and resolution effects within the release mechanism, even without thermal effects the relative short-term repeatability of consecutive releases can exceed 10^{-3}. Series of 30 repeated release events at least were performed and averaged for the determination of each value of *A* in order to overcome this instability of the CTWs. This is important, as a high value of the repeatability relative to the other coefficients is to be taken into account at the uncertainty estimations of them.

2.5 Relative reproducibility s_{rpr}:

The relative reproducibility s_{rpr} is defined as the relative difference between two independent measurements of *A* with one CTW.

Manufacturers of CTWs recommend readjusting them to minimum value after each use to avoid mechanical drifting during long-term storage due to the spring tension inside the release mechanism. Nevertheless, keeping up the tension of the CTW over the days of investigation turned out to be advantageous. The drift, that manufacturers warn against, could not be detected during extensive tests of the specimens. Therefore, avoiding the readjustment of the CTWs between measurements yields the benefit of a smaller value of s_{rpr} by eliminating the resolution uncertainty. The relative resolution of the CTW, which amounts from $2 \cdot 10^{-4}$ to $3 \cdot 10^{-3}$ for the specimens used in this work is one of the main uncertainty contributions for calibrations according to ISO 6789.

As usual, calibrations at the beginning and at the end of a transfer can deliver a reliable value of s_{rpr}. In this work, these calibrations were simulated by repeated remounting of the CTW while the adjustment was kept.

2.6 Relative coefficient of lever length c_{l}:

The distance between the pivot of the square drive and the support at the handheld of a CTW affects the amount of *K* supposedly by a cross force effect in the pivot. Furthermore, deviations of *K* correlative to the lever length could be caused by an eccentric female square drive in the calibration facility [2]. This has been avoided by careful alignment of the facility axis with an eccentricity of less than 0.05 mm. So it is possible to detect just such an eccentricity in the calibration facility under test during a transfer calibration using the CTW, by gaining increased values of c_{l} there.

To find the value of c_{l}, two additional series of 30 releases each are performed at a lever length 10 mm shorter or longer than the normal length. The relative coefficient of lever length thus can be found with

$$c_{\mathrm{l}} = \frac{S_{\mathrm{long}} - S_{\mathrm{short}}}{\bar{S}\,(l_{\mathrm{long}} - l_{\mathrm{short}})} \quad , \qquad (1)$$

where $\bar{S}$ is the average of peak signals of the calibration facility gained at the preliminary series mentioned above, and *S* is the averaged peak signal with the longer or the shorter lever respectively, which length is given by *l*.

Though the determination of c_{l} usually has to be performed at minimum level of torque adjustment, for the purposes of transfer measurements this should be done preferably at nominal torque adjustment in this context. In this way, no readjustment of the CTW takes place and the uncertainty contribution of adjustment reproducibility can be avoided.

2.7 Relative coefficient of temperature c_T:

The peak value of a CTW can be influenced by its temperature by way of altering the lubrication viscosity, by way of dimensional changes in the release mechanism or, if a strain gauge is integrated, by temperature dependence of the gauge sensitivity.

One possibility to get an estimation of c_T is to track the relaxation of a heated CTW from 40 °C by repeated series of 30 release events each to the normal laboratory temperature of 21 °C. The CTW can be heated inside a climate cabinet overnight and then it will have to be moved quickly into the calibration facility, which is assisted by the quick and easy mounting of the CTW with a square drive. At the beginning of the experiment, the repetition rate of the series should be high. Because of the downtime of measurements during the transport of the CTW from the climate cabinet into the calibration facility, the initial status of the CTW is only available by an extrapolation. The relaxated state, in contrast, is to be measured simply by waiting some hours until the stability of occasional measurements is equal to the repeatability of the CTW obtained at the preliminary measurement. This method is equivalent to the method which was proposed for simplified measurements of the relative humidity coefficient [3].

With this set-up, c_T can be obtained by

$$c_\mathrm{T} = \frac{S_\mathrm{Cab} - S_\mathrm{Lab}}{\bar{S}\,(T_\mathrm{Cab} - T_\mathrm{Lab})} \quad , \qquad (2)$$

where $\bar{S}$ and S are defined analogical to (1), but in the case of a temperature step $T_{Cab} - T_{Lab}$ between a climate cabinet and the laboratory.

In contrast to CTW calibration according to ISO 6789, transfer measurements can be reduced to very close limits of temperature, because these measurements are only reasonable in laboratories with low uncertainty budget and thereby with an efficient temperature control. Thus, the contribution of c_T in a transfer measurement usually remains small.

2.8 Relative coefficient of humidity c_F:

Like temperature, humidity can affect the lubrication of the mechanism or the sensitivity of a gauge within a CTW. In a similar way as described above [3], the humidity of a CTW can be changed in a climate cabinet and its relaxation to the laboratory level can be observed. Then c_F is given by

$$c_\mathrm{F} = \frac{S_\mathrm{Cab} - S_\mathrm{Lab}}{\bar{S}\,(F_\mathrm{Cab} - F_\mathrm{Lab})} \quad , \qquad (3)$$

with $\bar{S}$ and S defined analogical to (1), but in the case of a humidity step $F_\mathrm{Cab} - F_\mathrm{Lab}$ between a climate cabinet and the laboratory.

Strict humidity control is challenging and expensive even for ambitious laboratories. Therefore, humidity deviation between PTB and a laboratory under test is usually greater than 5 $\%_\mathrm{rF}$, often greater than 10 $\%_\mathrm{rF}$. Consequently, the impact of c_F on the uncertainty budget potentially could be higher than that of other coefficients discussed in this paper.

2.9 Relative coefficient of rise time c_tB:

The rise time t_B of a CTW release event is defined as the time between 80 % load and the release load which defines the 100 % load. The dedicated relative coefficient c_tB can be obtained by

$$c_\mathrm{tB} = \frac{S_\mathrm{fast} - S_\mathrm{slow}}{\bar{S}\,(t_\mathrm{B,fast} - t_\mathrm{B,slow})} \quad , \qquad (4)$$

with $\bar{S}$ and S defined analogical to (1), but in the case of a step in the rise time $t_\mathrm{B,fast} - t_\mathrm{B,slow}$.

Measurement of the rise time needs correction if the CTW under test exhibits a high reading error. Then the release torque is far away from the expected nominal value and the starting point of the rise time has to be shifted to 80 % of the actual release torque. In the most cases, shifting to an earlier time is necessary, which is possible if the loading curve was recorded completely as given in this work. If a calibration facility delivers only the peak value of the curve, correction of the rise time value is impossible.

2.10 Relative coefficient of square drive influence c_V:

The quality of the square drive can influence the result of a CTW calibration by reactive forces and moments which are possible if angularity, planarity and dimensional accuracy are inadequate. The usual procedure to determine c_V is to perform five series of 10 measurements with orientation alterations of the square drive by 90° between them.

During this investigation only a short version of this procedure was performed with 30 release events at 0° and 90° position of the square drive each, because of the great time need of such measurements. Then, a coefficient could be obtained using

$$c_\mathrm{V} = \frac{S_{0°} - S_{90°}}{\bar{S}} \quad , \qquad (5)$$

with $\bar{S}$ and S defined analogical to (1), but in the case of the alteration of the square drive position from 0° to 90°.

Of course, transfer measurements should be performed with a fixed position of the square drive in both calibration facilities involved, but the determination of c_V does not become dispensable. Assuming the female square drive of the PTB facility to be well aligned, an increased value of c_V in the facility under test would indicate some of the mechanical problems described above at the female square drive of the latter. In this sense, c_V is due to the properties of the calibration facility in the first order. Therefore, the contribution of c_V to the measurement uncertainty of the CTW should be taken into account if c_V is increased in the laboratory under test.

2.11 Relative coefficient of the ratchet influence c_{rch}:

If the CTW comes with a ratchet, eccentricity of the rotating part of it is an important source of deviation, as in the case of eccentricity of the machine's axis, mentioned in the chapter about c_{l}.

Because the ratchet is not a part of the calibration facility under test, in a transfer measurement this influence should be eliminated by using a fixed or labelled position of the ratchet in both facilities. Since ratchets often come with high angular resolution and are not usually fixable, an alteration of the ratchet position could take place unnoticed during each handling. Thus, the effect of the ratchet position alteration was determined by

$$c_{\mathrm{rch}} = \frac{S_{+1\,\mathrm{cog}} - S_{-1\,\mathrm{cog}}}{\bar{S}} \quad , \qquad (6)$$

with $\bar{S}$ and S defined analogical to (1), but in the case of the alteration in the ratchet position by ± 1 cog. Because of the sinusoidal character of the eccentricity this measurement was undertaken at a ratchet position of 0° and of 90°. The maximum value of c_{rch} was used.

2.12 Uncertainty of coefficients:

The uncertainties of the coefficient determinations described in this paragraph are dominated by that of S, which is given mainly by the repeatability s_{rpt} of the CTW. Therefore, the contribution of the coefficients to uncertainty is at least in the range of s_{rpt}. This underlines the importance of small repeatabilities for the value of a CTW for transfer measurements. The use of at least 30 release events for the determination of each value of A reduces the influence of the release instability by more than a factor of 5.

3 Specimens

In order to obtain an overview of possible properties of CTWs, some different types of them were investigated in the manner described in the chapter above (Table 1).

Most of them are of the common mechanical release type. These wrenches are equipped with a release mechanism consisting of an instable crank, which can be pre-stressed by a spring and thereby be adjusted for a certain release torque. When the torque load exceeds the adjusted value, the instable crank turns over and the torque load at the square drive falls abruptly.

While this mechanism is integrated into the body of the mechanical CTW, a buckling CTW is constructed to fold entirely at the half-way point of the lever. This design is out-dated and nowadays in use merely for screwing in workshops. One exponent of this type is used in the survey to have a look at the lower end of the state-of-the-art.

Table 1: CTWs used in this investigation.

No.	Type	Nom. torque in N·m	Release type
1	M210	210	mechanical
2	S.305 DA	350	mechanical
3	No 18	700	buckling
4	714/10	100	electromechanical
5	5122 CT	180	mechanical
6	1800 QL	180	mechanical
7	721Nf/80	800	mechanical
8	Typ D	760	mechanical

An electromechanical CTW includes a strain gauge to measure the torque load. When this measure exceeds a digitally preset limit, an electromagnetic force unlocks the square drive for release. This design is quite new, but nevertheless it raises expectations for solving some of the problems which are known about mechanical CTWs.

4 Results

4.1 Sampling rate

To obtain a CTW with a well-defined and repeatable release value, the act of releasing has to be as short as possible. The signal in time therefore tends to be discontinuous, which implies high requirements for the sampling rate of the amplifier which detects the release event. Comparisons of release measurements with different sampling rates exhibit relative deviations of the peak value up to $1.3 \cdot 10^{-3}$ (fig. 4).

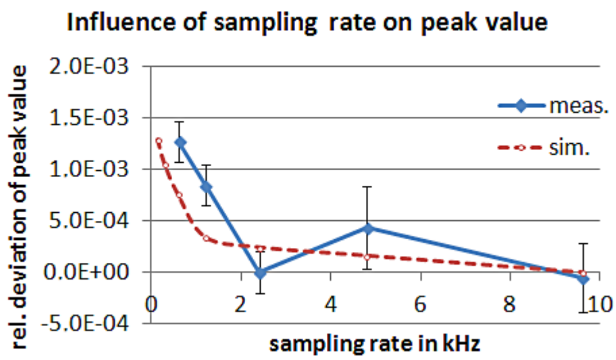

Figure 4: Relative deviation of peak value, depending on the sampling rate of the amplifier. The dashed curve is the result of a simulation which performs signal integrations with corresponding time periods at a measured release signal gained at a sampling rate of 9.6 kHz.

Using a signal of a release event measured with a sampling rate of 9.6 kHz, a simulation of signal integrations with time periods corresponding to lower sampling rates was calculated. This simulation curve shows a qualitative shape similar to that of the measurements. According to that, the curve should change from a high inclination at lower sampling rates to an approximately constant part for rates higher than 2 kHz. Therefore it is advisable for a comparison of two calibration facilities either to use a sampling rate of more than 2 kHz or to agree on a certain value of sampling rate, if only lower rates are available.

4.2 Rise time

In daily workshop use a CTW is loaded with torque by hand and as quickly as the worker is able to. Thus, the typical rise time of torque is shorter than one second. To accommodate this fact, in ISO 6789 values of t_B are required to be within 0.5 s and 4 s. The higher value is far beyond practical value for manual loading and is to be seen as a concession to the deficient speed of calibration machines.

The mechanical parts of CTWs are subject to inertia effects and to friction. Both depend on the velocity of the moving parts. In this way, rise time can affect the release torque value in CTWs. Electromechanical CTWs additionally have to face the runtime error of the release bolt and the influences of the sensing element resolution and of the internal sampling rate. In this spirit, a rise time of 0.5 s is unreasonably short for transfer measurements.

In this connection, the limits of ISO 6789 are too broad for practical application and too close for the requirements of transfer measurements. The situation becomes worse if the calibration facility under tests lacks a precise rise time gauging. Then the transfer measurement not only has to test the release torque measurement capability of the calibration machine under test. Besides this, the procedure should provide information about the rise time of the calibration machine in question.

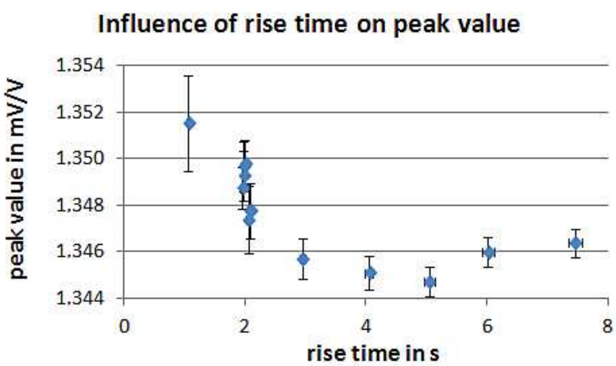

Figure 5: Peak value of a CTW depending on the torque load rise time.

Measurements with different rise times show a relative deviation of the release torque of some 10^{-3} per second at rise times shorter than 4 s, in agreement with the consideration above (fig. 5). In the range between 4 s and 5 s the dependence of the release torque on the rise time is minimal. Thus, for the purpose of transfer, measurements should be performed slowly with a rise time of 5 s. As manufacturers are obliged to design their calibration machines according to ISO 6789, the machines are often unable to run so slowly. In this case, the two comparing laboratories should agree upon rise time, which poses the problem of measuring the rise time exactly.

4.3 Selection of a transfer CTW

In order to rate the ability of the CTWs for transfer purposes, a table of the coefficients of the CTWs in the survey is given (Table 2). This survey is neither representative of the CTWs available on the market nor could a conclusion be drawn about the properties of a CTW type, this would require tests at a higher number of CTWs of a certain type. The survey shall give examples of which parameters are important. Better than a competition of coefficients, an analysis of their uncertainty impacts give evidence of the suitability of a CTW for transfer calibrations (Table 3).

The contributions in Table 3 indicate the priority for compensating the uncertainty sources of a CTW or for its improvement in order to qualify it for transfer measurements. The most influential contribution to the measurement uncertainty to be considered at the selection of a transfer CTW is the repeatability s_{rpt}.

Further parameters not included in Table 2 are the object of a qualitative appraisal. The shape of a release curve should feature a well defined peak value with a monotone rising and a fast break off, kickback-free for at least one second. The specific running-in of the release value from the initial increase to stable amounts has to be observed at preliminary tests and is to be considered at the calibrations by omitting the referring data points. Moreover, it has to be ensured by tests that keeping the CTW in tension during a transfer calibration would not increase repeatability uncertainty due to mechanical drift as mentioned in 2.5.

4.4 Uncertainty budgets

Coefficients c_{x} (x stands for one of the indices l, T, F, tB and rch introduced in chapter 2), stability contributions s_{rpr} and s_{rpt}, uncertainty of calibration conditions u_{x} (Table 4), and distribution functions were processed to relative standard uncertainty contributions w_{x} under the condition that the sampling rate is chosen adequately and c_{v} is equal in both laboratories. Because the complete analysis according to the *Guide to the Expression of Uncertainty in Measurement* is disproportionately extensive, a simplified approximation was used:

$$w_x = \left(u_x(NN) + u_{\mathrm{x}}(Lab)\right)\sqrt{\left[\frac{\left(c_{\mathrm{x}}/2\right)}{\sqrt{3}}\right]^2 + 2\left[\frac{s_{\mathrm{rpt}}}{\Delta x}\right]^2} \quad . (7)$$

While the uncertainty of the coefficient's detection - given mainly by the repeatability s_{rpt} - cannot be neglected, the contribution of a specific coefficient c_{x} has to be extended by the Δx^{th} fraction of s_{rpt}. Here, Δx is the step of the calibration condition quantity, in units of this quantity, performed during the detection of the coefficient. The contribution of the coefficient c_{x} is derived from a span, thus a rectangular distribution is to be taken into account. In contrast, the repeatability s_{rpt} originates from an averaging, thus a normal distribution is to be assumed. Because c_{x} is achieved by a difference, the extension due to the repeatability is to be taken into account twice.

Table 2: Absolute values of relative coefficients in 10^{-6} of CTWs listed in Table 1. Some data were not measured due to time constraints; the referring coefficients were treated as equalling zero.
1) Deviation due to friction-induced drift, treated as a systematic contribution.

rel. coefficient in 10^{-6}	1	2	3	4	5	6	7	8
c_l in mm^{-1}	2548	92	no data	326	394	636	330	37
c_T in K^{-1}	1041	351	no data	507	903	510	1008	181
c_F in $(\%_{rF})^{-1}$	1154	560	no data	20	268	77	no data	229
c_{tB} in s^{-1}	8153	6029	no data	2293	5749	1259	4537	3084
c_V	no data	4071	no data	220	7453	586	151	8041
c_{rch} (one cog)	6787	1249	no data	305	5783	2316	2635	no ratchet
s_{rpr}	2748	217	no data	143	3419	674	989	5184
s_{rpt}	3178	1282	6818[1)]	524	761	2870	3538	1829

Table 3: Relative standard measurement uncertainties *w* in % of CTWs listed in Table 1 due to examined quantities introduced in the text for a transfer measurement between a national standard machine and a calibration laboratory. The contributions of the specific coefficients listed in Table 2 are calculated using the calibration conditions listed in Table 4 both for a standard machine and for a calibration laboratory. The resulting combined expanded relative uncertainty W_{Ref} is given both under the assumptions given in Table 4 and neglecting the influence of a ratchet. The contributions, except for w_{rch}, are graded in reference to their amount by colour. The highest contributions are printed in red, the second highest in blue.

uncertainty in %	1	2	3	4	5	6	7	8
w_A	0.042	0.042	0.046	0.041	0.045	0.044	0.042	0.041
w_{rpr}	0.645	0.257	1.364	0.105	0.207	0.575	0.709	0.423
w_l	0.027	0.003	0.017	0.004	0.004	0.010	0.009	0.005
w_T	0.077	0.028	0.099	0.031	0.055	0.052	0.079	0.029
w_F	0.189	0.090	0.130	0.010	0.044	0.056	0.067	0.050
w_{tB}	0.166	0.100	0.246	0.039	0.089	0.105	0.144	0.080
w_{rch}	0.225	0.148	0.482	0.038	0.222	0.204	0.250	no ratchet
W_{Ref} , k=2	1.47	0.66	3.15	0.26	0.65	1.25	1.55	0.87
W_{Ref} , k=2 (no ratchet)	1.40	0.59	2.74	0.25	0.48	1.18	1.46	0.87

To obtain the actual contribution of the coefficients, the expanded specific coefficients have to be multiplied by the uncertainty of the corresponding calibration conditions u_x, which are given in Table 4 for the reference calibration with the national standard machine (NN) and for a typical accredited calibration laboratory (Lab). Thus the relative standard uncertainty w_x includes the impact of the CTW properties at both calibration facilities involved.

The uncertainty contribution of the stability w_{rpr} is calculated equivalent to the second part of (7) from the reproducibility s_{rpr} with a rectangular distribution and twice the repeatability s_{rpt} with a normal distribution.

As an overall result, the expanded relative combined uncertainty $W_{Ref}(k=2)$ is given for each CTW in Table 3. This uncertainty implies the contributions due to CTW properties in combination both with the calibration conditions in the national standard machine (TN-NN) and with those in a calibration machine of a laboratory under test (TN-Lab) as well as a contribution from the national standard machine (NN). If a transfer calibration should confirm the bmc of a calibration machine under test, the E_n value (8) must not exceed 1:

$$|E_n| = \left| \frac{K_{NN} - K_{Lab}}{\sqrt{U_{Ref}^2 + U_{Lab}^2}} \right| \leq 1 \quad . \tag{8}$$

The E_n value compares the difference between two measurements of the release torque K with the quadratic sum of uncertainties referring to these calibrations. In this work, the transfer CTW is to be understood as a part of the reference calibration, thus the referring expanded uncertainty U_{Ref} corresponds to the relative expanded uncertainty W_{Ref} given in Table 3:

$$U_{Ref}^2 = U_{NN}^2 + U_{TN\text{-}NN}^2 + U_{TN\text{-}Lab}^2 \quad . \tag{9}$$

The examination of U_{Ref} is important since (8) implies that even at equality of the two comparison measurements $(K_{NN} = K_{Lab})$, the smallest bmc the comparison could verify is $U_{Lab} = U_{Ref}$. Therefore, a CTW for transfer application without restriction in accredited laboratories according to fig. 1 should feature a value of W_{Ref} smaller than 0.2 %. No specimen meets this requirement. Only

No. 4 is able to be used in transfer measurements for laboratories with a bmc of 0.3 % and higher. The majority of bmc values in fig. 1 is greater than or equal to 0.5 %. Transfer to these laboratories is possible also with CTW No. 5 if no ratchet is used or the ratchet position is kept constant.

The best results were achieved with CTW No. 4 which is of the electromechanical type. Apparently the higher effort in engineering is reflected in a very low dependency of the release torque on calibration conditions.

In Table 3, the contributions are graded in reference to their amount by colour. The highest contributions are printed in red, the second highest in blue. Excluded is w_{rch}, because this contribution could be avoided by using no ratchet but rather a fixed square drive.

For No. 4, the contribution of w_A, which is mainly the uncertainty of the standard calibration facility, is the second highest, the contribution of w_{rpr} is the highest. A further improvement of this CTW should start with a reduction of the relative repeatability s_{rpt}. A decrease of this value from $5{\cdot}10^{-4}$ to $1.5{\cdot}10^{-4}$ would result in an overall relative expanded uncertainty below 0.2 % and hence would qualify this CTW to transfer measurements in all laboratories included in fig. 1. No less would the other CTWs in the survey benefit from such improvements of the repeatability. In this case, No. 6 would also be qualified for all transfers, while No. 2 and No. 7 would become suitable for transfers with a bmc of 0.3 % and higher.

Furthermore Table 3 displays the dominating role of the contribution concerning rise time among the laboratory conditions. Most of the CTWs could be improved essentially in this field.

Table 4: Uncertainty of calibration conditions u_x expressed as a half-span value used for the calculation of an uncertainty in a transfer measurement (Table 3). Given are measured values of the PTB standard calibration machine (NN) and assumed values for typical accredited calibration laboratories (Lab).

Condition	Index x	u_x (NN)	u_x (Lab)
Lever length	l	0.25 mm	0.25 mm
Temperature	T	0.5 K	2 K
Humidity	F	2 $\%_{rF}$	5 $\%_{rF}$
Rise time	tB	0.1 s	0.5 s
Ratchet position	R	0 cog	1 cog

CTW No. 3 exhibits friction-induced drift during the preliminary measurements. This drift is to be understood as a systematic contribution and therefore has to be taken into account by absolute value. Thus, this contribution on its own exceeds the requirements of transfer application and hence no more measurements were performed with this CTW. Coefficients which were not measured are marked in Table 2 with “no data”. These are counted as zero in order to get a lower estimation of W_{ref} at the end. Nevertheless, the uncertainty contributions w_x of these conditions are greater than zero because of the contribution of s_{rpt} in (7). For this reason, the repeatability of a CTW should not exceed the contribution of each coefficient. Most of the tested CTWs are far away from fulfillment of this requirement.

4.5 Procedure for transfer measurements

The measurements of the survey show that the procedure of ISO 6789 is not adequate for transfer measurements with CTWs.

Readjusting uncertainty of the CTWs can be avoided when the adjustment of the CTW is not changed during the measurements. This adjustment should be made at the nominal value of the CTW in order to use the best possible signal-to-noise ratio. Extensive tests with CTWs stored several days under the tension of this adjustment did not show a drift of the release torque. Furthermore, the CTW with the best overall uncertainty is of the electromechanical type and hence is free of mechanical tension due to adjustment.

The transfer measurement should consist of series of at least 30 release events to reduce the repeatability uncertainty.

The load rise time should be fixed to a certain value, preferably at 5 s.

Furthermore, the laboratories should agree on a fixed value of sampling rate, at best more than 2 kHz.

The position of the square drive and of the ratchet should be the same in both laboratories. Additional series after alteration of the square drive position by 90° should be performed at least for two positions.

The length of the lever, the temperature and the humidity should be controlled and documented.

5 Conclusions

The capability of CTWs for use as transfer transducers depends not only on their technical specifications. Restricted specifications could be compensated if adapted procedures are employed which can largely differ from those according to ISO 6789. The objective of these procedures should be an optimization of the reproducibility of the CTWs’ response. A suggested procedure designates the measurements required in ISO 6789 at 20 % and 60 % of the nominal value, but calls for at least 30 repeated measurements instead of 5. Parameters like rise time, positions of square drive and ratchet, sample rate, temperature, humidity and lever length are to be agreed upon and reproduced in the laboratories within narrow limits.

The survey shows that the use of transfer CTWs for DAkkS assessments is possible under special conditions and with adequate types of CTWs for laboratories with a bmc of 0.5 % and higher. Therefore, the development both of specific measurement procedures and of selection criteria for CTWs, which was carried out to complement the traceability of the laboratories working in the field of ISO 6789, should be supplemented by further improvement of the CTWs, especially of their repeatability.

The detected coefficients of the used specimens vary over a wide range of amounts. The selection of a CTW for transfer application therefore requires the analysis of the combined measurement uncertainty budget in the setup of the intended transfer measurement.

A new design of CTW with an electromechanical release mechanism yields the best results among the tested specimens. Here, only the contribution of w_{rpr} exceeds the contribution of the standard calibration facility. According to (7) the impact of the repeatability s_{rpt} dominates the uncertainty budget. Assuming a much better repeatability of about $1.5 \cdot 10^{-4}$, the best achievable uncertainty of a transfer measurement using a CTW would be 0.15 %. Hence, the repeatability is a criterion for the selection of CTWs for transfer function which is easy to achieve by measurements.

Acknowledgment

Thanks go to Sebastian Kaletka, who carefully performed hundreds of measurements for this investigation.

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