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Establishment of torque realisation up to 5 kN·m with a new design of the torque standard machine

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ABSTRACT
A Torque Standard Machine (TSM) with a rated capacity of 5 kN·m was designed and constructed by the Torque Laboratory, National Institute of Metrology (Thailand), NIMT. The machine had initially used a flexure bearing as a fulcrum. It had been developed based on the research of a 10 N·m suspended fulcrum TSM. However, the bearing structure was changed to a combination of eight elastic hinges in order to withstand larger cross-forces for providing greater strength and providing a shorter stabilising time, consuming the lever arm's swing. With a three-column weightlifting system, the machine provides five measuring ranges ranging from 100 N·m to 5,000 N·m in the same set of stacked weights.
The measurement results showed the sensitivity of the fulcrum within ± 0.005 N·m from 10 % to 100 % of the measurement range. The sensitivity of the fulcrum is one of the main sources of the uncertainty evaluation of the torque measurement. The Calibration and Measurement Capabilities (CMCs) of the torque measurement were 0.01 % (*k=2*) in the measurement range from 500 N·m to 5,000 N·m. To confirm the capability of the measurement, an informal comparison with Physikalisch-Technische Bundesanstalt (PTB) was conducted. The results were satisfactory, with the $|E_n|$ less than 1.

Section: RESEARCH PAPER

Keywords: Torque standard machine; Sensitivity of fulcrum; Elastic hinge

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1. INTRODUCTION

In general, the fulcrum of the Torque Standard Machine (TSM) is one of the most important parts of the machine. National Metrology Institutes (NMIs) usually provide torque standard machines by using air bearing [1]-[5] or using flexure bearing as a fulcrum [6]-[7]. An air bearing is best suited for the fulcrum because it is a good method of minimising friction [8]-[10]. However, it is expensive, needs continuous maintenance, and requires the operator to have strong experience in its operation.

Even though the flexure bearing has not been confirmed as being as accurate as air bearing [11], there are obvious advantages, such as its lower cost, easier operation, and lower maintenance requirements. It has been developed continuously so as to enhance the bearing sensitivity. Recently, a TSM with a suspended fulcrum was developed in the range of 0.1 N·m to 10 N·m [12], as shown in Figure 1. A bilateral comparison between the 10-N·m-DWTSM of the National Metrology Institute of Japan (NMIJ) and the 10-N·m-DWTSM of the Thai National Institute of Metrology (NIMT) in the calibration range of 0.1 N·m to 1.0 N·m were conducted to confirm NIMT's capability [13].

However, the length of long thin metal sheet that used as the suspended fulcrum mainly affected the position of the fulcrum and the lever arm stability. Thus, the authors of this article are interested in designing and developing a 5 kN·m TSM with the flexure bearing as a main part thereof. It was designed on the principle of an eightfold elastic hinge, which was found to be more rigid and stable than the suspended one. The machine capability is confirmed by two informal comparisons.

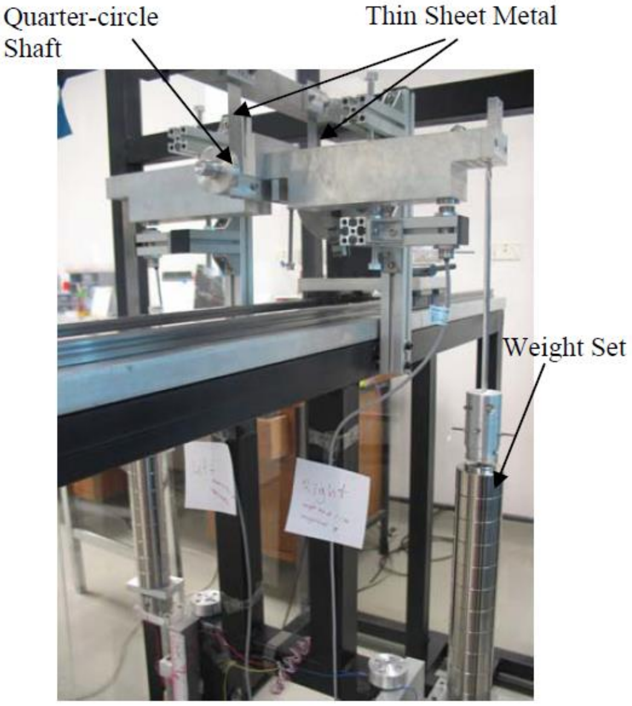
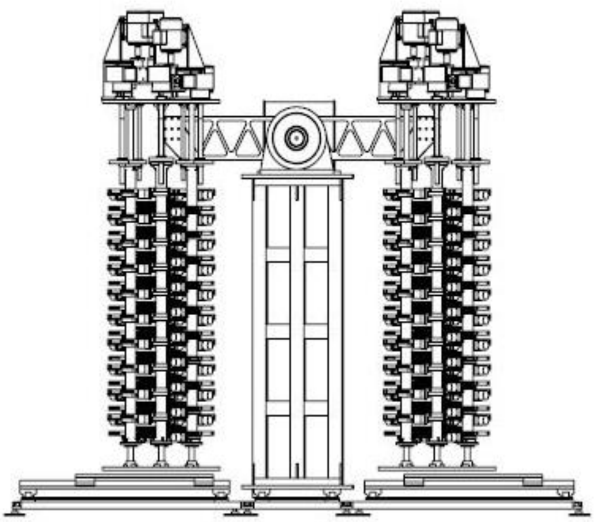


Figure 1. Suspended-Fulcrum Torque standard machine of NIMT (10-N·m-DWTSM).



(a)

(b)

Figure 2. The schematic diagram (a) and photograph (b) of 5 kN·m TSM.

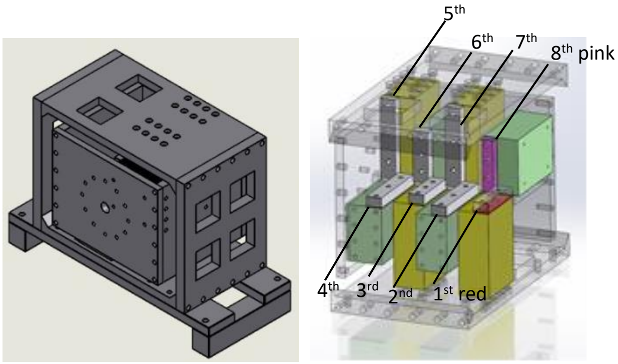


Figure 3. Schematic diagram of flexure bearing with eight elastic hinges (four pieces, highlighted in red, and four pieces highlighted in pink).

2. CONCEPTUAL DESIGN

The 5 kN·m TSM (Model: Pramann 02 [named to honour the machine's constructor] S/N: 02), is shown in Figure 2. The main parts are the flexure bearing, lever arm, two sets of stacked weights, two motor gears, and magnetic damping. The machine can have the torque transducer installed on both sides of the lever arm because it is equipped with two sets of motor gears at either side. The advantage of this flexure bearing is that it can be used as a part of a torque calibration machine. There are five measurement ranges, ranging from 100 N·m to 5 kN·m, in a selectable mode. The swing of the stacked weights was restrained by magnetic damping.

2.1. Flexure bearing

The fulcrum is one of the main components of the TSM. This machine was designed by the flexure bearing used for the lever fulcrum. Its structure is based on the principle of an eightfold elastic hinge, as shown in Figure 3. It consists of eight pieces of elastic hinge, which are independently and simultaneously moveable when applying the force on the lever arm. The design was developed based on previous research on the existing 10 N·m suspended-fulcrum TSM in order to reduce the swing, endure the cross-force effect, and give the lever arm greater strength.

2.2. Lever arm

The design of the lever arm of the TSM is shown in Figure 4. The nominal length of the full lever arm was 2 m. The hollow shape was designed to reduce the weight of the lever arm. The strength of the lever arm was confirmed by using finite element analysis before construction. The lever arm and stacked weight were bound to each other by a thin metal plate,

Figure 4. A schematic diagram of the lever arm.

which had the following dimensions: 300 mm × 400 mm × 0.05 mm.

2.3. Stacked weights

The machine consists of two sets of stacked weight (for clockwise and counter-clockwise directions) with a three-column weightlifting system. Each set of stacked weight comprises 50 pieces of 100 N weight disks, as shown in Figure 5. It can be operated in five measurement ranges from 100 N·m to 5 kN·m in the same stacked weight. The weights were automatically loaded according to the calibration sequence. Firstly, the lifting system was inserted under the selected stacked weight and then the motor drove the column upward, lifting the stacked weight. The lever arm was free, without torque applied. Thereafter, the column was driven downward, and the lifting system was removed. In this step, the stacked weight was loaded onto the lever arm.

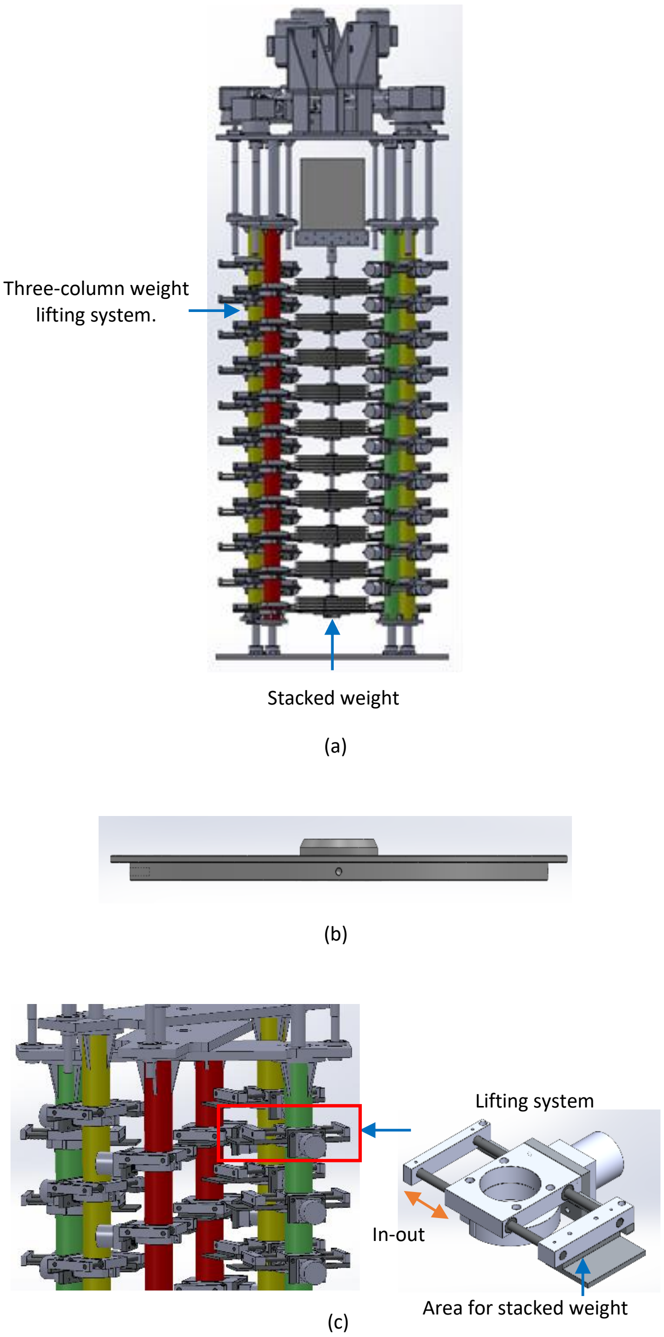


Figure 5. (a) A schematic overview of the stacked weight with the lifting system. (b) One piece of the weight disk. (c) Three-column (highlighted in red, yellow, and green columns) weightlifting system.

Figure 6. The LabView program used for controlling the machine.

2.4. Operational system

A torque measuring device was connected to the machine, using flexible coupling to avoid misalignment. The machine applied force to the torque measuring device using the motor gears, which was controlled by the LabView program. The calibration was performed according to DIN 51309: 2005-12. Magnetic damping was used to stabilise the lever arm when applying the force. The automatic weight loading was controlled by computer using the LabView program, as shown in Figure 6.

3. MEASUREMENT RESULTS

3.1. The uncertainty of the torque standard machine

The 5 kN·m TSM is directly traceable to the SI units of mass, length, acceleration, and density by weighing the calibrated mass disks onto a frictionless supported lever. The lever support and the force coupling were based on the principle of flexure bearing. The machine was designed for the calibration of a torque measuring device. The mathematical model for the generated torque is as follows:

$$M_{std} = m_c \cdot g_{local} \cdot \left(1 - \frac{\rho_a}{\rho_m}\right) \cdot l + M_{res} \qquad (1)$$

where:

M_{std} is the torque standard in newton metres, N·m

m_c is the conventional mass in kilograms, kg

g_{local} is the local gravitational acceleration in metres per second squared, m/s²

ρ_a is the density of moist air in kilograms per cubic metre, kg/m³

ρ_m is the density of mass in kilograms per cubic metre, kg/m³

l is the lever arm length in metres, m

M_{res} is the residual torque in newton metres, N·m

The uncertainty of the torque standard machine was evaluated with a combination of force, length, air density, mass density, local gravitational acceleration, and residual torque, as shown in Equation (1).

The relative expanded uncertainty of torque standard machine was expressed at a coverage factor $k = 2$ for measurement range 200 N·m to 2 kN·m as shown in Equation (2).

Table 1. The environmental conditions during the comparison carried out in 2016.

Environmental condition	NIMT	PTB
Temperature (°C)	22.5 (CW) and 22.6 (CCW)	21.1 (CW) and 21.1 (CCW)
Relative humidity (%)	52.4 (CW) and 51.8 (CCW)	40.5 (CW) and 40.5 (CCW)
Atmospheric pressure (hPa)	1006.5 ± 18	996
CW means a clockwise direction, and CCW means a counter-clockwise direction		

$$W(M_{std}) = \{0.0042 + 26 \cdot [M/(\mathrm{N{\cdot}m})]\}^{-1.935}\ \% \qquad (2)$$

where:

$W(M_{std})$ is the confirmed uncertainty of torque standard

M is the nominal torque

0.0042 is the expanded uncertainty of torque standard

Equation (2) was determined based on interpolation of the relative expanded uncertainty of the torque standard at any nominal torque value.

3.2. Comparison results of a measurement range 200 N·m to 2,000 N·m

An informal comparison between NIMT and Physikalisch-Technische Bundesanstalt (PTB) was conducted in 2016 to confirm the capability of NIMT's 5 kN·m TSM. The comparison method was made in accordance with DIN 51309: 2005-12 [14]. The artefact was the torque transducer, capacity: 2 kN·m, model: TB2/2000 N·m and S/N: 122530099.

The TSM of PTB is a 20 kN·m deadweight torque standard machine, with its claimed uncertainty ranging from 0.002 % to 0.003 %.

The environmental conditions and the measurement results of the comparison are shown in Table 1 and Table 2, respectively.

The comparison results were reported at the temperature of 21.1 °C with the artefact's temperature coefficient of 0.00004/K [15]-[16]. The $|E_n|$ of the comparison results between 0.18 and 0.91 are shown in Figure 7.

3.3. Comparison results of the measurement range 500 N·m to 5,000 N·m

The informal comparison was conducted in 2016 in the measurement range of 200 N·m to 2,000 N·m. The comparison results were satisfactory [17], as described in section 3.2.

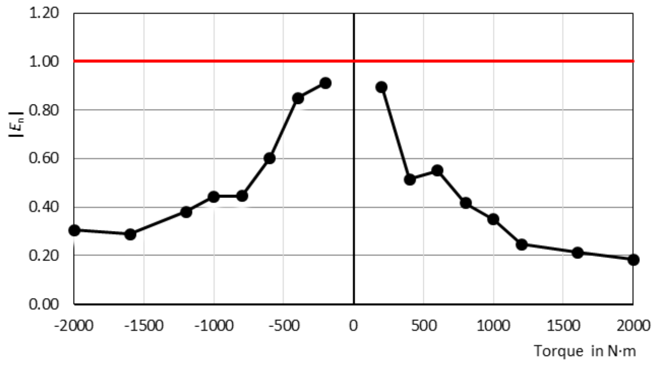


Figure 7. The $|E_n|$ evaluated based on the comparison, ranging from 200 N·m to 2,000 N·m.

Table 2. The measurement results of NIMT and PTB, ranging from 200 N·m to 2,000 N·m.

Torque (N·m)	NIMT		PTB	
	Output Signal (mV/V)	W (k = 2)	Output Signal (mV/V)	W (k = 2)
0	-	-	-	-
-200	-0.100026	0.010	-0.100009	0.005
-400	-0.200049	0.010	-0.200022	0.003
-600	-0.300071	0.010	-0.300042	0.003
-800	-0.400095	0.010	-0.400067	0.003
-1000	-0.500121	0.010	-0.500086	0.003
-1200	-0.600151	0.010	-0.600115	0.003
-1600	-0.800210	0.010	-0.800174	0.003
-2000	-1.000288	0.010	-1.000240	0.003
0	-	-	-	-
200	0.100025	0.010	0.100010	0.004
400	0.200045	0.010	0.200029	0.003
600	0.300065	0.010	0.300046	0.003
800	0.400087	0.010	0.400068	0.003
1000	0.500114	0.010	0.500094	0.003
1200	0.600141	0.010	0.600124	0.003
1600	0.800197	0.010	0.800178	0.003
2000	1.000268	0.010	1.000247	0.003

Thereafter, the authors extended the scope of the work up to 5,000 N·m, which is the maximum capacity of the standard machine with its claimed CMCs of 0.01 %, as confirmed by the comparison results.

Since early 2018, the laboratory has sent the torque transducer (model: TB2/5000 N·m, S/N: 123330449) for calibration at PTB. The calibration ranges are 500 N·m to 5,000 N·m according to DIN 51309: 2005-12. To compare the results, NIMT carried out a calibration of the torque transducer again according to the same procedure.

The environmental conditions and the measurement results of comparison are shown in Table 3 and Table 4, respectively.

The comparison results of the measurement range from 500 N·m to 5,000 N·m in 2018 were reported at a temperature of 21.1 °C with the artefact's temperature coefficient as described in section 3.2.

The difference in arm length between both sides of the machine (Δl) evaluated by using the weight balancing technique [18]-[19] are shown in Figure 8. The results showed positive Δl, which shows that the lever arm length in the clockwise

Table 3. The environmental conditions during the comparison carried out in 2018.

Environmental condition	NIMT	PTB
Temperature (°C)	21.6 (CW) and 22.4 (CCW)	21.1 (CW) and 21.1 (CCW)
Relative humidity (%)	51.6 (CW) and 53.9 (CCW)	38.9 (CW) and 38.9 (CCW)
Atmospheric pressure (hPa)	1006.5 ± 18	983
CW means a clockwise direction and CCW means a counter-clockwise direction		

Table 4. The measurement results reported by NIMT and PTB ranging from 500 N·m to 5,000 N·m.

Torque (N·m)	NIMT		PTB	
	Output Signal (mV/V)	*W* (*k* = 2)	Output Signal (mV/V)	*W* (*k* = 2)
0	-	-	-	-
-500	-0.100059	0.011	-0.100050	0.005
-1000	-0.200129	0.010	-0.200117	0.003
-1500	-0.300198	0.010	-0.300185	0.003
-2000	-0.400267	0.010	-0.400256	0.003
-2500	-0.500339	0.010	-0.500324	0.003
-3000	-0.600416	0.010	-0.600400	0.003
-4000	-0.800558	0.010	-0.800549	0.003
-5000	-1.000728	0.010	-1.000709	0.003
0	-	-	-	-
500	0.100061	0.011	0.100056	0.004
1000	0.200133	0.010	0.200121	0.003
1500	0.300207	0.010	0.300185	0.003
2000	0.400286	0.010	0.400257	0.003
2500	0.500363	0.010	0.500332	0.003
3000	0.600445	0.010	0.600409	0.003
4000	0.800606	0.010	0.800562	0.003
5000	1.000801	0.010	1.000726	0.003

direction was longer than it was in the anti-clockwise direction. Consequently, the comparison results were corrected due to the difference in the arm length of the machine.

After the correction of the results due to the temperature sensitivity and the difference in arm length, the reference values were calculated according to Procedure A suggested in the guidelines for the evaluation of key comparison data [20].

The $|E_n|$ from 0.07 to 0.66 was observed from the informal bilateral comparison between NIMT and PTB on the torque measurement ranging from 500 N·m to 5000 N·m as shown in Figure 9. Since the range of this comparison was close to the machine's capability, the results showed better agreement than one compared in the range of 200 N·m to 2000 N·m.

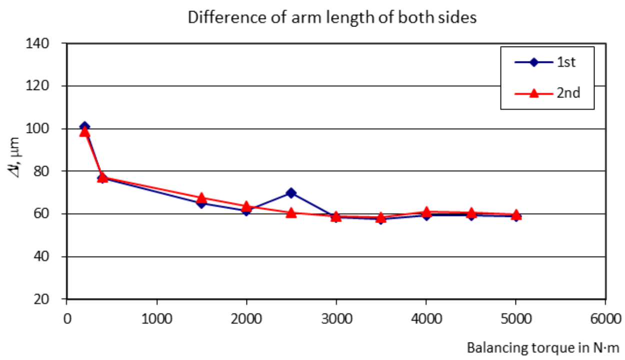


Figure 8. The difference in arm length (Δl) of both sides of the machine.
1st represents the first series of the measurement.
2nd represents the second series of the measurement.

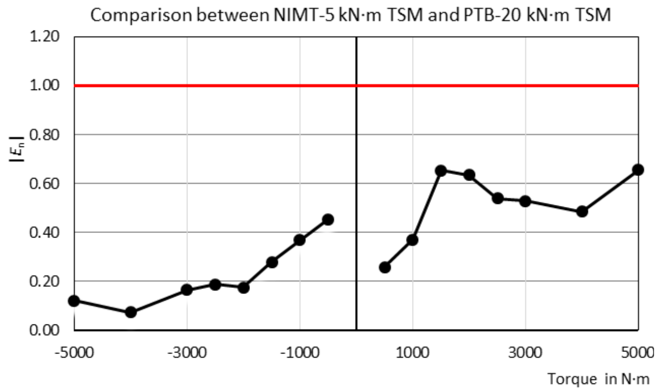


Figure 9. The $|E_n|$ evaluated from the comparison, ranging from 500 N·m to 5,000 N·m.

4. CONCLUSIONS

NIMT developed the calibration capability of a torque measuring device up to 5 kN·m by using a 5 kN·m TSM with its CMCs at 0.01 % (k = 2) in the measurement range of 500 N·m to 5,000 N·m. The flexure bearing was designed as a fulcrum in order to withstand larger cross-forces and to provide a shorter time for damping the lever arm's oscillating movement. The capability of the TSM was confirmed (see Figure 10), with satisfactory results of $|E_n|$ obtained from the informal comparison with the well-recognised NMI.

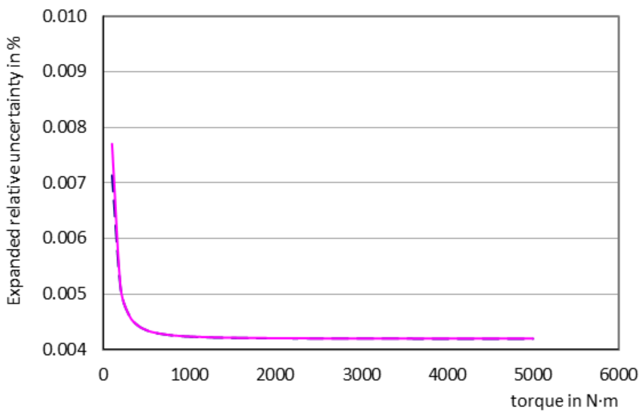


Figure 10. The confirmed uncertainty (solid pink line) and the expanded uncertainty (dash blue line) of the 5 kN·m torque standard.

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