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TORQUE WRENCH CALIBRATION AND UNCERTAINTY OF MEASUREMENT

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Abstract: Torque wrenches (TW) are widely used in the automotive, aviation and building industry. TW are used to control torque in assembly and fastening operations. Regular calibration of torque tools guarantees traceability to international standards. At KEBS, a torque wrench calibrator with four interchangeable torque transducers and torque meters are used to calibrate both type I and type II torque wrenches as per ISO 6789:2003. In compliance to “Guide for evaluation of uncertainty in measurement” (GUM), it is a requirement that a complete measurement result should include its uncertainty, a proposed method with an example on how to estimate measurement uncertainties for torque wrenches is presented after taking into account the various influencing quantities. Uncertainty values of ± 2.54 N·m, ±1.15 N·m, and ±1.33 N·m are estimated at 20%, 60% and 100% respectively of a type II class A torque wrench with a nominal value of 1000 N·m. The paper aims to provide guideline information for TW calibration and uncertainty evaluation.

Keywords: Calibration, ISO 6789:2003, Torque Tools, Torque wrenches, Uncertainty.

1. INTRODUCTION

Torque is one of the important physical parameters, widely used in several industries such as aviation, automobile, mechanical, pharmaceutical, power and agriculture. Applications for torque sensors include determining the amount of power an engine, motor, turbine, or other rotating device generates or consumes [1]. Other industrial applications of torque sensors include the calibration of torque tools and sensors; measuring peel forces, friction, and bottle cap torque; and testing springs. The importance of the torque measurements is to control the fastening force on assembly parts and to measure mechanical power. Torque is, generally, measured by mechanical type torque wrenches/ meters. A torque wrench is a tool used to precisely apply a specific torque to a fastener such as a nut or bolt. Torque screwdrivers and torque wrenches have similar purposes and mechanisms [2]. Regular calibration of torque tools guarantees traceability to international standards. Calibration procedures for hand torque tools are defined in the ISO 6789:2003 standard [3]. ISO 6789:2003 however, does not provide any information or guidelines on how to evaluate the uncertainty of measurement [4]. On the other hand, according to GUM [6], it is necessary to report a complete measurement result including its uncertainty. Also IEC/ISO 17025:2005 standard [8] requires that a calibration laboratory, performing its own calibrations, shall have and shall apply a procedure to estimate the uncertainty of measurement. This paper presents the classification and calibration, and suggests a measurement uncertainty budget for torque wrenches as per GUM. The aim of this paper is to provide guideline information for TW calibration and uncertainty evaluation to quality managers with a view to encouraging setting up a torque wrench calibration facility in their own organisations.

2. CLASSIFICATIONS OF HAND TORQUE TOOLS

According to ISO 6789:2003, hand torque tools are classified as follows: Type I – indicating torque tools and Type II – setting torque tools. Below is a description of Type I and Type II.

2.1. Type I: Indicating torque tools

These are tools that indicate by means of a mechanical scale, dial or electronic display, the value of torque exerted by the tool at the output drive [3]. The classes in type I are;

- Class A: wrench, torsion or flexion bar
- Class B: wrench, rigid housing, with scale or dial or display
- Class C: wrench, rigid housing and electronic measurement
- Class D: screwdriver, with scale or dial or display
- Class E: screwdriver, with electronic measurement

Below is a description of a few of type I wrenches;

Dial indicating torque wrenches: You just turn until the dial indicates the torque you want (See Fig. 1).

Fig1: Dial indicating torque wrench [5]

Bending beam torque wrenches: The large centre beam bends as you apply torque, while the unbending pointer beam lets you read the torque directly. When the desired torque is reached (see Fig. 2), the operator stops applying force. The disadvantages are that your eyeball has to be parked directly above the pointer while you read the scale, which is tough in hard-to-reach places and calibration cannot be performed automatically, since the operator has to look at the indicator and write manually the value.

Fig. 2: Beam type torque wrench [2].

2.2. Type II: Setting torque tools

These tools are pre-set to a certain torque value, so that when the prescribed value of torque is exerted by the tool at the output drive, a signal is released (e.g. audibly, visibly, and perceptibly) [3]. The classifications in type II are;

2.2.1 Adjustable graduated torque tool (Type II, Class A, Class D and Class G)

These tools are designed to be adjusted by the user, which have a scale or a display to assist adjustment.

2.2.2 Adjustable non-graduated torque tool (Type II, Class C and Class F)

These tools are designed to be adjusted by the user with the aid of a calibration device

2.2.3 Torque tool with fixed adjustment (Type II, Class B and Class E)

Tools not designed to be adjusted by the user, i.e. having a single setting. Below is a description of a few of type II wrenches;

Click torque wrenches (adjustable by the user): This pro-grade tool is preset to the desired torque and will click tactilely and audibly when it reaches the desired torque (See Fig. 3). At the point where the desired torque is reached, the clutch slips, signalling the desired torque and preventing additional tightening. It should always be turned down and stored at the lowest possible setting. The continuous "stress" on the internal spring can be responsible for a long-term decrease in accuracy. It is necessary, before performing calibration, to keep the torque at the minimum setting for a certain amount of time (12 hours), in order to exclude or reduce this effect [9]. Even so, it should be calibrated regularly if used for critical parts like suspension and internal engine fasteners.

Fig 3: Click type torque wrench [2]

Fig. 4: shows the inside structure of a click TW, with a multi-lever action. The spring in the hilt applies a force against one or more elements, which are connected, through a multi-lever system, to the square drive. Setting the TW means compressing the spring and applying a higher force to the elements. When the user operates the TW and the force balance is reached, there is a click point (peak value) and an immediate decrease of the torque value [9].

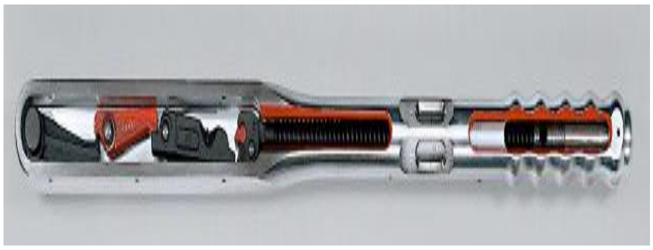

Fig. 4: Multi-lever inside mechanism of a click torque wrench [9].

Slipper torque wrenches: A variant of the previous one, this TW type cannot be adjusted directly by the user, as it doesn't have a setting scale or indicator. It is also known as "production type TW", and is normally set against a torque wrench analyzer or Torque Wrench Calibration Device (TWCD) (see Fig. 5) and then dedicated to a particular application, where modifications of the value of the nominal torque are not frequently required. From the metrological point of view, this is the "safest" tightening system, as it eliminates over-tightening and discourages unauthorized alteration. It has a smooth decreasing curve after the peak value [9].

Fig. 5: Slipper torque wrench (production type) [2]

Electronic torque wrenches: For electronic torque wrenches (see Fig. 6) measurement is by means of a strain gauge attached to the torsion rod. The signal generated is converted by the transducer to the required unit of torque (N·m, lbf·ft etc.) and shown on the digital display. A number of different joints (measurement details or limit values) can be stored. These programmed limit values are then permanently displayed during the tightening process by means of LEDs or the display. At the same time, this generation of torque wrenches can store all the measurements made in an internal readings memory. This readings memory can then be easily transferred to a PC via the interface (RS232) or printed straight to a printer. [2].

Fig. 6: Electronic torque wrenches [2]

3.0 CALIBRATION OF TORQUE WRENCHES

Calibration shall be carried out at a temperature fluctuating by not more than ± 1 °C. This temperature shall be in the range between 18 °C to 28 °C (maximum relative humidity 90 %) and shall be documented [3]. In general, the calibration procedure consists of one and five pre-loadings for Type I and Type II respectively with the maximum torque without recording the values, followed by testing first at 20 % and then at about 60 % and at 100 % of the maximum torque value of the torque tools (or at the nominal/set value for tools of Type II, Classes B and E). All readings shall be within the maximum tolerances specified in ISO 6789:2003 and shall be recorded. The conformity can be declared if the deviations are within the limit set by the standard (± 4%, respectively ± 6% for some classes). There is no measurement uncertainty taken into account in contradiction to the IEC/ISO 17025:2005 standard which requires that conformity statements must be made including the uncertainty of measurement [7]. This is very important for accredited calibration laboratories [4]. Calibration can be performed with automatic or manual calibration devices. See Fig. 7 and Fig. 8 for manual and automatic TWCD.

Fig.7: Manual calibration device (digital meter) used at KEBS

Fig. 8: Automatic Torque Wrench Calibrator used at KEBS.

3.1 Evaluation of the Calibration result

The evaluation of the deviation shall be made by the following formula [3]:

$$A_s\ (\%) = \frac{(X_a - X_r)100}{X_r} \quad (1)$$

Where:
A_s (%) is the calculated relative deviation of the torque tool;
X_a is the indicated value of the torque tool;
X_r is the reference value (determined by the calibration device).

In the special case of Type II classes C and F tools (without scale), the value of X_a is calculated as mean of the ten reference torques X_r measured by the calibration facility. This value is then used in formula (1) [4].

3.2 Tolerances

According to ISO 6789:2003, permissible deviation of the torque value indicated by the tool, from the simultaneous indication of the calibration device, is as given in Table 1-3 below [3];

Indicating torque tools (Type I)

Table 1: Permissible deviation (Type I)

Class[a]	Maximum torque Value	
	≤ 10 N·m	> **10** N·m
A and D	± 6 %	
B, C and E	± 6 %	± 4 %

Setting torque tools (Type II)

Table 2: Permissible deviation (Type II, Classes A, B, D, E and G)

Class[a]	Maximum torque Value	
	≤10 N·m	>**10** N·m
A and B	± 6 %	± 4 %
D, E and G	± 6 %	± 6 %

Table 3: Permissible deviation (Type II, Classes C and F)

Class	Maximum torque Value	
	≤10 N·m	>**10** N·m
C	± 6 % ±	± 4 %
F	± 6 %	

For Classes C and F, the torque value set is equal to the arithmetical mean of the 10 test readings

4.0 EVALUATION OF THE UNCERTAINTY OF MEASUREMENT

Uncertainty of measurement shall be calculated in accordance with the GUM [6]. The GUM Steps are**;**

- Model the measurement
- Identify and quantify the sources of uncertainty
- Categorize as type A or type B
- Manipulate appropriately to obtain

    i. Standard uncertainties, $u(xi)$
    ii. Sensitivity coefficients, *ci*
    iii. Uncertainty contributor, *u(yi)*

- Combine to obtain combined standard uncertainty, $u_c(y)$
- Expand to obtain an expanded uncertainty, *U*
- Report the result

4.1 Measurement Model

The calibration result is the output signal of the torque measuring device and is obtained from the approximate mathematical model [10]:

$$\bar{X} = M_K . \prod_{i-1}^{n}(1 - \delta M_i) \quad (5)$$

Where:
δM_1 Influence of resolution of the TW, *r*
δM_2 Influence of repeatability error, *b'*
δM_3 Influence of the relative uncertainty w_{tcd} of the values of the reference torque transducer.

4.2 Identifying the sources of uncertainty

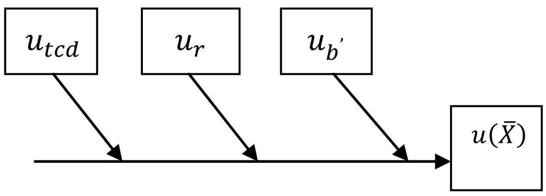

Fig. 9: Sources of uncertainty for TW.

4.3 Quantifying the sources of uncertainty

The following contributions can generally be taken into account:

Contribution of the Reference torque (u_{tcd}): This is the uncertainty due to the torque transducer of the TWCD. This value should be taken from the manufacturer's calibration certificate, for the corresponding measuring range or defined position, divided by the coverage factor (usually k=2). This uncertainty component is a combination of influences from repeatability in unchanged mounting position, reproducibility in different mounting positions, deviation resulting from the fitting curve and instrument resolution.
As an example (see Table 4) 0.52% is the actual value corresponding to the 200 N·m position. Interpolation can be necessary if that particular calibration position is not included in the certificate.

Table 4: Results from a Calibration Certificate [7]

Clockwise				
Actual Applied Torque	**Average transducer readings**	**Output using fitting equation**	**Relative expanded uncertainty (k=2)**	**Transducer Class**
N·m	mV/V	mV/V	± %.	
0	0.0000	0.0000	0.0000	
200	0.1004	0.1003	0.519	1.0
400	0.2005	0.2006	0.353	0.5
600	0.3008	0.3009	0.241	0.5
800	0.4012	0.4011	0.416	1.0
1000	0.5017	0.5013	0.254	0.5
1200	0.6012	0.6015	0.365	1.0
1400	0.7018	0.7017	0.283	1.0
1600	0.8019	0.8018	0.238	0.5
1800	0.9018	0.9020	0.306	1.0
2000	1.1021	1.1020	0.258	0.5

Contribution of the resolution (u_r): This is due to the resolution of the TW scale divided by a standard value. Each deflection value is calculated from two readings (the reading with an applied torque minus the reading at zero torque). Because of this, the resolution of the indicator needs to be included twice. This is the range of the rectangular distribution. Consider a TW with a resolution of 2 N·m and therefore the semi-range is (2 N·m /2) =1 N·m. The divisor for rectangular distributed uncertainty contributors is √3 [6].

Contribution of the TW repeatability ($u_{b'}$): This result from the variability in the measurement results obtained after repeating the measurement five (or ten) times. It can be dealt with either as "repeatability" or as "reproducibility". This contribution is considered as a type A uncertainty and is not divided by the coverage factor.

Environmental factors: Too extreme temperatures and humidity should be avoided [4]. Temperature variation less than ± 1 °C and humidity lower than 90% during calibration should be maintained [3].

4.4 Categorize as type A or type B

- u_{tcd} - type B, not statistically determined
- u_r - type B, not statistically determined
- $u_{b'}$ - type A, statistically determined (standard deviation)

4.5 Manipulate appropriately to obtain

    i. Standard uncertainties, $u(xi)$
    ii. Sensitivity coefficients, *ci*
    iii. Uncertainty contributor, *u(yi)*

- Combine to obtain combined standard uncertainty, $u_c(y)$
- Expand to obtain an expanded uncertainty, *U*, at an appropriate level of confidence

4.6 Uncertainty budget

The standard uncertainty $u(\bar{X})$ expressed in units of indication and the relative standard uncertainty $w(\bar{X})$ is obtained by the law of propagation of uncertainty in the approximation of non-correlated variables [11]:

$$u(\bar{X}) = \sqrt{\sum_{i=1}^{3}\left(\frac{\partial \bar{X}}{\partial xi}\right)^2 u^2(xi)} \qquad (6)$$

$$w(\bar{X}) = \frac{u(\bar{X})}{\bar{X}} \cdot 100 \qquad (7)$$

With

$$u(\bar{X}) = \sqrt{u^2{}_{tcd} + 2u^2{}_r + u^2{}_{b'}} \qquad (8)$$

$$w(\bar{X}) = \sqrt{w^2{}_{tcd} + 2w^2{}_r + w_{b'}} \qquad (9)$$

The expanded uncertainty of measurement U or the expanded relative uncertainty of measurement W for each calibration step is calculated from the combined uncertainty of measurement, using equation (10 or 11), with coverage factor k= 2:

$$U = k \cdot u_c(\bar{X}) \qquad (10)$$

$$W = k \cdot w_c(\bar{X}) \qquad (11)$$

Table 5 below contain the symbols and designations used in this paper.

Table 5: Symbols, designations and units

Symbol	Designation	Unit
M_K	applied calibration torque	N·m
X_a	indicated torque values	N·m
$\bar{X}$	mean value of the torque measuring device of increasing steps	N·m
b'	repeatability	N·m
b	reproducibility	N·m
n	number of increasing series	
j	index of selected series	N·m
r	resolution of the torque tools	N·m
u_r	uncertainty contribution of resolution	N·m
w_r	relative uncertainty contribution of resolution	%
$u_{b'}$	uncertainty contribution of repeatability	N·m
$w_{b'}$	relative uncertainty contribution of repeatability	%
u_{tcd}	uncertainty contribution of the applied torque value of the torque standard devices	N·m
w_{tcd}	relative uncertainty contribution of the applied torque value of the torque standard devices	%
u_c	combined standard uncertainty of measurement	N·m
w_c	combined relative standard uncertainty of measurement	%
U	expanded uncertainty of measurement	N·m
W	expanded relative uncertainty of measurement	%
$u(\bar{X})$	standard uncertainty of measurement	N·m
$w(\bar{X})$	relative standard uncertainty of measurement	%

Table 6: Proposed distributions and corresponding standard uncertainties for important parameters

Quantity	**Evaluation of standard uncertainty**	**Distribution function**	**Standard uncertainty u in N·m**	**relative standard uncertainty w , %**
Repeatability, *b'*	type A	Rectangular	$u_{b'} = \sqrt{\frac{\sum_{j=1}^{n}(x_j - \bar{X})^2}{(n-1)}}$	$w_{b'} = \frac{b'}{\sqrt{3}} \times \frac{100}{\bar{X}}$
Resolution of the torque tools r	Type B	Rectangular	$u_r = \frac{r}{\sqrt{12}}$	$w_r = \frac{\left(\frac{r}{2}\right)}{\sqrt{3}} \cdot \frac{100}{M_k}$
Reference torque	Type B	Normal	u_{tcd}	w_{tcd}
Combined standard uncertainty $u_c = \sqrt{u_{b'}{}^2 + 2.u_r{}^2 + u_{tcd}{}^2}$				
Combined relative standard uncertainty $w_c = \sqrt{w_{b'}{}^2 + 2.w_r{}^2 + W_{tcd}{}^2}$				
Expanded uncertainty $U = k.u_c$, k = 2				
Expanded relative uncertainty of measurement $W = k.w_c$, , k = 2				

Table 7: Sample calibration data of setting torque wrench type II class A with nominal value of 1000 N·m, resolution: 2 N·m

Readings (%)	**Set readings in N·m**	**Readings in N·m**						**Std dev of readings (%)**
		1	**2**	**3**	**4**	**5**	**Average readings**	
20	200	201.5	201.2	199.8	201.2	199.8	200.7	0.82
60	600	599.7	599.3	599.4	599.3	600.1	599.5	0.35
100	1000	1002.8	1003.1	1002.0	1003.2	1002.0	1003.0	0.45

Table 8: Example of uncertainty budget of setting torque wrench type II class A at 200 N·m, resolution 2 N·m

Quantity	**Estimate X_i, N·m**	**Relative Standard uncertainty W (X_i) , %**	**Probability Distribution**	**Sensitivity coefficient C_i**	**Relative uncertainty contribution W_i (y) , %**
X_a	200				
$\bar{X}$	200.7				
r		0.58	Rectangular	1	0.58
b'		0.82	Normal	1	0.82
u_{tcd}		0.52	Normal	1	0.52
Combined relative uncertainty, w_c					1.27
Expanded rel. uncertainty, W at k =2					2.54

From the sample calibration data in Table 7, uncertainties are calculated according to Table 6 and are shown in Table 9.

Table 9: Calculated uncertainties

Readings, %	**in N·m**					
	Set readings	u_{tcd}	$u_{b'}$	u_r	u_c	**U**
20.00	200.00	0.52	0.82	0.58	1.27	2.54
60.00	600.00	0.24	0.35	0.58	0.58	1.15
100.00	1000.00	0.25	0.45	0.58	0.66	1.33

4.6 Report the result

The uncertainty of measurement of the torque wrench at the measuring position of 200 Nm would then be given as 200.7 **± 2.54 Nm**, at a Level of Confidence of 95,45**%**.

5.0 CALIBRATION CERTIFICATE AND DURATION OF VALIDITY

Where the calibration of a torque measuring device has satisfied the requirements of the standard, the calibration laboratory should draw up a certificate stating the following information [11], in addition to that shown in guide EA-4/01 [12].

a) Identify all the elements of the torque measuring device and its components, including mechanical coupling components to the calibration equipment;
b) The method used, identifying whether clockwise and/or anti-clockwise torque, incremental and together with reference to ISO 6789:2003 standard;
c) The resolution of the torque measuring device;
d) The temperature at which the calibration was performed;
e) A statement on the expanded uncertainty of measurement and the equation of the fitting curve where applicable;
f) Where required, a statement regarding the conformity of the calibration results to a particular classification at the criteria used

5.1 Re-calibration of torque wrenches

The calibration interval shall be chosen on the basis of the factors of operation such as required accuracy, frequency of use, typical load during operation as well as ambient conditions during operation and storage conditions. The interval shall be adapted according to the procedures specified for the control of test devices and by evaluating the experience gained during recalibration. If the user does not utilize a control procedure, a period of use of 12 months, or approximately 5000 cycles, can be taken as a default value for the recalibration interval. This period should be reduced when the tool is frequently used. The TW shall be recalibrated when it has been subjected to an overload higher than that applied in the overloading test, after repair or after inexpert handling, which may have an effect on the uncertainty of measurement [3].

6. CONCLUSIONS

This paper presents the classification and calibration of torque wrenches as per ISO 6789:2003 standard. In compliance to GUM, a method of determining important and relevant influencing quantities in torque wrench calibration is described. Example of uncertainty budget of setting torque wrench type II class A is presented and the expanded relative uncertainty values were found to be ± 2.54 N·m, ±1.15 N·m, and ±1.33 N·m at 20%, 60% and 100% respectively of the nominal value of 1000 N·m.

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