IMEKO 23rd TC3, 13th TC5 and 4th TC22 International Conference
30 May to 1 June, 2017, Helsinki, Finland

REALIZATION OF A MICROTORQUE STANDARD BY USING AN ELECTROMAGNETIC FORCE TYPE TORQUE STANDARD MACHINE

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Abstract: In order to realize a microtorque standard, we investigated the principle of a torque generating method using an electromagnetic force by referring to watt balance experiments for the redefinition of the kilogram. Then, we have developed an electromagnetic force type torque standard machine (EMTSM), and the SI traceable torque was successfully realized for the first time using a method which does not refer to the gravitational force. In this study, we studied on the realization of torque less than 1 mN·m based on this principle. As a result, torque down to 0.3 µN·m was successful realized by using a highly accurate programmable voltage/current source.

Keywords: torque, torque standard, microtorque, watt balance, electromagnetic force.

1. INTRODUCTION

All primary torque standard machines developed at many National Metrology Institutes (NMIs) were adopted a torque generation method using the force of gravity. In generally, these torque standard machines are called deadweight torque standard machines (DWTSMs). The lowest primary torque standard based on this method was 1 mN·m, and a realizable DWTSM was only a 1 N·m torque standard machine developed at the Physikalisch-Technische Bundesanstalt (PTB) in Germany [1]. At the National Metrology Institute of Japan (NMIJ), three DWTSMs with nominal capacity of 10 N·m, 1 kN·m and 20 kN·m were developed [2–4], and the torque traceability system in Japan was constructed [5]. The calibration range of torque measuring devices (TMDs) is from 0.1 N·m to 20 kN·m. Moreover, in order to expand the calibration range of TMDs in the microscopic region, we focused on the possible application of the watt balance method used for redefining the kilogram [6, 7].

Then, we designed and developed a new torque standard machine based on a torque generation method using an electromagnetic force, and the SI-traceable torque was successfully realized for the first time using a method which does not refer to the gravitational force [8]. In the previous study, the lowest torque that we could realize by using the new torque standard machine was 1 mN·m. In the present study, we studied on the realization of torque less than 1 mN·m based on the principle of the torque generation method using an electromagnetic force.

2. A TORQUE GENERATION METHOD BASED ON THE WATT BALANCE PRINCIPLE

A rectangular coil is installed in a homogeneous magnetic field. When the electric current, I, flows through the rectangular coil, the torque, T_e, is generated. T_e is given by:

$$T_e = NABI\cos\theta, \qquad (1)$$

where N is the number of turns of the rectangular coil, A is the cross-sectional area of the rectangular coil and B is the magnetic flux density, and their product NAB is called the magnetic flux passing through the rectangular coil. When the normal vector of the rectangular coil is orthogonal to the magnetic field vector, T_e reaches its maximum value as follows:

$$T_e = NABI. \qquad (1)'$$

In order to realize SI-traceable torque based on Eq. (1)', NAB and I must be evaluated rigorously. However, rigorous evaluation of NAB is very difficult due to the imperfectness in the coil shape and the non-uniformity in the magnetic flux density. On the other hand, when the rectangular coil installed in the homogeneous magnetic field is rotated at constant angular velocity, ω, the induced electromotive force, V, is generated. V is given by:

$$V = NAB\omega sin\omega t, \qquad (2)$$

where t is time. When the normal vector of the rectangular coil is orthogonal to the magnetic field vector, V reaches its maximum value as follows:

$$NAB = V/\omega. \qquad (2)'$$

So, T_e can be calculated from equations (1)' and (2)' as:

$$T_e\omega = VI. \qquad (3)$$

T_e can be evaluated by measuring ω, V and I. Thus, SI traceable torque can be realized by referring to the angle standard, frequency standard, voltage standard and current standard, respectively. Equation (3) shows that the electrical power and the mechanical power are equal in the rotating coordinate system.

3. EXPERIMENTAL CONDITIONS

First, we give an overview of a new torque standard machine based on a torque generation method using an electromagnetic force. Next, a highly accurate programmable voltage/current source and a high accuracy low nominal capacity torque measuring device using in present study are shown. Finally, the torque generation procedure by using the new torque standard machine is described.

3.1 A NEW TORQUE STANDARD MACHINE BASED ON A TORQUE GENERATION METHOD USING ELECTROMAGNETIC FORCE

Figure 1 shows a photograph of a torque standard machine based on a torque generation method using an electromagnetic force. This new machine is called the electromagnetic force type torque standard machine (EMTSM). Its basic hardware components are (1) a servo motor with a reduction gear system, (2) couplings, (3) a low nominal capacity TMD, (4) an aerostatic bearing, (5) an optical rotary encoder, (6) an electric current/voltage measuring system, (7) a rectangular coil, and (8) a magnetic circuit with two neodymium magnets. The machine is set up vertically.

The torque generation method based on the watt balance experiments consist of two phases: evaluation of the magnetic flux passing through the rectangular coil and generation of torque. In the previous study, the magnetic flux passing through was evaluated, its value was estimated to be 4.355×10^{-2} V·s (=kg·m^2·s^{-2}·A^{-1}). Also, the angular position of the rectangular coil, p_0, at which V reached its maximum value has already been evaluated. In the phase of the torque generation, the electric current I was supplied to the rectangular coil from the battery mounted on the electric current/voltage measuring system. However, this battery system cannot supply current to the rectangular coil less than 1 mA. In this study, we adopted a highly accurate programmable voltage/current source to supply current to the rectangular coil less than 1 mA as shown next section.

3.2. A HIGHLY ACCURATE PROGRAMMABLE VOLTAGE/CURRENT SOURCE

Figure 2 shows a photograph of a B2912A from Keysight Technologies Inc. that is a highly accurate programmable voltage/current source. The B2912A incorporates voltage/current measurement functions. It's called a source/measure unit (SMU). Its minimum source resolutions and its minimum measurement resolutions are 10 fA and 100 nV, respectively.

3.3. HIGH ACCURACY LOW NOMINAL CAPACITY TORQUE MEASURING DEVICE

Figure 3 shows a photograph of a newly developed high accuracy low nominal capacity TMD. Its nominal capacity is 0.1 N·m. This TMD was calibrated by using the 10-N·m-DWTSM to expand its calibration range. The resolution of this TMD with DPM40S2 (Amplifier/indicator, from HBM

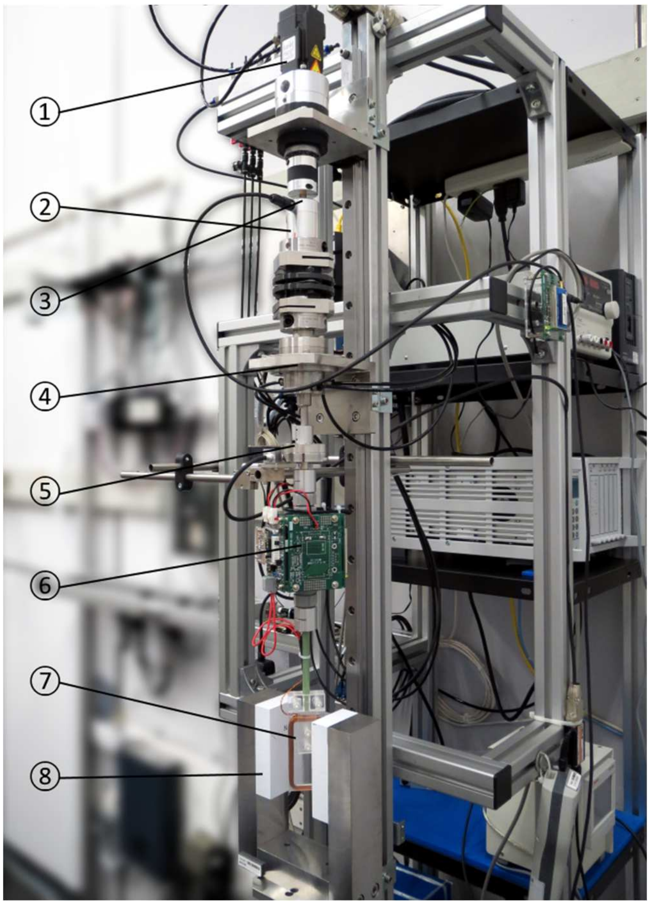

Figure 1. Photograph of the TSM based on the torque generation method using electromagnetic force.

Figure 2. Photograph of a highly accurate programable voltage/current source with voltage/current measurement functions.

GmbH) was 1×10^{-6} mV/V, and its value was approximately equivalent to a torque of 0.09 µN·m. In this study, the TMD was installed in the EMTSM to check the torque generated by the electromagnetic force.

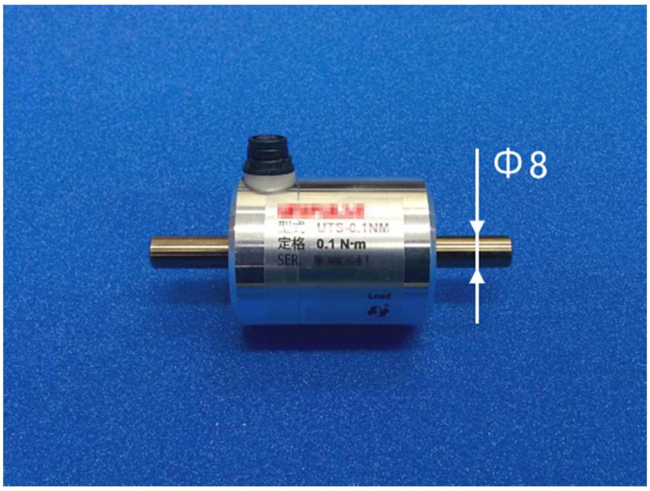

Figure 3. Photograph of the low nominal capacity torque measuring device with a nominal capacity of 0.1 N·m.

3.4. A TORQUE GENERATION METHOD BY USING ELECTROMAGNETIC FORCE TYPE TORQUE STANDARD MACHINE

The torque generation procedure by using the EMTSM is as follows. First, the TMD with the nominal capacity of 0.1 N·m was installed on the EMTSM. Next, the position of the rectangular coil was adjusted by using the servo motor with the reduction gear system such that the angular position of the rectangular coil was maintained at p_0. Feedback control for maintaining the position of the rectangular coil at p_0 had been performed during the torque generation process. Next, the SMU and the rectangular coil were connected. Then, *I* flowed through the rectangular coil. *I* was supplied to the rectangular coil for 35 seconds. The output of the TMD was measured for 10 seconds before the end of measurement at the interval of 0.5 seconds.

4. RESULTS AND DISCUSSION

Figure 4 shows the relationship between the electric current *I* and the torque *T*. Horizontal and vertical axes are both expressed with common logarithms. This figure includes the torque realized by the EMTSM T_{EMTSM}, the torque measured by the TMD T_{TMD}, and the torque calculated from equation (1)' T_{Cal}. Here, we used actual measurement values of the magnetic flux passing through the rectangular coil, $N\bar{A}\bar{B}$. The apparent cross-sectional area of the rectangular coil $\bar{A}$ as measured by a vernier caliper is estimated to be 2.627×10^{-3} m^2. The apparent magnetic flux density $\bar{B}$ was estimated to be 323.8 mT based on the test report submitted by the manufacturer of the magnetic circuit. The number of turn *N* was 50. Thus, $N\bar{A}\bar{B}$ was estimated to be 4.253×10^{-2} V·s. In Figure 4, it was found that the torque realized by using the EMTSM approximately was 0.3 μN·m when the electric current flowing through the rectangular coil was estimated to be 5 μA.

The EMTSM was a prototype used confirm the watt balance method in rotating coordinate system. The

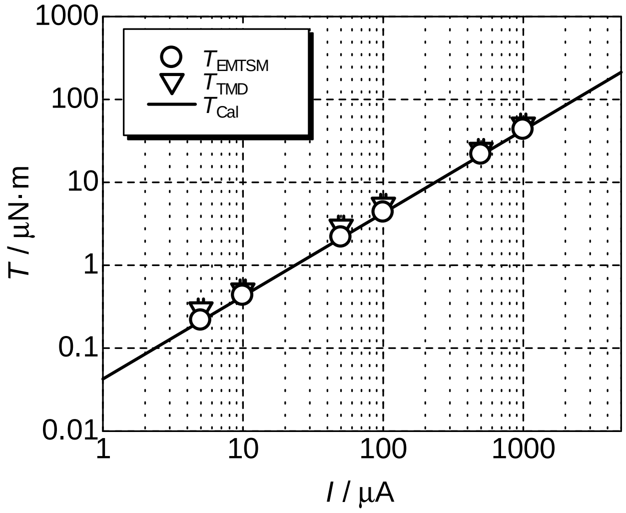

Figure 4. Relationship between the electric current *I* and the torque *T*.

uncertainty of torque realized by the EMTSM was roughly estimated as a trial calculation in our previous work. The relative expanded uncertainty of the torque realized by EMTSM, $W_{\mathrm{tsm\_e}}$, was evaluated as: [8]

$$W_{\mathrm{tsm_e}} = k \cdot w_{\mathrm{tsm_e}} = k \cdot \sqrt{w_V^2 + w_A^2 + w_\omega^2 + w_{p0}^2} \quad (4)$$

where w_{V}, w_{A}, w_ω and w_{p0} are the relative combined uncertainties ascribable to the voltmeter, the ammeter, and the angular velocity measurement, respectively, and the relative standard uncertainty ascribable to the determination of p_0. *k* is the coverage factor (k = 2). In previous study, $W_{\mathrm{tsm\_e}}$ was estimated to be 1.6×10^{-3} in the torque range from 1 mN·m to 40 mN·m. In present study, in order to supply current to the rectangular coil less than 1 mA, the highly accurate programmable SMU was substituted for the battery. Thus, w_{A} was re-evaluated in this study. w_{A} is given by:

$$w_A^2 = w_{A\_ref}^2 + w_{A\_res}^2 + w_{A\_var}^2, \quad (5)$$

where $w_{\mathrm{A\_ref}}$, $w_{\mathrm{A\_res}}$ and $w_{\mathrm{A\_var}}$ are the relative combined uncertainty ascribable to the SMU used as the reference standard, the relative standard uncertainty due to the resolution of the SMU and the relative standard uncertainty due to the variation of the measured data, respectively. $w_{\mathrm{A\_var}}$ was evaluated by Type A evaluation, and the others were evaluated by Type B evaluation. w_{A} near 5 μA was evaluated as:

$$w_A = 5.3 \times 10^{-4}. \quad (6)$$

Thus, $W_{\mathrm{tsm\_e}}$ was evaluated to be 1.7×10^{-3}, with the coverage factor *k* of 2, in the torque range from 0.3 μN·m to 50 μN·m. So, the torque generation method using electromagnetic force can realize lower torque than the torque generation method using the force of gravity.

5. CONCLUSIONS

In order to realize a microtorque standard, the EMTSM have been developed at NMIJ/AIST. The principle of the torque generation method of the EMTSM was based on the watt balance principle. In the previous work, we could realize in the range down to 1 mN·m by using the EMTSM. In present study, we investigated the realization of torque less than 1 mN·m by using the EMTSM. The highly accurate programmable voltage/current source was introduced as the power supply. As a result, we successfully realized in the torque range down to 0.3 μN·m by using the highly accurate programmable voltage/current source.

6. ACKNOWLEDGEMENTS

This work was supported by JSPS KAKENHI Grant Number 15K18081. We would like to thank the staff at NMIJ/AIST, particularly Dr Kenichi Fujii, a prime senior researcher in the Research Institute for Engineering Measurement (RIEM), for his assistance with investigating the principle of a torque generating method using an electromagnetic force, and Dr Koji Ogushi, a group leader of Force and Torque Standards Group in RIEM, for his support with investigating torque standard.

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