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Design of a torque standard component of an integrated calibration equipment

Abstract. This paper describes the establishment of a torque standard component (TSC) of an integrated calibration equipment (ICE). The TSC was developed for on-site automated calibration of several hand torque wrenches (like as setting type torque wrenches, indicating type torque wrenches and hand torque screwdrivers). Based on integrated idea and lightweight design, The TSC was optimized to weight only 5 kg, which saved much room, reduced gross weight of the ICE itself, and brought great benefit to on-site calibration. The relative expanded uncertainty of torque realized by the TSC was estimated to be 0.9% from 0.5 Nm to 60 Nm, with the coverage factor $k=2$. Performance of the TSC was examined by carrying comparison experiments with a reference torque standard (RTS) at our lab. As a result, torque realized by the TSC was shown to be equivalent to that realized by the RTS within the calmed uncertainties.

1. Introduction

Hand torque wrenches are widely used to accurately control torque in assembly and fastening operations in mechanical manufacturing, chemical engineering, automotive industry, ship-building, aerospace, power, railway and other assembling lines. In order to maintain consistent accuracy, calibration or verification of torque wrenches or screwdrivers on a periodic basis would be advisable. However, this is only part of the requirement. Data obtained from the calibration of hundreds of wrenches over several year period indicates that there is still a big probability that wrench failure occurs prior to periodic recalibration, especially those overused. Those disqualified wrenches may cause bolting related failure, even catastrophic accidents. Consequently, it is reasonable that wrenches themselves need to be calibrated on the site of customer just before applying whenever necessary. It is more and more being realized that for the quality control of assembling, those torque tools need to be on-site calibrated. In consequence, Engineers have begun developing portable torque wrench testers with which laboratories or factories would be able to calibrate wrenches whenever needed. In addition, there are many commercial portable torque wrench testers available for on-site calibration of hand torque tools. However, most of the commercial portable torque wrench testers are still manually handling, which was normally a much time consuming procedure and a laboured task. Furthermore, those so called ‘portable testers’ usually weight dozens of kilograms to cover a large calibration range, most of which are seldom used.

Besides, in recent years the demand for the calibration of multiple instruments with an integrated calibration equipment (ICE) has increased sharply. To meet the customized requirements, we developed an ICE with the aim of on-site calibration of several geometric instruments, thermal instruments, and mechanical instruments, in which a torque standard component (TSC) was designed for on-site calibration of several commonly used hand torque tools. The relative expanded uncertainty of torque realized by the TSC was evaluated in the 0.5~60 Nm torque range and was estimated to be 0.9%, with a coverage factor, k , being equal to 2. The TSC was compared with a reference torque standard (RTS) at our lab. The calibration results obtained by these two devices were coincided within the claimed uncertainties. Details about the TSC will be described in the following section, followed by uncertainty evaluation and finishing with comparison results of the TSC and RTS.



2. Design

2.1. Establishment of equipment

The ICE was designed to perform calibrating various geometric, thermal and mechanical instruments, by taking into account several standard components working as transfer standards, all of which are traceable to national standards. The TSC is one of the standard components to calibrate several hand torque wrenches, namely setting type torque wrenches (STWs), indicating type torque wrenches (ITWs) and hand torque screwdrivers (STWs). A schematic diagram of the ICE is shown in figure 1, on top of which is part of the TSC as illustrated in figure 2.

The TSC was designed on the basis of a portable torque wrench tester [1] by means of integrating to the ICE and was optimized to weight only 5 kg by integrated design and finite element analysis. Mechanical parts of the TSC mainly consists of a motor, a gearbox, two standard torque transducers, a driver and clamping structures as depicted in figure 3. Two alternative torque transducers covering the calibration range from 0.5 Nm to 60 Nm were employed to measure torque value of the calibrated wrench. Various easily detachable square drives were prepared in different sizes to enable torque wrenches of various sizes and shapes to be installed on either of the two torque transducers. A calibrated torque wrench was mounted on a torque transducer through a square drive and supported by a rod for loading point at its handle. Unlike our previous independent version, guiders of the portable torque wrench tester in figure 1 at literature [1] were omitted, and instead, part of framework of the ICE as shown in figure 2 was designed as the sliding guide. Thus the sliding block has been improved to a much simplified one. A slightly loose fit between an adapter fixed to the output shaft of gearbox and the input of transducer so as to measure and transfer torque, simultaneously. A gearbox with a magnification coefficient of 50 was chosen such as to amplify the torque outputted from the motor and lower the loading speed. A motor with a rated torque of 1.4 Nm is driven by a driver controlled by a control unit in the ICE, which receives the commands from a laptop via USB interface. The laptop evaluates signals from the torque transducer and controls the motor in a closed loop.

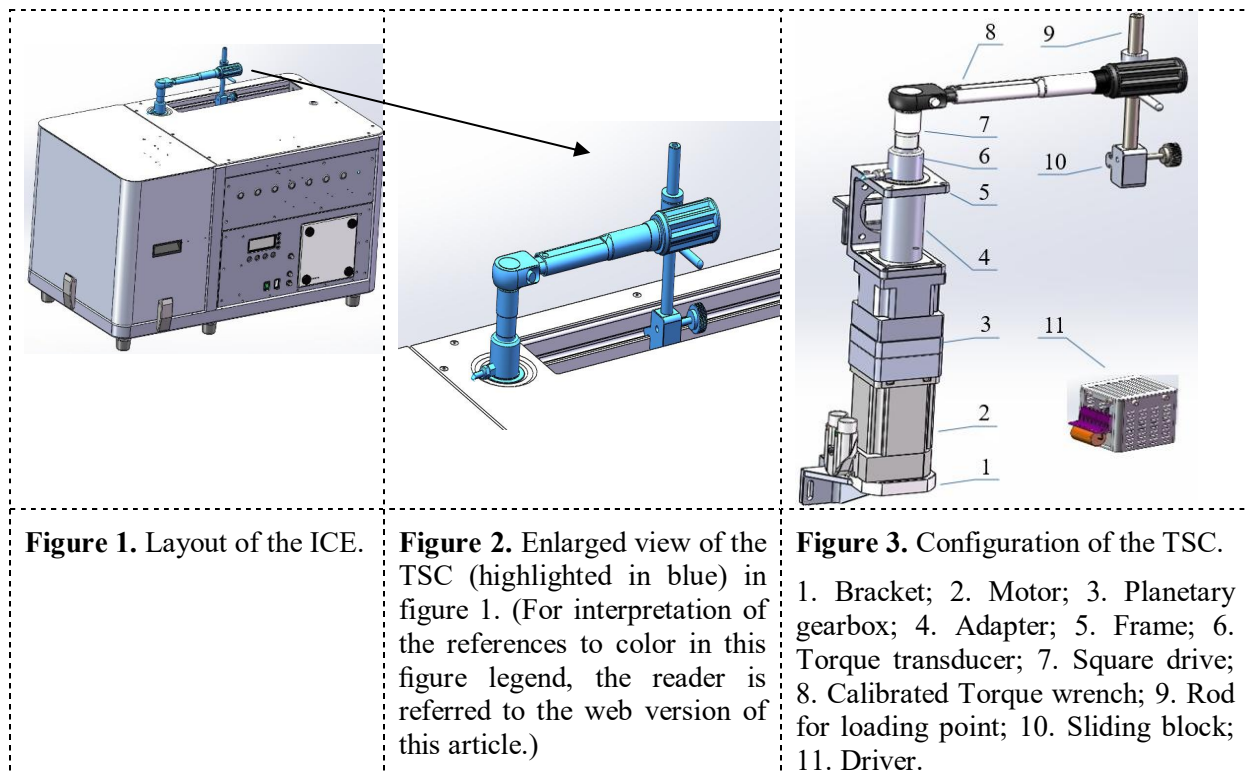


Figure 1. Layout of the ICE.

Figure 2. Enlarged view of the TSC (highlighted in blue) in figure 1. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Figure 3. Configuration of the TSC.

1. Bracket; 2. Motor; 3. Planetary gearbox; 4. Adapter; 5. Frame; 6. Torque transducer; 7. Square drive; 8. Calibrated Torque wrench; 9. Rod for loading point; 10. Sliding block; 11. Driver.

2.2. Calibration procedures

A laptop with a graphical user interface installed was employed to run automated calibration procedures by means of controlling rotary movements of the motor via giving command to the control unit in the ICE. As a final product, the program elaborates the calibration certification, automatically. Different calibration procedures were designed for each type of wrenches due to diversity of operating principles. For more details about the calibration procedures one can refer to our prior work [1].

3. Uncertainty evaluation

3.1. Uncertainty of the calibration results

The performance of the new developed TSC were evaluated according to GJB 2749A [2] whereas uncertainty of calibration was evaluated according to ISO/IEC guide 98-3 [3], and evaluation methods are described as following. The relative expanded uncertainty U_r of calibration results for every measuring point is expressed by the following equation:

$$U_r = k \cdot u_c = k \cdot (u_{\text{rep}}^2 + u_{\text{pro}}^2 + u_{\text{ind}}^2 + u_{\text{sta}}^2 + u_{\text{res}}^2)^{1/2} \quad (1)$$

Where u_c is the relative combined standard uncertainty of calibration. A coverage factor of $k = 2$ was used in calculation of all expanded uncertainties in this paper, which correspond to the level of confidence of approximate 95 %. u_{rep} is uncertainty contribution of repeatability without a change in the mounting position, u_{pro} is that for the reproducibility with a change in the mounting position, u_{ind} is uncertainty due to indication difference from the reference value, u_{sta} is uncertainty due to long stability of transducer sensitivity, u_{res} is that due to the resolution.

3.2. Repeatability in the same mounting position

The repeatability with the unchanged mounting position u_{rep} was evaluated by certain number of repeated tests with the wrench, rod for loading point, square drive and torque transducer in the same mounting position. The relative repeatability with the unchanged mounting position is calculated as:

$$u_{\text{rep}} = \frac{1}{\bar{S}_i} \left(\frac{\sum_{i=1}^n (S_i - \bar{S}_i)^2}{n-1} \right)^{1/2} \quad (2)$$

Where, i and n are the indexes of cycles and the total number of cycles (here $n=10$), respectively. S_i is the measurement value obtained from each cycle and $\bar{S}_i$ is the mean of S_i .

3.3. Reproducibility with changing mounting position

In consideration of the influence of mounting position on the calibration results, Reproducibility with changing mounting position u_{pro} was evaluated by a certain number of repeated tests in a way that after each test, the wrench and rod for loading point were reinstalled and square drive and torque transducer were rotated to a different position. The relative reproducibility with different mounting positions is calculated according to equation (3) as the experimental standard deviation for the measurement values of each mounting position:

$$u_{\text{pro}} = \frac{1}{\bar{S}_j} \left(\frac{\sum_{j=1}^k (S_j - \bar{S}_j)^2}{k-1} \right)^{1/2} \quad (3)$$

Where, j and k are the indexes of different mounting position and the total number of mounting positions (here $k=10$), respectively. S_j is the measurement value obtained from each mounting position and $\bar{S}_j$ is the mean of S_j .

3.4. Deviation due to indication

The relative deviation due to the indication u_{ind} is calculated as the deviation between reference values indicated by a reference torque wrench or a weight-bar-system of higher grade and the indicating results of TSC. Components related to this term might be calculated from the certificate.

3.5. Stability

The TSC was calibrated four times by using a torque standard of higher grade over approximately one year in order to investigate its long-term stability. Relative standard uncertainty due to stability u_{sta} is calculated as:

$$u_{sta} = \frac{S_{max} - S_{min}}{d_m \cdot S_{mean}} \quad (4)$$

Where, S_{max} , S_{min} and S_{mean} are the maximum, minimum and mean of the 4 calibration results, respectively. Here, d_m equals to 2.06 ascribed to 4 calibration results [2].

3.6. Resolution

The resolution r of the indication is defined as the smallest fraction of a scale division that is readable in the case of analogue scale. In the case of digital scale, r is considered to be one increment of the last active number of the numerical indicator, provided that the indication does not fluctuate when the TSC is under the non-loading condition. Relative standard uncertainty due to resolution u_{res} is calculated according to equation (5), by determining r as a half-width of the rectangular distribution:

$$u_{res} = \left(\frac{2}{3}\right)^{1/2} \cdot \frac{r}{2T_i} \quad (5)$$

Where, T_i means applied torque. u_{res} is multiplied by $(2)^{1/2}$ considering that the measurement value is obtained as the difference between the indicated values of the loaded torque step and non-loading zero step before starting the cycle (double readings) [4].

Table 1. Uncertainty budget.

Torque	0.5 Nm	2 Nm	5 Nm	30 Nm	60 Nm
u_{rep}	0.12%	0.11%	0.09%	0.08%	0.05%
u_{pro}	0.27%	0.25%	0.24%	0.23%	0.15%
u_{ind}	0.29%	0.29%	0.29%	0.29%	0.29%
u_{sta}	0.16%	0.15%	0.11%	0.12%	0.08%
u_{res}	0.08%	0.02%	0.01%	0.00%	0.00%
u_c	0.45%	0.43%	0.40%	0.40%	0.34%
U_r	0.90%	0.85%	0.80%	0.79%	0.68%

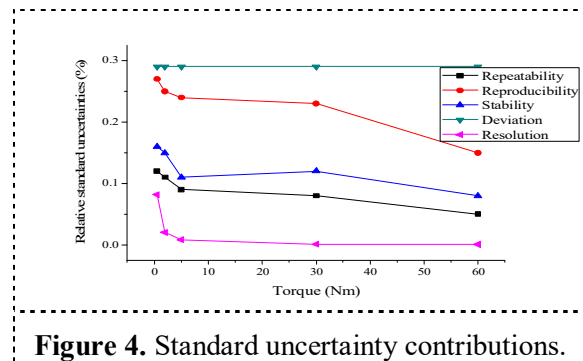


Figure 4. Standard uncertainty contributions.

3.7. Results of uncertainty evaluation

Uncertainty of the calibration results was evaluated at 0.5 Nm, 2 Nm, 5 Nm, 30 Nm and 60 Nm. The relative expanded uncertainty U_r of every point is calculated by equation (1) and summarized in table 1. In all the evaluated cases, the expanded relative uncertainty of calibration results within 0.9% could be obtained. Thus, the relative expanded uncertainty of torque realized by the TSC was estimated to be 0.9% in the range from 0.5 Nm to 60 Nm, with the coverage factor $k=2$. To make it more intuitive, standard uncertainties were plotted as a function of measuring points in figure 4 to visualise contributions each factor makes to the overall combined standard uncertainties. In general, relative standard uncertainties are larger in lower torque cases since it's harder to yield accurate calibration results in the lower range of the standard transducer as compared to the results of higher range. It was obvious that u_{ind} was dominant uncertainty contribution in all cases. In addition, Reproducibility due to

changing mounting position have profound effect on the combined uncertainty since remounting a wrench or those moving clamping parts at the same positions is scarcely possible. While uncertainties due to resolution are sufficiently small compared with other terms which can be ignored, especially for larger rated capacity.

4. Verification of the uncertainty evaluation results

4.1. Verification method

In order to investigate the validity of uncertainty estimation of torque realized by the TSC, intra-laboratory comparison was conducted between the TSC and a RTS at our lab using several torque wrenches as transfer devices. The E_n ratio between TSC and the RTS for each measuring point was evaluated using the following equation:

$$E_n = \frac{S_1 - S_2}{(U_1^2 + U_2^2)^{1/2}} \quad (6)$$

Where, S_1 , S_2 denote calibration results of the same point of a transfer device given by TSC and the RTS, and U_1 , U_2 are the associated expanded uncertainties.

4.2. Results of comparison

Table 2 summarizes the results of the E_n number evaluation between TSC and the reference standard. The E_n numbers were all far less than one over the calibration range from 0.5 Nm to 60 Nm. The comparison results showed good agreement within the uncertainties in all cases. Thus, the torque realized by the TSC was shown to be equivalent to that achieved by the reference standard.

Table 2. Results of E_n evaluation.

Torque	0.5 Nm	2 Nm	5 Nm	30 Nm	60 Nm
S_1	0.498	1.995	4.776	30.135	63.061
S_2	0.499	1.998	4.782	30.102	63.126
E_n	0.18	0.13	0.11	0.10	0.09

5. Summary

In this study, a torque standard component of an integrated calibration equipment is proposed that allows the on-site calibration of several commonly used hand torque tools. The relative expanded uncertainty was estimated to be 0.9% for the calibration range from 0.5 Nm to 60 Nm, with the coverage factor $k=2$. A comparison experiment has been performed between the torque standard component and a reference torque standard at our lab to confirm the validity of uncertainty evaluation. As a result, sufficiently small deviations were obtained and the consistency between those two devices has been verified under the claimed uncertainties.

References

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