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SENSITIVITY EVALUATION OF THE FULCRUM IN THE 10 N·m DEAD WEIGHT TORQUE STANDARD MACHINE AND PERFORMANCE EXAMINATION OF A 1 N·m TORQUE MEASURING DEVICE

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Abstract – Many torque tools, such as torque wrenches and torque screwdrivers, as well as torque measuring devices (TMDs) of rated capacity of less than 5 N·m are being used. Thus, a small-rated-capacity torque standard has to be established as soon as possible. To this end, design and development of a dead-weight torque standard machine with a rated capacity of 10 N·m (10 N·m-DWTSM) started in 2006 at the National Metrology Institute of Japan, part of the National Institute of Advanced Industrial Science and Technology. In this report, overviews are given of the 10 N·m-DWTSM and a new 1 N·m TMD developed by way of trial. The sensitivity limit of the fulcrum in the 10 N·m-DWTSM was estimated, and the new 1 N·m TMD was calibrated with the 10 N·m-DWTSM to investigate its characteristics. The fulcrum of the 10 N·m-DWTSM was found to have sufficient sensitivity for two conditions: with the weight loading components only, and with loaded weights. In particular, the sensitivity limit of the fulcrum was a relative value of 5×10^{-6} for 1 N·m when weights of 200 g were loaded on the weight loading components. Characteristic curves of the new 1 N·m TMD were obtained by calibrating it with the 10 N·m-DWTSM.

Keywords: torque, small-rated-capacity, sensitivity

1. INTRODUCTION

Precise torque measuring devices (TMDs) of small rated capacity are required in various industries. Thus, a small-rated-capacity torque standard has to be established as soon as possible. A dead-weight torque standard machine with a rated capacity of 10 N·m (10 N·m-DWTSM) was designed and has been under development since 2006 at the National Metrology Institute of Japan (NMIJ), part of the National Institute of Advanced Industrial Science and Technology (AIST). The sensitivity limit of the fulcrum in the 10 N·m-DWTSM was previously estimated without the weight loading components.[1] It was found that the 10 N·m-DWTSM had sufficient sensitivity up to 0.5 μN·m. However, the sensitivity limit of the fulcrum was reduced when weights were loaded.[2] In this study, the sensitivity limit of the fulcrum was investigated with weights loaded on the weight loading components.

Moreover, high-accuracy torque transducers will be indispensable in disseminating the small-rated-capacity torque standard throughout various industries. Thus, a new TMD has been developed by way of trial in parallel with the development of the 10 N·m-DWTSM. The new TMD, which had a rated capacity of 1 N·m, was calibrated with the 10 N·m-DWTSM to evaluate its characteristics.

2. 10 N·m-DWTSM

The 10 N·m-DWTSM is illustrated in Fig. 1. Its basic hardware components are: (1) a moment arm component, (2) weight loading components, (3) a counter bearing drive component, (4) an installation component for a torque transducer, (5) a pedestal, and (6) a windshield (not illustrated).

Figure 2 shows the control systems for the 10 N·m-DWTSM. The basic software programs are: (a) a main measurement program (MMP), (b) a control program for the weight loading components (CPW), and (c) an environmental measurement program (EMP). These components and control programs are described below.

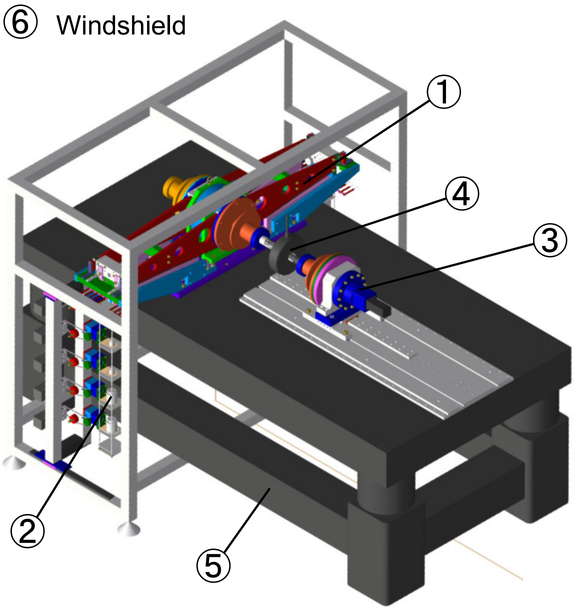

Fig. 1 Schematic of the 10 N·m-DWTSM

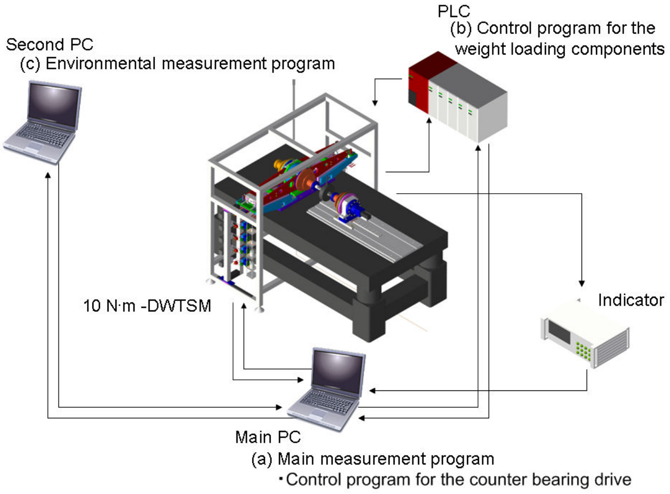

Fig. 2 The control systems of the 10 N·m-DWTSM

2.1. Moment arm component

The moment arm component consists of an aerostatic bearing serving as the fulcrum, the main parts of the moment arm, metal bands, and linear scales installed on both ends of the moment arm. The linear scales are photoelectric reflective scales with a resolution of 0.01 µm. Figure 3 shows a schematic front view of the moment arm and an enlarged view of one of the metal bands. The moment arm component is line-symmetric with respect to the axial direction. The aerostatic bearing is used as the fulcrum supporting the moment arm to minimize the rotational friction. The designed pressure of compressed air supplied to the aerostatic bearing is 0.50 MPa. The main parts of the moment arm are made from low thermal-expansion alloy (super INVAR). The total nominal length of the main parts is 1000 mm and the thickness is 10 mm. Fixing plates 1 and 2 attached at the edges of the main parts are from austenitic stainless steel (SUS304). The thin metal bands are supported by the fixing plates and are also made from SUS304. The thickness of the metal bands is 10 µm. The initial length of the moment arm (geometrical length), L_0, is defined as follows:

$$t_w = L' - (L_u + h_1) \qquad (1)$$

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

where t_{w} is the thickness of the metal band, L' is the length from the centre of the measurement axis to the outer side of the fixing plate 1, L_{u} is the length from the centre of the measurement axis to the fixing plate 2, and h_1 is the thickness of the fixing plate 1. The dimensions L', L_{u}, and h_1 were measured with a coordinate measuring machine (CMM).

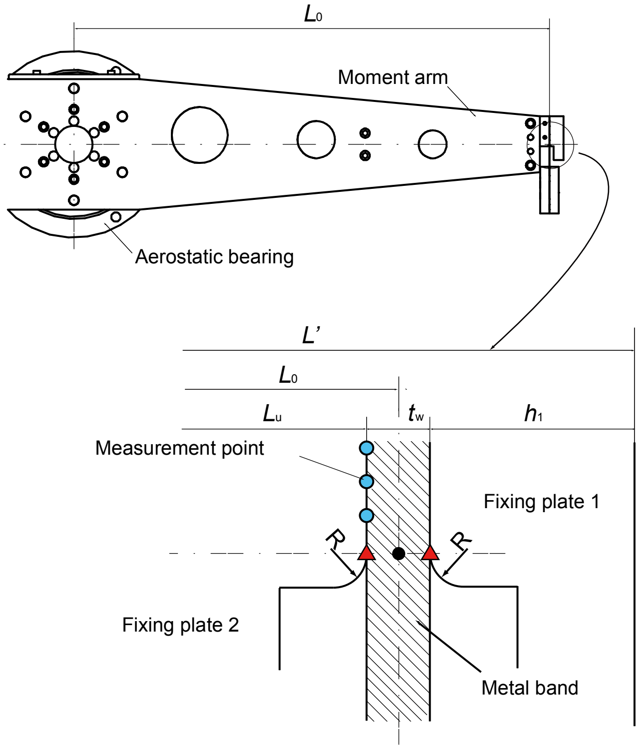

Fig.3 Schematic of the moment arm component

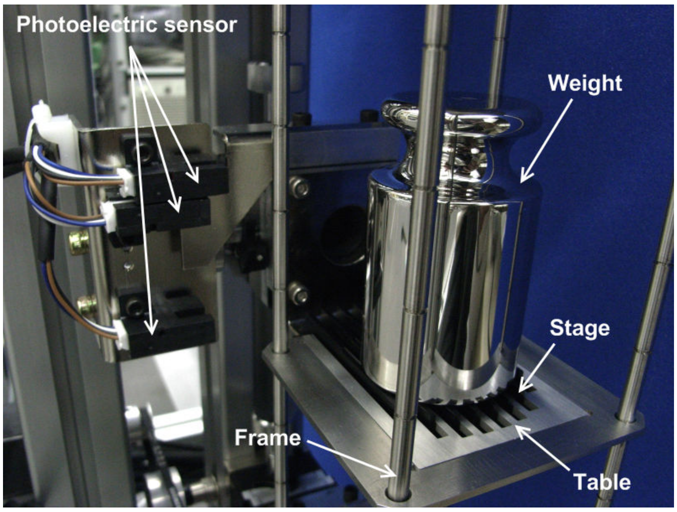

Fig. 4 Photograph of the weight loading stage

2.2. Weight loading components

Figure 4 is a photograph of the weight loading stage. Binary mass stack exchange systems are set as the weight loading components under both the right and left tips of the moment arm. Weights according to OIML R111 were prepared in a series from 1 mg to 1 kg in advance. The structures of the hanger parts look like baskets. A weight is placed on the L-shaped stage, and loading or unloading of the weights is performed by moving the stage up and down. To do so, the motors in the weight loading components are controlled by the CPW, as shown in Figure 2.

2.3. Counter bearing drive component

The counter bearing drive component consists of a double harmonic drive gearing system and a servomotor. The resolution of the servomotor is 131 072 pulse/rev. The servomotor is controlled by the control program for the counter bearing drive component (CPC) included in the MMP, as shown in Figure 2.

2.4. Installation Component for a torque transducer

Misalignment in the measurement axis might affect the uncertainty of the torque realized by a TSM. Therefore, the measurement axis of the 10 N·m-DWTSM was aligned using a micrometer. In the installation component for a torque transducer, single diaphragm couplings are adopted to reduce the influence of the bending moments and transverse forces at both the moment arm side and the counter bearing side. Friction joints (ETP hydraulic clamps: ETP-T) are used to facilitate installation of the torque transducer at both ends of the shaft.

2.5. Pedestal

The 10 N·m-DWTSM has been set up on a vibration-free table made from stone. The thickness of the stone table is 150 mm. Anti-vibration rubber elements with a thickness of about 40 mm are installed under the table. This is a temporary pedestal; in the future, it will be replaced with a new, specially designed pedestal.

2.6. Windshield

The 10 N·m-DWTSM is covered with a windshield made from acrylic plates. No air-cleaning system is used. Sliding doors are installed in the windshield to allow an operator enter when changing the mount position of a torque transducer. In the future, an air-conditioning control system will be introduced to control the ambient temperature.

2.7. Main measurement program (MMP)

The MMP is written in LabVIEW (National Instruments). The MMP is installed on a main PC, as shown in Fig. 2. The MMP reads position data from the linear scales installed on both ends of the moment arm. The CPC included in the MMP receives position data and controls the servomotor in the counter bearing drive component to return the moment arm to the horizontal position. The CPC can finely control the rotating speed of the servomotor. The MMP reads output data from an indicator. If an output value from a torque transducer exceeds a preset limit, the MMP discontinues measurement at once and stops the servomotor. The MMP sends commands to the programmable logic controller (PLC) to load or unload weights and also receives commands from the PLC. If the MMP receives an emergency halt command from the PLC, measurement is discontinued immediately. The MMP can communicate with the EMP via Ethernet. The MMP can obtain environmental data during the measurement from the EMP. If there is an unexpected value in the environmental data, such as a pressure drop of the compressed air supplied to the aerostatic bearing, the MMP immediately clamps the moment arm and stops the measurement.

2.8. Control program for weight loading components (CPW)

The CPW is installed in the PLC. The CPW can control the ten motors in the weight loading components. The PLC is connected to the main PC by a serial communication link. The CPW receives commands from the MMP and sends commands to the servo amplifiers. The CPW can check the movement of motors in the weight loading components in the following instruments. Photoelectric sensors are installed near the top and bottom of each weight loading stage. The CPW reads position data from these sensors, and if there is any problem in the weight loading components, such as malfunction of the motor drive units, the CPW can deactivate all motors and send an emergency halt command to the MMP.

2.9. Environmental measurement program (EMP)

The EMP is also written in LabVIEW. The EMP reads environmental data, including the environmental temperature, humidity, and atmospheric pressure, as well as the temperature of the transducer. The EMP can also monitor the condition of the compressed air supplied to the aerostatic bearing, such as the pressure, flow volume, and temperature. The EMP can communicate with the MMP via Ethernet. The EMP sends environmental data when requested by the MMP. The EMP records the environmental values of the laboratory for the past 24 hours.

3. THE NEW 1 N·m TMD

Highly accurate small-rated-capacity TMDs will be indispensable in disseminating the small-rated-capacity torque standard in various industries. A trial small-rated-capacity TMD (TP-1N-0302) has been developed in parallel with the development of the 10 N·m-DWTSM. Figure 5 shows the TP-1N-0302, together with an MGCplus system which is used as an indicator/amplifier. The capacity of the TP-1N-0302 is 1 N·m. The total length is 165 mm, and the diameter of the shaft is 15 mm. The housing of the TP-1N-0302 is made from aluminium alloy. Hollow aluminium alloy tubes are used for the shafts to attain a lighter body. The measuring amplifier system (MGCplus ML38) has a carrier frequency of 225 Hz and a digital resolution of 1 000 000 digits.

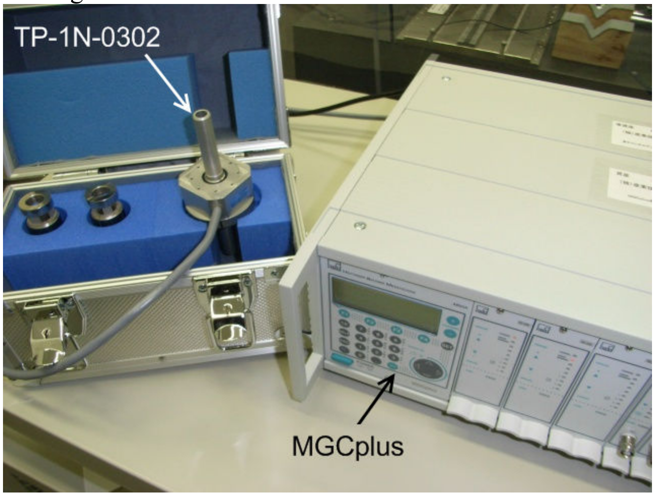

Fig. 5 Photograph of the TP-1N-0302 and the MGCplus

4. EXPERIMENTAL CONDITIONS

4.1. Sensitivity evaluation of the fulcrum

The aerostatic bearing installed in the moment arm component is used for the fulcrum. It has previously been confirmed that the sensitivity limit of the fulcrum was sufficient for the mass range from 1.0 mg to 0.1 mg without the weight loading components.[1] In this study, the

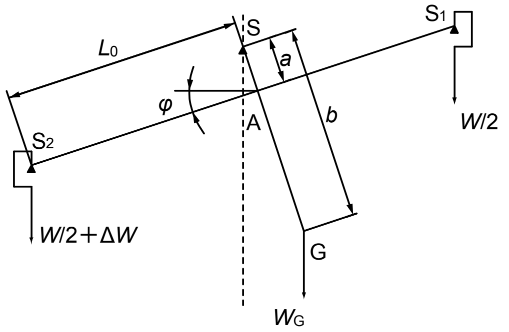

Fig. 6 Principle of the balance [2]

sensitivity limit of the fulcrum was investigated with weights loaded on the weight loading components. In particular, it was evaluated whether the 10 N·m-DWTMS had sufficient sensitivity for calibration of the new 1 N·m TMD. Figure 6 shows the principle of the balance.[2] The sensitivity of the balance, ϕ, is given by:

$$\tan\phi = \frac{L_0 \cdot \Delta W}{W_G \cdot b + a(W + \Delta W)} \quad (3),$$

where L_0 is the lever length, ΔW is mass of a small weight, W_G is mass of the lever, and W is total mass of a radial load. In Fig. 6, S indicates the fulcrum point and G indicates the centre of gravity. Also, S_1 and S_2 are load points, A is the intersection of the line connecting S_1 and S_2 and the line connecting S and G, a is the distance from S to A, and b is the distance from S to G. The centre of gravity of the 10 N·m-DWTSM was adjusted to be above the fulcrum point to improve the sensitivity. If there is no friction in the fulcrum under this condition, the moment arm cannot maintain a horizontal position. To measure the sensitivity limit of the fulcrum, the horizontal position of the moment arm was adjusted by attaching weights under the fulcrum point to make the centre of gravity lower than the fulcrum point. Therefore, this condition was worse than the usual calibration condition for the sensitivity of the fulcrum. Moreover, the larger the radial load, the smaller the sensitivity limit of the fulcrum becomes.[2] When weights were loaded to generate 1 N·m in the calibration of the new 1 N·m TMD, the radial load became the maximum. In other words, this condition was the worst condition for the sensitivity when calibrating the new 1 N·m TMD. Thus, the sensitivity limit of the fulcrum was investigated for two conditions: The first was the case where only the weight loading components were installed (case 1), and the second was the case where the maximum radial load was applied to the weight loading components (case 2). It was necessary to load a weight of 200 g on the right or left side of the moment arm to generate 1 N·m. To generate a radial load equivalent to this condition, weights of 100 g were loaded on both main parts of the moment arm, that is, a total weight of 200 g, to balance the moment arm. The 1.0 mg and 0.1 mg weights were made especially and measured in the Mass and Force Standards Section of NIMJ. In case 1, the 0.1 mg weight was loaded, generating a torque of 0.5 μN·m. In case 2, the 1.0 mg weight was loaded, generating a torque equivalent to 5.0 μN·m. The relative value was 5×10^{-6} for 1 N·m. The inclination of the moment arm was measured with the linear scales installed on both ends of the moment arm. Loading and unloading of the small weights were performed five times for each case.

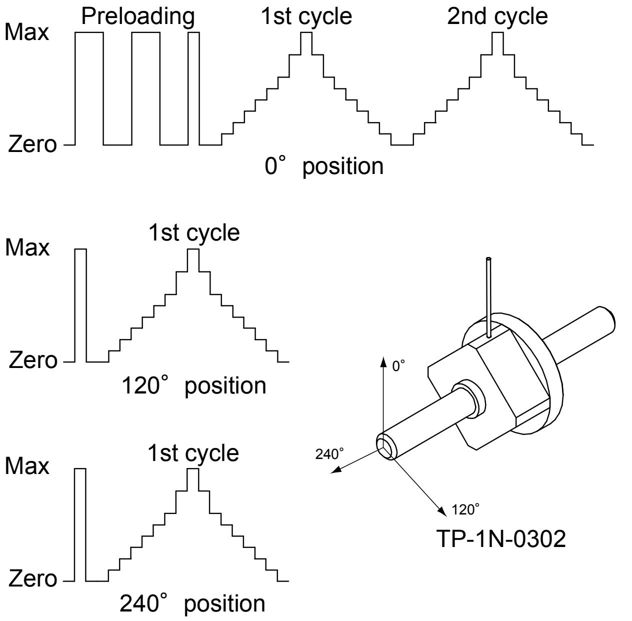

Fig. 7 Loading cycles for the 10 N·m-DWTSM

4.2. Calibration of the new 1 N·m TMD

In this study, the characteristics of the new 1 N·m TMD were evaluated. Figure 7 shows the loading cycles used for calibration with the 10 N·m-DWTSM.[3] There were eight calibration steps (0.1 N·m, 0.2 N·m, 0.3 N·m, 0.4 N·m, 0.5 N·m, 0.6 N·m, 0.8 N·m, and 1.0 N·m). The mount position was changed three times (0°, 120° and 240°). After the output from the TMD reached a prescribed value in each calibration step, the 10 N·m-DWTSM was maintained in the horizontal position for 50 seconds, and 20 points were measured at intervals of 0.5 seconds. The TMD was calibrated separately for the clockwise (CW) and the counter-clockwise (CCW) directions. Additionally, for reference, the TMD was also calibrated with a 1 kN·m-DWTSM; however, because the ordinary calibration range of the 1 kN·m-DWTSM was more than 5 N·m, this calibration served merely as a trial. Two calibration steps were used (0.5 N·m and 1.0 N·m), and the other conditions were the same as in the calibration with the 10 N·m-DWTSM. The MGCplus ML38 was used as an indicator/amplifier, and a 0.1 Hz Bessel filter was employed as a low pass filter.

5. RESULTS AND DISCUSSION

5.1. Sensitivity evaluation of the fulcrum

Figure 8 shows the results for case 1. When the 0.1 mg weight was loaded, the inclined level was an average of 0.37 μm. Also, when this weight was unloaded, the inclined level almost returned to the horizontal position. Figure 9 shows the results for case 2. The inclined level was an average of 0.29 μm when the 1.0 mg weight was loaded, and it returned almost to the horizontal position when unloaded. Thus, the sensitivity limit of the fulcrum was found to be sufficient in both cases.

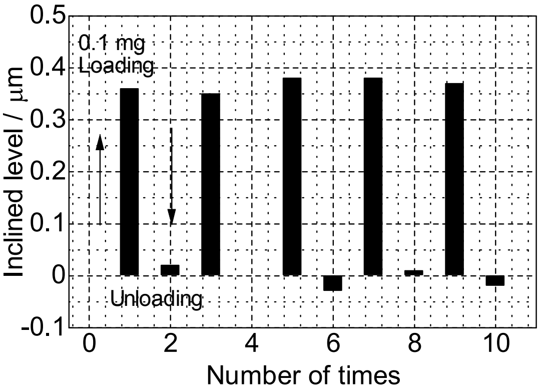

Fig. 8 Inclined level of the moment arm (case 1)

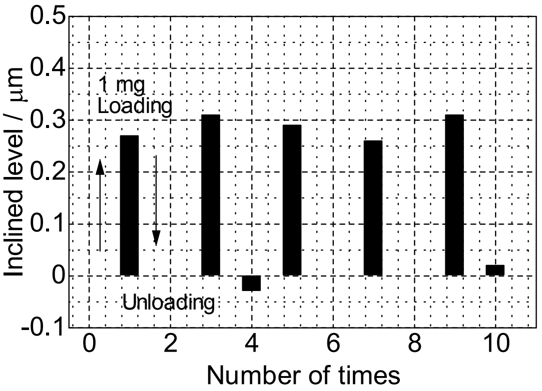

Fig.9 Inclined level of the moment arm (case 2)

In this study, because the centre of gravity was set lower than the fulcrum point in order to balance the moment arm, this condition was worse than the actual calibration condition for the sensitivity limit of the fulcrum. Thus, there is a possibility that the sensitivity limit of the fulcrum under the actual calibration condition is better than this result because the centre of gravity is adjusted to be above the fulcrum point when no weight is loaded.

5.2. Calibration of the new 1 N·m TMD

Figure 10 shows characteristic curves of the TP-1N-0302 calibrated with the 10 N·m-DWTSM. These curves show the characteristics of a transducer with only one graph.[4] Regarding the measurement results for increasing torque S'_{ije} and decreasing torque S''_{ije}, the characteristic relative deviations (R.D.) D'_{ije} and D''_{ije} are calculated according to Eq. (4) and Eq. (5) below:

$$D'_{ije} = \frac{\left(S'_{ije} - \frac{T_i}{T_{\max}} \overline{S'_n} \right)}{\left| \overline{S'_n} \right|} \tag{4}$$

$$D''_{ije} = \frac{\left(S''_{ije} - \frac{T_i}{T_{\max}} \overline{S'_n} \right)}{\left| \overline{S'_n} \right|} \tag{5}$$

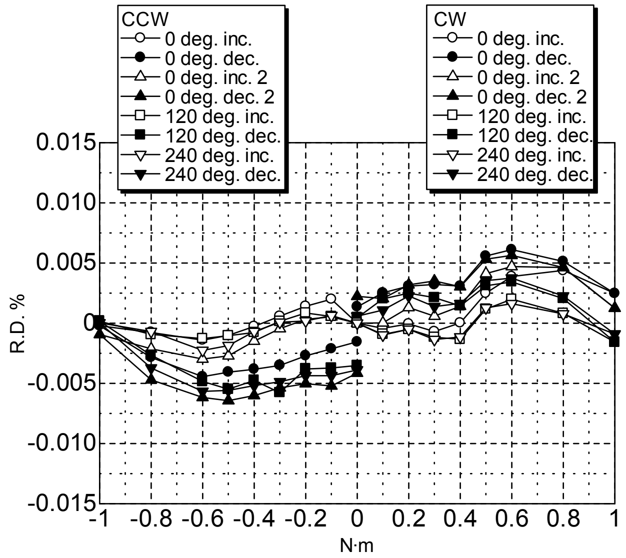

Fig. 10 Characteristic curve of TP-1N-0302 calibrated with the 10 N·m-DWTSM

Here, $\overline{S'_n}$ is the total average value of $T_{\max}$, which is the maximum value of the 1st cycle at each mount position, j is the index of the calibration cycle, and e is the index of the series. The characteristic curves were almost symmetrical around the boundary of 0 N·m, as shown in Fig. 10. Moreover, the characteristic curves for increasing torque were coincident with the characteristic curves for decreasing torque, indicating that the reproducibility was good.

The calibration results and the relative expanded uncertainties attributed to a TMD, U_{tra}, are shown in Table 1. The relative expanded uncertainties were calculated based on JMIF-015.[3] The calibration results obtained with the 10 N·m-DWTSM and those obtained with the 1 kN·m-DWTSM can be considered to be equivalent at ±1 N·m and ±0.5 N·m when considering the calibration uncertainties. The relative expanded uncertainties obtained with the 10 N·m-DWTSM were smaller than those obtained with the 1 kN·m-DWTSM. The relative expanded uncertainties of the 10 N·m-DWTSM were $U_{\mathrm{tra\_CW}} = 0.0061$ and $U_{\mathrm{tra\_CCW}} = 0.0054$ at the rated capacity. On the other hand, the relative expanded uncertainties of the 1 kN·m-DWTSM were $U_{\mathrm{tra\_CW}} = 0.0178$ and $U_{\mathrm{tra\_CCW}} = 0.0152$ at the rated capacity. One of the causes for this result was the difference of the calibration steps. Also, it was thought that the counter bearing drive control programs for the 10 N·m-DWTSM and the 1 kN·m-DWTSM were different. The counter bearing drive control program for the 10 N·m-DWTSM can finely adjust the rotating speed to prevent the servomotor from overshooting in the near horizontal position. It is thought that this program had a positive effect on the calibration results. Thus, it was considered that the technique for controlling the counter bearing drive is important for small-rated-capacity torque transducers.

The long-term stability of the TP-1N-0302 will be evaluated in the future.

Table 1 Calibration results and uncertainties of the calibration (TP-1N-0302)

		10 N·m-DWTSM				1 k N·m-DWTSM			
		CW		CCW		CW		CCW	
Torque	N·m	Calibration results mV/V	Relative expanded uncertainty %, ($k = 2$)	Calibration results mV/V	Relative expanded uncertainty %, ($k = 2$)	Calibration results mV/V	Relative expanded uncertainty %, ($k = 2$)	Calibration results mV/V	Relative expanded uncertainty %, ($k = 2$)
Increasing	0.1	0.116869	0.0098	-0.116858	0.0205				
	0.2	0.233752	0.0106	-0.233730	0.0094				
	0.3	0.350621	0.0077	-0.350607	0.0070				
	0.4	0.467502	0.0075	-0.467486	0.0065				
	0.5	0.584409	0.0070	-0.584365	0.0068	0.584377	0.0290	-0.584227	0.0270
	0.6	0.701297	0.0062	-0.701239	0.0063				
	0.8	0.935047	0.0062	-0.934969	0.0057				
-----	1.0	1.168780	0.0061	-1.168699	0.0054	1.168806	0.0178	-1.168679	0.0152
Decreasing	0.8	0.935061	0.0060	-0.934996	0.0060				
	0.6	0.701320	0.0062	-0.701278	0.0064				
	0.5	0.584437	0.0063	-0.584409	0.0079	0.584600	0.0540	-0.584465	0.0286
	0.4	0.467536	0.0066	-0.467533	0.0086				
	0.3	0.350660	0.0067	-0.350665	0.0101				
	0.2	0.233786	0.0072	-0.233782	0.0156				
	0.1	0.116900	0.0126	-0.116910	0.0389				

6. SUMMARY

In this study, an overview of the 10 N·m-DWTSM currently under development at NMIJ was described. The new 1 N·m TMD that was developed in parallel with the 10 N·m-DWTSM was also introduced. The sensitivity limit of the fulcrum was investigated for two experimental conditions. The first was loading a 0.1 mg weight using only the weight loading components. The second was loading a 1.0 mg weight when 100 g weights were loaded on the weight loading components. In addition, the new 1 N·m TMD was calibrated with the 10 N·m-DWTSM to evaluate its characteristics.

The sensitivity limit of the fulcrum was found to be sufficient for both conditions. In particular, the sensitivity limit of the fulcrum when loading 100 g weights on the weight loading components was a relative value of 5×10^{-6} for 1 N·m, which was sufficient for the calibration of small capacity TMDs.

The new 1 N·m TMD was calibrated with the 10 N·m-DWTSM, and the characteristic curves were drawn. The reproducibility in the calibration results was good. The relative expanded uncertainties were $U_{\mathrm{tra\_CW}} = 0.0061$ and $U_{\mathrm{tra\_CCW}} = 0.0054$ at the rated capacity.

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