

# DESIGN OF A LINEAR-MOTION TYPE MICROFORCE GENERATING MACHINE USING ELECTROMAGNETIC FORCE

J. F. Zhu<sup>1</sup>, T. Hayashi<sup>2</sup>, K. Ogushi<sup>3</sup>

National Metrology Institute of Japan (NMIJ), AIST, Tsukuba, Japan  
<sup>1</sup>zhu-junfang@aist.go.jp, <sup>2</sup>t-hayashi@aist.go.jp, <sup>3</sup>kji.ogushi@aist.go.jp

## Abstract:

This paper reports the design of a linear-motion type microforce generating machine by applying the principle of Kibble balance. A novel schematic diagram of the machine is proposed. “Microforce” in the order of micronewton to millinewton can precisely be generated by this newly designed machine. The machine is under development. It is expected to contribute to improving the reliability of microforce measurement.

**Keywords:** microforce generating machine; linear-motion type; electromagnetic force; force standard; Kibble balance

## 1. INTRODUCTION

“Microforce” measurements from the micronewton to millinewton range are applied in many industries and research fields, such as evaluating material mechanical property by conducting nanoindentation tests. To ensure the reliability of these measurements, several national metrology institutes have developed various facilities, including microforce comparators with electromagnetic balances that use electromagnetic force, to establish traceability, which needs to be traceable to mass standards in the sub-gram and milligram range [1]. However, there is a limitation in precise force generation due to mechanical factors such as manufacturing technology and calibration of small weights. Therefore, the Kibble balance [2], [3], initially to measure the Planck constant for the redefinition of the kilogram, opens a new path for microforce measurement [4], [5], [6].

By applying the principle of the Kibble balance experiment, we designed a linear-motion type microforce generating machine using electromagnetic force and liquid buoyancy. We aim to generate microforce from micronewton to millinewton range with a relative uncertainty in the order of  $10^{-3}$  to  $10^{-4}$ .

## 2. DESIGN OF THE NEW MACHINE

Figure 1 shows a conventional Kibble balance experiment [2], [3]. There are two measurement

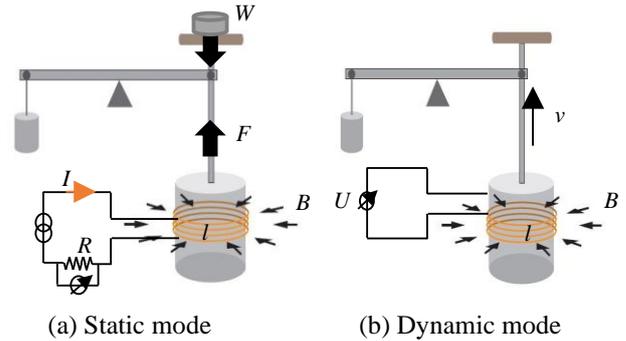


Figure 1: Principle of the Kibble balance experiment

modes: a static mode for measuring the gravitational force  $W$  of a standard weight and a dynamic mode for evaluating the proportional constant associated with the coil and magnet equipped in the Kibble balance.

In the static mode, when an electric current  $I$  flows through a coil in a magnetic field with a magnetic flux density  $B$ , an electromagnetic force  $F$  is generated to balance the gravitational force  $W$  loaded on the weighing plate.  $W$  and  $F$  can be expressed as:

$$W = F = B l I \quad (1)$$

where  $l$  is the length of the coil,  $Bl$  can be considered as the proportional constant of  $W$  and  $I$ .

In the dynamic mode, when the coil moves in the magnetic field at a constant velocity  $v$ , an induced electromotive force  $U$  is generated as:

$$U = B l v \quad (2)$$

$Bl$  is also the proportional constant of  $U$  and  $v$ . Therefore,  $W$  and  $F$  can be expressed as:

$$W = F = U I / v \quad (3)$$

and can be obtained from measuring  $U$  and  $v$  in the dynamic mode and  $I$  in the static mode.

The microforce generating machine aims to generate precise microforces for the calibration of the microforce transducers. Unlike the conventional Kibble balance, Figure 2 shows a novel schematic diagram of the machine with a balance mechanism using liquid buoyancy  $F_{\text{buoy}}$ . The liquid is introduced as a fulcrum in the balance mechanism.

The gravity  $F_{\text{grav}}$ , derived from the loading frame, the coil, and others, is balanced by the buoyancy  $F_{\text{buoy}}$ . It is thought that a precise sensitivity limit (high resolution) can be obtained by using the buoyancy of the liquid. Therefore, the electromagnetic force  $F$  can be loaded to a microforce transducer to be calibrated.

Figure 3 shows a design of the linear-motion type microforce generating machine. Figure 4 shows a photograph of the machine under development. It mainly consists of a loading frame, a clamp, a coil, a cylindrical permanent magnet, a linear stage, a liquid container, two linear encoders, and an XYZ stage. The coil is fastened to the loading frame. Figure 5 shows a photograph of the control system of the microforce generating machine. Three drivers are connected to the motors used in the clamp, the linear stage, and the XYZ stage separately. A programmable logic controller is used to control the drivers. In the dynamic mode, the linear stage is used to move the magnet and the clamp fixes the coil so that it does not move. The linear encoders are used to measure and monitor the position of the magnet, the loading frame. In the static mode, the clamp releases the coil, and a microforce transducer is installed on the top of the XYZ stage in contact with the loading frame to create an initial stage of the microforce measurement. Then we can pass an electric current supplied by the source measure unit through the coil to generate a required microforce and load the microforce on the microforce transducer.

We discussed possible uncertainty components of realising microforce by the principle and the design. We will consider the proportional constant  $Bl$  relative to the induced electromotive force  $U$  and constant velocity  $v$ , the current  $I$  applying to the coil, and the sensitivity limit of balance mechanism using liquid buoyancy  $F_{\text{buoy}}$  as the less-friction fulcrum in the evaluation of uncertainty.

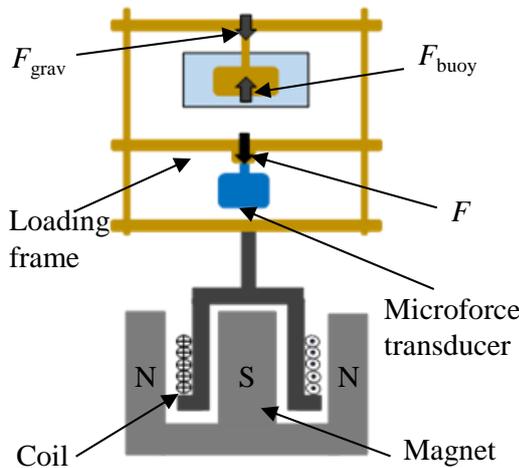


Figure 2: Schematic diagram of the microforce generating machine

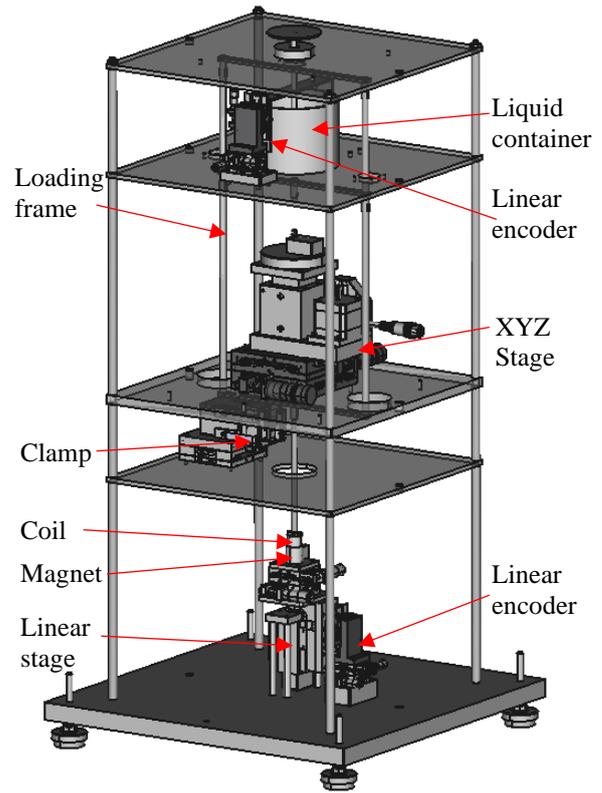


Figure 3: Design of the microforce generating machine

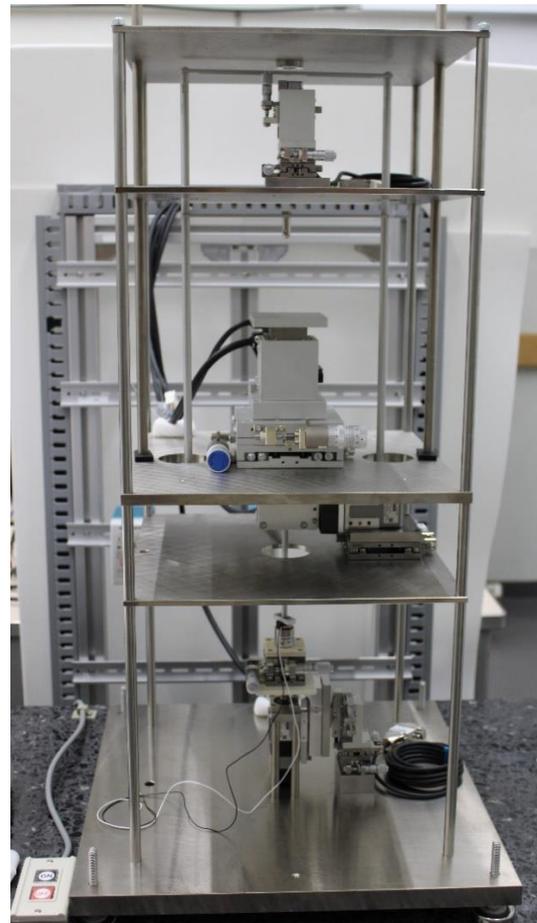


Figure 4: Photograph of the microforce generating machine under development



Figure 5: Photograph of the control system of the microforce generating machine under development

### 3. SUMMARY

We designed a linear-motion type microforce generating machine by combining the principle of Kibble balance and liquid buoyancy. The machine is being assembled. We plan to conduct a performance test after the machine is completed. We expect that it will improve the reliability of microforce measurement in the future by using the new linear-motion type microforce generating machine.

### 4. ACKNOWLEDGEMENT

This work was supported by JSPS KAKENHI Grant Number JP 21K14176.

### 5. REFERENCES

- [1] M. S. Kim, J. R. Pratt, U. Brand, C. W. Jones, "Report on the first international comparison of small force facilities: a pilot study at the micronewton level", *Metrologia* vol. 49, no. 1, pp. 70-81, 2012.  
DOI: [10.1088/0026-1394/49/1/011](https://doi.org/10.1088/0026-1394/49/1/011)
- [2] B. P. Kibble, "A measurement of the gyromagnetic ratio of the proton by the strong field method", *Atomic masses and fundamental constants 5*, pp. 545-551, 1976.  
DOI: [10.1007/978-1-4684-2682-3\\_80](https://doi.org/10.1007/978-1-4684-2682-3_80)
- [3] B. P. Kibble, I. A. Robinson, J. H. Belliss, "A Realisation of the SI Watt by the NPL Moving-coil Balance", *Metrologia*, vol. 27, no. 4, pp. 173-192, 1990.  
DOI: [10.1088/0026-1394/27/4/002](https://doi.org/10.1088/0026-1394/27/4/002)
- [4] C. Rothleitner, J. Schleichert, N. Rogge, L. Günther, S. Vasilyan, F. Hilbrunner, D. Knopf, T. Fröhlich, F. Härtig, "The Planck-Balance - using a fixed value of the Planck constant to calibrate  $E_1/E_2$ -weights", *Meas. Sci. Technol.*, vol. 29, no. 7, 074003 (9 pp), 2018.  
DOI: [10.1088/1361-6501/aabc9e](https://doi.org/10.1088/1361-6501/aabc9e)
- [5] L. Chao, F. Seifert, D. Haddad, J. Pratt, D. Newell, S. Schlamminger, "The performance of the KIBB-g1 tabletop Kibble balance at NIST", *Metrologia*, vol. 57, no. 3, 035014 (10 pp), 2020.  
DOI: [10.1088/1681-7575/ab507d](https://doi.org/10.1088/1681-7575/ab507d)
- [6] J. F. Zhu, T. Hayashi, A. Nishino, K. Ogushi, "Development of a novel microforce-generating machine based on a force generation method using electromagnetic force", *Meas. Sci. Technol.*, vol. 33, no. 1, 015010 (10 pp), 2022.  
DOI: [10.1088/1361-6501/ac2e2f](https://doi.org/10.1088/1361-6501/ac2e2f)