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Expansion of the calibration range and improvement of the uncertainty in the 1 kN·m deadweight torque standard machine

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Abstract

Expansion of the calibration range and improvement of the uncertainty of realized torque in the 1 kN·m deadweight torque standard machine were investigated. The lower limit of the calibration range was lowered from 5 N·m to 0.5 N·m by developing new small linkage weight series. In addition, the sensitivity limit at the fulcrum was reevaluated. The moment-arm length was also re-measured after changing the thin metal bands at the ends of the moment-arm. As a result of these evaluations, relative expanded uncertainties (k = 2) of 7.3×10^{-5} and 2.9×10^{-5} could be obtained in the range from 0.5 N·m to 20 N·m and from 5 N·m to 1 kN·m, respectively.

Keywords: Torque, Sensitivity limit, Deadweight

1. Introduction

Two deadweight torque standard machines (TSMs), having rated capacities of 1 kN·m and 20 kN·m (1 kN·m-DWTSM and 20 kN·m-DWTSM), have been constructed, and the torque standard in the range of from 5 N·m to 20 kN·m has been disseminated to Japanese industry since 2004 by the National Metrology Institute of Japan (NMIJ) of the National Institute of Advanced Industrial Science and Technology (AIST)[1][2]. However, the dissemination range of this torque standard is insufficient for the demands of the industry. Many hand torque tools as well as torque measuring devices (TMDs) with rated capacities of less than 5 N·m are used for the measurement and control of audio-visual equipment, office automation devices, mobile equipment and so on. At the NMIJ, a torque standard machine of smaller range of from 10 mN·m to 10 N·m is currently under development with the highest quality[3]. However the dissemination of this range of standard will take a few years. As a temporary solution for industry, the authors herein attempted expansion of the lower limit of the calibration range from 5 N·m to 0.5 N·m by developing new small linkage weight series in the 1 kN·m-DWTSM.

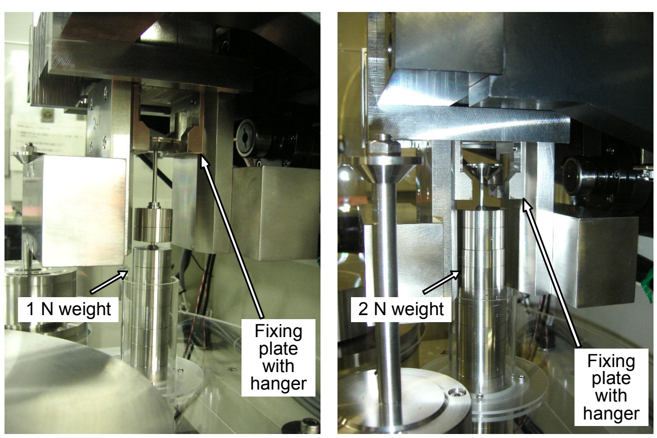
In addition, the sensitivity at the fulcrum was reevaluated after mounting a new auxiliary radial/thrust aerostatic bearing with the main aerostatic bearing in series, which was developed for strengthening the fulcrum against the bending-moment caused by the torque loading on to the torque transducer with the form of the torque wrench (Reference Torque Wrench: RTW)[4]. The moment-arm length was also re-measured after changing the metal band thickness from 100 μm to 50 μm at the ends of the moment-arm, which determines the loading point of the deadweight[5].

Finally, uncertainty evaluation of the torque realized by the 1 kN·m-DWTSM was described integrating all other uncertainty contributions.

2. Installation of Small Linkage Weight Series

Two new deadweight series that have a linkage structure of the one-inner type and disk shape, as shown in Fig. 1(a), were developed and placed under both ends of the moment-arm. One series is a 1 N series and the other series is 2 N series. Photographs of these weight series are shown in Fig.1(b) and Fig.1(c). One linkage weight from each series can realize a force of 1 N and 2 N under the local field of acceleration of gravity of g_{local} = 9.799 484 1 m/s^2. These weights were made of austenitic stainless steel (SUS304). These new deadweight series are as follows:

(1) 1 N x 11 disks x 2 sets (realizing a torque of 5.5 N·m by a pitch of 0.5 N·m) and (2) 2 N x 22 disks x 2 sets (realizing a torque of 22 N·m by a pitch of 1 N·m).



(a) Dimensions (b) 1 N series (c) 2 N series

Fig. 1 New linkage deadweight series

The mass of the weights m_A was adjusted to objective values with a relative deviation of less than 1×10^{-6} (except for the two top weights of the 2 N series, which have deviations of 3×10^{-6}), using the following equation in consideration of the g_{local} and the influence of air buoyancy:

$$m_A = \frac{F}{g_{local}} \frac{1}{1 - \rho_{as}/\rho_s}, \qquad (1)$$

where F is the objective force [N], ρ_{as} is reference air density (1.2 kg/m^3) and ρ_s is the reference density of the weight (8000 kg/m^3). Using a mass comparator, the mass of the weights was measured in comparison with the reference weights. As a result, a relative standard uncertainty w_{mass} of less than 3.1×10^{-6} was obtained.

3. Sensitivity Evaluation at the Fulcrum

3.1 Double Aerostatic Bearings

The double aerostatic bearings in the 1 kN·m-DWTSM are shown in Fig. 2. The new auxiliary radial/thrust aerostatic bearing could support the bending moments and transverse forces caused by a torque loading to the RTW of up to 1 kN·m without any direct contact between the rotor and stators [4]. After installing the double aerostatic bearings, the sensitivity limit (sensitivity reciprocal) should be reevaluated.

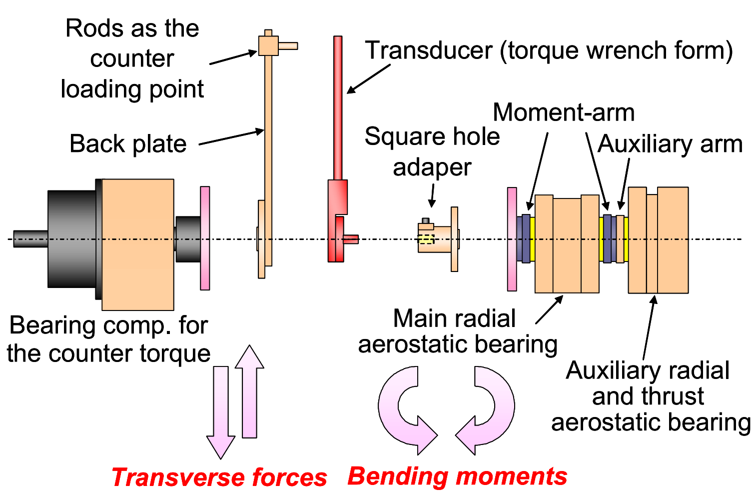


Fig. 2 New auxiliary radial/thrust aerostatic bearing

3.2 Sensitivity Measurement

The existence of an insensitive band is possible, primarily due to oscillation of the moment-arm, even though it is generally said that the aerostatic bearing has no friction. The authors believe that the sensitivity limit at the fulcrum is the one of the most important contributions for the uncertainty evaluation of realized torque in the TSM, because this limit may be dominant in the determination of the uncertainty at the lower limit of the calibration range. For example, for a TSM having a calibration range from 1 N·m to 100 N·m, a laboratory must demonstrate a sensitivity at the fulcrum of less than 10 μN·m (equivalent to a weight loading of approximately 2 mg at the end of the moment-arm if the arm length is 500 mm) for any deadweight loading condition if the laboratory declares the relative expanded uncertainty to be 2.0×10^{-5} (k = 2) for the realized torque.

3.2.1 Experimental Procedure

Three weight series and two or three radial loadings that were appropriately scattered in the calibration range of the 1 kN·m-DWTSM were selected. The radial loadings were given by equal deadweight loadings at both ends of the moment-arm (the cancelled torque occurring in both the clockwise and counterclockwise directions is called "the equivalent torque"). Under each radial loading condition including the zero balance position (F = 0 N), a small weight was loaded and unloaded at one end of the moment-arm, and a subtle output variation from a torque transducer was recorded. Loading/unloading of the small weight was repeated five times. Table 1 shows the experimental conditions, including the selected weight series, radial loading (equivalent torque), mass of small weights, torque transducers, and output torque per digit from the transducer.

3.2.2 Experimental Results

The relative standard uncertainty due to the sensitivity reciprocal w_{sr} was calculated as follows:

$$w_{\mathrm{sr}}{}^2 = \frac{1}{3}\left(\frac{\Delta(sr)_{\mathrm{rel}}}{2}\right)^2 + \Delta(dev)_{\mathrm{rel}}{}^2 + \Delta(var)_{\mathrm{rel}}{}^2, \qquad (2)$$

where $\Delta(sr)_{\mathrm{rel}}$ is the small torque ΔT just calculated from the small weight loading, $\Delta(dev)_{\mathrm{rel}}$ is the average deviation of the output torque of the transducer from ΔT , and $\Delta(var)_{\mathrm{rel}}$ is the standard deviation of the five times measurements. These values are all relative to each equivalent torque T_{eq}.

The results are shown in Fig. 3. The relative standard uncertainties of the sensitivity reciprocal w_{sr} were evaluated as 1.9×10^{-5} for the range of from 0.5 N·m to 1 kN·m and 3.0×10^{-6} for the range of from 5 N·m to 1 kN·m.

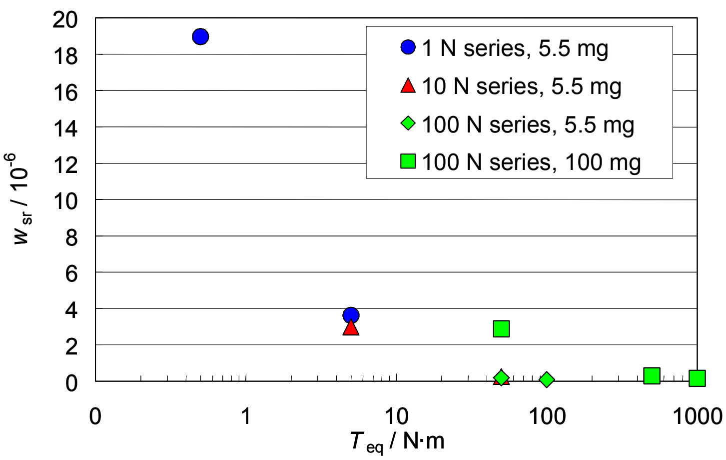


Fig. 3 Evaluation results of the sensitivity limit

4. Reevaluation of the Moment-Arm Length

4.1 Initial Moment-Arm Length and Actual Moment-Arm Length

In order to improve the uncertainty of the moment-arm length, the 100 -μm metal bands (MBs) at the ends of the moment-arm were exchanged for thinner 50 μm MBs. The dimensions of the moment-arm are defined as shown in Fig. 4. The initial moment-arm length (geometrical length at 20 °C) was evaluated by measuring the thickness of fixing plates with MB and without MB using a precise height gauge in comparison with gauge blocks. The initial moment-arm length L_0 is calculated with the main arm length L_u and MB thickness t_w as follows:

$$L_0 = L_u + (h' - h_1)/2 = L_u + t_w/2 \,. \qquad (3)$$

L_0 and its standard uncertainty $u(L_0)$ (relative value $w(L_0)$) were evaluated as follows: $L_{0(L)}$ = 499.9928 mm, $L_{0(R)}$ = 499.9899 mm, $u(L_0)$ = 2.5 μm and $w(L_0) = 5.1 \times 10^{-6}$, where subscripts(L) and (R) denote the left-hand and right-hand sides of the moment-arm, respectively.

The actual moment-arm length $L_0|_{23}$ at the environment of the torque calibration room (23 °C) was also reevaluated taking the temperature correction into consideration[6]. As a result, $L_{0(L)}|_{23}$ = 500.0167 mm, $L_{0(R)}|_{23}$ = 500.0137 mm were obtained. The relative standard uncertainty w_{act_lgt} was evaluated as 6.0 × 10^{-6} including the uncertainty of the initial moment-arm length. It is possible to correct the actual moment-arm length in the temperature range of from 17 °C to 26 °C.

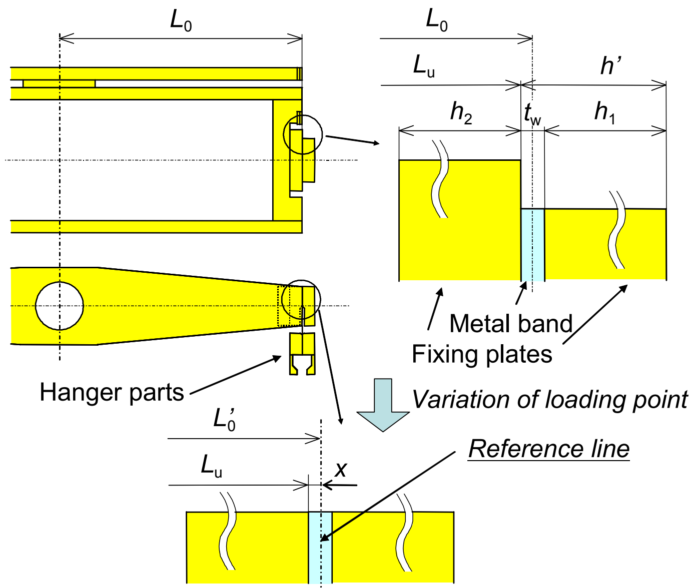


Fig. 4 Dimensional definition of the moment-arm length

4.2 Influence of the Reference Line Variation

4.2.1 Experimental Procedure

The reference line in the MB thickness direction could be moved depending on the deadweight loading (see Fig. 4). According to the asymmetric stress distribution model [5], the arm-balancing test was conducted, where deadweights of equal mass at both sides of the moment-arm were loaded and a small torque output ΔT (equivalent to the difference in length of the right-hand and left-hand sides) from the torque transducer was recorded. The difference of the outputs was also measured changing the MB thickness from 50 μm to 30 μm. However, in this case using 30 μm MB, the deadweight loading was limited up to 1600 N (T_{eq} = 800 N·m) because of the lack of tensile strength. Figure 5 defines the reference line and associated values. Reference [5] can be referred for a more detailed description of the experimental procedure.

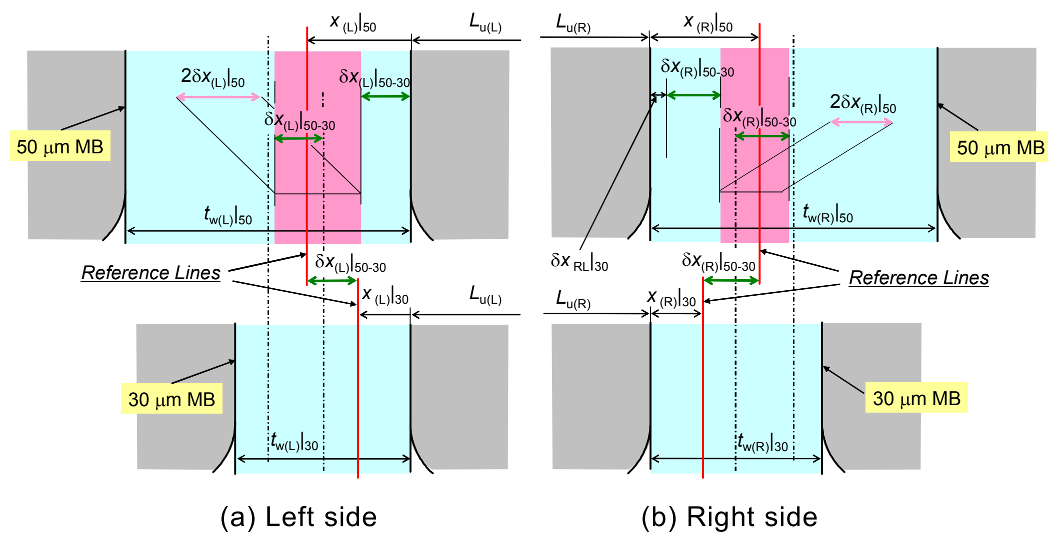


Fig. 5 Dimensional definitions of reference line positions

4.2.2 Experimental Results

Figure 6 shows the measured torque ratio $\Delta T/T_{eq}$ obtained by experiments A through D (for various combinations of MB thickness, see the legend). The torque ratios were almost constant under the same conditions. The maximum variation (by peak to peak) was 6.5 × 10^{-6}. Then, the re-estimated values of the arm length at 20 °C when using a 50 μm MB on each side were calculated as follows:

$L_{0(L)}' = L_{u(L)} + x_{(L)}$ = 499.9761 mm, and $L_{0(R)}' = L_{u(R)} + x_{(R)}$ = 499.9889 mm.

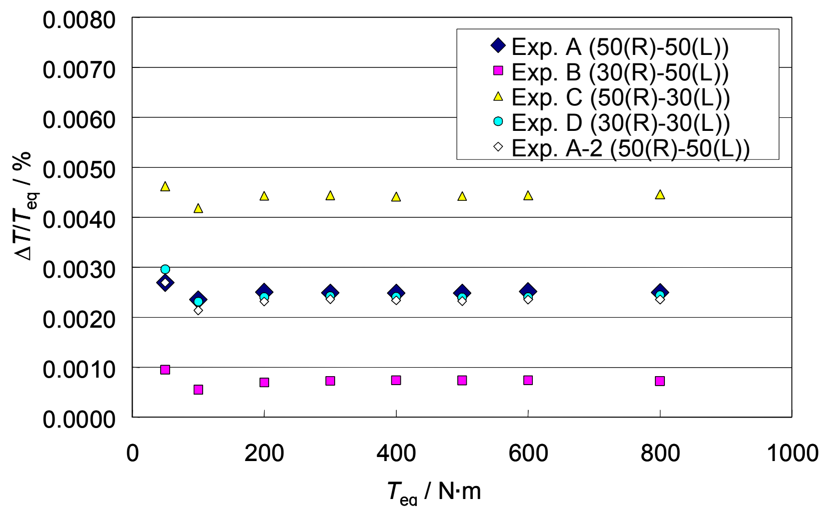


Fig. 6 Measurement results of the torque ratios changing the MB thickness combinations

The measurement and calculation results are listed in Table 2 for each length defined in Fig. 5, together with the related uncertainties.

The load dependency of the torque ratio in the entire range of the 1 kN·m-DWTSM is shown in Fig. 7. The results were obtained by an arm-balancing test using 50 μm MBs at both ends of the moment-arm. Each point indicates the average value of three measurements. The torque ratios were almost constant though the data scattering became slightly larger in the ranges of 1 N and 2 N weight series as compared to the other ranges. The relative standard uncertainty due to load dependency $w_{load.dpd}$ was evaluated by the maximum deviation from the substantial reference value ($\Delta T/T_{eq}$ = 0.0025 %) at T_{eq} = 1000 N·m as the standard deviation of the normal distribution.

The relative standard uncertainty ascribable to the deadweight load dependency of the arm lengths (reference line variation) is expressed by $w_{load.lgt}$, combining the net torque deviations due to the load dependency $w_{load.dpd}$ and the uncertainty of the reference line position of the MB ($w(x|_{50})$). $w_{load.lgt}$ were evaluated as 3.0×10^{-5} for the range of from 0.5 N·m to 20 N·m and 1.2×10^{-5} for the range of from 5 N·m to 1 kN·m.

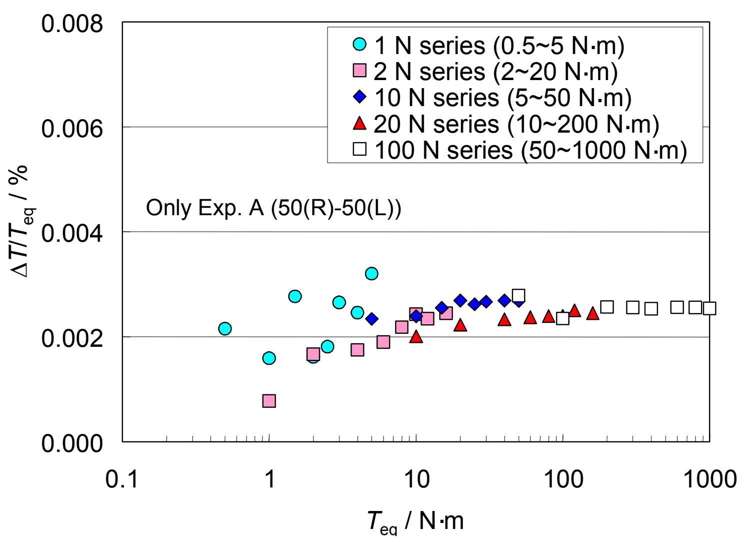


Fig.7 Deadweight load dependency of the torque ratios in the entire range of the 1 kN·m-DWTSM

5. Uncertainty of Torque Realized by The 1 kN·m-DWTSM

The relative expanded uncertainties W_{tsm} of the torque realized by the 1 kN·m-DWTSM were evaluated as shown in Table 3, integrating the other uncertainty contributions evaluated previously [1][5][6]. W_{tsm} of 7.3×10^{-5} for the range of from 0.5 N·m to 20 N·m and 2.9×10^{-5} for the range from 5 N·m to 1 kN·m could be obtained.

6. Conclusion

Expansion of the calibration range and improvement of the uncertainty of the realized torque in the 1 kN·m-DWTSM were attempted. The lower limit of the calibration range was lowered from 5 N·m to 0.5 N·m by developing new small linkage weight series. In addition, the sensitivity limit at the fulcrum and the moment-arm length were also re-evaluated. As a result, relative expanded uncertainties (k = 2) of 7.3×10^{-5} and 2.9×10^{-5} could be obtained in the range from 0.5 N·m to 20 N·m and from 5 N·m to 1 kN·m, respectively.

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Table 1 Experimental conditions for the evaluation of sensitivity limit

Weight Series: 1 N		Mass of small weight / mg			Transducer, Type Rated capacity / N·m Rated output / (mV/V) Torque per digit / μN·m *2)
Equivalent Torque *T* / N·m	Radial Loading *1) 2*F* / N		(Equivalent torque / μN·m)	[its relative value / 10^{-6}]	
0	0	5.5	-----		TTRB-10N 10 1.109 9.0
0.5	2	5.5	(27)	[54]	
5	20	5.5	(27)	[5.4]	

Weight Series: 10 N		Mass of small weight / mg			Transducer, Type Rated capacity / N·m Rated output / (mV/V) Torque per digit / μN·m *2)
Equivalent Torque *T* / N·m	Radial Loading *1) 2 *F* / N		(Equivalent torque / μN·m)	[its relative value / 10^{-6}]	
0	0	5.5	-----		TTRB-10N 10 1.109 9.0
5	20	5.5	(27)	[5.4]	
50	200	5.5	(27)	[0.5]	

Weight Series: 100 N		Mass of small weight / mg			Transducer, Type Rated capacity / N·m Rated output / (mV/V) Torque per digit / μN·m *2)
Equivalent Torque *T* / N·m	Radial Loading *1) 2 *F* / N		(Equivalent torque / μN·m)	[its relative value / 10^{-6}]	
0	0	5.5	-----		TTRB-10N 10 1.109 9.0
50	200	5.5	(27)	[0.5]	
100	400		(27)	[0.3]	

Weight Series: 100 N		Mass of small weight / mg			Transducer, Type Rated capacity / N·m Rated output / (mV/V) Torque per digit / μN·m *2)
Equivalent Torque *T* / N·m	Radial Loading *1) 2 *F* / N		(Equivalent torque / μN·m)	[its relative value / 10^{-6}]	
0	0	100	-----		TB1S/100Nm 100 1.757 57
50	200	100	(490)	[9.8]	
500	2000	100	(490)	[1.0]	
1000	4000	100	(490)	[0.5]	

*1) The deadweight loading of *F* at one end of the moment-arm

*2) The digital resolution of the indicator/amplifier DMP40S2 is 0.000001 mV/V.

Table 2 Evaluation results of reference line positions

Lengths			
$t_{w(L)}\|_{50}$ / μm	51.7	$t_{w(R)}\|_{50}$ / μm	50.8
$t_{w(L)}\|_{30}$ / μm	30.9	$t_{w(R)}\|_{30}$ / μm	30.5
		$\delta x_{RL}\|_{30}$ / μm	14.7
$\delta x_{(L)}\|_{50\text{-}30}$ / μm	9.2	$\delta x_{(R)}\|_{50\text{-}30}$ / μm	9.5
$\delta x_{(L)}\|_{50}$ / μm	7.7	$\delta x_{(R)}\|_{50}$ / μm	0.3
$x_{(L)}\|_{50}$ / μm	9.2	$x_{(R)}\|_{50}$ / μm	24.5
Uncertainty			
$u(t_{w(L)}\|_{30})$ / μm	1.5	$u(t_{w(R)}\|_{30})$ / μm	1.5
$u(\delta x_{(L)}\|_{50\text{-}30})$ / μm	0.6	$u(\delta x_{(R)}\|_{50\text{-}30})$ / μm	0.6
$u(\delta x_{(L)}\|_{50})$ / μm	4.5	$u(\delta x_{(R)}\|_{50})$ / μm	0.2
$u(x_{(L)}\|_{50})$ / μm	4.7	$u(x_{(R)}\|_{50})$ / μm	1.5
$w(x_{(L)}\|_{50})$ / 10^{-6}	9.4	$w(x_{(R)}\|_{50})$ / 10^{-6}	3.1

Table 3(a) Uncertainty budget table for the range from 0.5 N·m to 20 N·m

Uncertainty in the realization of the unit of torque by the TSM		$\times 10^{-6}$
Mass of linkage weights	w_{mass}	3.1
Local acceleration of gravity	w_{c_grav}	0.22
Force due to air buoyancy fluctuation	w_{c_buoy}	3.5
Actual moment-arm length at torque cal. Lab. (23 °C)	$w_{act.lgt}$	6.0
Influence of flexure on the moment-arm length	$w_{flx.lgt}$	2.0
Influence of load dependency on the moment-arm length	$w_{load.lgt}$	30
Sensitivity limit at the fulcrum (aerostatic bearing)	w_{sr}	19
Relative combined standard uncertainty	w_{c_tsm}	36
Relative expanded uncertainty (*k*=2)	W_{tsm}	73

Table 3(b) Uncertainty budget table for the range from 5 N·m to 1 kN·m

Uncertainty in the realization of the unit of torque by the TSM		$\times 10^{-6}$
Mass of linkage weights	w_{mass}	2.5
Local acceleration of gravity	w_{c_grav}	0.22
Force due to air buoyancy fluctuation	w_{c_buoy}	3.5
Actual moment-arm length at torque cal. Lab. (23 °C)	$w_{act.lgt}$	6.0
Influence of flexure on the moment-arm length	$w_{flx.lgt}$	2.0
Influence of load dependency on the moment-arm length	$w_{load.lgt}$	12
Sensitivity limit at the fulcrum (aerostatic bearing)	w_{sr}	3.0
Relative combined standard uncertainty	w_{c_tsm}	14
Relative expanded uncertainty (*k*=2)	W_{tsm}	29