XXI IMEKO World Congress “Measurement in Research and Industry”
August 30 – September 4, 2015, Prague, Czech Republic

DESIGN OF A NEW TORQUE STANDARD MACHINE BASED ON THE TORQUE GENERATING METHOD USING ELECTROMAGNETIC FORCE

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Abstract – We have developed torque standard machines based on the lever deadweight system, that is to say the torque generating method using gravity. However, this method is not suitable for expanding low-torque range because weights and moment arms have limitations in size. In this study, we investigated the working principle of torque generating method using electromagnetic force by referring to watt balance experiments for the redefinition of the kilogram.

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

1. INTRODUCTION

The torque traceability system in Japan consists of two processes, one for “pure torque” loading without any parasitic components, and the other for “torque wrench” loading with unavoidable transverse force and bending moment, as shown in Figure 1 [1]. In order to expand the lower range of the torque standard, a dead weight torque standard machine with a rated capacity of 10 N·m (10-N·m-DWTSM) has been developed at the National Metrology Institute of Japan (NMIJ). Figure 2 shows a photograph of the 10-N·m-DWTSM. By 2012, the relative expanded uncertainty of torque, W_{tsm}, realized by the 10-N·m-DWTSM was evaluated to be 6.6×10^{-5}, with the coverage factor k being equal to 2, in a range from 0.1 N·m to 10 N·m [2]. After evaluating the newly developed TSM, we made a bilateral comparison of measurement capabilities with the 1 N·m and 1 kN·m TSMs at Physikalisch-Technische Bundesanstalt (PTB) in the torque range from 0.1 N·m to 10 N·m [3], and confirmed the equivalence between torque realized by the TSMs of the both institutes. On the other hand, the lower range of calibrations of reference torque wrenches (RTWs) was also expanded by affixing newly-designed RTW holders to the 10-N·m-DWTSM [4]. Moreover, we developed high-accuracy torque transducers with rated capacity of 1 N·m and 5 N·m[5]. Thus, by 2014, we started calibration services for both TMDs and RTWs in the range from 0.1 N·m to 10 N·m by using the 10-N·m-DWTSM.

Up to the present, we have developed three TSMs covering a wide torque range from 0.1 N·m to 20 kN·m. All of these TSMs are based on the lever deadweight system, that is to say the torque generating method using gravity. However, this method is not promising for the torque standard in the microscopic region, because weights and moment arms have limitations in size. So, we focused on the working principle

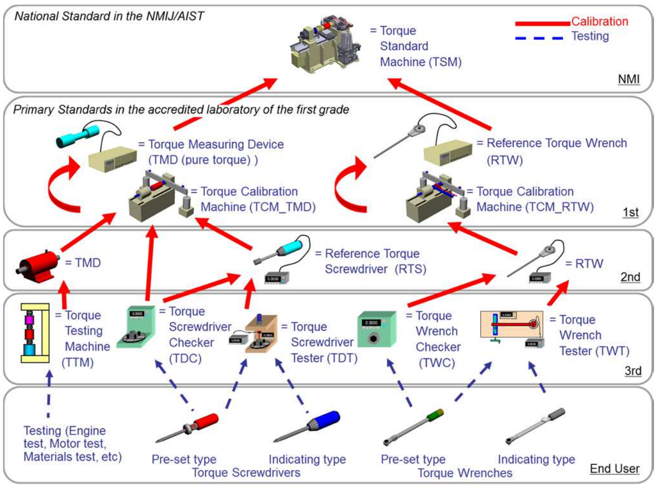

Fig. 1. SI traceability system of torque in Japan [1]

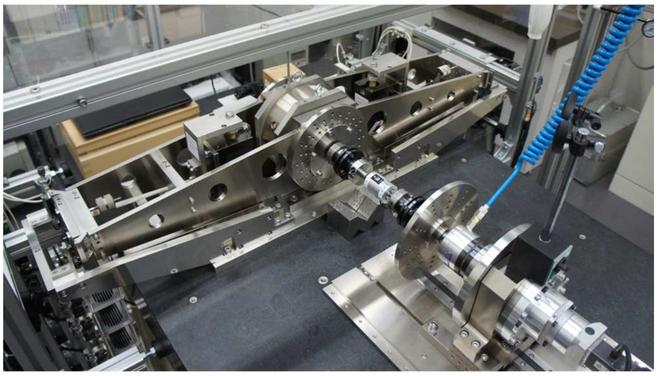
Fig. 2. Photograph of the 10-N·m-DWTSM

of watt balances for redefining the kilogram [6, 7], and investigated the torque generating method using electromagnetic force. This paper presents the working principle of this method, an overview of the new torque standard machine under designing and the developed various elemental technologies.

2. PRINCIPLE OF THE TORQUE GENERATING METHOD USING ELECTROMAGNETIC FORCE

The watt balance experiments for redefining kilogram consists of two phases, one for “the weighting experiment”, and the other for “the moving experiment” [6], in which electrical power and mechanical power are equal to each other as shown in Eq. (1).

$$UI = Fv = mgv \,, \tag{1}$$

where U is voltage, I is electric current, F is force, m is mass, g is the local acceleration of gravity and v is velocity when a coil moves vertically in a magnetic field. In this experiment, the coil is moved along a straight line. So, in order to apply this method to generation of torque, the coordinate is transformed to the rotating coordinate system. Figure 3 shows the schematic of the principle of the torque generating method using electromagnetic force. The rectangle coil is installed in the homogeneous magnetic field. When the electric current, I, flows through the rectangle coil, the Lorentz force, F, is generated as shown Eq. (2).

$$F = IBl \text{ or } F = -IBl \,, \tag{2}$$

where l is length of the rectangle coil parallel to the rotation axis, O-O'. Because two forces are opposite and magnitude of them are same, consequently Torque, T, is generated as shown in Figure 3(a). T is calculated by Eq. (3).

$$T = NABI \cos\theta \,, \tag{3}$$

where A (= hl) is the area of the rectangle coil, N is the number of turns of the rectangular coil and B is the magnetic flux density. It is necessary to measure B, A and N to evaluate T. However, the rigorous evaluations of A and B are very difficult. Next, the rectangular coil is rotated at constant angular velocity, ω, as depicted in Figure 3(b). Then, an induced electromotive force, V, is generated. The force, V is calculated by Eq. (4).

$$V = NAB\omega \sin \omega t \,. \tag{4}$$

Here, when $\sin\omega t$ equals unity, V takes the maximum, V_{max},

$$NAB = \frac{V_{max}}{\omega} \,. \tag{5}$$

On the other hand, when $\cos\theta$ equals unity, T reaches the maximum, T_{max}. Thus, T_{max} can be calculated by Eq. (3) and (5).

$$T_{max}\omega = V_{max} I \,. \tag{6}$$

Eq. (6) shows that the electrical power and the mechanical power are equal in the rotating coordinate system. By measuring V, ω and I in each mode, T can be evaluated.

3. DESIGN OF A NEW TORQUE STANDARD MACHINE BASED ON THE TORQUE GENERATING METHOD USING ELECTROMAGNETIC FORCE

Figure 4 and 5 respectively show a schematic and a photograph of a torque standard machine based on the proposed torque generating method using electromagnetic force. The photo was taken when the machine was still under development. Its basic hardware components are a servo motor, couplings, a torque measuring device, an aerostatic bearing, a rotary encoder, a digital multi-meter, a rectangular coil and Neodymium magnetics. This machine is set vertically. Overview of the main components are as follows.

3.1. Couplings

A new coupling shown in Figure 6 consists of a metal disc spring coupling, an adapter, a hydraulic bushing (ETP-T-8). In this study, the new hydraulic bushing which the hole diameter is 8 mm is developed. This bushing has the function to prevent a torque measuring device from overloading when it is mounted on the TSM.

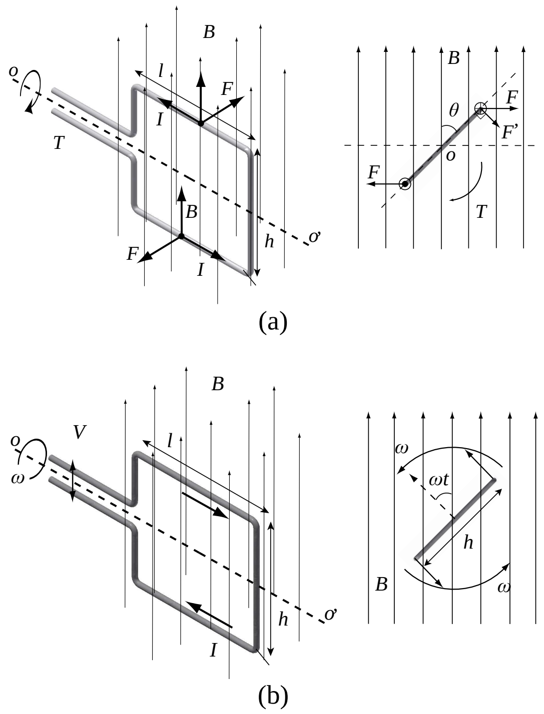

Fig. 3. Schematic of the principle of the torque generating method using electromagnetic force, showing (a) Torque, T, generating mode, and (b) induced electromotive force, V, generating mode.

3.2. Low nominal capacity TMD

Figure 7 shows a photograph of a new low nominal capacity TMD as a trial. The nominal capacity is 0.1 N·m. Although JMIF-015:2004-8 technical guideline recommends shaft diameter of 15 mm for TMDs having nominal capacity equal to or less than 20 N·m [8], the shaft diameter of 8 mm was adopted for this TMD. The reason for adopting the thin shaft is its light weight to avoid overloading. Now, we have been designing another TMD having nominal capacity lower than 0.1 N·m with the cooperation of a manufacturer.

3.3. Aerostatic bearing

Figure 8 shows a photograph of a new aerostatic bearing. The existing aerostatic bearing has problem that the shaft installed in it is rotated under the influence of supplied compressed air. This new aerostatic bearing has three supply ports to control flow of supplied compressed air. Digital speed controllers are installed in each supply port.

3.4. Rotary encoder

As this method requires precise measurement of angular position, a high-response and high-accuracy rotary encoder is adopted. We have selected an optical rotary encoder.

3.5. Electric current/voltage measuring system with a rectangular coil

The electric current/voltage measuring system with a rectangular coil is still in development. Figure 9 shows a schematic of this measuring system. This measuring system is an original device. This is a 60-millimeter cube. This device

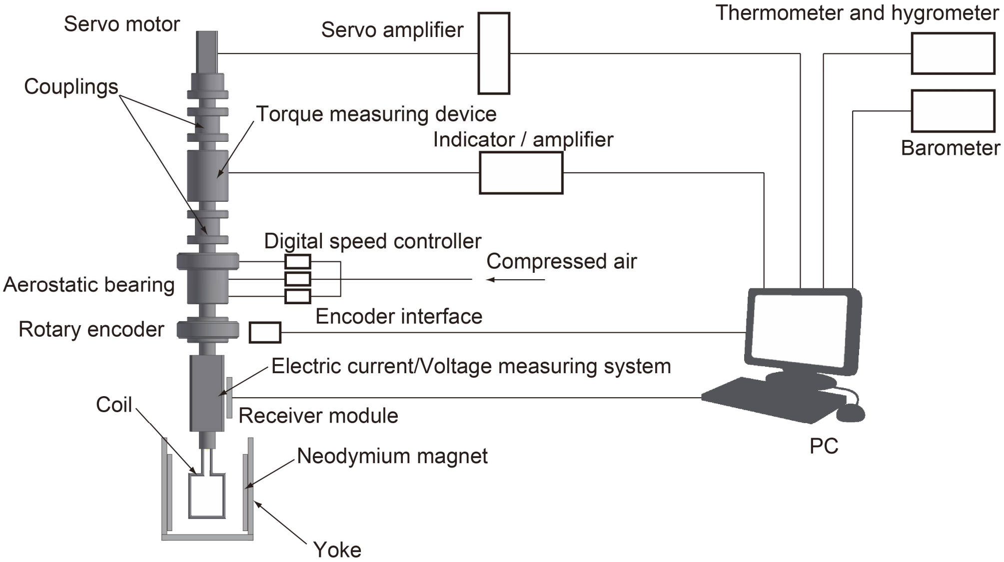

Fig. 4. Schematic of a torque standard machine based on the torque generating method using electromagnetic force.

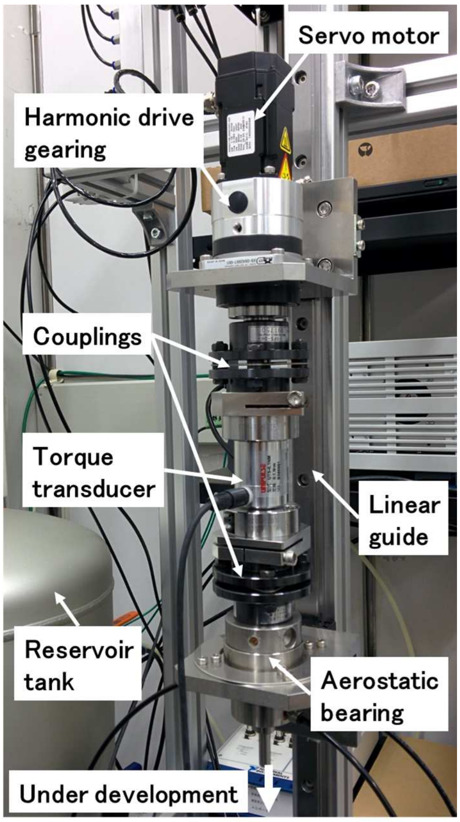

Fig. 5. Photograph of a torque standard machine based on the torque generating method using electromagnetic force.

consists of a CPU module, a transmitter module, a battery module, an electric current/voltage measuring module, a shaft, and a main frame. A rectangular coil is attached to this measuring system. Induced electromotive force to be generated when the rectangular coil rotates is measured by this system. Moreover, this system can measure an electric current passing through the rectangular coil which is supplied by a battery mounted on this system. The signals outputted by this measuring system are to be transmitted wirelessly. The timings of the changeover of the switch of the battery is

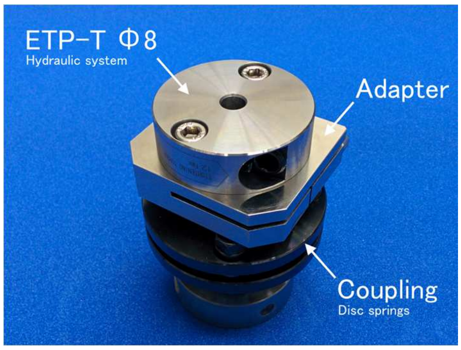

Fig. 6. Photograph of the new coupling.

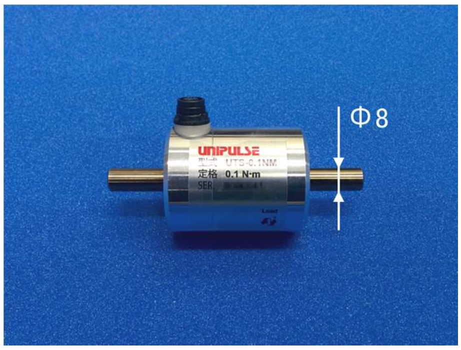

Fig. 7. Photograph of a low nominal capacity TMD.

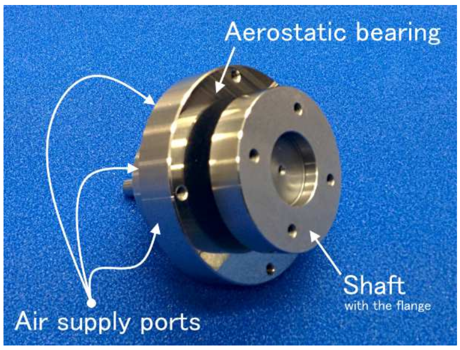

Fig. 8. Photograph of a new aerostatic bearing.

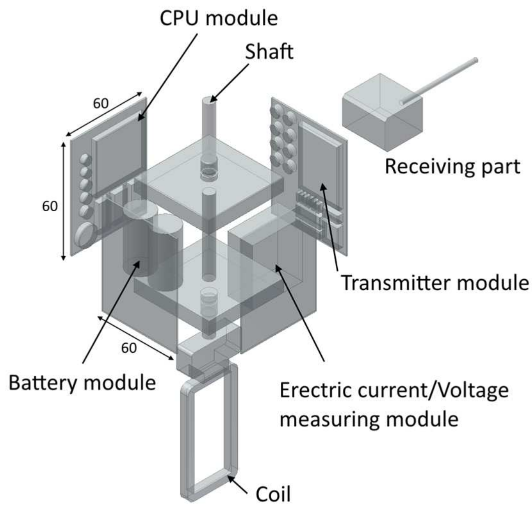

Fig. 9. Schematic of the electric current/voltage measureing system with a recutangle coil

controlled by a control command from PC.

3.6. Magnetic circuit

The magnetic circuit is still in the design stage, too. This circuit consists of Neodymium magnets and yoke. The Neodymium magnets are placed so that different pole surfaces oppose to each other. We analysed the distribution of the magnetic flux density in the measurement area before producing the magnetic circuit. As a result, it was shown that the magnetic flux density was more than 0.3 T in the center of the measurement area.

4. TORQUE GENERATING METHOD USING ELECTROMAGNETIC FORCE

4.1. Evaluation procedure of B, A and N

As previously noted, B, A and N are expressed by relation between V_{max} and ω. In order to evaluate B, A and N, the rectangular coil put into the magnetic circuit is rotated by a servo motor at constant angular velocity, ω_i, and V_i is measured. Moreover, the angular position, p_{0_i}, when V_i reaches the maximum value, V_{max_i}, is measured by using the optical rotary encoder. When ω_i is considered as a horizontal axis and V_{max_i} is considered as a vertical axis, its inclination is equal to NAB as shown in Eq. (5). This value is the specific value for the torque generating machine using electromagnetic force. All p_{0_i} become the same value in theory. So, a mean of p_{0_i}, $\overline{p_0}$, is defined as the angular position when V takes the maximum value.

4.2. Torque generating method using electromagnetic force

When the angular position of the rectangular coil reaches $\overline{p_0}$, torque generated by electromagnetic force takes the maximum value, T_{max}. First, the rectangular coil is maintained at $\overline{p_0}$ by the servo motor. Next, the electric current flows through the rectangular coil by using a battery mounted on the electric current/voltage measuring system. Because V_{max}/ω (= NAB) is evaluated already, T_{max} is obtained to measure the electric current as shown in Eq. (6). By varying the electric current, torque generated by this machine can be changed.

5. CONSIDERATION OF UNCERTAINTY OF TORQUE REALIZED BY A TSM BASED ON THE TORQUE GENERATING METHOD OF ELECTROMAGNETIC FORCE

We think that the relative expanded uncertainty of torque, W_{tsm_e}, realized by the torque standard machine based on the new torque generating method using electromagnetic force can be estimated by the following equation:

$$W_{tsm\_e} = k \cdot w_{tsm\_e} = k \cdot \sqrt{w_{volt}^2 + w_{resi}^2 + w_{angl}^2 + w_{freq}^2}, \quad (6)$$

where w_{volt} is the relative standard uncertainty of voltage, w_{resi} is the relative standard uncertainty of resistance, w_{angl} is the relative standard uncertainty of angular position and w_{freq} is the relative standard uncertainty of frequency. They can be able to trace back to voltage standard, resistance standard, angle standard and frequency standard, respectively.

6. SUMMARY

In this study, by noticing the working principle of the watt balances for redefining the kilogram, we investigated the torque generating method using electromagnetic force. We are now developing the torque standard machine based on this method.

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