技 術 報 告

International Comparison of Torque Standards in the Range of 0.5 to 20 kN·m between PTB and NMIJ

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Abstract

An international comparison of torque standards was conducted between the National Metrology Institute of Japan (NMIJ) in the National Institute of Advanced Industrial Science and Technology (AIST) and the Physikalisch-Technische Bundesanstalt (PTB) in the range of 500 N·m to 20 kN·m. These are the only two National Metrology Institutes (NMIs) that can attain the national torque standard using deadweight machines in the relatively high rated capacity of 20 kN·m. Two high-performance torque transducers measuring "pure torque" and one bridge calibrator were used as transfer devices. Two identical amplifier/indicators, one at each laboratory, were used for the comparison. Two transducers, with rated capacities of 5 kN·m and 20 kN·m, were transferred from the PTB to the NMIJ. The relative deviations of the calibration results were less than $8.3 \cdot 10^{-5}$ for increasing torque, and were less than $8.9 \cdot 10^{-5}$ for decreasing torque. Sufficiently small deviations relative to the Calibration and Measurement Capabilities ($7.0 \cdot 10^{-5}$ in the NMIJ, whereas $2.0 \cdot 10^{-5}$ in the PTB, as relative expanded uncertainties) were obtained, so the equivalence of the torque standards between the NMIJ and the PTB were confirmed.

Keywords: Torque Standard Machine, Bilateral Comparison, Transfer Standard, Bridge Calibrator

1 Introduction

Torque is an important mechanical quantity that is used in various fields, such as the fastening control of bolts, nuts and caps, or the power measurement and control of rotational equipment (such as electric motors, car engines, and generators). Torque, however, is a younger quantity in the sense of metrological standards, when compared to other mechanical quantities. Although the establishment of national standards of torque has progressed remarkably in recent days, the number of National Metrology Institutes (NMIs) that keep the intrinsic primary torque standards is far smaller than the number of NMIs that keep primary force standards. Under these circumstances, bilateral international comparison of torque standards was conducted between the National Metrology Institute of Japan (NMIJ) in the National Institute of Advanced Industrial Science and Technology (AIST) and the Physikalisch-Technische Bundesanstalt (PTB) in the range of 500 N·m to 20 kN·m. Both NMIs have well-established deadweight type torque standard machines (TSMs), and only these two NMIs can realize the national torque standard using deadweight machines in the relatively high rated capacity of 20 kN·m.

This comparison was performed from June 14th, 2004 to August 5th, 2004. The authors insist that sufficiently small deviations were obtained between the calibration results of the two NMIs when contrasted with their CMCs, although different daily calibration procedures were used in each laboratory. This paper describes the comparison preparations, procedures and results.

2 Equipment

2.1 Torque standard machine at PTB

The PTB used a TSM with a rated capacity of 20 kN·m (20-kN·m-Dm-NME), for the comparison. In this machine, the torque is generated by dead-weights subjected to the gravitational field of the earth that are suspended by a double moment-arm[1)]. In order to maintain the force on the arm, the

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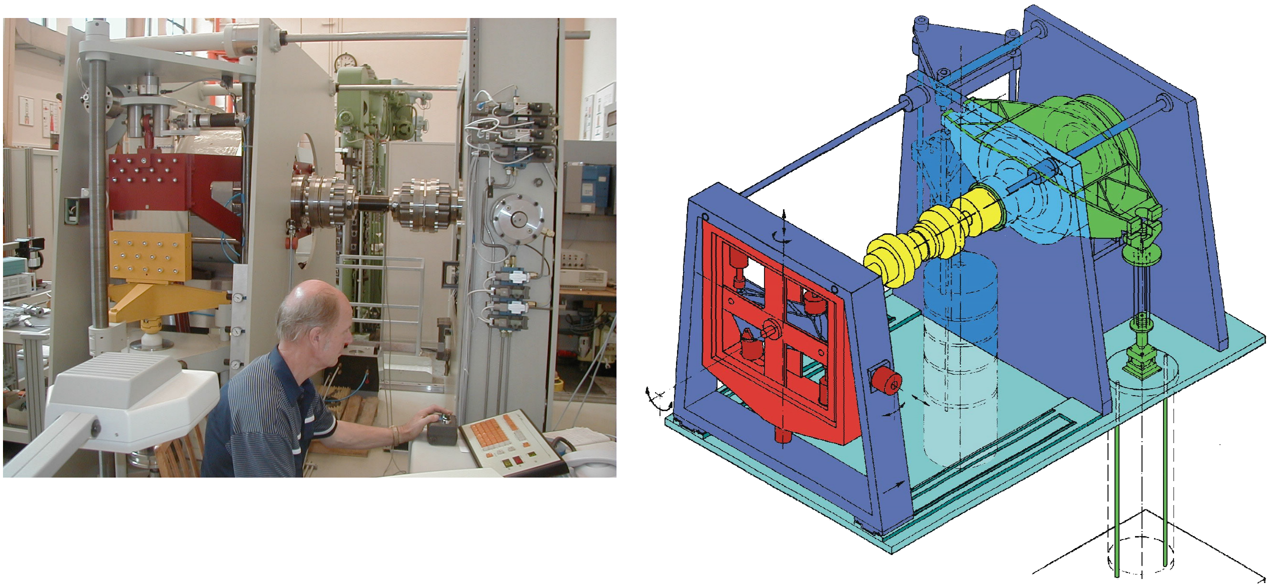


Fig. 1 Photograph and a schematic of the 20-kN·m-Dm-NME at PTB

dead-weights were mounted via thin metal bands of 50 µm thickness that are free from bending moments generated by the dead-weight loading. Figure 1 shows a photograph and a schematic of the 20-kN·m-Dm-NME.

The arm is comprised of a special steel (Super Invar) with a thermal expansion coefficient of less than $2{\cdot}10^{-7}$ K^{-1}, and is supported by a radial aerostatic bearing in order to minimize frictional influences. Two small additional axial aerostatic bearings (pads) are mounted on the machine corpus to ensure axial fixation. The arm length was measured together with the main aerostatic bearing with an uncertainty of 1 µm. Together with the uncertainty of the line of force in the leaf metal band, the uncertainty of the effective lever arm length was determined and experimentally verified to be 5 µm at a total length of 1000 mm. The horizontal position of the arm is controlled by non-contact displacement sensors and is adjusted to the base position with an accuracy of less than 40 µm using the main drive of the counter bearing.

The overall relative expanded uncertainty of realized torque U_{tsm} of the 20-kN·m-Dm-NME is calculated to be $2{\cdot}10^{-5}$ (k=2). The 20-kN·m-Dm-NME has calibration range from 100 N·m to 20 kN·m in 100 N·m steps using the combination system of the decimal exchanging weight stacks and a sequential weight stack.

2.2 Torque standard machine at NMIJ

The NMIJ used a TSM that also has a rated capacity of 20 kN·m (20 kN·m-DWTSM) for the comparison. A photograph and the schematics of the 20 kN·m-DWTSM[2)] are shown in Fig. 2. The 20 kN·m-DWTSM has a calibration range from 200 N·m to 20 kN·m using linkage weight stacks. The TSM consists primarily of the following components: (1) Pedestal parts, which are highly resistant to any deformation resulting from the application of torque through the deadweight and moment-arm, (2) Bearing parts for the fulcrums that consist mainly of a double aerostatic bearing unit designed to minimize the friction at the fulcrum, (3) Arm parts designed to allow for the application of both clockwise (CW) and counterclockwise (CCW) torques and to enable the precise measurement of moment-arm lengths. The moment-arms are made of stainless steel (with a thermal expansion coefficient of $1.6{\cdot}10^{-5}$ K^{-1}), (4) Weight loading parts, which consist of sequential linkage deadweight series, weight loading elevators, and turntables or slider tables to change the weight stacks, (5) Bearing parts for the counter torque, which reacts to the torque generated by the weight loading and returns the inclined arm to the horizontal position, (6) Torque transducer installation parts, which include, base flanges, diaphragm couplings, friction joints, and torque transducer connecting flanges. The installation parts are used for mounting the torque transducer on the TSM.

The relative expanded uncertainties U_{tsm} of the torque realized with the TSM was less than $6.7{\cdot}10^{-5}$, as determined by the results of an investigation of all uncertainty contributions. The CMC, which is equivalent to the relative expanded uncertainties (k = 2) of the calibration with almost ideal torque transducers, was less than $7.0{\cdot}10^{-5}$.

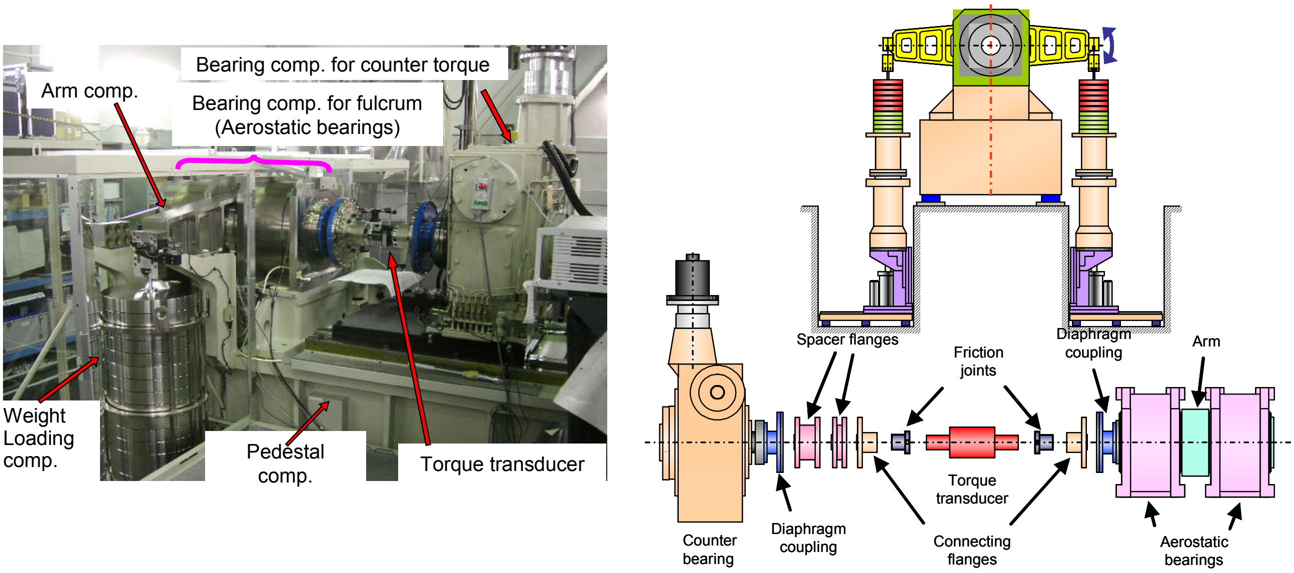
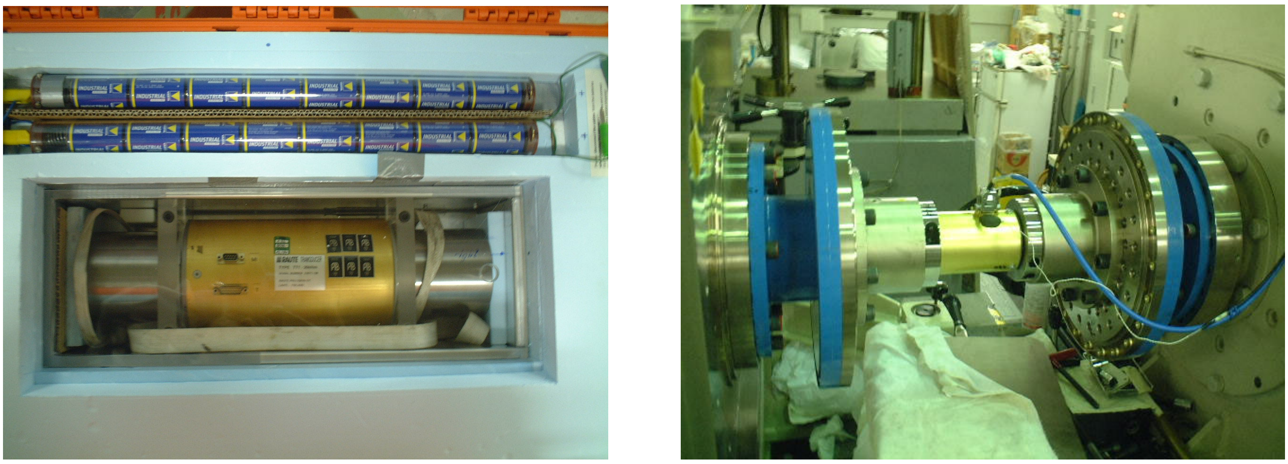


Fig. 2 Photograph and schematics of the 20 kN·m-DWTSM at NMIJ

2.3 Torque transducers (transfer devices)

Two torque transducers having different capacities were used as transfer standards for this comparison. The rated capacities of the transducers were 5 kN·m (TT1/5kNm) and 20 kN·m (TT1/20kNm), and were transferred from the PTB to the NMIJ by an air transport. Figure 3(a) shows the TT1/20kNm in the special container that included heating devices that controlled the internal temperature up to 20 °C. Figure 3(b) shows the TT1/5kNm mounted on the 20 kN·m-DWTSM. Thermo/hygrometers were placed into the containers to monitor the environmental conditions during the transportation.

The rated outputs of the transducers are approximately 1.5 mV/V and their long-term stabilities for approximately one year have been evaluated at the PTB to be less than $5.0 \cdot 10^{-5}$. Creep deviations of the transducers over 20 min. at rated output were also examined to be less than $1.0 \cdot 10^{-5}$. The temperature coefficient of the sensitivity in each transducer is $3 \cdot 10^{-6}$ K^{-1} for the TT1/20kNm and approximately $5 \cdot 10^{-6}$ K^{-1} for the TT1/5kNm.



(a) TT1/20kNm and its container

(b) TT1/5kNm mounted on the TSM of NMIJ

Fig. 3 Photographs of torque transducers

Fig.4 Bridge calibrator (BN100A) and its container

Fig.5 Amplifier/indicator (DMP40S2) at each NMI

2.4 Bridge calibrator (transfer device) and amplifier/indicator

Bridge calibrator BN100A, which calibrates the AC bridge voltage with an excitation voltage of 5 V and a carrier frequency of 225 Hz, was also transferred from the PTB to the NMIJ by air transport. Figure 4 shows a photograph of the BN100A and its container. In the torque calibration at each NMI, the amplifier/indicator of each NMI (DMP40S2(G) at the PTB and DMP40S2(J) at the NMIJ) was connected to the transfer transducers during each torque calibration. Figure 5 shows the two DMP40S2s. The amplifier/indicators were calibrated after each torque calibration by the BN100A.

The reference voltage ratios of the bridge calibrators were measured using the amplifier/indicators, at steps of +0, +0.1, +0.2, +0.4, +0.6, +0.8, +1.0, +1.2, +1.4, +1.6, +1.8 and +2.0 mV/V, and then same but negative steps. A bridge voltage calibration was carried out one time at the PTB and four times at the NMIJ. During the four calibrations at the NMIJ, a power voltage of 100 V was used two times, and 220 V was used the other two times. A power voltage of 220 V was used in the DMP40S2 calibration at the PTB.

3 Calibration conditions

3.1 Calibration schedule and environmental conditions

As shown in Table 1, pre- and post-calibration were conducted at the PTB using TT1/20kNm and TT1/5kNm before and after the on-site calibration at the NMIJ. Environmental conditions at the calibration at each NMI and during transportation are summarized in Table 2. The maximum temperature was around 30 °C during transport because the comparison was conducted during the summer and the special containers were equipped with only a heater but not a cooler. The maximum temperature would be recorded when the transducers were being stored at the warehouse in the airport. The typical temperature conditions during the calibrations were from 19.9 to 21.4 °C, and the humidity varied from 41.6 to 52.1 %RH. The influence of the humidity on the calibration results is discussed in chapter 4.

3.2 Loading timetable

The loading timetable for the calibration is shown in Fig. 6. Torque calibration was conducted separately in both the CW and CCW directions.

Three different rotational mounting positions were utilized by changing the pitch of every 120°. First, after three pre-loadings up to the maximum torque (rated capacity of the torque transducer), the calibration torque was loaded at 10, 20, 30, 40, 50, 60, 80 and 100 % of the maximum torque (eight steps) at the 0° direction. In the first cycle, the torque steps first increased and then decreased, whereas the torque steps in the second cycle only increased. The loading cycles performed at the 120° and 240° directions were nearly identical to those at the 0° direction, with the exception that one pre-loading cycle and one increasing and decreasing calibration cycle were performed. Each indicated value was acquired after 30 seconds passed after arriving at the target torque step.

Table 1 Calibration schedule

Calibration	NMI	Period
Pre.	PTB	Jun. 14th-Jun. 15th, 2004
Transport	-----	Jun. 24th -Jul. 2nd, 2004
On-site	NMIJ	Jul. 8th -Jul. 12th, 2004
Transport	-----	Jul. 16th -Jul. 27th, 2004
Post	PTB	Aug. 3rd -Aug. 5th, 2004

Table 2 Environmental conditions

Calibration	Temp. in °C		Humidity in %RH	
	Max.	Min.	Max.	Min.
Pre.	20.7	19.9	45.1	41.6
Transport	29.5	19.4	61.2	34.2
On-site	20.6	20.3	52.1	47.8
Transport	33.2	19.8	52.4	44.7
Post	21.4	21.2	44.7	43.1

The most notable point was that the loading speeds and time interval in each step were different depending on the procedure of each NMI and the performance of each TSM. In other words, the authors attempted to compare the calibration results obtained by daily calibration procedure in the PTB and the NMIJ. In addition, a voltage of 220 V was used for the calibration at the PTB, whereas 110 V was used at the NMIJ, because these are normally supplied values in these respective countries.

4 Results and Discussion

4.1 The difference of voltage span in amplifier/ indicators

The voltage ratio calibration results of the amplifier/ indicators (DMP40S2(G) and DMP40S2(J)) by the bridge calibrator (BN100A) are shown in Fig. 7. Figure 7(a) shows the deviation of the values at the NMIJ from those at the PTB by digits (one digit in DMP40S2 is 0.000001 mV/V). Figure 7(b) shows the relative deviation version of Figure 7(a) for each voltage ratio step. It was found that an approximately constant relative deviation (1 to $2 \cdot 10^{-5}$) occurred in across the entire 0 to ± 2.0 mV/V range when the 100 V power supply was used instead of 220 V. Moreover, a relatively large deviation occurred at the ± 0.1 mV/V steps even when identical 220 V power supplies were employed. The supply voltage should coincide for the amplifier/indicator, and lower voltage ratio steps (lower than 0.2 mV/V in these cases) shouldn't be used when the national torque standards realized by each TSM are strictly compared. The influence of the voltage span difference on the calibration results isn't considered in this comparison because one of the objectives of this paper is to investigate the equality of respective daily calibration procedures between the NMIJ and the PTB.

4.2 Comparison results of torque

The calibration results were calculated using the following equations for both the increasing and decreasing torques, as the mean values of measured values, which were the values subtracted the zero value at the prior loading cycle from each indicated value, at the first cycles for all mounting positions:

$$\overline{S'_{\mathrm{i}}} = \frac{1}{n_{\mathrm{rot}}} \sum_{\mathrm{e}=1}^{n_{\mathrm{rot}}} S'_{\mathrm{i1e}} , \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (1a)$$

$$\overline{S''_{\mathrm{i}}} = \frac{1}{n_{\mathrm{rot}}} \sum_{\mathrm{e}=1}^{n_{\mathrm{rot}}} S''_{\mathrm{i1e}} . \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (1b)$$

S'_{ije} and S''_{ije} express the measured values at the increasing and decreasing torque for step i, cycle j and series e, where "series" indicates a successive calibration sequence within the same mounting position. Here, n_{rot} is the number of rotational mounting positions (n_{rot} = 3). The relative deviations of the calibration results obtained at the NMIJ from the mean results of the pre- and post-calibration at the PTB are shown in Fig. 8 for the TT1/5kNm and TT1/20kNm.

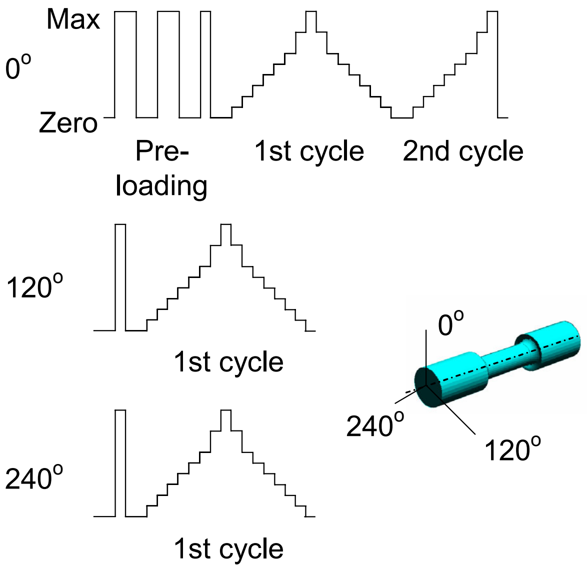
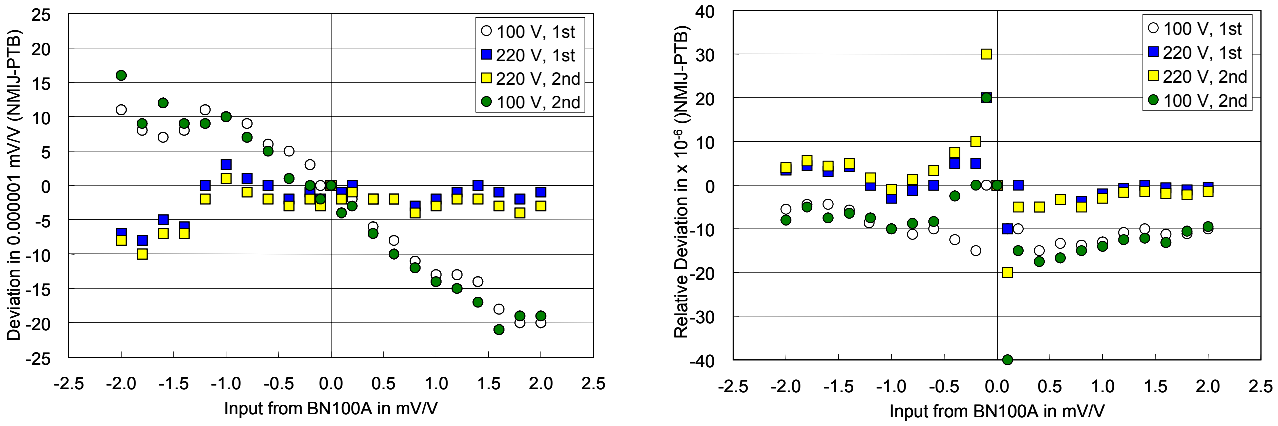


Fig. 6 Timetable of the calibration



(a) Deviations in digits of indicated values in DMP40S2(J) from (G)

(b) Relative deviation version of (a)

Fig.7 Calibration results of voltage span of amplifier/indicator by the bridge calibrator

In the calibration range of 500 N·m to 20 kN·m, the relative deviations were less than $8.3 \cdot 10^{-5}$ for increasing torque and less than $8.9 \cdot 10^{-5}$ for decreasing torque. The differences in the deviations between increasing and decreasing torque could be ascribed to the different TSM loading mechanisms. The TSM at the NMIJ have linkage sequential weight stacks of one-inner weight series (without the arm-clamping/unclamping operation), whereas the TSM at the PTB has a combination system containing the five decimal exchanging weight stacks and a sequential weight stack (with the arm-clamping/ unclamping operation). Strictly speaking, these two types of weight loading mechanisms could be responsible for the different strain histories in the torque transducers during progression to the next torque step, and the difference might be larger for decreasing torque than for increasing torque. The influence of the different weight loading mechanisms may be a general problem in the precise international comparison of torque standards, so further discussion of this issue is required.

The relative short-term drifts between the pre- and post-calibration results are shown in Fig. 9. Figure 9 shows the stability results for the TT1/5kNm and TT1/20kNm at the PTB. The short-term drifts of the transducers were $2.2 \cdot 10^{-5} \sim 6.2 \cdot 10^{-5}$ over approximately one and half months. One of reasons was presumed that the slightly higher temperature during transport might have affected the transducer sensitivities. The influence of humidity was suspected to be another cause of the difference between pre- and post-calibration results as follows:

After post-calibration at the PTB, the authors found that the sensitivity in the TT1 transducers[3)] was dependant on the humidity. The relative humidity dependencies of the sensitivity (relative humidity coefficients) in the two transducers were $5 \cdot 10^{-6}$ per 1 %, so that this coefficient should be considered when a more precise comparison (less than $2 \cdot 10^{-5}$) is carried out.

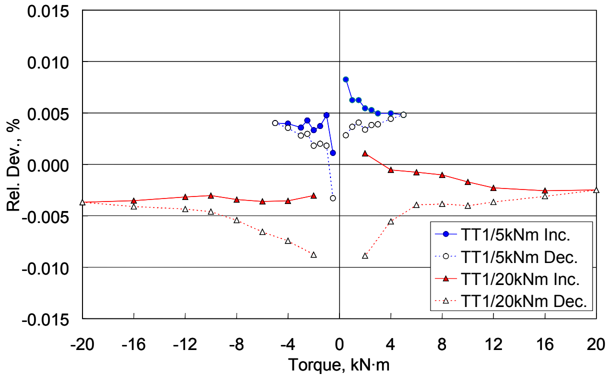


Fig. 8 Relative deviations of calibration results from NMIJ to PTB

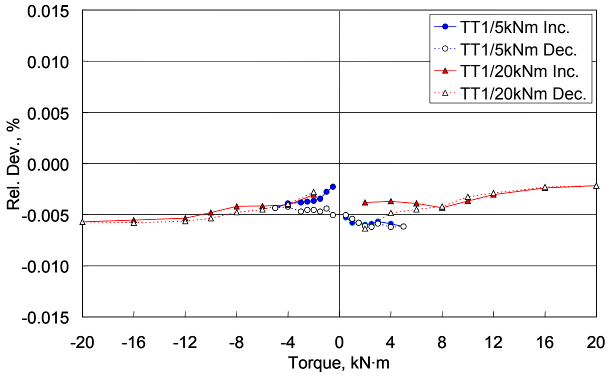


Fig. 9 Short term drifts of the transducers

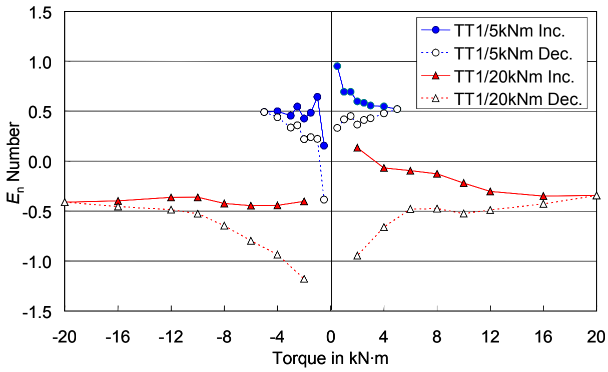


Fig. 10 Results of E_n evaluation

4.3 Evaluation of E_n number

In the calculation of the E_n number, uncertainties ascribed to the calibration of the torque transducer (reproducibility, repeatability, resolution, zero shift error, and so on) were not considered. That is, the E_n number was evaluated using the following equation:

$$E_{\mathrm{n,i}} = \frac{\left(\overline{S'_{\mathrm{lab,i}}} - \overline{S'_{\mathrm{ref,i}}}\right)\Big/\overline{S'_{\mathrm{ref,i}}}}{\sqrt{U_{\mathrm{lab,i}}{}^{2} + U_{\mathrm{ref,i}}{}^{2}}}\ , \cdots\cdots\cdots\cdots\cdots\cdots\cdots (2)$$

where $\overline{S'_{\mathrm{lab,i}}}$ denotes the result of the on-site calibration and $\overline{S'_{\mathrm{ref,i}}}$ is the mean of $\overline{S'_{\mathrm{pre,i}}}$ and $\overline{S'_{\mathrm{post,i}}}$ (pre- and post-calibration results).

The relative expanded uncertainties of calibration at the compared lab (which conducted the on-site calibration) were calculated using the following equations:

$$U_{\mathrm{lab,i}} = k \cdot u_{\mathrm{c\_lab,i}} = k \cdot \sqrt{u_{\mathrm{tsm.MNIJ}}{}^{2}}\ . \cdots\cdots\cdots\cdots\cdots (3)$$

$u_{\mathrm{tsm.NMIJ}} = 3.4 \cdot 10^{-5}$ for the range from 200 N·m to 20 kN·m.

The relative expanded uncertainties of calibration at the reference lab (which conducted pre- and post-calibrations) were calculated by the following equations:

$$U_{\mathrm{ref,i}} = k \cdot u_{\mathrm{c\_ref,i}} = k \cdot \sqrt{u_{\mathrm{dft,i}}{}^{2} + u_{\mathrm{tsm.PTB}}{}^{2}}\ . \cdots\cdots\cdots\cdots (4)$$

$u_{\mathrm{tsm.PTB}} = 1.0 \cdot 10^{-5}$ for the range from 100 N·m to 20 kN·m.

The uncertainty due to the short-term drift of the torque transducer during pre- and post-calibration was calculated using the following equation:

$$u_{\mathrm{dft,i}}{}^{2} = \frac{1}{3}\left(\frac{\overline{S'_{\mathrm{post,i}}} - \overline{S'_{\mathrm{pre,i}}}}{2\overline{S'_{\mathrm{ref,i}}}}\right)^{2}\ . \cdots\cdots\cdots\cdots\cdots\cdots\cdots (5)$$

The same calculations were conducted for decreasing torque steps.

Figure 10 summarizes the results of the E_n number evaluation. The E_n numbers were all less than one over the calibration range of 500 N·m to 20 kN·m, with the exception of the 10 % step for the CCW direction in TT1/20kNm. If the uncertainties ascribed to the calibration of the torque transducer were considered, the E_n numbers would become smaller than values in Fig. 10. Therefore, the equivalence of the calibration ability at the NMIJ and the PTB in this range was confirmed. The influence of temperature and humidity dependency, corrections due to the difference of voltage spans for the amplifier/indicators, the loading schedule (loading speed, waiting time and so on), and uncertainties ascribed to the calibration of the torque transducer (reproducibility, repeatability, resolution, zero shift error, and so on) should be considered in future comparisons such as the CIPM Key comparison of torque4).

5 Conclusions

A bilateral international comparison of torque calibration was conducted between the NMIJ and the PTB in the range of 500 N·m to 20 kN·m. The relative deviations were found to be less than $8.3 \cdot 10^{-5}$ for increasing torque and less than $8.9 \cdot 10^{-5}$ for decreasing torque.

The two laboratories used different daily calibration procedures. Nevertheless, sufficiently small deviations were obtained between the calibration results of the two NMIs as contrasted with their CMCs. The equivalence of the daily calibration results was verified.

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