

NEW MICROFORCE GENERATING MACHINE USING ELECTROMAGNETIC FORCE

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Abstract:

This paper reports a new microforce generating machine under development at NMIJ, AIST. We proposed a new microforce generating method by referring to the principle of the Kibble balance experiment and planned to apply it to a rotary type machine. Microforce in the micronewton and millinewton range can precisely be generated using this newly developed machine.

Keywords: microforce, electromagnetic force, Kibble balance, rotary type machine, force standard

1. INTRODUCTION

Microforce measurements in the micronewton and millinewton range have been applied in many industries and research fields, and the reliability of these measurements becomes essential, for example, for the evaluation of material mechanical property using an atomic force microscope (AFM). Therefore, several national metrology institutes (NMIs) have developed various facilities, including microforce comparators that use the principle of the electromagnetic balance, to establish the traceability of microforce [1–3]. The National Metrology Institute of Japan (NMIJ), National Institute of Advanced Industrial Science and Technology (AIST), has developed a 2 N dead-weight type force standard machine that uses gravity force and can extend the Japanese force standard down to 10 mN [4]. The above facilities all need to be traceable to mass in the sub-gram and milligram range. However, there is a limitation due to factors such as manufacturing technology and calibration of small weights.

By referring to the principle of Kibble balance experiment [5, 6], and an electromagnetic force type torque standard machine developed in NMIJ [7], we proposed a new microforce generating method using electromagnetic force and planned to apply it to a rotary type machine.

2. PRINCIPLE OF PROPOSED METHOD

As in the Kibble balance experiment, there are two modes in measurement: static mode and

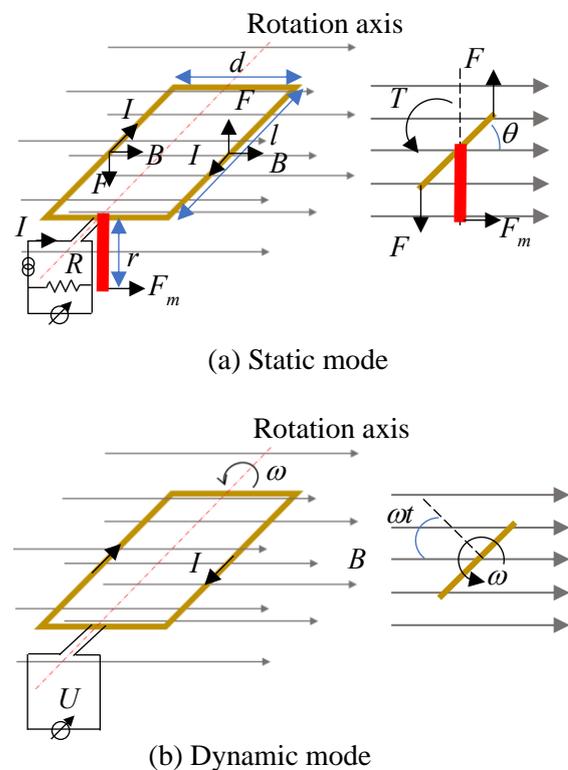


Figure 1: Principle of the proposed method

dynamic mode, as shown in Fig. 1. A rotating coordinate system was applied.

In the static mode, when an electric current I flows through a rectangular coil with a rotation axis shown in the broken red line in a magnetic field of a magnetic flux density B , an electromagnetic force F is generated as:

$$F = BIl \text{ or } F = -BIl, \tag{1}$$

where l is the length of the rectangular coil parallel to the rotation axis. These two forces are in opposite directions, and their magnitudes are equal. Therefore, a torque T is generated around the

rotation axis of the coil indicated by the broken red line as:

$$T = NBAI \cos\theta , \quad (2)$$

where N is the number of turns of the rectangular coil, $A (= ld)$ is the area of the rectangle coil. If an arm with a length r is attached from the center of the coil in rotation axis, a force F_m can be generalized and expressed as:

$$F_m = T/r = NBAI \cos\theta / r . \quad (3)$$

In the dynamic mode, when the rectangular coil is rotated with the rotation axis indicated by the broken red line to in the magnetic field at a constant angular velocity ω , an induced electromotive force U is generated as:

$$U = NBA\omega \sin\omega t . \quad (4)$$

When the magnetic flux lines and the rectangular coil are parallel in both static and dynamic modes, F_m and U reach their maximum values F_{mmax} and U_{max} . By considering the NBA is a value associated

with the machine developed, F_{mmax} can be expressed as:

$$F_{mmax} = U_{max}I/(\omega r) . \quad (5)$$

Therefore, F_{mmax} is obtained from measuring U_{max} and ω in the dynamic mode, I in the static mode and r .

3. DESIGN

Figure 2 shows an overview of the new machine in developing. It mainly consists of a servo motor, a rotary encoder, a pair of neodymium magnets fixed to a yoke, a rectangular coil, a balancing arm, a self-developed aerostatic bearing, a loading frame, counterweights, a laser displacement sensor, and a lifting mechanism of the force transducer. A force transducer to be calibrated is installed on top of an exchangeable X, Y, θ stage. More details of main mechanisms are described in the following sections.

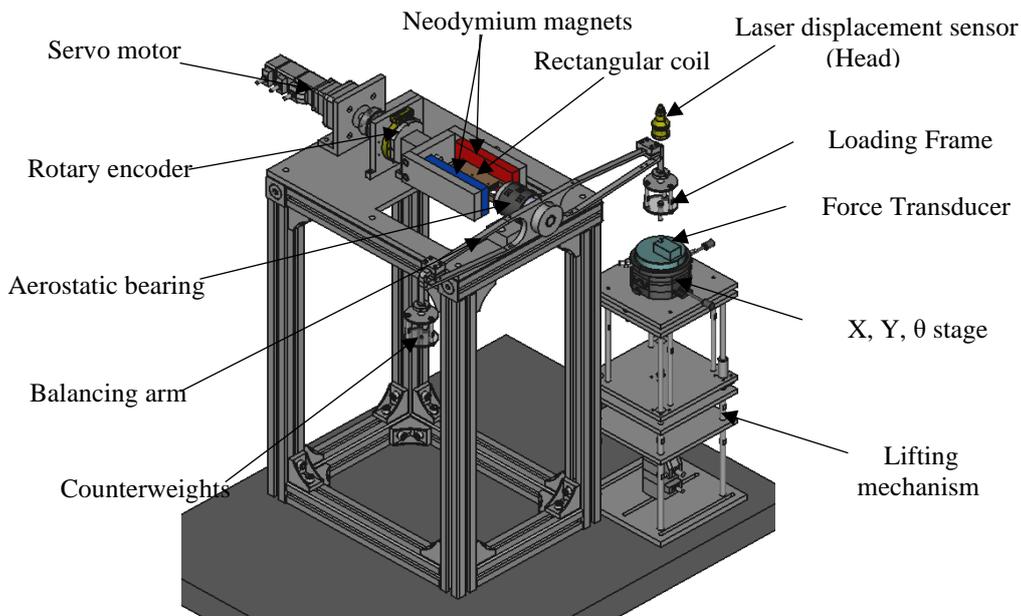


Figure 2: Overview of the new machine

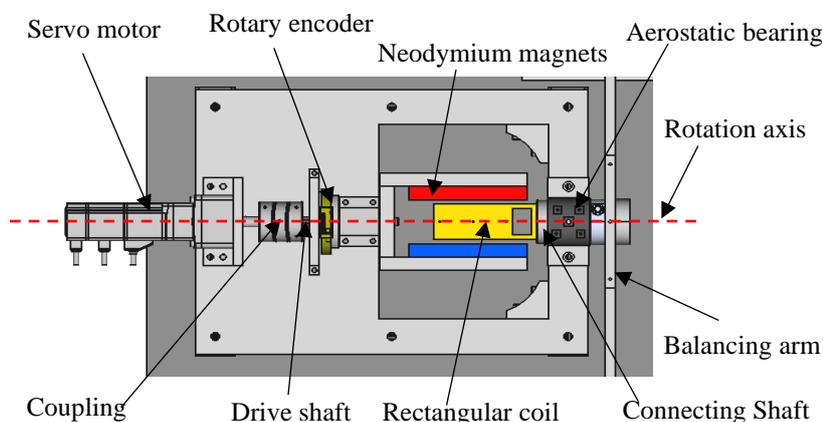


Figure 3: Arrangement of the magnets and the coil

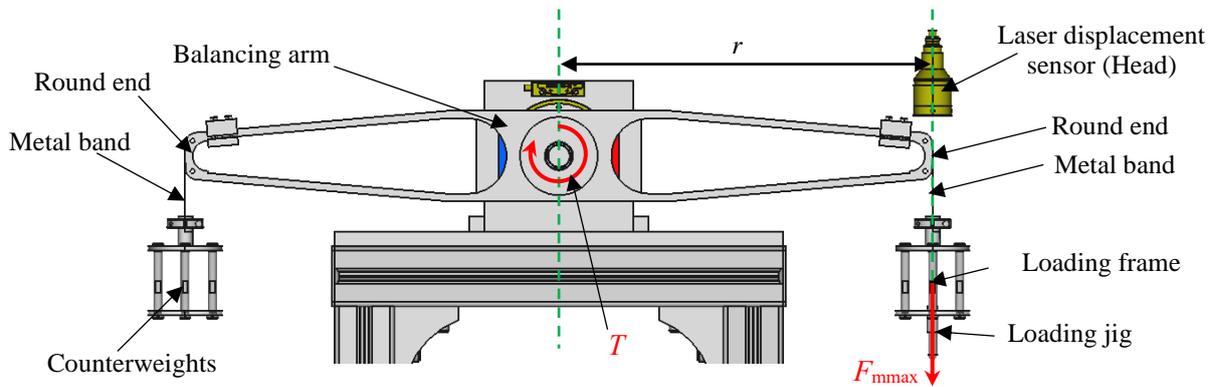


Figure 4: Force transmission mechanism

3.1. Neodymium magnets and coil

Figure 3 shows the arrangement of the magnets and the coil viewed from the top. The neodymium magnets can be rotated with the rotation axis by connecting to the servo motor through a drive shaft and a coupling. The ring of the rotary encoder is mounted coaxially on the driveshaft to monitor the angle of the neodymium magnets. The coil is fixed to the balancing arm through a connecting shaft inserted in the aerostatic bearing. In fact, in the dynamic mode, the neodymium magnets are rotated by the Servo motor, and the rectangular coil is fixed in an equilibrium position to induce the electromotive force U . We visually confirm the rectangular coil parallel to the neodymium magnets before the measuring of the dynamic mode. After measuring, a specific angular position of the neodymium magnets in U_{max} can be defined. Currently, the neodymium magnets have already been manufactured, the distribution of the magnetic flux density was evaluated by the manufacturer, and the average value of the magnetic field where the coil passes was estimated to be approximately 350

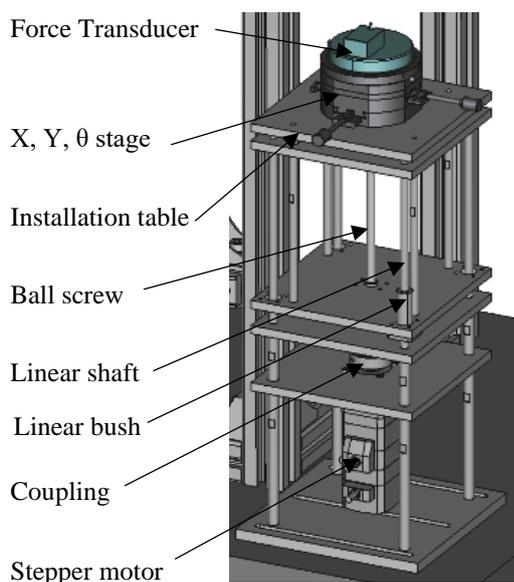


Figure 5: Force transducers lifting mechanism

mT by the manufacturer's test report. We also have determined the area of the rectangular coil A , and the number of turns N is adjusted by referring to the estimated relationship between the magnitude of force generated F_{mmax} and the magnitude of current I .

3.2. Force transmission mechanism

Figure 4 shows an overview of the force transmission mechanism viewed from the front. The loading frame is linked to the balancing arm by a five- μ m-thick metal band to act as an elastic hinge and can apply a compressive or tensile force on a force transducer. Counterweights are set on the other end of the balancing arm and used to cancel out the force acting on the loading frame by monitor the equilibrium position of the balancing arm using a high precision laser displacement sensor. Similar to the previous study [4], the aerostatic bearing is adopted as a high sensitivity less friction fulcrum. The length r indicating distance between fulcrum and force action point will be precisely measured and traceable to length standard. Since the two ends of the balancing arm are processed into round ends with a radius of 250 mm centered on the fulcrum, it is considered that r does not change even if the balancing arm is rotated a certain angle. Therefore, in the static mode, the neodymium magnets are fixed in the specific angular position, and the rectangular coil is free. When an electric current I flows through a rectangular coil, the torque T is generated, and the force F_{mmax} can be applied to the force transducer in compressive calibration, as shown in Fig. 4.

3.3. Force transducer lifting mechanism

Again, the previous study showed the contact point between the loading frame and the force transducer under calibration has to be maintained during calibration irrespective of the height and stiffness of the transducer [4]. Figure 5 shows the force transducer lifting mechanism newly developed with improvements by referring to the arrangement of the previous study [4]. This mechanism consists of a stepper motor, a coupling, a precision ball screw, four pairs of linear shafts and

linear bushes, an installation table, and some connection parts. The force transducer to be calibrated is installed on top of an X, Y, θ stage mounted on the installation table, and it is driven vertically by a stepper motor via a precision ball screw with a resolution of 1 μm . We can manually adjust the horizontal position and the rotation angle of the vertical axis of the force transducer in the X, Y, and θ stages. However, in many cases of microforce transducers, the displacements of their elastic body in the rated capacity is small in several micrometer order; a lifting mechanism with the resolution in nanometer (nm) order is necessary in the future.

4. SUMMARY

We proposed a new method for generating microforces by referring to the principle of Kibble balance experiment. Based on the technique, we are developing a newly rotary type machine. We plan to verify our proposed method after the machine completed. In the future, we expect to realize a microforce standard using the new microforce generating machine in NMIJ.

5. ACKNOWLEDGMENTS

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