RECALIBRATION OF THE MOMENT ARM LENGTH OF A 10 N·m DEAD WEIGHT TORQUE STANDARD MACHINE AND COMPARISON WITH A 1 kN·m DEAD WEIGHT TORQUE STANDARD MACHINE

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Abstract: A 10 N·m dead weight torque standard machine (10-N·m-DWTSM) has been developed and evaluated since 2006. The main parts of the moment arm in the 10-N·m-DWTSM are made of low thermal-expansion alloy (Super Invar). It is known that parts made of Super Invar vary in length with age. In this study, the moment arm length was recalibrated using a 3D coordinate measurement machine. As a result, the moment arm length was found to have lengthened by an average of 6.3 μm in five years. Also, the relative expanded uncertainty of torque, W_{tsm}, realized by the 10-N·m-DWTSM was revaluated in a range from 0.1 N·m to 10 N·m, and W_{tsm} was 7.0×10^{-5}, with the coverage factor k being equal to 2. In addition, the 10-N·m-DWTSM was compared with the 1-kN·m-DWTSM at NMIJ/AIST by using torque measuring devices after estimating W_{tsm} realized by the 10-N·m-DWTSM. Equivalence between the two DWTSMs was confirmed within the uncertainty of comparison.

Keywords: Torque, Uncertainty, Super Invar, Secular length change, Small torque, Intra-comparison.

1. INTRODUCTION

Many experimental apparatuses and laboratories in the National Metrology Institute of Japan, part of the National Institute of Advanced Industrial Science and Technology (NMIJ/AIST), suffered considerable damage from the Great East Japan Earthquake on March 11th, 2011. At the time of the earthquake, a small-rated-capacity torque measuring device (TMD) was being calibrated by using a 10 N·m dead weight torque standard machine (10-N·m-DWTSM). Fortunately the 10-N·m-DWTSM and the TMD did not suffer serious damage themselves, because the 10-N·m-DWTSM was immediately stopped and locked at that time.

Figure 1 shows a photograph of the 10-N·m-DWTSM. The 10-N·m-DWTSM has been under development since 2006 at NMIJ/AIST. The hardware and software components have been almost completed. The uncertainties of the torque realized by the machine have been evaluated, such as the moment arm length[1] and the sensitivity limit of the fulcrum[2], and the machine has been gradually improved. The uncertainty budget table of the 10-N·m-DWTSM is near completion. In addition, special problems in the field of small-rated-capacity torque have been considered. For example, an overload protection device was designed for the 10-N·m-DWTSM.[3] The 10-N·m- DWTSM has been

Fig. 1 Photograph of the 10-N·m-DWTSM

steadily developed to disseminate the small-rated-capacity torque standard to Japanese industry.

On the other hand, five years have passed since starting development of the 10-N·m-DWTSM, and secular changes should be considered. One of the secular changes is the moment arm length. The moment arm length was measured by using a 3D coordinate measurement machine (CMM) of the Dimensional Standard Section at NMIJ in 2007. Figure 2 illustrates the moment arm in the 10-N·m-DWTSM. The main arms are made of low-thermal-expansion alloy (Super Invar). The fixing plates and the metal bands are made of austenitic stainless steel (SUS304), and they are attached at both ends of the main arms. It is known that the length of a mechanical part made of low-thermal-expansion alloy slightly varies with age.[4] The secular length change varies widely for a while after the part is manufactured. The main arms of the 10-N·m-DWTSM were manufactured five years ago. In this study, the length of the moment arm was revaluated by using the CMM to investigate the secular length change.

The uncertainty budget table of the 10-N·m-DWTSM was almost completed by revaluating the moment arm length. Therefore, the 10-N·m-DWTSM was compared with the 1-kN·m-DWTSM in NMIJ by using a small-rated-capacity TMD.
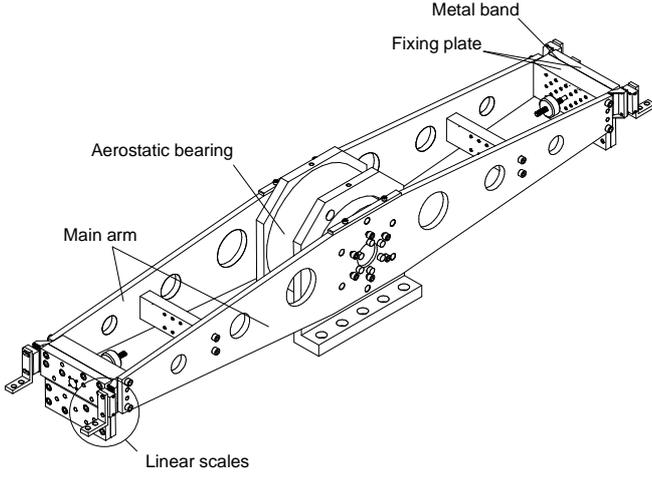
Fig. 2 Illustration of the moment arm component in the 10-N·m-DWTSM.

2. THE MOMENT ARM LENGTH

Figure 3 shows a schematic front view of the moment arm and an enlarged view at one of the metal bands. The main arms are made of low-thermal-expansion alloy, and they are attached to an aerostatic bearing. The total nominal length of each main arm is 1000 mm, and the thickness is 10 mm. Two fixing plates (fixing plates 1 and 2) are attached at the ends of the main arms. The thin metal bands are supported by the fixing plates, and they are made of austenitic stainless steel (SUS304).

Table 1 shows the last measurement results of the lengths of the moment arm. L_u is the distance from the centre of rotation to the fixing plate 2, and L' is the distance from the centre of rotation to the fixing plate 1. The thickness of the fixing plate 1 is h. L_u, L' and h were measured using the CMM. The thin metal band thickness, t_w, and the initial moment arm length, L_0, were calculated using the following equations:

$$t_w = L' - (L_u + h), \qquad (1)$$

$$L_0 = L_u + \frac{t_w}{2} \cdot \qquad (2)$$

In the previous results, the right-hand side length, $L_{0,CW}$, was 510.2773 mm, the left-hand side length, $L_{0,CCW}$, was 510.2657 mm. The combined standard uncertainties, $u(L_u)$ and $u(L_0)$, are also shown in Table 1. Here $u(L_0)$ is defined as follows:

$$u(L_0)^2 = u(L_u)^2 + u(h)^2 + u(t_w)^2 + u(L_T)^2, \qquad (3)$$

where $u(h)$ is the combined standard uncertainty of h, $u(t_w)$ is the standard uncertainty of t_w, and $u(L_T)$ is the standard uncertainty of the change of the moment arm length influenced by the environmental temperature.[5]

In this study, L_u was recalibrated only to investigate the secular length change of the main arms because the main arms are made of low-thermal-expansion alloy.
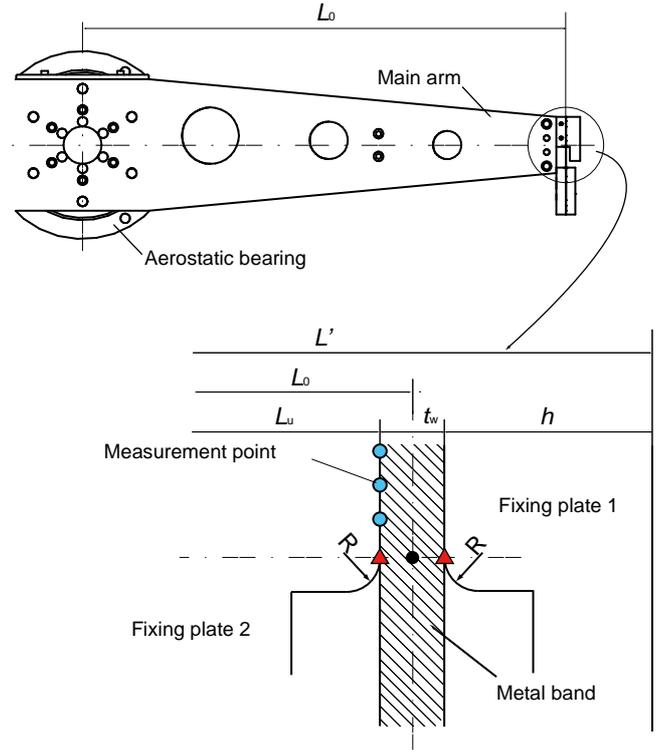

Fig. 3 Schematic front view of the moment arm and enlarged view at the one of the metal bands.

Table 1 Initial moment arm lengths measured in 2007.

	Left-hand side (CCW)	Right-hand side (CW)
L_u	510.2583 mm	510.2711 mm
$u(L_u)$	2.07 μm	2.86 μm
L_0	510.2657 mm	510.2773 mm
$u(L_0)$	8.66 μm	6.61 μm

3. COMPARISON BETWEEN THE 10-N·m-DWTSM AND THE 1-kN·m-DWTSM

The relative combined standard uncertainty of torque, w_{tsm}, realized by the 10-N·m-DWTSM was revaluated after recalibrating the moment arm length. After estimating w_{tsm}, we made a comparison between the 10-N·m-DWTSM and the 1-kN·m-DWTSM in NMIJ using a small-rated-capacity TMD. The basic calibration conditions in this comparison were based on the CIPM Key Comparison, CCM.T-K2 protocol. Figure 4 shows a photograph of the TMD and an indicator/amplifier used in this comparison. The TMD was a DmTN/10Nm (GTM GmbH). The indicator/amplifier was a DMP40S2 (HBM GmbH).

In general, the various characteristics of the TMD used as a travelling standard could affect the results of comparison with TSMs. The various characteristics of the TMD include the creep characteristic, the temperature dependence characteristic, the humidity dependence characteristic, short-term drift, and so on. The 10-N·m-DWTSM and the 1-kN·m-DWTSM have been placed in different laboratories. The environmental conditions were made to substantially coincide by shortening the experimental period. Thus, we decided not to consider the

Fig. 4 Photograph of the TMD and the indicator/amplifier

temperature dependence characteristic and the humidity dependence characteristic. The short-term drift was considered by taking measurements in the following order: the 10-N·m-DWTSM, the 1-kN·m-DWTSM, and the 10-N·m-DWTSM again. Because the 10-N·m-DWTSM and the 1-kN·m-DWTSM differ in their designs, the loading times of weights were different. Thus, the creep characteristic could influence the results of this intra-laboratory comparison. Before making the comparison between the 10-N·m-DWTSM and the 1-kN·m-DWTSM, the creep characteristics of the DmTN/10Nm were estimated.

3.1 Creep characteristics of the DmTN/10Nm

The creep characteristics of the DmTN/10Nm were examined by using the 10-N·m-DWTSM. Figure 5 shows the timetable for the creep testing. First, a torque equal to 100 % of the rated capacity of the transducer was loaded instantaneously, and then that torque was maintained and change in the output was measured for 20 minutes. After that, the torque was unloaded immediately, and then the zero balance was maintained and the change of indication was also observed. These operations were repeated three times. The TMDs were tested separately for the clockwise (CW) and the counter-clockwise (CCW) directions.

3.2 Comparison between the 10-N·m-DWTSM and the 1-kN·m-DWTSM

The basic calibration conditions for comparison between the 10-N·m-DWTSM and the 1-kN·m-DWTSM were based on the CIPM Key Comparison, CCM.T-K2 protocol. Figure 6 shows the timetable for this intra-laboratory comparison. The transfers were calibrated separately for the CW and the CCW directions. The transfers were rotated from 0° to 720° with 120° steps. The measurement interval was 6 minutes, and the mounting position was changed at 10 minute intervals.

4. RESULT AND DISSCUSSIONS

4.1 Moment arm length

Table 2 shows the measurement results of the lengths of the moment arm obtained using the CMM. The right-hand
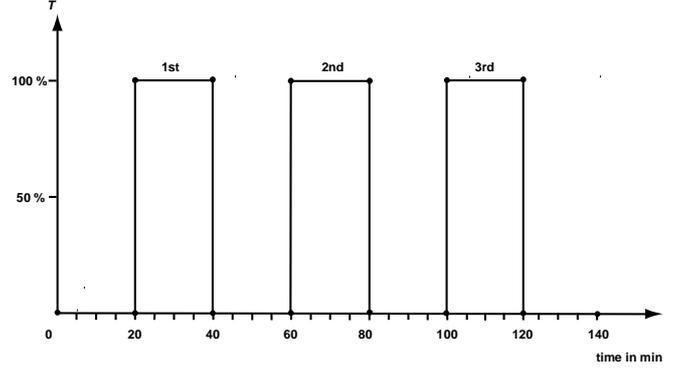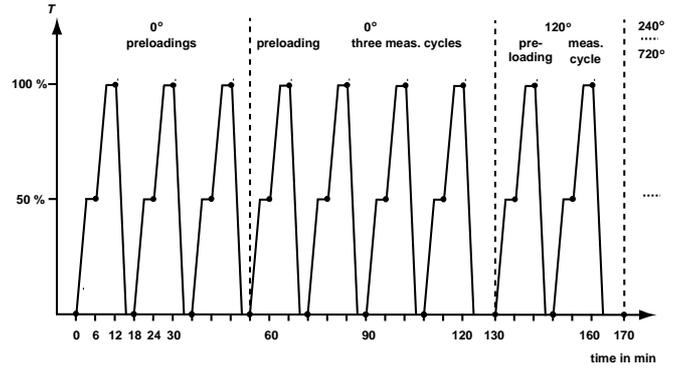

Fig. 5 Timetable for the creep testing

Fig. 6 Timetable for the intra-comparison
(according to CCM.T-K2 protocol)

side length $L_{u,CW}$ expanded by $\Delta L_{u,CW} = 4.9$ μm, and the left-hand side length $L_{u,CCW}$ expanded by $\Delta L_{u,CCW} = 7.7$ μm. L_0 was recalculated based on the current result. $u(L_0)$ was revaluated in consideration of the uncertainty of secular length change, u_{cs}. Here u_{sc} was assumed to be a rectangular distribution whose half-width was the average of $\Delta L_{u,CW}$ and $\Delta L_{u,CCW}$ and the following equation:

$$u_{sc}^2 = \frac{1}{3}\left(\frac{\Delta L_{u,CW} + \Delta L_{u,CCW}}{2}\right)^2, \qquad (4)$$

$$u(L_0)^2 = u(L_u)^2 + u(h)^2 + u(t_w)^2 + u(L_T)^2 + u_{sc}^2. \quad (5)$$

In this study, u_{sc} was estimated to be a relatively large uncertainty. Katsuma *et al.* showed that the secular length change of an Invar baseline tape varied widely for a while after it was manufactured, and the change was extremely small after seven years.[4] We consider that the moment arm length will stabilize in the next several years, and u_{sc} will be smaller than the current result. In the future, the length of the moment arm will be recalibrated to check whether it has stabilized, and u_{sc} will be estimated again.

The relative expanded uncertainty of torque, W_{tsm}, realized by the 10-N·m-DWTSM was revaluated over a torque range from 0.1 N·m to 10 N·m. W_{tsm} is expressed by the following equation:

$$W_{tsm} = k \cdot w_{tsm}$$
$$= k \cdot \sqrt{w_{mass}^2 + w_{grav}^2 + w_{buoy}^2 + w_{arm}^2 + w_{sr}^2 + w_{ssv}^2} \qquad (6)$$

Table 2 Initial moment arm lengths in 2011

	Left-hand side (CCW)	Right-hand side (CW)
L_u	510.2660 mm	510.2760 mm
$u(L_u)$	1.57 μm	2.45 μm
ΔL_u	7.7 μm	4.9 μm
L_0	510.2734 mm	510.2822 mm
$u(L_0)$	9.28 μm	7.39 μm

where w_{mass} is the relative standard uncertainty of mass of the dead weights, w_{grav} is the relative standard uncertainty of gravity at the location of the DWTSM, w_{buoy} is the relative standard uncertainty ascribable to variations in air buoyancy, w_{arm} is the relative combined standard uncertainty of the moment arm length (w_{arm} is given by Eq. (5)), w_{sr} is the relative standard uncertainty due to the sensitivity limit of the fulcrum, w_{ssr} is the relative standard uncertainty due to reproducibility of the sensitivity limit, and k is the coverage factor. W_{tsm} was evaluated to be 7.0×10^{-5} with the coverage factor k being equal to 2.

4.2 Comparison between the 10-N·m-DWTSM and the 1-kN·m-DWTSM

In this study, we used a TMD (DmTN/10Nm) for the comparison between the 10-N·m-DWTSM and the 1-kN·m-DWTSM.

4.2.1 Characteristics of the transducer

The creep test results are shown in Fig. 7, where (a) is for the CW direction, and (b) is for the CCW direction. The vertical axis is the relative variation from the stable zero value after the holding time of 20 minutes. These results were calculated based on the analysis method of the creep test.[6] A maximum relative creep variation of less than 1.2×10^{-5} and a maximum relative creep recovery of less than 1.0×10^{-5} were obtained. The loading time of the 10-N·m-DWTSM was about 180 seconds, and the loading time of the 1-kN·m-DWTSM was about 60 seconds. When the measurement interval was 6 minutes, the holding time gap between the 10-N·m-DWTSM and the 1-kN·m-DWTSM was about 120 seconds. In this creep test, the relative creep variation from 3 to 6 minutes after the torque application was about 2×10^{-6}, which was quite small. Thus, we decided not to correct for the influence of the creep characteristics of the DmTN/10Nm in this intra-laboratory comparison.

4.2.3 Comparison between the 10-N·m-DWTSM and the 1-kN·m-DWTSM

The comparison results at 5 N·m steps and 10 N·m steps for the DmTN/10Nm are shown in Figures 8 and 9. The calibration results were the arithmetic average, $\overline{S'}$, of the results at 120°, 240°, 360°, 480°, 600°, and 720°. The relative deviation, RD, is expressed by the following equation:

$$\overline{S'}_{A\_ave} = \frac{\overline{S'}_{A\_pre} + \overline{S'}_{A\_post}}{2}, \qquad (7)$$

$$RD = \frac{\overline{S'}_B - \overline{S'}_{A\_ave}}{\left|\overline{S'}_{A\_ave}\right|}, \qquad (8)$$
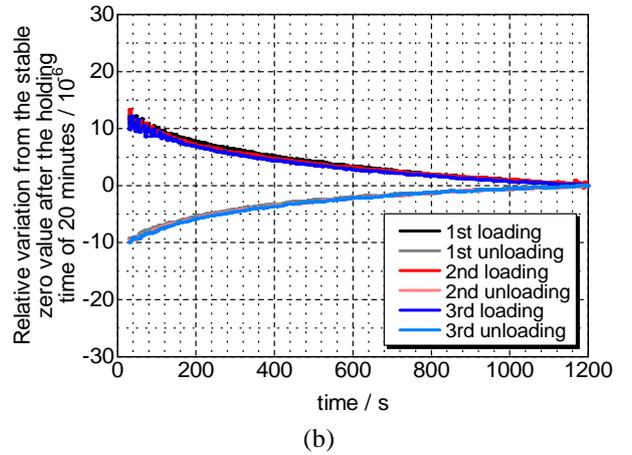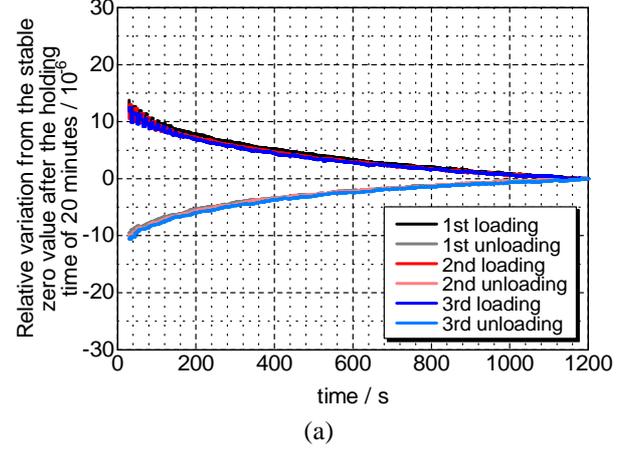

(a)

(b)

Fig. 7 Creep test results of the DmTN/10Nm, for (a) the CW direction and (b) the CCW direction.

where $\overline{S'}_{A\_pre}$ and $\overline{S'}_{A\_post}$ are respectively the results of the pre-calibration and the post-calibration using the 10-N·m-DWTSM, and $\overline{S'}_B$ is the calibration result of the 1-kN·m-DWTSM. In Figs. 8 and 9, zero on the vertical axis is the average of the pre- and post-calibration results using the 10-N·m-DWTSM. The error bars express W_A and W_B, which are the relative expanded uncertainties of torques realized by the 10-N·m-DWTSM and the 1-kN·m-DWTSM, respectively, as described later. In these figures, the calibration results showed good agreement within the uncertainties of calibration. Moreover, we provide objective evaluation of the calibration results by using a relative expanded uncertainty of comparison, W_{comp}, expressed by the following equation:

$$W_{comp} = \sqrt{W_A^2 + W_B^2}, \qquad (9)$$

where W is the relative expanded uncertainty of calibration, and the subscripts A and B indicate the results for the 10-N·m-DWTSM and the 1-kN·m-DWTSM, respectively. W_A and W_B are given by the following equations:

Table 3 Comparison results for the DmTN/10Nm.

T / N·m	Direction	RD	W_{comp}	W_A		W_B	
				W_{tsm_A}	W_{tra_A}	W_{tsm_B}	W_{tra_B}
5	CW	3.4×10^{-5}	8.6×10^{-5}	7.0×10^{-5}	9.7×10^{-6}	4.9×10^{-5}	1.1×10^{-5}
	CCW	1.4×10^{-5}	8.7×10^{-5}	7.0×10^{-5}	9.1×10^{-6}	4.9×10^{-5}	1.3×10^{-5}
10	CW	2.2×10^{-5}	8.6×10^{-5}	7.0×10^{-5}	9.8×10^{-6}	4.9×10^{-5}	6.4×10^{-6}
	CCW	2.6×10^{-6}	8.6×10^{-5}	7.0×10^{-5}	8.5×10^{-6}	4.9×10^{-5}	6.1×10^{-6}
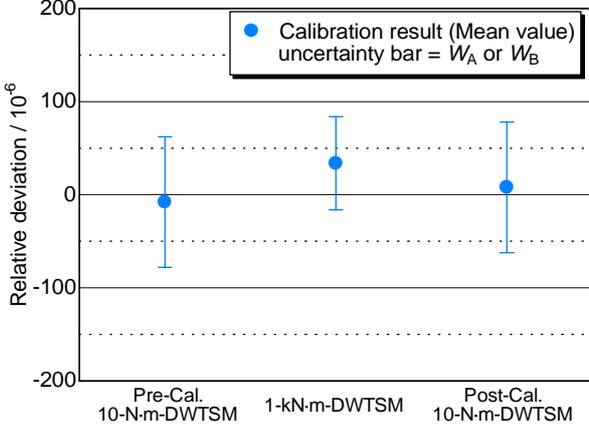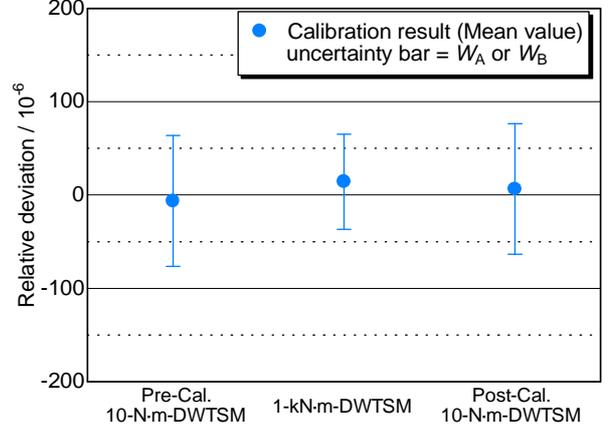
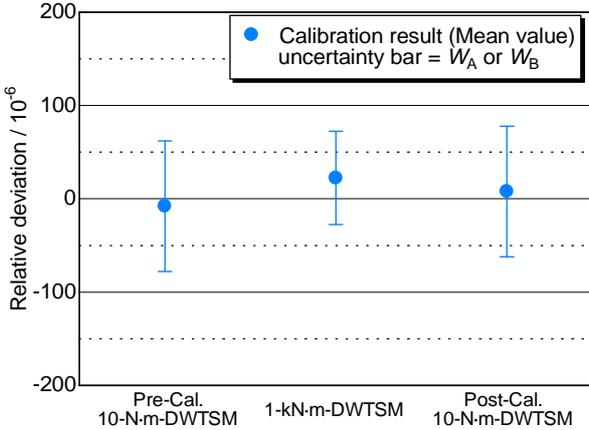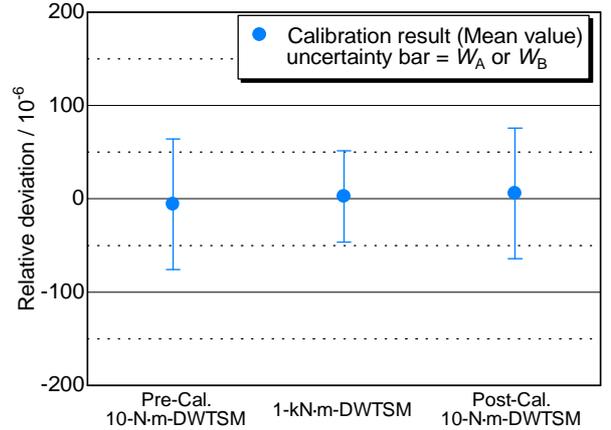(a)   (b)

Fig. 8 Comparison results at 5 N·m steps for the DmTN/10Nm, showing (a) the CW direction and (b) the CCW direction.

(a)   (b)

Fig. 9 Comparison results at 10 N·m steps for the DmTN/10Nm, showing (a) the CW direction, and (b) the CCW direction.

$$W_A = k \cdot w_A = k\sqrt{w_{tsm\_A}{}^2 + w_{tra\_A}{}^2} , \qquad (10)$$

$$W_B = k \cdot w_B = k\sqrt{w_{tsm\_B}{}^2 + w_{tra\_B}{}^2} , \qquad (11)$$

where w_{tra} is the relative combined standard uncertainty ascribable to the measurement of the TMD. W_{tra} for the two machines are given by the following equations:

$$
\begin{aligned}
W_{tra\_A} &= k \cdot w_{tra\_A} \\
&= k\sqrt{w_{rot\_A}{}^2 + w_{rep\_A}{}^2 + w_{res\_A}{}^2 + w_{drf}{}^2}
\end{aligned} , \qquad (12)
$$

$$W_{tra\_B} = k \cdot w_{tra\_B} = k\sqrt{w_{rot\_B}{}^2 + w_{rep\_B}{}^2 + w_{res\_B}{}^2} , \qquad (13)$$

where w_{rot}, w_{rep}, w_{res}, and w_{drf} are the relative standard uncertainty due to reproducibility when changing mounting position, the relative standard uncertainty due to repeatability without changing the mounting position, the relative standard uncertainty due to the resolution of the TMD, and the relative standard uncertainty due to the short term drift of the TMD. Table 3 shows the results of the comparison. From Table 3, RD was less than W_{comp} in all cases. Thus, the TMD calibration capability using the 10-N·m-DWTSM was shown to be equivalent to the TMD calibration capability using the 1-kN·m-DWTSM.

5. SUMMARY

The 10-N·m-DWTSM has been under development since 2006 at NMIJ/AIST. The hardware and software components have been almost completed. In this study, the secular length change of the moment arm was investigated. Then, the 10-N·m-DWTSM was compared with the 1-kN·m-DWTSM in NMIJ by using small-rated-capacity TMDs.

As a result, the right-hand side length $L_{u,CW}$ expanded by $\Delta L_{u,CW} = 4.9$ μm, and the left-hand side length $L_{u,CCW}$ expanded by $\Delta L_{u,CCW} = 7.7$ μm. The combined standard uncertainties of the initial moment arm lengths were revaluated with the standard uncertainty of the secular length change. The relative expanded uncertainty of torque, W_{tsm}, realized by the 10-N·m-DWTSM was revaluated to be 7.0×10^{-5}, with the coverage factor k being equal to 2, over a torque range from 0.1 N·m to 10 N·m.

In the intra-laboratory comparison between the 10-N·m-DWTSM and the 1-kN·m-DWTSM by using the DmTN/10Nm, the results showed good agreement within the uncertainty of comparison. Therefore, the TMD calibration capability using the 10-N·m-DWTSM was shown to be equivalent to that using the 1-kN·m-DWTSM.

6. ACKNOWLEDGEMENT

7. REFFERENCES

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