Review of the Levitation Mass Method (LMM)

Yusaku Fujii

***Abstract*—** The present status and the future prospects of a method for precision mass and force measurement, the levitation mass method (LMM), are reviewed. The LMM has been proposed and improved by the author. In the LMM, the inertial force of a mass levitated using a pneumatic linear bearing is used as the reference force applied to the objects under test, such as force transducers, materials or structures. The inertial force of the levitated mass is measured using an optical interferometer. Major applications of the LMM, such as dynamic calibration for force transducers, material testers without use of force transducers and the mass measurement device (MMD) for use in the International Space Station (LMM), are reviewed.

***Keywords*—** Levitation Mass Method, Dynamic force correction; Impact force; Force transducer; Inertial force; Inertial mass; Optical interferometer; Levitation Mass Method.

I. Introduction

FORCE, one of the most basic mechanical quantities, is usually measured using force transducers which are usually calibrated by using static method. In other words, the dynamic force generated by actuators or materials can't be accurately measured by transducers. So far, no standard dynamic calibration method for force transducers has been established. Two major problems are existence: (1) the uncertainty in the measured value of the varying force is difficult to estimate. (2) the uncertainty in the time at which the measured varying force is also difficult to evaluate.

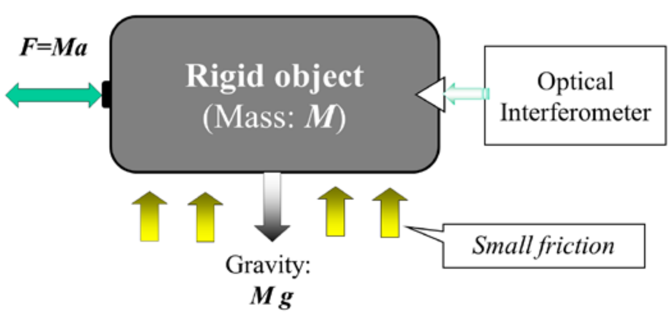

Fig. 1 Principle of the Levitation Mass Method

A method "Levitation Mass Method" (LMM) has been put forward by the authors for dynamic measurement and calibration. In the LMM, a mass is levitated by a pneumatic linear bearing with sufficiently small friction. Fig.1 shows the principle of the Levitation Mass Method (LMM). The Doppler shift frequency of laser beam measured by using an optical interferometer is used to calculate position, velocity and acceleration of mass. The dynamic force $\boldsymbol{F}$ is calculated as: $\boldsymbol{F}=-\boldsymbol{Ma}$ which $\boldsymbol{a}$ is the acceleration. This method has been applied to all the three categories of the dynamic force calibration such as: dynamic calibration method under impact load [1], the dynamic calibration method under oscillation load [2] and the dynamic calibration method under step load [3]. The LMM is also applied to evaluate the viscoelasticity of material under an oscillating load [6] and an impact load [7,8], material friction [9,10], biomechanics [11-12], dynamic performance of a liner motor [13], mass in the International Space Station (ISS) [14-18], dynamic response of an impact hammers [19] and micro-Newton level forces [20-23]. The LMM is also used to investigate the frictional characteristics of pneumatic linear bearings [24,25] and the linear ball bearing [26,27,41]. A pendulum mechanism [28] and a frequency measurement technique [29-31] have been developed to improve LMM, and the effect of the inertial mass on dynamic force measurements has been proposed based on LMM [32-34]. The optical interferometer also has been improved [35-37], such us dual beat-frequencies laser Doppler interferometer for removing the velocity limitation [38] and for two-dimensional directional discrimination [39,40].

In this paper, the dynamic force calibration method for force transducers is explained as an example of the applications of the Levitation Mass Method (LMM).

II. Dynamic Force Calibration

For dynamic force calibration, the inertial force of a mass is used as the known dynamic force, and this reference force is applied to a force transducer under test. The inertial force is measured by an optical interferometer as the product of mass and acceleration.

Fig.2 shows a schematic diagram for force transducer calibration under impact force. The force transducer under test is firmly attached to the base. A metal block combined with a corner-cube prism (CC) and a damper is considered as a moving part which is levitated by an aerostatic linear bearing. A Zeeman-type He-Ne laser is used as the light source of the optical interferometer. This laser has a pair orthogonal polarize light with frequency difference 2.6MHz. The light from the laser is divided into two beams, signal and reference beam, by a polarizing beam splitter (PBS). The signal beam is introduced to the moving part and reflected by the CC of moving part. The reference beam is reflected by a CC which is statically. Two beams interfere at a photodiode (PD) after through a Glan-Thompson prism. Two frequency counters (Advantest R5363) are used to calculate the beat frequency fbeat and rest

Department of Electronic Engineering, Faculty of Engineering, Gunma University 1-5-1 Tenjin-cho, Kiryu, 376-8515, Japan (fujii@el.gunma-u.ac.jp)

frequency frest which is equal to fbeat when the moving part is statically. The output of the force transducer is measured by a digital voltmeter (DVM, HP3458A).

The force acting on the force transducer from the moving part is equal to its inertial force according to the law of inertia if other forces, such as the frictional force inside the bearing, can be ignored. In this condition, the force acting on the moving part from the force transducer can be identified as: $\boldsymbol{F} = \boldsymbol{M}\ \boldsymbol{a}$. The acceleration is calculated from the velocity of the moving part which is measured as Doppler shift frequency of the signal beam of a laser interferometer, f_{Doppler}, which can be expressed as:

$$\boldsymbol{v} = \lambda_{\mathrm{air}}\ (f_{\mathrm{Doppler}})/2,$$

$$f_{\mathrm{Doppler}} = -\ (f_{\mathrm{beat}} - f_{\mathrm{rest}}),$$

where λ_{air} is the wavelength of the signal, f_{beat} is the beat frequency, i.e., the frequency difference between the signal beam and the reference beam, f_{rest} is the rest frequency which is the value of f_{beat} when the moving part is at a standstill, and the direction of the coordinate system for the velocity, the acceleration and the force acting on the moving part is towards the right in Fig. 1.

The two frequency counters are triggered by means of a sharp trigger signal generated using a digital to analog converter. This signal is initiated by means of a light switch, a combination of a laser-diode and a photodiode.

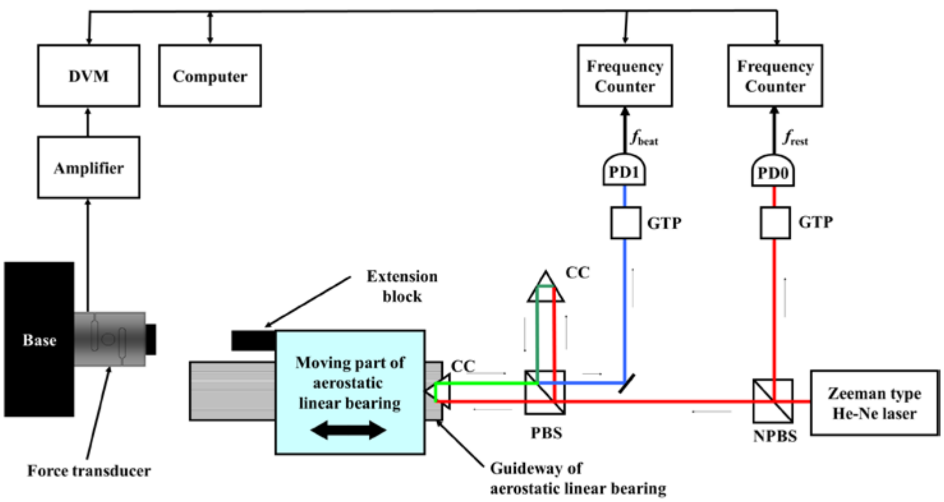

Fig. 2. Experimental setup for transducer calibration. Code: CC= cube corner prism, PBS= polarizing beam splitter, NPBS= non- polarizing beam splitter, GTP= Glan-Thompson prism, PD= photo diode, DVM=digital voltmeter.

III. Results

Fig. 3 shows the force measured by the force transducer based on the static calibration $\boldsymbol{F}_{\mathrm{trans}}$ and the force measured by the Levitation Mass Method as the inertial force of the moving mass $\boldsymbol{F}_{\mathrm{mass}}$. Their difference $\boldsymbol{F}_{\mathrm{diff}} = \boldsymbol{F}_{\mathrm{trans}} - \boldsymbol{F}_{\mathrm{mass}}$ is also shown in Fig.1. The difference is thought to come from the difference of the static characteristics and the dynamic characteristics of the force transducer.

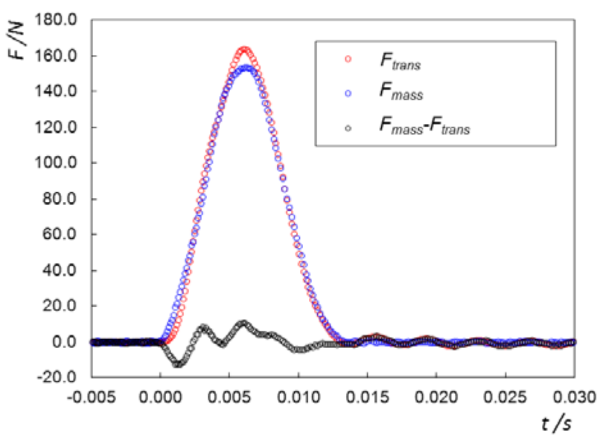

Fig. 1 Force measured by transducer and proposed method

IV. Discussion

A design for realizing a low cost instrument is now also planning to be developed. In this case, a laser diode is used instead of a Zeeman-type two-frequency He-Ne laser and a pendulum is used instead of a pneumatic linear bearing.

The author would like to develop the following technologies and make them being commercialized.

Dynamic calibration method for force transducers: With this, the correction and the uncertainty evaluation of the measured forces with arbitrary waveform can be possible.

High precision material tester based on the LMM: In the tester, only the Doppler shift frequency is measure. Neither a force transducer nor a position sensor is used. Force is calculated according to its definition, that is the product of mass and acceleration.

There is still much room for further improvement as described in the paper.

V. Conclusions

The present status and the future prospects of a method for precision mass and force measurement, the levitation mass method (LMM), are reviewed. The LMM has been proposed and improved by the author. In the LMM, the inertial force of a mass levitated using a pneumatic linear bearing is used as the reference force applied to the objects under test, such as force transducers, materials or structures. The inertial force of the levitated mass is measured using an optical interferometer. Major applications of the LMM, such as dynamic calibration for force transducers, material testers without use of force transducers and the mass measurement device (MMD) for use in the International Space Station (LMM), are reviewed.

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Yusaku Fujii was born in Tokyo, japan, in 1965. He received the B. E., M.E., and Ph.D. degrees from Tokyo University, Tokyo, Japan, in 1989, 1991 and 2001, respectively.

In 1991, he joined Kawasaki Steel Corporation. In 1995, he moved to the National Research Laboratory of Metrology, Tsuskuba, Japan, where he studied the replacement of the kilogram using superconducting magnetic levitation. In 2002, he moved to Gunma University, Kiryu, Japan, where he was invented and studied the levitation mass method as precision force measurement method.