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Establishment of torque standards in KRISS of Korea

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Abstract

Korea Research Institute of Standards and Science(KRISS) has developed a 100 Nm and a 2 kNm deadweight torque standard machines. The 100 Nm torque machine can generate torque from 0.1 Nm to 110 Nm. The length of its torque arm is 0.25 m for both sides. It uses continuous deadweight stack. At each side, it has three different deadweight stacks. By rotating the base plate on which the deadweight stacks are located, the machine can adjust a suitable deadweight stack of appropriate torque range. Its relative uncertainty is 5×10^{-4} from 0.1 Nm to 1 Nm and 5×10^{-5} from 1 Nm to 110 Nm.

The 2 kNm deadweight torque machine uses a continuous deadweight stack at the left side and a binary type combination deadweight stack at the right side. By combining both deadweight stacks, the machine can generate torque from 10 Nm to 2200 Nm for both clockwise and counter-clockwise directions. The machine fixes its torque arm when changing the torque to maintain previous torque level. Its relative expanded uncertainty is 5×10^{-5}.

Keywords: Torque, Torque standard machine, Uncertainty, Intercomparison

Symbols

m = mass of deadweight

g_{loc} = local gravitational acceleration

L = length of torque arm

ρ_a = density of air

ρ_w = density of the deadweight

T_f = friction torque in the air bearing

w = relative uncertainty component

1. Introduction

Torque is a physical measure of rotational force relating to bolt tightening, power transmission, etc. Many torque sensors are used for different purposes in industrial processes and various research fields. In industry, torque measurement is widely performed in production and process control, but it is also essential for research and evaluation in developing new technologies. Both quality improvement and product innovation in technology have been driven by the improvement in torque measurement.

The most accurate way to realize torque is to support deadweights of known masses at the end of a torque arm. The mechanical apparatus and structure used to handle and control such dead weights and torque arm is known as a deadweight torque machine. Several national measurement institutes (NMIs) in the world established their national torque standards by using deadweight torque standard machines. PTB of Germany [1] and NMIJ of Japan [2, 3] established 1 kNm and 20 kNm deadweight torque standard machines. NPL in the UK recently developed a 2 kNm deadweight torque standard machine [4]. Some NMIs in other countries established their own torque standard machines. The NMIs have declared the uncertainties in their deadweight torque standard machines to be between 2×10^{-5} and 7×10^{-5}.

The Korea Research Institute of Standards and Science (KRISS) has developed a 100 Nm and a 2 kNm deadweight torque standard machines. This paper describes the deadweight torque machines. The structure, uncertainty and intercomparison of the machines will be described in this paper.

2. 100 Nm Deadweight Torque Standard Machine

Figure 1 is a photograph of the 100 Nm deadweight torque standard machine developed by KRISS. The machine consists of a torque arm, an air bearing, a counter motor, six deadweight stacks, a main body, two flexible couplings, two friction joints, a laser displacement sensor, stepping motors to activate weight stacks, cam system to fix the torque arm, and control system for the machine.

The torque arm is constructed from two main INVAR plates. The two plates are assembled with spacers between them. On the side surface of each spacer, an additional plate was assembled. The thickness of the additional plate was accurately controlled to set the equivalent length including the additional plate of the torque arm to be (250 - 0.025) mm. The equivalent length of the torque arm is 250 mm on each side, therefore 500 mm total length. At the ends of the torque arm, stainless alloy bends with a thickness of 50 μm are attached. The bends are mounted on the end surface of the torque arm by bolted fixing plates sandwiching them to the arm. The centre of the torque arm is mounted on the air bearing.

The torque standard machine has three deadweight stacks on each side, therefore six stacks on both sides. The combinations of deadweights in the stacks are as follows.

- Stack 1: 12 × 0.1 Nm (0.4 N), 5 × 0.2 Nm (0.8 N), total 17 weights
- Stack 2: 12 × 0.5 Nm (2.0 N), 6 × 1.0 Nm (4.0 N), 5 × 2.0 Nm (8.0 N), total 23 weights
- Stack 3: 12 × 5.0 Nm (20.0 N), 5 × 10.0 Nm (40.0 N), total 17 weights

The torque standard machine has 57 weights on each side, therefore 114 weights at both sides. Stack 1 is used to calibrate 1 Nm- and 2 Nm-capacity torque transducers; stack 2 calibrates 5 Nm, 10 Nm and 20 Nm transducers; and stack 3 is used for 50 Nm and 100 Nm torque transducers. The weights in stack 1 are made of aluminium to reduce mass, with the structurally weak load bearing parts made of stainless steel. The masses of the weights in stack 1 are about 40 g and 80 g. All weights in stacks 2 and 3 are made of stainless steel. The appropriate weight stack can be selected by rotating the base plate supporting the stacks. In the unloaded condition, the weights rest in conical support sockets, which are connected to the rotating base plate. When the rotating base plate is moved down, the weights are loaded at the end of the torque arm from upper to lower. The vertical motion of the base plate is activated by a stepping motor. On the top of each deadweight stack, there is an adaptor to suspend it from the metal bend on the torque arm. The first load is created by the adaptor. However, because it was difficult to manufacture the adaptor to have as small a mass as 40 g (the smallest mass of the torque machine) the mass of the adaptor was compensated for by loading the adaptors on both sides of the torque arm simultaneously. At the start of operation, the torque machine always loads adaptors on both sides. When the machine is in rest, its torque arm should be fixed for safety. A cam is used for this purpose. Two cams, one on each side of torque arm, are mounted under the torque arm so that when the wing of the cam is directed upward, it clamps the torque arm.

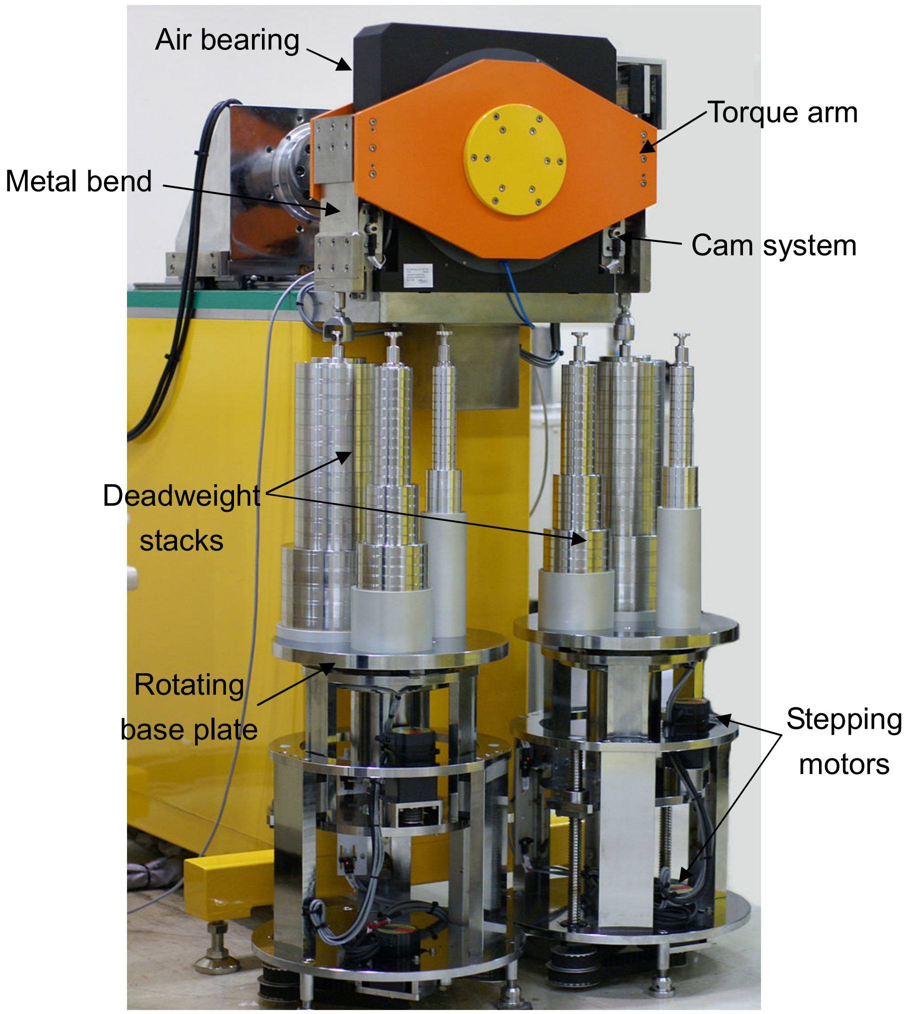

Figure 1. 100 Nm deadweight torque standard machine.

3. 2 kNm Deadweight Torque Standard Machine

Figure 2 is a photograph of the 2 kNm deadweight torque standard machine developed by KRISS. The structure of the machine is similar to that of the 100 Nm torque machine. The machine has a torque arm, an air bearing, a counter motor, two deadweight stacks, a main body, two flexible couplings, two friction joints, a laser displacement sensor, a stepping motor to activate sequential type weight stack, pneumatic system to activate combination type weight stack, torque arm fixing system, and control system for the machine.

The torque arm is constructed from two main INVAR plates. The equivalent length of the torque arm is 1000 mm on each side, therefore 2000 mm total length. At the ends of the torque arm, stainless alloy bends with a thickness of 50 μm are attached. The bends are mounted on the end surface of the torque arm using the same method to that used in the 100 Nm torque machine.

The torque standard machine has different deadweight stacks on clockwise and counter-clockwise sides. For the clockwise torque, the machine has a binary combination weight stack. The combination of deadweights in the stack is as follows.

- 4 × 400 Nm, 2 × 200 Nm, 1 × 100 Nm, 1 × 50 Nm, 2 × 20 Nm, 1 × 10 Nm, total 11 weights

For the counter-clockwise torque, the machine has a sequential type weight stack. The combination of deadweights in the stack is as follows.

- 5 × 200 Nm, 2 × 500 Nm, 1 × 200 Nm, total 8 weights

The net counter clockwise torque is the difference between the torques generated by counter clockwise deadweights and clockwise deadweights. Therefore, the machine can generate counter clockwise torque same as clockwise torque by using the counter clockwise and clockwise deadweights simultaneously. All weights in stacks are made of stainless steel. Because the machine uses binary combination weight stack, it maintains loading torque by fixing the torque arm during the change of torque.

Figure 2. 2 kNm deadweight torque standard machine.

4. Uncertainty Evaluation

Torque realization using a deadweight torque machine can be represented as:

$$T = m\, g_{loc}\, L \left(1 - \frac{\rho_a}{\rho_w}\right) - T_f \quad (1)$$

where, m = mass of deadweight

g_{loc} = local gravitational acceleration

L = length of torque arm

ρ_a = density of air

ρ_w = density of the deadweight

T_f = friction torque in the air bearing.

Then the relative combined uncertainty can be estimated as follows.

$$w_c = \sqrt{{w_m}^2 + {w_g}^2 + {w_L}^2 + [{w_{\rho a}}^2 + {w_{\rho w}}^2]\cdot(\frac{\rho_a}{\rho_w - \rho_a})^2 + {w_{Tf}}^2}\ . \quad (2)$$

Among the uncertainty components, the uncertainty component due to torque arm, w_L, can be estimated as a combined uncertainty of uncertainty component induced by inexact length measurement (w_{Lm}), uncertainty component induced by torque arm deviation from the nominal value (w_{Ld}), uncertainty component due to the torque arm length variation caused by temperature variation (w_{LT}), uncertainty component due to bending of the torque arm (w_{Lb}) and uncertainty component induced by deviation of the arm from a horizontal position (w_{Lh}). The uncertainty components of torque arm length are listed in Table 1.

By using Equation (2), the relative combined uncertainty and the relative expanded uncertainty of the 100 Nm and 2 kNm deadweight torque standard machines can be estimated as Table 2. The table represents standard uncertainty components and the relative expanded uncertainty of the deadweight torque standard machines.

Table 1. Uncertainty components of the torque arms.

Uncertainty component	Relative uncertainty	
	100 Nm	2 kNm
Uncert. of inexact length measurement (w_{Lm})	4.00×10^{-6}	1.25×10^{-6}
Uncert. due to deviation from nominal value (w_{Ld})	1.20×10^{-5}	6.60×10^{-6}
Uncert. due to temperature variation (w_{LT})	1.74×10^{-6}	1.74×10^{-6}
Uncert. due to bending of the torque arm (w_{Lb})	0	1.33×10^{-9}
Uncert. due to non-horizontality (w_{Lh})	1.85×10^{-9}	1.22×10^{-8}
Combined uncertainty of torque arm (w_L)	1.28×10^{-5}	6.94×10^{-6}

Table 2. Uncertainty evaluation of the deadweight torque standard machines.

Uncertainty component	Relative uncertainty	
	100 Nm	2 kNm
Uncert. due to mass (w_m)	1.23×10^{-6}	1.52×10^{-6}
Uncert. due to gravitational acceleration (w_g)	5.89×10^{-7}	5.89×10^{-7}
Uncert. due to torque arm (w_L)	1.28×10^{-5}	6.94×10^{-6}
Uncert. due to density of air ($w_{\rho a}$)	2.45×10^{-2}	2.45×10^{-2}
Uncert. due to density of weight ($w_{\rho w}$)	5.77×10^{-3}	5.77×10^{-3}
Uncert. due to friction (w_{Tf})	1.73×10^{-4} (0.1~1 Nm) 1.73×10^{-5} (1~110 Nm)	1.16×10^{-6}
Combined uncertainty (w_c)	1.74×10^{-4} (0.1~1 Nm) 2.20×10^{-5} (1~110 Nm)	8.25×10^{-6}
Expanded uncertainty (W)	3.48×10^{-4} (0.1~1 Nm) 4.40×10^{-5} (1~110 Nm)	1.65×10^{-5}

There are additional uncertainty components that have not been considered in this uncertainty evaluation, such as the interaction between the torque transducer and the torque machine. Considering these unknown uncertainty components, the relative expanded uncertainty of the 100 Nm deadweight torque standard machine was declared as 5×10^{-4} for the range of 0.1 Nm to 1 Nm and 5×10^{-5} for the range of 1 Nm to 110 Nm with a confidence limit of approximately 95%. And the relative uncertainty of the 2 kNm deadweight torque machine was declared as 5×10^{-5} for the range of 10 Nm to 2200 Nm with a confidence limit of approximately 95%.

In order to check the accuracy level of the deadweight torque machines, the torque machines were compared with other deadweight torque standard machines. The accuracy level of the 2 kNm torque machine was confirmed by a bilateral comparison with 1 kNm and 20 kNm deadweight torque standard machines in NMIJ of Japan [5]. In the bilateral comparison, three transfer standards of which capacities are 500 Nm, 1 kNm and 2 kNm were used and the maximum deviation was less than 4×10^{-5} for the increasing torque. By considering that the declared relative uncertainty of the 2 kNm torque machine and NMIJ torque machines are 5×10^{-5}, we could confirm the accuracy level of the 2 kNm deadweight torque standard machine.

The 100 Nm torque standard machine was compared with the 2 kNm deadweight torque standard machine [6]. Because of the narrow torque range in which the two torque machines' generating torque ranges overlap, only the torque transducer with a capacity of 100 Nm was used in the comparison. In the comparison, the relative deviation was less than 4.1×10^{-5}, and we conclude that the 100 Nm torque standard machine has a sufficient level of accuracy.

5. Conclusions

KRISS have developed 100 Nm and 2 kNm deadweight torque standard machines for the national torque standards in Korea. The relative uncertainty of the 100 Nm torque machine is 5.0×10^{-4} from 0.1 Nm to 1 Nm and 5.0×10^{-5} from 1 Nm to 110 Nm. The relative uncertainty of the 2 Nm torque machine is 5.0×10^{-5} from 10 Nm to 2200 Nm.

The torque machines consist of a torque arm, air bearing, deadweight stacks, counter motor, etc. The torque arms were made of INVAR and their length are 250 mm for the 100 Nm machine and 1000 mm for the 2 kNm machine.

The relative expanded uncertainty of the torque machine was estimated. The most dominant uncertainty component of the torque machine is that caused by the friction torque in the air bearing for the 100 Nm torque machine. For a small capacity deadweight torque machine, the bearing friction is the most dominant uncertainty component.

The 2 kNm torque machine was compared with deadweight torque machines in NMIJ of Japan and the 100 Nm torque standard machine was compared with the 2 kNm deadweight torque standard machine in KRISS. From the intercomparisons, we conclude that the torque standard machines have sufficient level of accuracy, as predicted from the evaluation of their uncertainty.

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