

Estimation of Best Measurement Capability in the 1 kN·m Deadweight Torque Standard

Machine

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Abstract

The uncertainty of each component in the developed deadweight torque standard machine of rated capacity 1 kN·m has been evaluated at the National Metrological Institute of Japan (NMIJ). For estimating Best Measurement Capability, the following evaluations had remained: actual moment-arm length during torque calibration, influence of measurement axis misalignment due to the coupling condition. Therefore, the actual moment-arm length was estimated by measuring the temperature distribution of the moment-arm in the environment of the torque calibration room. In addition, the length variation of the moment-arm under deadweight loading was measured with a laser interferometer system. Moreover, the difference in the output of the torque transducer was observed for three connection methods when mounting the torque transducer on the torque standard machine. Consequently, the Best Measurement Capability in the torque standard machine was brought within ± 25 ppm as the relative expanded uncertainty for the calibration range from 5 N·m to 1 kN·m.

1. Introduction

In order to promptly establish the torque traceability system in Japan, research and development of a torque standard machine has been conducted since 1997. The torque standard machine (1 kN·m-DWTSM) that was initially developed is shown in Fig. 1. This is a

deadweight / moment-arm type, and has the calibration range from 5 N·m to 1 kN·m. The following evaluations of uncertainty components in the 1 kN·m-DWTSM [1] [2] have been completed:

(1) Mass of linkage weights, $U_{\text{mass}}: \pm 5$ ppm

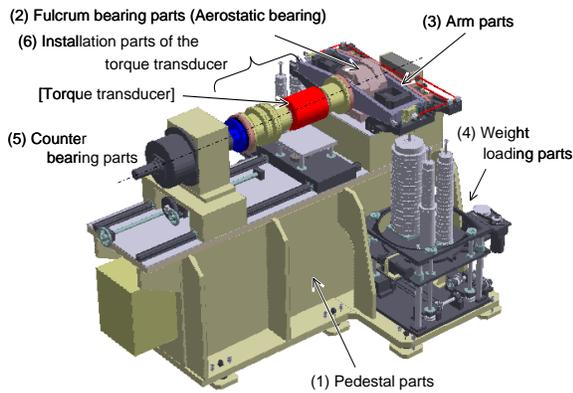


Figure 1. Schematic of the 1 kN·m-DWTSM

- (2) Initial length of the moment-arm at 20 °C, $U_{ini_lgt}: \pm 10$ ppm
- (3) Reproducibility of the sensitivity in the fulcrum, $U_{ssv}: \pm 4$ ppm
- (4) Sensitivity reciprocal, $U_{sr}: \pm 20$ ppm

In this paper, in order to estimate the Best Measurement Capability of the 1 kN·m-DWTSM, the results of evaluating the following items are described:

- (1) Temperature compensation of the moment-arm length in the torque calibration environment,
- (2) Length variation due to flexure of the moment-arm, and
- (3) Influence of the coupling on the output sensitivity of a torque transducer.

2. Temperature Compensation of the Moment-Arm Length

2.1. Experimental Procedure

Temperature dependence of the moment-arm length cannot be disregarded in the torque

calibration environment because the arm is made

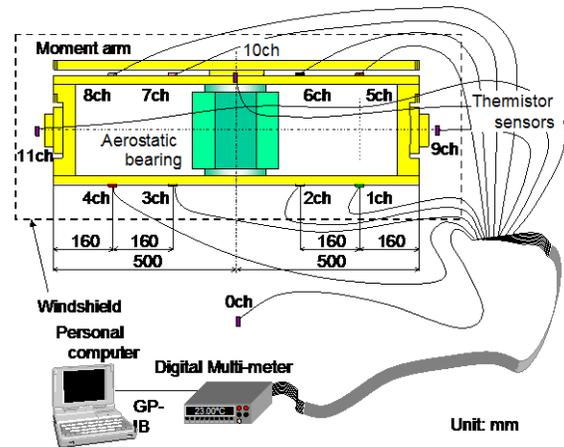


Figure 2. Temperature measurement system

of austenitic stainless steel (SUS304) which has a coefficient of expansion of $1.59 \times 10^{-5}/K$. Thus, the temperature measurement of the moment-arm was performed in the torque calibration room.

Twelve NTC thermistor sensors were manufactured for this measurement. The reference platinum resistance thermometer calibrated these sensors before and after the measurement. The temperature measurement system is shown in Fig. 2. Channel 0 (0ch) was installed in the air environment at the center of the 1 kN·m-DWTSM. Channels 9, 10, and 11 (9, 10 and 11ch) were also installed in the air environment but near the moment-arm in the windshield. Channels 1 to 8 (1 to 8ch) were insulated from the surrounding environment and were adhered on the moment arm directly as shown in Fig.2.

In order to reproduce the conditions during the torque calibration, temperature was measured

from the moment the power supply was turned on, followed by supply of compressed air to the aerostatic bearing (fulcrum unit), and control of the moment-arm to the horizontal level, through until the power supply was turned off. Measurement were made continuously for about nine hours a day, repeated for four days.

2.2. Experimental Results

As a result of pre- and post-calibration, the uncertainty of the thermistor sensors U_{it} became ± 0.1 K. One of temperature measurement results are shown in Fig.3. This graph shows that the temperature in the calibration environment (0ch) was hardly different from that of the moment-arm (1-8ch) although the air temperature in the windshield (9-11ch) was about 0.4 K higher than that of the moment-arm during the operation of the 1 kN·m-DWTSM. This result was the same in all measurements for the four days. Therefore, the temperature of the moment-arm can be estimated by the temperature measurement of 0ch. The calculation from the temperature measurement results of Fig. 3 (This result had the largest variation in the four-days measurements) brought us the uncertainty of temperature measurement of the moment-arm U_{tlv} of ± 0.39 K.

The actual moment-arm length in the torque calibration room L is expressed by the following equation when the initial moment-arm length at 20 °C is L_0 , the coefficient of expansion of the moment-arm material is α and deviation of the calibration environment temperature from 20 °C

is Δt :

$$L = L_0(1 + \alpha \cdot \Delta t) . \quad (1)$$

The combined standard uncertainty $u_c(L)$ can be

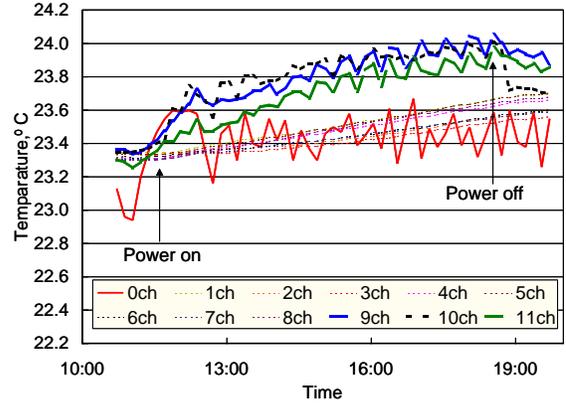


Figure3. Example of temperature measurement results

calculated by the partially differentiating equation (1) as follows:

$$\begin{aligned} u_c^2(L) = & (1 + \alpha \cdot \Delta t)^2 \cdot u^2(L_0) \\ & + L_0^2 \cdot (\Delta t)^2 \cdot u^2(\alpha) \\ & + L_0^2 \cdot \alpha^2 \cdot u^2(\Delta t) . \end{aligned} \quad (2)$$

The values of L_0 , $u(L_0)$, α and $u(\alpha)$ had already been obtained by the previous evaluation result [1]. For example, Table 1 shows the calculation result from equation (2) when using the measurement results in Fig. 3 for Δt and $u(\Delta t) = u_c(tlv) = U_{tlv}/2$. The expanded relative uncertainty U_{act_lv} of ± 11.6 ppm was obtained. The authors currently believe that the expanded relative uncertainty does not exceed ± 12 ppm if the environmental temperature range is from 20 to 25 °C and the temperature control condition does not change in a certain period. However, the above temperature measurement must be

conducted periodically to maintain this uncertainty all year round because the temperature condition in the torque calibration room at the NMIJ somewhat depends on the season.

Table 1. Example of the uncertainty calculation result of the actual moment-arm length

	Left-hand (ACW)	Right-hand (CW)
L_0 , mm	500.0174	500.0149
α , 1/K	1.59E-05	
Δt , K	3.47	
L , mm	500.0450	500.0425
Uncertainty		
$u(L_0)$, μm	2.42	
$u(\alpha)$, 1/K	2.00E-07	
$u_c(t/\nu)$, K	0.197	
$u_c(L)$, μm	2.90	
$U_{\text{act}_\text{lvr}}$, μm	5.8	
$U_{\text{act}_\text{lvr}}$, ppm	11.6	

3. Length Variation due to Flexure of the Moment-arm

Figure 4 shows the configuration of the moment-arm. The 1 kN·m-DWTSM has a function of carrying out feedback control of the inclined moment-arm due to the deadweight loading to the horizontal position using the servo-motor by the side of counter bearing parts. The sequence controller always observes the vertical displacement at both ends of the auxiliary-arm with the photoelectric reflection type linear encoders (1R, 1L). No loading occurs on the auxiliary-arm.

First, a torque transducer having a rated capacity of 1 kN·m was mounted on the 1 kN·m-DWTSM. Then both clockwise torque and anticlockwise torque were loaded in step of 100

N·m to 1 kN·m in a series. Flexure and length variation were measured by the linear encoders (2R, 2L) and the interferometer system, respectively. The uncertainties of the calibration of linear encoders and the interferometer system are $\pm 1 \mu\text{m}$ and $\pm 10^{-6} \Delta L$ (ΔL is the measurement length). Twice simple repetition and five repeated the series of measurements

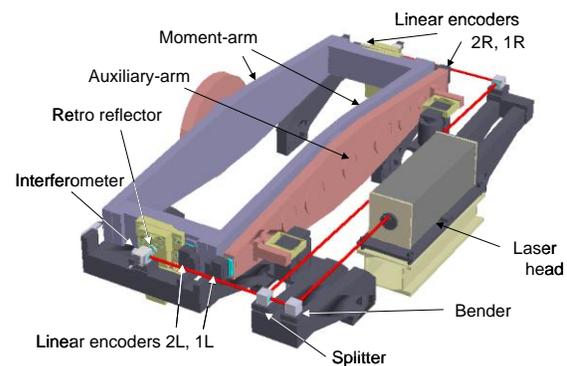


Figure 4. Configuration of the moment-arm

times by remounting the torque transducer and its adapters, making ten times in all.

The measurement results of flexure and length variation show the maximum reproducibility errors in ten series did not exceed $1 \mu\text{m}$ and $0.05 \mu\text{m}$. It was obvious that the uncertainty of the length variation $U_{\text{flx}_\text{lgt}}$ was less than $\pm 2 \mu\text{m}$ in the range of $\pm 1 \text{ kN}\cdot\text{m}$. This is equivalent to $\pm 4 \text{ ppm}$ for the nominal length of 500 mm.

4. Influence of the Coupling in the Torque Standard Machine

4.1. Experimental Procedure

The Influence of misalignment on the output

sensitivity of a torque transducer has been investigated by Brüge et al. [3] in detail. In this study, the authors investigated how much the output sensitivity of a torque transducer would be affected by the misalignment of the 1 kN·m-DWTSM itself. The misalignment of the measurement axis in the 1 kN·m-DWTSM has been adjusted to $\pm 10 \mu\text{m}$. However, an aerostatic bearing is used for the fulcrum of the 1 kN·m-DWTSM, and because of the narrow clearance between the shaft and housing of less than $27 \mu\text{m}$, there is a risk of direct contact due to the misalignment caused by mounting the torque transducer. Therefore, diaphragm flanges (single couplings) were assembled between the torque transducer and the 1 kN·m-DWTSM as shown in the bottom part of Fig. 5. The influence of these diaphragm flanges, which are not adapter parts but composition parts of the 1 kN·m-DWTSM, on the output sensitivity of the torque transducer was investigated.

The output sensitivity variation of the torque transducer was examined under the following three conditions (see also Fig. 5):

- (a) Rigid connection without diaphragm flanges (RC),
- (b) One-side diaphragm flange (OD), and
- (c) Both-sides diaphragm flanges (BD).

A thin disk shape, high efficiency torque transducer TF1000 was used for this experiment. As the torque sequence, after three times of preloading up to the rated capacity, i.e. 1 kN·m, clockwise torque and anticlockwise torque were loaded, respectively, under the conditions of 100

Nm/step. Two increase-and-decrease series were conducted with unchanged mounting position. This sequence was then repeated four times with changed mounting rotational positions including 360 deg. at intervals of 120 deg. In order to remove the influence of creep, the data acquisition was carried out strictly according to the predetermined timetable.

4.2. Experimental Result

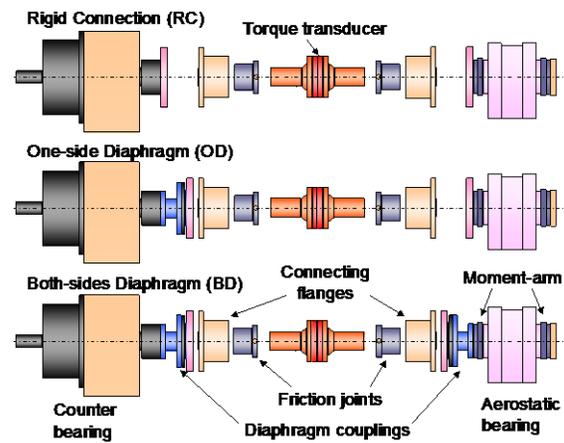


Figure 5. Connecting conditions

The calculated repeatability error with unchanged mounting position is shown in Fig. 6. It is clear that the repeatability characteristic of the torque transducer itself is independent of the coupling conditions. Deviations among the values of each condition did not exceed $\pm 3 \text{ ppm}$.

Next, relative deviation of the average value in each condition (calibration result) for the total average value is shown in Fig. 7. The maximum difference among coupling conditions was less than $\pm 13 \text{ ppm}$. Taken together with the result of Fig. 6, it can be concluded that the existence of diaphragm flanges is not related to the output

sensitivity. Moreover, deviation errors greater than the above result does not appear during

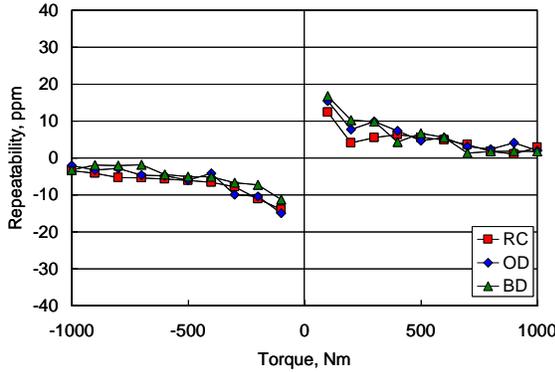


Figure 6. Comparison of the output sensitivity
-Repeatability-

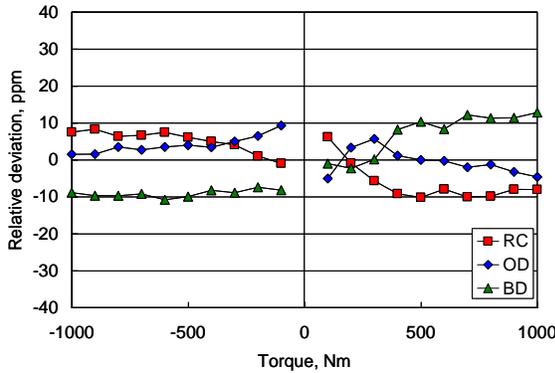


Figure7. Comparison of the output sensitivity
-Calibration result-

usual torque calibration because we never change the coupling conditions from BD. Therefore, the influence of coupling can be excluded from the estimate of the Best Measurement Capability.

5. Conclusion

The following equations allow us to estimate the Best Measurement Capability U_{tsm} taking all uncertainty components into consideration,

which are: Mass of linkage weights U_{mass} , temperature compensation of the moment-arm length in the calibration environment U_{act_lgt} (including uncertainty of initial length U_{ini_lgt}), reproducibility of the sensitivity in the fulcrum U_{ssv} , sensitivity reciprocal U_{sr} and length variation due to flexure of the moment-arm U_{flx_lgt} .

$$u^2_{c_tsm} = (U_{mass}/2)^2 + (U_{act_lgt}/2)^2 + (U_{ssv}/2)^2 + (U_{sr}/2)^2 + (U_{flx_lgt}/2)^2 \quad (3)$$

$$U_{tsm} = k \cdot u_{c_tsm} \quad (k = 2) \quad (4)$$

As a result of calculation, U_{tsm} of less than ± 25 ppm were obtained in the calibration range from 5 N·m to 1 kN·m. However, we must measure the temperature of the moment-arm periodically to maintain the uncertainty U_{act_lgt} . Moreover, it is expected that less than ± 20 ppm of the Best Measurement Capability will be achieved by refinement of the sensitivity measurement of the fulcrum (U_{sr}).

6. References

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