Report on the CCM.T-K2.1 Key Comparison

Measurand Torque:
10 kN·m and 20 kN·m,

Final Report

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1. Introduction

The comparison of torque in the range of {10 kN·m and 20 kN·m} was organized and conducted between two laboratories, the National Metrology Institute of Japan (NMIJ) in the National Institute of Advanced Industrial Science and Technology (AIST) in Japan, and the National Metrology Institute of South Africa (NMISA) in South Africa. This comparison aims to link the national torque standards in South Africa to CCM.T-K2 so that NMISA can achieve the degree of equivalence (DOE) of the CMCs of its torque standards. NMIJ, which had joined CCM.T-K2 key comparison in 2008 [1], played a role of a link laboratory. The results of this comparison are not used to determine the key comparison reference values (KCRVs) for CCM.T-K2, but rather the KCRVs of CCM.T-K2 will be used as reference values as usual in a follow-up comparison. Details of this comparison will be described in Chapters 2 through 4. We mainly referred to the final report of CCM.T-K1.3 [2] to investigate the linking method of a bilateral comparison to a primary key comparison.

2. Comparison on measurand torque at 10 kN·m and 20 kN·m

2.1 Participants' details

The participating laboratories are NMIJ (pilot, Japan) and NMISA (South Africa). Their torque standard machine (TSM), torque calibration machine (TCM), and contact details are listed in Tables 1 and 2. A 20 kN·m deadweight type torque standard machine at NMIJ (20-kN·m-DWTSM) had been provided to the key comparison of CCM.T-K2 at the torque steps of {10 kN·m and 20 kN·m}. A good equivalence with other NMIs has been proved. On the other hand, the calibration and measurement capability (CMC) of a 20 kN·m reference type torque calibration machine (20-kN·m-RTCM) at NMISA was evaluated as 0.030 % using torque transducers of different rated capacities as inner reference standards in the range from 50 N·m to 20 kN·m, which had been calibrated in PTB. The 20-kN·m-RTCM had no experience to be compared with TSMs in other NMIs, which capability did not correlate with PTB's one, except for the range from 50 N·m to 1000 N·m compared with the deadweight type torque standard machine in INMETRO, Brazil.

2.2 Comparison Protocol

The protocol of this CCM.T-K2.1 almost coincides with that of the CCM.T-K2 key comparison [1]. Some particular points are as follows;

Table 1: Participated institutes and TSM or TCM

NMI	TSM or TCM			Note
	Capacity / kN·m	Type	Calibration and measurement capability (relative expanded uncertainty) / %	
NMIJ	20	Deadweight	0.0070	Link Lab.
NMISA	20	Reference (Comparison) (Vertical)	0.030	Reference transducers traceable to PTB

Table 2: Contact details

NMIJ / AIST Koji OGUSHI Tsukuba Central 3, 1-1-1 Umezono, Tsukuba, Ibaraki, 305-8563, **JAPAN** E-mail: kji.ogushi<a>aist.go.jp Tel: +81 29 861 4012	**NMISA** Sipho DLAMINI CSIR Campus, Building 5, Meiring Naude Road, Brummeria Pretoria 0182 Private Bag X34, Lynnwood Ridge, 0040, **SOUTH AFRICA** E-mail: sdlamini<a>nmisa.org Tel: +27 12 947 2868

*<a> represents @

(1) One traveling standard with 10 kN·m capacity was used to compare 10 kN·m and 20 kN·m torques. The transducer, TB2, was manufactured by HBM GmbH, Germany. TB2 is a strain gauge type, hermetical, and spoke-type transducer. TB2 is allowable to be subjected to 200 % overloading of the capacity.

(2) We strictly followed the measurement time sequence of CCM.T-K2.

(3) Each bridge amplifier (DMP40 at NMIJ and DMP41 at NMISA, both manufactured by HBM GmbH) was used to indicate the traveling standard (the torque transducer) at both laboratories. In contrast, a bridge calibration unit (BN100A manufactured by HBM GmbH) was used to calibrate each amplifier. BN100A was also transferred as one of the traveling standards.

(4) We tried to coincide the conditions of room temperature and relative humidity with those for the CCM.T-K2; they were 20 °C ± 0.2 °C and 40 % ±2 %. However, it was difficult to maintain those conditions, as mentioned later.

The measurement time sequence is listed in Table 3 and depicted in Figure 1.

Table 3: Measurement sequence of the torque KC CCM.T-K2.1

Loadings	Position / °	Steps
3 initial pre-loadings	0	10 kN·m, 20 kN·m
1 pre-loading		
3 measurement cycles		
1 pre-loading	120	
1 measurement cycle		
1 pre-loading	240	
1 measurement cycle		
1 pre-loading	360	
1 measurement cycle		
1 pre-loading	480	
1 measurement cycle		
1 pre-loading	600	
1 measurement cycle		
1 pre-loading	720	
1 measurement cycle		

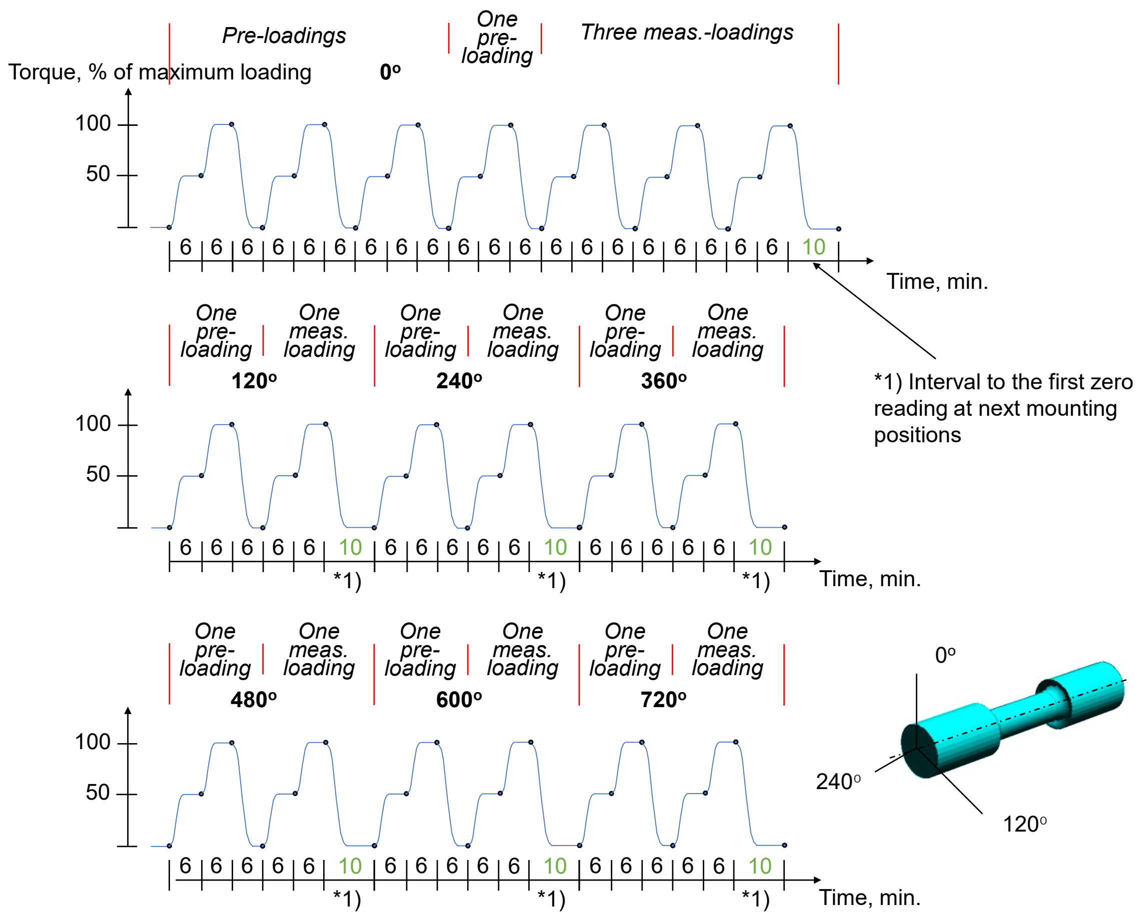

Figure 1: Diagram of the measurement sequence of the torque KC (CCM.T-K2.1).

2.3 Traveling standard

A torque transducer with a capacity of 10 kN·m (belonging to NMISA) was used. Its details are listed as follows:

- Manufacturer: Hottinger Baldwin Messtechnik GmbH, Germany
- Type: TB2
- Serial number / Capacity: ##204130007 / 10 kN·m
- Adaptation: $\phi 110^{h7}$, length of 155 mm shaft end on both sides

The details of each bridge amplifier (belonging to NMISA / NMIJ) used in this comparison and those settings are as follows:

[NMISA]

- Manufacturer: Hottinger Baldwin Messtechnik GmbH, Germany
- Type: DMP41-T2
- Serial number: #831891701
- Filter: 0.1 Hz Bessel
- Signal reading: Absolute
- Measuring range: 2.5 mV/V
- Supply voltage: AC 220 V
- Carrier frequency: 225 Hz
- Excitation voltage: 5 V
- Auto calibration: Acal OFF

[NMIJ]

- Manufacturer: Hottinger Baldwin Messtechnik GmbH, Germany
- Type: DMP40S2
- Serial number: #091620073
- Filter: 0.1 Hz Bessel
- Signal reading: Absolute
- Measuring range: 2.5 mV/V
- Supply voltage: AC 220 V
- Carrier frequency: 225 Hz
- Excitation voltage: 5 V
- Auto calibration: Acal OFF

The details of the bridge calibrator (belonging to NMISA) used in this comparison and its settings are as follows:

- Manufacturer: Hottinger Baldwin Messtechnik GmbH, Germany
- Type: BN100A
- Serial number: #001
- Setting range: 0.1 mV/V…1.0 mV/V, 1.0 mV/V…10 mV/V, 10 mV/V…100 mV/V (positive and negative)
- Supply voltage: AC 220 V
- Carrier frequency: 225 Hz

2.4 Comparison formation

The measurement was carried out once at NMIJ, whereas the measurements were conducted at NMISA before and after the measurement at NMIJ. They were called pre- and post-measurements. In order to reduce the effect of the long-term stability of the traveling standard, the time interval between two successive measurements was tried to be set to approximately one month, which includes transportation time and thermal stabilization time of the traveling standard at each laboratory. However, the total measurement took around seven months because of an electric noise problem, stabilization of temperature and humidity, and the prioritization of the domestic calibration service schedule at NMIJ. Table 4 shows the whole comparison schedule.

Table 4: Chronological order of the calibrations during the key comparison

NMI	CW	CCW
NMISA, pre.	14.12.2021	15.12.2021
NMIJ	22.02.2022	28.02.2022
NMISA, post.	01.06.2022	02.06.2022

3. Measurement results

3.1 Reported deflections

The measurement result is the mean deflection calculated from six original readings measured in six orientations (120° to 360° for two rotations) for each of the two torque steps and the two directions (clockwise (CW) and counterclockwise (CCW)). The measurement uncertainty has to be calculated for the mean deflection measured with the transducer and each amplifier. No corrections for the creep effect were applied in those results because the time duration only affects the deadweight type TSMs. We investigated the influence of the span of voltage ratio for each amplifier, temperature, and humidity in the later sections.

The measurement uncertainty was calculated according to the protocol of CCM.T-K2, and the same worksheets were used to report the results. The measurement results are listed in Table 5. Here, the uncertainty for the average values of pre- and post-measurement at NMISA (NMISA, avg.) includes the contribution of the short-term drift (They were less than 20 ppm as the relative standard uncertainties).

Table 5: Reported deflections and relative expanded uncertainties (k = 2)

NMI	CW			
	10 kN·m		20 kN·m	
	Deflection / (mV/V)	Relative expanded uncertainty / %	Deflection / (mV/V)	Relative expanded uncertainty / %
NMISA, pre.	1.000953	0.0301	2.001802	0.0300
NMIJ	1.001034	0.0066	2.002248	0.0066
NMISA, post.	1.000965	0.0302	2.001769	0.0304
NMISA, avg.	1.000959	0.0303	2.001785	0.0304
NMI	CCW			
	-10 kN·m		-20 kN·m	
	Deflection / (mV/V)	Relative expanded uncertainty / %	Deflection / (mV/V)	Relative expanded uncertainty / %
NMISA, pre.	-1.000965	0.0300	-2.001841	0.0300
NMIJ	-1.001057	0.0066	-2.002368	0.0066
NMISA, post.	-1.001003	0.0302	-2.001857	0.0301
NMISA, avg.	-1.000984	0.0310	-2.001849	0.0301

3.2 Influence of the amplifiers

The variations in the voltage ratio span of amplifiers during comparison were observed using BN100A(#001) of NMISA. Figure 4 shows relative deviations of observed voltage ratios from the start of measurement, which was before the first measurement at NMISA, at all steps of +0.1 mV/V, +0.9 mV/V, +1.0 mV/V, +1.1 mV/V, +1.9 mV/V, +2.0 mV/V, +2.1 mV/V, and -0.1 mV/V, -0.9 mV/V, -1.0 mV/V, -1.1 mV/V, -1.9 mV/V, -2.0 mV/V and -2.1 mV/V. The relative deviations of less than 10^{-5} were observed except for steps of ± 0.1 mV/V. Therefore, we did not apply any correction for the measurement results with the differences in voltage spans.

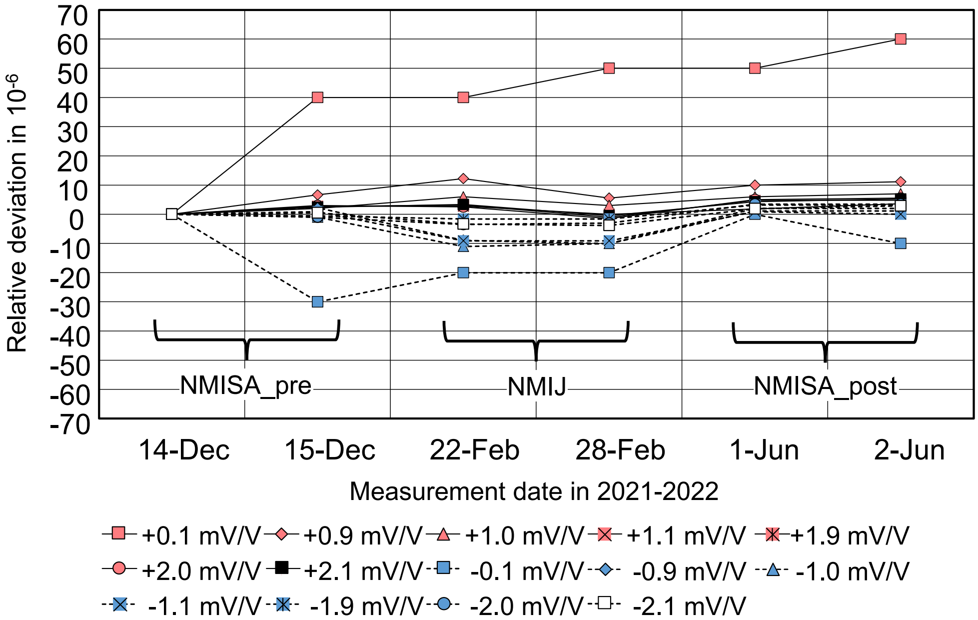

Figure 4: Relative deviations of voltage ratio span of DMP40 and DMP41 by using BN100A

3.3 Influence of temperature and Humidity

Environmental conditions of room temperature and relative humidity recorded at each measurement were summarized in Table 6. We tried to coincide the conditions of room temperature and relative humidity with those for the CCM.T-K2; they were 20 °C ± 0.2 °C and 40 % ±2 %. However, it was not easy to maintain those conditions. First, 40 % of relative humidity could not be achieved for the pre-measurement at NMISA because of the mid-summer season in December and the low capability of the air-conditioning system.

However, NMISA accomplished 40 % by introducing the additional drier system. Second, NMIJ could not keep the temperature of 20 °C but 23 °C because it had to deal with domestic calibration services (for Japanese customers).

On the other hand, we measured the temperature and humidity coefficients of the output in the torque transducer, TB2, at the conditions of 20 °C to 23 °C, and 40 % to 50 % at NMIJ. As a result, relative temperature and humidity coefficients were found to be approximately "-0.9 ppm/°C ± 0.4 ppm/°C" and "0.2 ppm/% ± 0.1 ppm/%." The uncertainties are relative standard deviations. Coefficients were pretty small, and it would be understandable against the transducer type of TB2 for the torque experts. Then, we could determine the influence of the environmental condition was negligible.

Table 6: Environmental conditions

NMI	CW		CCW	
	Temperature / °C	Rel. humidity / %	Temperature / °C	Rel. humidity / %
NMISA, pre.	20.5	58	21.2	57
NMIJ	23.3	38	23.0	41
NMISA, post,	20.2	41	20.0	42

4. Discussion

The analysis is usually performed according to [3] to check the equivalence of reported data among NMIs. We did calculate accordingly, too. However, we did not need to consider the influence of the correlation between data of NMIJ and NMISA.

4.1 Deviation of the measurement values

From Table 5, we can calculate the deviations and their uncertainties. Deviations of the measurement results of NMISA (x'_{NMISA}) (the average values of pre- and post-measurements) from those of NMIJ (x'_{NMIJ}) can be calculated as follows:

$$d_{\mathrm{S-J}} = x'_{\mathrm{NMISA}} - x'_{\mathrm{NMIJ}}. \tag{1}$$

The standard uncertainties of the deviations, $u(d_{\mathrm{S-J}})$, are to be evaluated as follows:

$$u(d_{\mathrm{S-J}}) = \sqrt{u^2(x'_{\mathrm{NMIJ}}) + u^2(x'_{\mathrm{NMISA}})}. \tag{2}$$

The calculated deviations $d_{\mathrm{S-J}}$ and the expanded uncertainty $U(d_{\mathrm{S-J}})$ are tabulated in Table

7. Now, the coverage factor k equals 2, including all the following cases in this report. Results are also graphically summarized in Figure 2 and Figure 3. Those deviations can be converted to the torque unit by using the following equations:

$$D_{\mathrm{S-J}} = T_{\mathrm{KCRV}} \cdot d_{\mathrm{S-J}} / x'_{\mathrm{NMIJ}}, \tag{3}$$

$$U(D_{\mathrm{S-J}}) = T_{\mathrm{KCRV}} \cdot U(d_{\mathrm{S-J}}) / x'_{\mathrm{NMIJ}}. \tag{4}$$

Here, T_{KCRV} is just the torque values of the torque steps (+10 kN·m, -10 kN·m, +20 kN·m, or -20 kN·m).

Table 8 shows deviations and their uncertainties in N·m.

Table 7: Deviations (nV/V) of the measured values of NMISA from the pilot, NMIJ

Torque / (kN·m)	Deviation from the pilot	
	$d_{\mathrm{S-J}}$ / (nV/V)	$U(d_{\mathrm{S-J}})$ / (nV/V)
10	-75	310
20	-463	623
-10	73	318
-20	519	617

Table 8: Deviations (N·m) of the measured values of NMISA from the pilot, NMIJ

Torque / (kN·m) = T_{KCRV}	Deviation from the pilot	
	$D_{\mathrm{S-J}}$ / (N·m)	$U(D_{\mathrm{S-J}})$ / (N·m)
10	-0.75	3.1
20	-4.6	6.2
-10	0.73	3.2
-20	5.2	6.2

Here, the DOE of NMISA, D_{S} to the KCRV can be expressed in the following equations:

$$D_{\mathrm{S}} = D_{\mathrm{S-J}} + D_{\mathrm{J-KCRV}}, \tag{5}$$

$$U(D_{\mathrm{S}}) = k \cdot u(D_{\mathrm{S}}) = k \cdot \sqrt{u^2(D_{\mathrm{S-J}}) + u^2(D_{\mathrm{J-KCRV}})}. \tag{6}$$

We have to calculate the DOE of NMIJ to the key comparison reference value (KCRV) $D_{\mathrm{J-KCRV}}$ in order to link the results of CCM.T-K2.1 to those of CCM.T-K2.

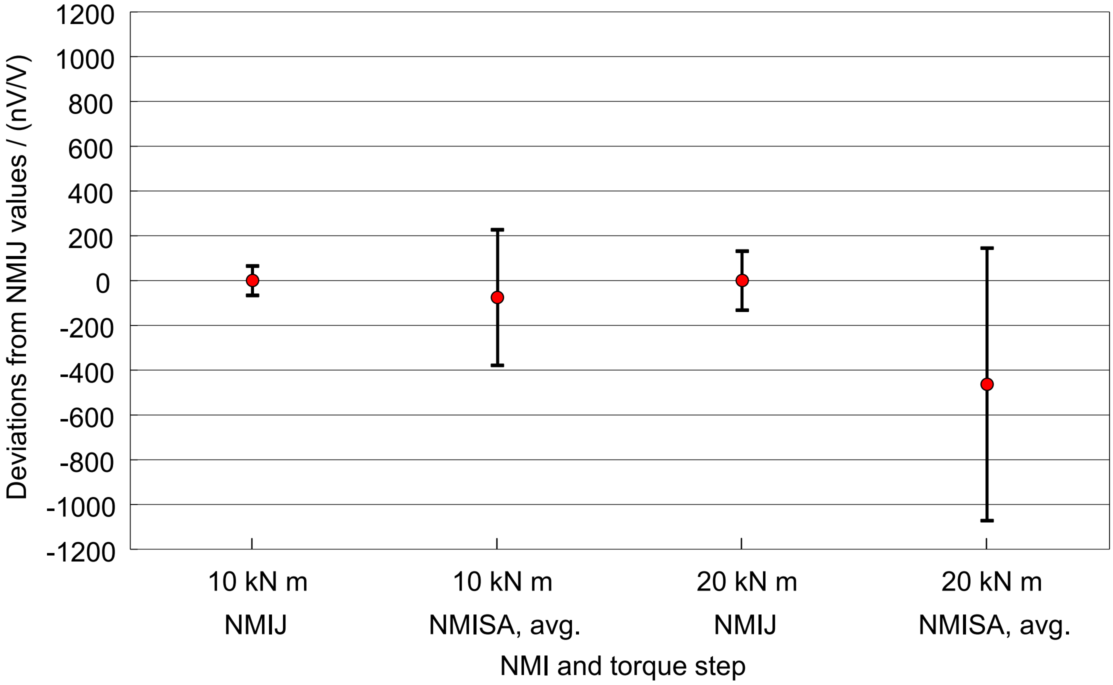

Figure 2: Deviations of measured values of NMISA from NMIJ results in CW direction.

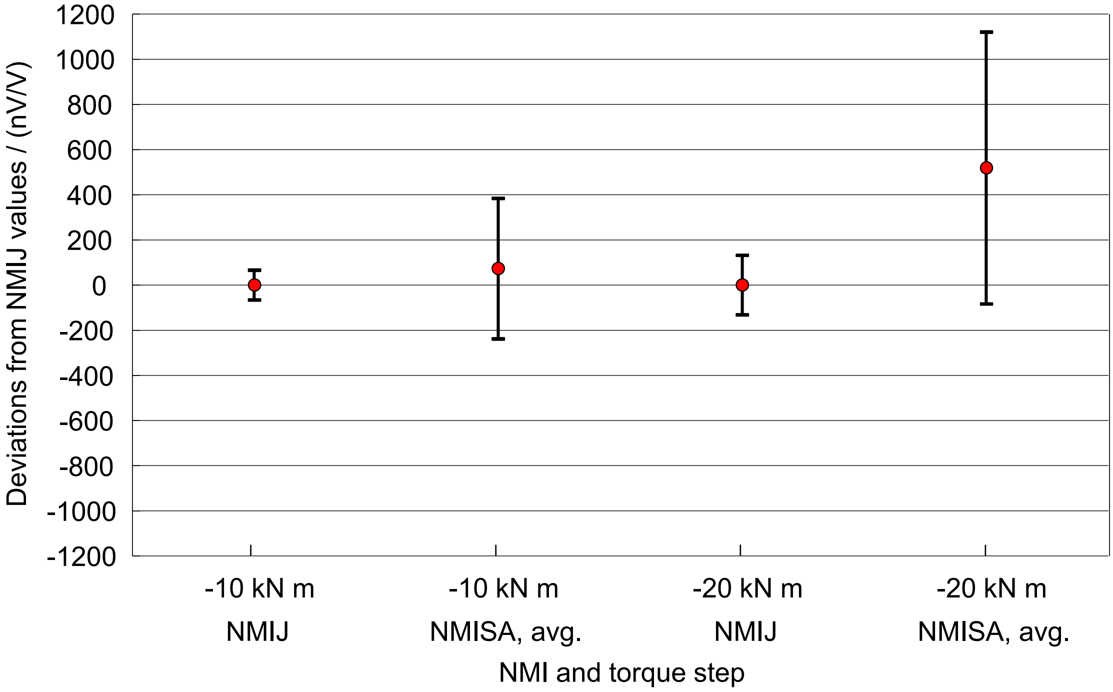

Figure 3: Deviations of measured values of NMISA from NMIJ results in CCW direction.

4.2 Linking the key comparison CCM.T-K2.1 to CCM.T-K2

In the final report of CCM.T-K2 [1], not only the Key Comparison Reference Values (KCRVs) but also each measurement result obtained by each NMI were converted from the unit of “mV/V” to “N·m.” Table 9 shows the NMIJ results of measurement on CCM.T-K2 from Table A16 [1].

Table 9: NMIJ results of measurement on CCM.T-K2 [1]

Torque / (kN·m)	Overall	
	x_{NMIJ} / (kN·m)	$U(x_{\mathrm{NMIJ}})$ / (N·m)
10	10.0004	0.68
20	20.0009	1.4
-10	-10.0004	0.68
-20	-20.0008	1.4

On the other hand, the final report of CCM.T-K2 did not show the merging results of two artifacts, TB2 and TT1 type transducers, as shown in Table A14 [1]. Therefore, we calculated the overall KCRVs and their uncertainties in the unit of torque. Table 10 expresses KCRVs in mV/V of two transducers according to CCM.T-K2, Table A13 [1].

Table 10: KCRVs in mV/V of two transducers on CCM.T-K2 [1]

Torque / (kN·m)	TB2		TT1	
	$x'_{\mathrm{ref.TB2}}$ / (mV/V)	$u(x'_{\mathrm{ref.TB2}})$ / (nV/V)	$x'_{\mathrm{ref.TT1}}$ / (mV/V)	$u(x'_{\mathrm{ref.TT1}})$ / (nV/V)
10	1.0006264	17.4	0.6568664	18.4
20	2.0015468	32.8	1.3138357	37.8
-10	-1.0006524	18.6	-0.6568706	18.5
-20	-2.0016264	35.0	-1.3138425	37.6

The weighted means and their corresponding uncertainties were calculated according to the following equations [2]:

$$x_{\mathrm{ref}} = x_{\mathrm{ref.TB2}} = x_{\mathrm{ref.TT1}} = T_{\mathrm{KCRV}}, \quad (7)$$

$$u(x_{\mathrm{ref.TB2}}) = T_{\mathrm{KCRV}} \cdot u(x'_{\mathrm{ref.TB2}})/x'_{\mathrm{ref.TB2}}, \quad (8)$$

$$u(x_{\mathrm{ref.TT1}}) = T_{\mathrm{KCRV}} \cdot u(x'_{\mathrm{ref.TT1}})/x'_{\mathrm{ref.TT1}}, \quad (9)$$

$$u(x_{\mathrm{ref}}) = \frac{u(x_{\mathrm{ref.TB2}}) \cdot u(x_{\mathrm{ref.TT1}})}{u^2(x_{\mathrm{ref.TB2}}) + u^2(x_{\mathrm{ref.TT1}})} \sqrt{\begin{matrix} u^2(x_{\mathrm{ref.TB2}}) + u^2(x_{\mathrm{ref.TT1}}) \\ +2r(x_{\mathrm{ref.TB2}}, x_{\mathrm{ref.TT1}}) \\ \cdot u(x_{\mathrm{ref.TB2}}) \cdot u(x_{\mathrm{ref.TT1}}) \end{matrix}}$$

$$u(x_{\mathrm{ref}}) = u(x_{\mathrm{ref.TB2}}) \cdot u(x_{\mathrm{ref.TT1}}) / \sqrt{u^2(x_{\mathrm{ref.TB2}}) + u^2(x_{\mathrm{ref.TT1}})}. \tag{10}$$

$$U(x_{\mathrm{ref}}) = k \cdot u(x_{\mathrm{ref}}). \tag{11}$$

The uncertainties were calculated, assuming no correlation existed between the two results ($r = 0$). The overall KCRVs of CCM.T-K2 were expressed in Table 11 and Table 12.

Table 11: KCRVs in torque unit of two transducers on CCM.T-K2 and overall KCRVs

Torque / (kN·m)	TB2		TT1		Overall	
	$x_{\mathrm{ref.TB2}}$ / (kN·m)	$u(x_{\mathrm{ref.TB2}})$ / (N·m)	$x_{\mathrm{ref.TT1}}$ / (kN·m)	$u(x_{\mathrm{ref.TT1}})$ / (N·m)	x_{ref} / (kN·m)	$u(x_{\mathrm{ref}})$ / (N·m)
10	10.0000	0.17	10.0000	0.28	10.0000	0.15
20	20.0000	0.33	20.0000	0.58	20.0000	0.28
-10	-10.0000	0.19	-10.0000	0.28	-10.0000	0.16
-20	-20.0000	0.35	-20.0000	0.57	-20.0000	0.30

Table 12: KCRVs and their expanded uncertainties on CCM.T-K2

Torque / (kN·m)	Overall	
	x_{ref} / (kN·m)	$U(x_{\mathrm{ref}})$ / (N·m)
10	10.0000	0.30
20	20.0000	0.57
-10	-10.0000	0.31
-20	-20.0000	0.60

The DOE of NMIJ in CCM.T-K2 can be calculated from the following equations:

$$D_{\mathrm{J-KCRV}} = x_{\mathrm{NMIJ}} - x_{\mathrm{ref}}, \tag{12}$$

$$U(D_{\mathrm{J-KCRV}}) = k \cdot u(D_{\mathrm{J-KCRV}}) = k \cdot \sqrt{u^2(x_{\mathrm{NMIJ}}) - u^2(x_{\mathrm{ref}})}. \tag{13}$$

The DOE of NMISA was evaluated using equations (5), (6), (12), and (13). The results are listed in Table 13, next to the DOE of NMIJ in CCM.T-K2. Figures 4 and 5 also graphically express the final results. As the DOE of NMIJ has already been calculated and shown in Table A17 of CCM.T-K2 final report [1], here is just the reference.

The KCRV was calculated, in part, with the PTB results in CCM.T-K2, whereas the inner torque transducers of the NMISA machine had been calibrated in PTB. However, the declared relative expanded uncertainty of NMISA machine is 15 times larger than that of

PTB one. Then, the correlation factor may become much less than 0.1. We decided that the influence of this correlation was negligible.

Table 13: DOE of NMIJ in CCM.T-K2 and DOE of NMISA

Torque / (kN·m)	DOE of NMIJ		DOE of NMISA	
	$D_{\text{J-KCRV}}$ / (N·m)	$U(D_{\text{J-KCRV}})$ / (N·m)	D_{S} / (N·m)	$U(D_{\text{S}})$ / (N·m)
10	0.4	0.61	-0.4	3.2
20	0.9	1.2	-3.7	6.3
-10	-0.4	0.61	0.3	3.2
-20	-0.7	1.2	4.4	6.3

5. Summary

Bilateral comparisons between NMIJ and NMISA were conducted at the torques of 10 kN·m and 20 kN·m as an extension of the key comparison CCM.T-K2. As clearly shown in Figures 4 and 5, all NMISA results are matched with those of NMIJ within their claimed uncertainties. Because of a few bad experimental conditions in NMIJ, a certain deviation, especially in the step of 20 kN·m, might occur. We hope the comparison results will become better in the next CCM.T-K2 comparison.

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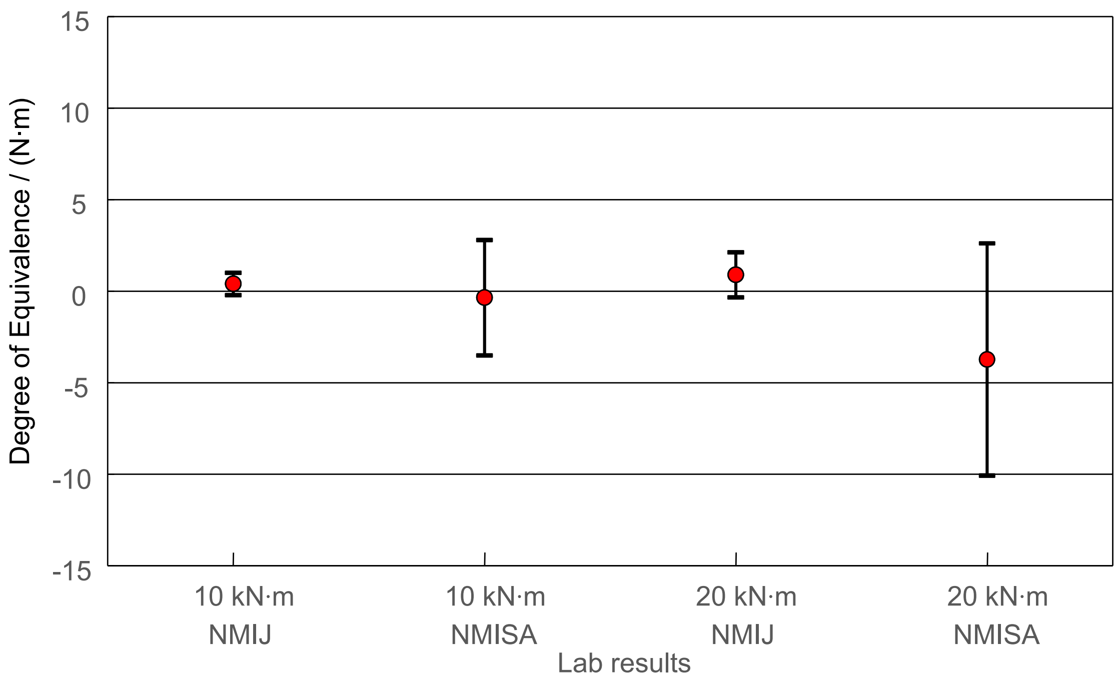

Figure 4: The degree of equivalence (DOE) of NMIJ and NMISA results to KCRVs in CW direction.

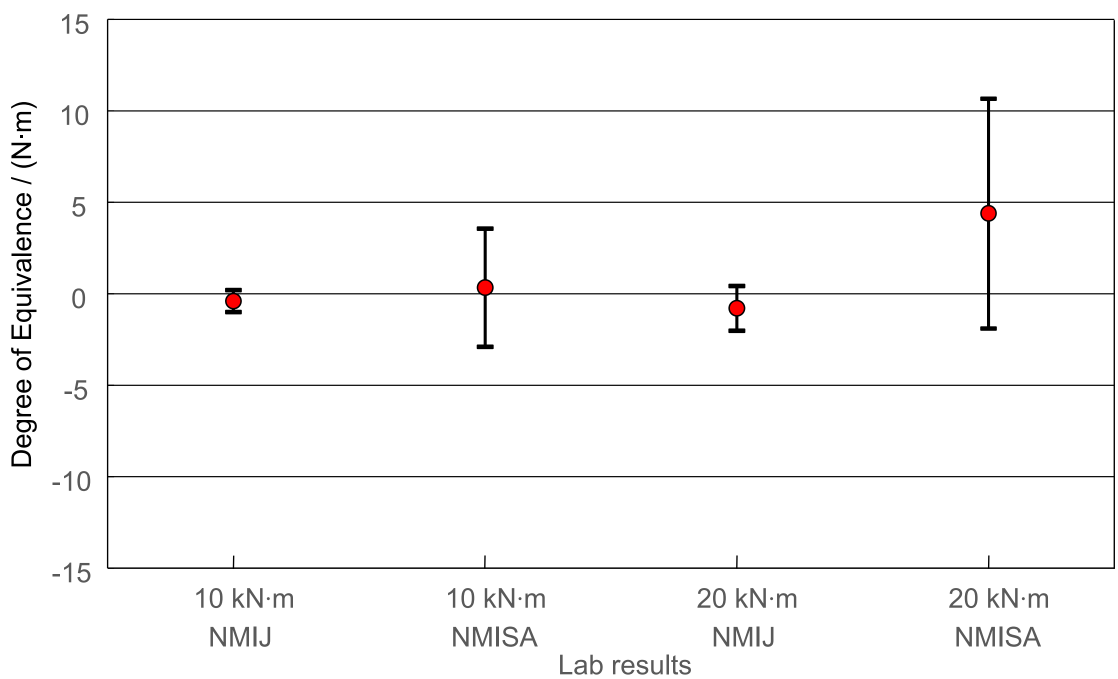

Figure 5: The degree of equivalence (DOE) of NMIJ and NMISA results to KCRVs in CCW direction.

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