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SUSPENDED-FULCRUM TORQUE STANDARD MACHINE

T. Sanponpute, P. Chantaraksa, N. Saenkhum, N. Arksonnarong

Torque Laboratory, Department of Mechanical Metrology, National Institute of Metrology (Thailand), Pathumthani, Thailand, tassanai@nimt.or.th

Abstract – National Institute of Metrology Thailand (NIMT) has designed and developed suspended-fulcrum torque standard machine. The main design is to replace air bearing with the 30-µm-sheet metal as a fulcrum. The advantages of the design are the lower cost and maintenance than air bearing-fulcrum type. The experiment was done to evaluate the sensitivity of the suspended fulcrum, which is directly affected by the bending stiffness of the thin metal sheet. Also, the different between left and right arm length is calculated from the trimmed mass used for equilibrium balancing at each applied torque. Finally, all the uncertainty of fulcrum, weight set and arm length are used to calculate the relative expanded uncertainty of torque measurement, which is 5×10^{-5}.

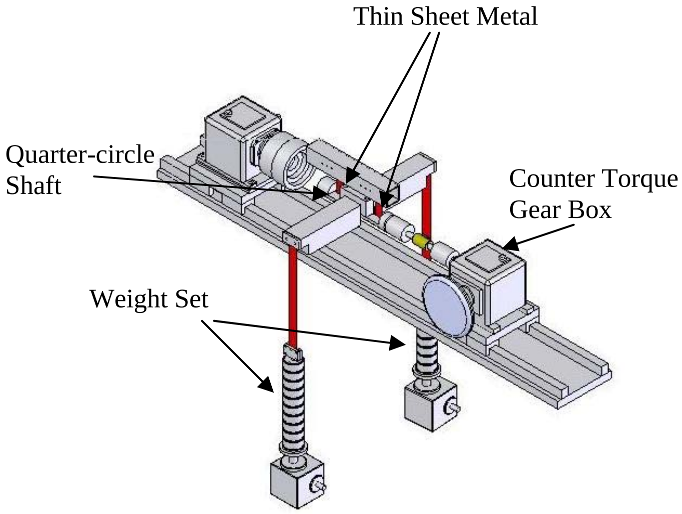
Keywords: Torque standard machine, suspended-fulcrum**,** bending stiffness

1. INTRODUCTION

The range of torque standard machine at National Institute of Metrology Thailand (NIMT) is 1000 N·m. However, with this range, it is not appropriate to operate in smaller range such as 10 N·m., which is highly demanded in Thai industry. In most NIMs, their deadweight torque standard machines use air bearing to support the lever arm [1-5]. In principle, air bearing is a good fulcrum, but it is expensive and requires high maintenance. Thus, NIMT has designed and established the 10 N·m torque standard machine with low-cost and low-maintenance concept. Instead of using air bearing as a fulcrum to support the lever arm, a 30-mm-thick metal sheet is used to suspend the lever arm from the frame to act as a suspended fulcrum. This paper describes the design concept and detail of the machine structure such as fulcrum, weight set, counter torque reaction, and computer control. The sensitivity of suspended fulcrum will be evaluated with different mean of calculating air bearing-typed fulcrum. The bending stiffness of the metal sheet will be used to evaluate sensitivity in place of friction. Besides the method of calculating sensitivity of fulcrum, the determination of lever arm length is also different from other's torque machine. The lever arm length is evaluated by balancing both sides of the arm and calculated from the trimmed weight. Finally, all the uncertainty contributed from each component will be evaluated to find the uncertainty of torque measurement from this suspended-fulcrum torque standard machine.

2. DESCRIPTION

The suspended-fulcrum 10 N·m torque standard machine schematic is shown in the figure 1. The main components of are as following.



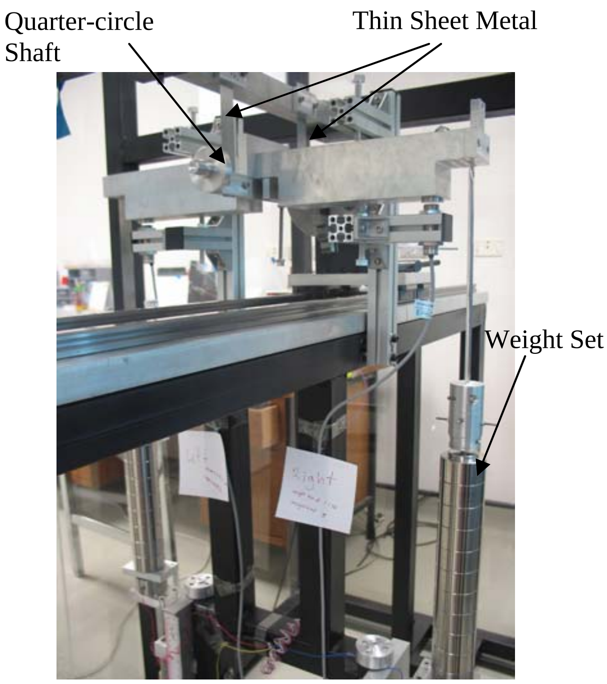


Fig. 1. Suspended-fulcrum torque standard machine

2.1. Suspended Fulcrum

A quarter-circle-cross sectioned-shaft with diameter 50 mm is used to support the lever arm and is hung with 30-mm-thick metal sheet at the front and the rear of the shaft. The bending stiffness of thin metal affects directly to the sensitivity of fulcrum. So, two analog proximity sensors are installed below both sides of the lever arm for computing the angle displacement of lever arm with 0.0001° resolution. This angle measurement will be used to evaluate the sensitivity of the fulcrum later.

2.2 Weight set

Weight set is designed to be 1 N·m per step from 1 N·m to 10 N·m. Nominal weight is calculated under the condition of 9.78312 m/s2 local gravity and 250 mm of nominal arm length. The weight set is calibrated by mass laboratory of NIMT with uncertainty at 0.002 g.

2.3 Lever arm

The lever arm is made of aluminium grade A7075-T6. Overall arm length, l0 between the two ends is designed to be 500 mm. It is calibrated by CMM from length laboratory of NIMT. The overall arm length, l_0, is defined by the length from the middle of metal sheet of the left side to the one of the right side of the lever arm as in (1).

$$l_0 = l_u + \frac{t_{w\_right}}{2} + \frac{t_{w\_left}}{2} \quad (1)$$

where l_u is dimensional calibration result of overall arm length and t_w is the thickness of thin metal.

Measurement result is described in the table 1.

Table 1. Measured value and uncertainty of parameter of overall arm length.

Parameter	Result	Uncertainty
l_u	499.989 mm	3.00 μm
t_{w_right}	30 μm	1.00 μm
t_{w_left}	30 μm	1.00 μm
l_0	500.019 mm	3.32 μm

2.4 Counter torque

Stepping motor with 1.8 degree/step driving the gear component with ratio 1:3600 generates the counter torque. Thus, the resolution of counter torque component is 720,000 step/rev.

2.5 Computer control

The computer is used as a user-interface to operate two motors: load-applying motor and stepping motor for counter torque. It also monitors the plane angle and collects data from transducer. The panel control is shown in figure 2.

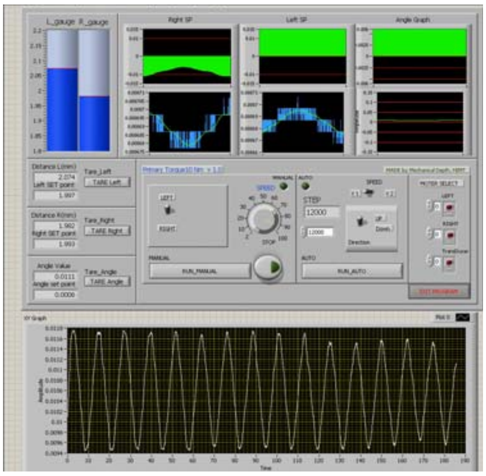


Fig. 2. Torque standard machine controller screen

3. EXPERIMENT METHOD AND RESULT

To confirm the accuracy of suspended fulcrum torque standard machine, the experiments is carried out to determine sensitivity of fulcrum as well as different arm length of the left and the right side. Then, the relative uncertainty of torque standard machine will be evaluated from sensitivity of fulcrum, arm length and relative uncertainty of force.

3.1 Sensitivity of fulcrum

When the thin metal sheet is used as a fulcrum for the lever arm, the bending stiffness of metal sheet will be accounted in sensitivity of fulcrum instead of the friction as in air bearing fulcrum. To determine the sensitivity of fulcrum, the lever arm is hung without a weight applied. Then, small weight as 1 mg, 2 mg, 3 mg and 4 mg are applied respectively and the inclined angle of the lever arm for each applied weight is recorded. The measurement is repeated for 4 times and the result shows in figure 3. The bending stiffness of suspended fulcrum is calculated to be used in compensating when the angle plane of lever arm is different from reference position. The error of interpolation shows that the sensitivity of fulcrum is within ± 0.6 μN·m as in figure 3 and table 2.

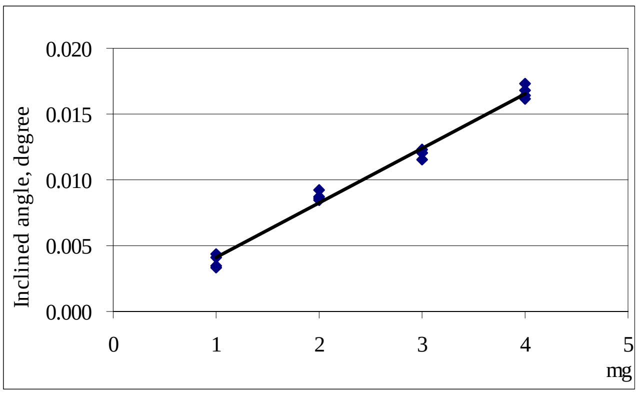


Fig. 3. Result and interpolation of sensitivity of fulcrum

Table 2. Result and interpolation of sensitivity of fulcrum

Mass mg	Torque μNm	Inclined Angle degree	Interpolation torque μNm	Interpolation Error μNm
1	2.476	0.0047	2.760	0.284
1	2.476	0.0043	2.486	0.010
1	2.476	0.0018	1.061	-1.416
1	2.476	0.0037	2.183	-0.293
2	4.953	0.0114	6.638	1.686
2	4.953	0.0095	5.539	0.586
2	4.953	0.0099	5.809	0.857
2	4.953	0.0077	4.493	-0.459
3	7.429	0.0116	6.764	-0.665
3	7.429	0.0120	7.018	-0.411
3	7.429	0.0121	7.062	-0.367
3	7.429	0.0123	7.175	-0.254
4	9.905	0.0162	9.459	-0.446
4	9.905	0.0173	10.110	0.205
4	9.905	0.0164	9.595	-0.310
4	9.905	0.0168	9.848	-0.057

3.2 Different arm length of both sides

Author believes that it is difficult to measure the effective arm length by dimensional measurement. Thus, in this suspended-fulcrum system, the arm length of both left and right sides are determined by balancing the lever arm to the equilibrium state when both sides are loaded with 1 N·m to 10 N·m. The trimmed mass that is added to equilibrium balancing will be used to calculate the different arm length Δl as (2). The detail is shown in figure 4.

$$\Delta l = \frac{(F_1 - F_2) \times \frac{l_0}{2}}{(F_1 + F_2)} \qquad (2)$$

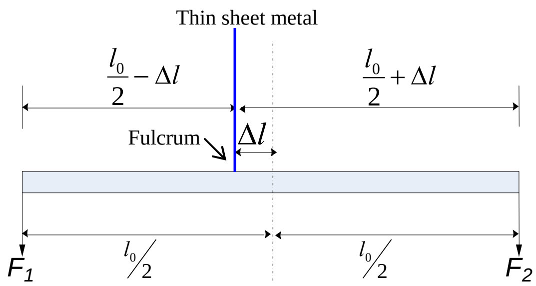


Fig. 4. Lever arm length

Figure 5 shows the different arm length between both sides. The average value is -8.9 μm. The uncertainty of Δl can be determined from standard deviation of the result at 1 N·m to 10 N·m and the smallest trim mass that used to ensure the sensitivity of arm length. The uncertainty is 3.2 μm.

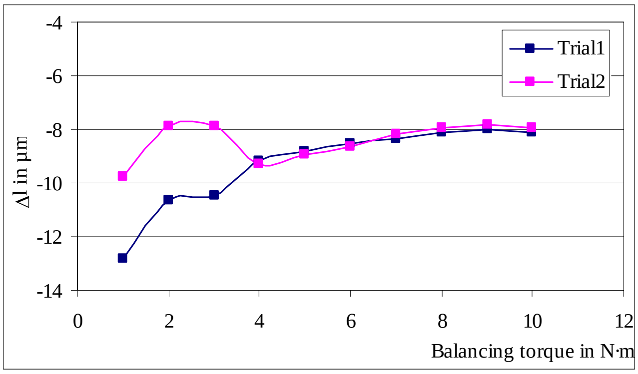


Fig. 5. Different arm length between both sides of lever arm for each balancing torque

From the result of overall arm length and different arm length, the arm length can be calculated from (3) and (4).

$$l_{cw} = \frac{l_0}{2} + \Delta l \qquad (3)$$

$$l_{ccw} = \frac{l_0}{2} - \Delta l \qquad (4)$$

The result of arm length is shown in table 3.

Table 3. Lever arm length.

	Result	Uncertainty
l_0	500.0190 mm	3.32 μm
Δl	-8.9 μm	3.20 μm
l_{cw}	250.0184 mm	4.62 μm
l_{ccw}	250.0006 mm	4.62 μm

3.3 Uncertainty evaluation

Torque measurement can be expressed with mathematical model as in (5) and (6).

$$M_{std} = F \cdot l - M_{sen} \qquad (5)$$

$$F = m \cdot g_{local} \cdot \left(1 - \frac{\rho_a}{\rho_m}\right) \qquad (6)$$

Where
F = Applied force
l = Lever arm length
M_{sen} = Sensitivity of fulcrum
m = Mass
g_{local} = Local gravitation acceleration
ρ_a = Air density
ρ_m = Density of mass

The uncertainty of torque measurement can be evaluated by (7) and (8).

$$W(M_{std}) = \sqrt{\left(\frac{\partial M_{std}}{\partial F}\cdot W(F)\right)^2 + \left(\frac{\partial M_{std}}{\partial l}\cdot W(l)\right)^2 + \left(\frac{\partial M_{std}}{\partial M_{sen}}\cdot W(M_{sen})\right)^2} \quad (7)$$

$$W(F) = \sqrt{\left(\frac{\partial F}{\partial m}\cdot W(m)\right)^2 + \left(\frac{\partial F}{\partial g_{local}}\cdot W(g_{local})\right)^2 + \left(\frac{\partial F}{\partial \rho_a}\cdot W(\rho_a)\right)^2 + \left(\frac{\partial F}{\partial \rho_m}\cdot W(\rho_m)\right)^2} \quad (8)$$

The relative uncertainty budget at 1 N·m and 10 N·m are 1.99×10^{-5} and 1.98×10^{-5} respectively. The details of uncertainty budget are shown in Table4, Table5 and Table6. Therefore, this torque standard machine can be declared as 5×10^{-5} for range 1 N·m to 10 N·m.

Table 4. Uncertainty budget of force at 4 N

Quantity X_i	Estimate x_i	Relative Standard uncertainty $w(x_i)$	Probability distribution	Sensitivity coefficient C_i	Relative uncertainty contribution
m_C	0.408929 kg	2.45.E-06	Normal	1	2.45E-06
g	9.783124 m/s^2	1.00.E-06	Normal	1	1.00E-06
ρ_a	1.2 kg/m^3	1.00.E-02	Rectangular	-1.50E-04	-1.50E-06
ρ_m	8000 kg/m^4	1.25.E-02	Rectangular	1.50E-04	1.88E-06
Force	4.0000 N	Combined relative uncertainty			3.57E-06
		Expanded relative uncertainty, *k=2*			7.14E-06

Table 5. Uncertainty budget of torque at 1 N·m

Quantity X_i	Estimate x_i	Relative Standard uncertainty $w(x_i)$	Probability distribution	Sensitivity coefficient C_i	Relative uncertainty contribution $w_i(y)$
F	4 N	3.6E-06	Normal	1	3.57E-06
l	0.25 m	9.2E-06	Normal	1	9.24E-06
M_{sen}	0 N·m	1.2.E-06	Rectangular	1	1.15E-06
M	1.00 N·m	Combined relative uncertainty			9.97E-06
		Expanded relative uncertainty, *k=2*			1.99E-05

Table 6. Uncertainty budget of torque at 10 N·m

Quantity X_i	Estimate x_i	Relative Standard uncertainty $w(x_i)$	Probability distribution	Sensitivity coefficient C_i	Relative uncertainty contribution $w_i(y)$
F	40 N	3.6E-06	Normal	1	3.57E-06
l	0.25 m	9.2E-06	Normal	1	9.24E-06
M_{sen}	0 N·m	1.2.E-07	Rectangular	1	1.15E-07
M	10.00 N·m	Combined relative uncertainty			9.91E-06
		Expanded relative uncertainty, *k=2*			1.98E-05

4. CONCLUSIONS

The experiment result demonstrates that the suspended-fulcrum working in place of air bearing has sensitivity within ±2 μm. Overall arm length evaluated by dimensional measurement is 500.019 mm ±3.32 μm. The different left of right and left side of the lever arm, evaluated from equilibrium balancing of torque in clockwise and counter-clockwise directions at 1 N·m to 10 N·m is –8.9 μm with uncertainty ±3.2 μm. Then the effective arm length is calculated from two parameters as above and its value is 250.0184 mm and 250.0006 mm with uncertainty ±4.62μm for clockwise and counter-clockwise respectively. From the uncertainty budget, relative expanded uncertainty of torque measurement is 1.99×10^{-5} at 1 N·m and 1.98×10^{-5} at 10 N·m. Thus, relative expanded uncertainty of this torque standard machine can be declared as 5×10^{-5} at 1 N·m to 10 N·m working range.

Although lower-cost and lower-maintenance are the advantages of suspended fulcrum torque standard machine compared to air bearing, the machine cannot be used to measure torque with cross force such as torque transfer wrench. Thus, the future work is to develop this suspended-fulcrum design to be able to operate with torque with cross force

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