Material tester with static and dynamic micro forces

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Abstract

Material testers with static and dynamic micro forces based on the Levitation Mass Method (LMM) are reviewed. 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. The previous achievements and the future prospects on the methods of generating and measuring the static and dynamic micro-Newton level forces based on the LMM are discussed.

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1. Introduction

The requirements for evaluating small force in the range of 1\textmu N to 1N have increased in industrial and research fields. However, it is difficult to evaluate small force, properly. The difficulties mainly come from the following reasons.

Any method for measuring micro-Newton level forces has not yet been established even for static force. Some methods for supporting a direct realization of micro-Newton level forces linked to the International System of Units (SI) below 1 N are currently being developed by some institutes.

Small force to be measured is usually a varying force and any dynamic calibration technique for force sensors has not yet been established. In other words, this fact means that both the uncertainty evaluation for the measured value of the small force and the uncertainty evaluation for the time of the measurement are very difficult.

The author has proposed a method, the Levitation Mass Method (LMM). Figure 1 shows the principle of the LMM. In the LMM, the inertial force of a mass levitated using a pneumatic linear bearing is used as the reference

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force applied to the objects under test, such as force transducers, materials or structures. The inertial force of the levitated mass is accurately measured using an optical interferometer.

The author has modified it as calibration methods for three categories of the dynamic force calibration [1-3], that are the 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 way to establishment of the dynamic force calibration system has been discussed [4]. A method for evaluating the electrical and mechanical responses of force transducers has been proposed and a novel finding has been obtained [5]. Based on the novel finding, a method for correcting the dynamic force error has been proposed [6].

The authors have applied the LMM for material testing, such as methods for evaluating material viscoelasticity under an oscillating load [7] and under an impact load [8], methods for evaluating material friction [9] and friction coefficient [10], a method for evaluating biomechanics [11,12], a method for measuring the body mass of astronaut [13-15], and a method for evaluating dynamic response of impact hammers [16].

The author has also applied the LMM as a method for generating and measuring a micro-Newton level forces [17-20], a method for investigating the frictional characteristics of pneumatic linear bearings [21,22] and the linear ball bearing [23].

To improve the efficiency of the LMM, a pendulum mechanism [24] for use as a substitute of a pneumatic linear bearing and a frequency measurement technique [25-27] using a digitizer instead of an electronic frequency counter have been developed.

2. Dynamic Small Forces

In this section, methods for measuring dynamic small forces proposed based on the LMM are discussed [17, 18,20].

Figure 1 shows a schematic diagram of the experimental setup for evaluating the mechanical response of an actuator arm of a hard disk drive (HDD) against an impact load. The inertial force of a moving mass is used as the reference force applied to the material under test. An aerostatic linear bearing is used to obtain linear motion with negligible friction acting on the mass, i.e., the piston-shaped moving part of the bearing. The impact force is generated and applied to the object under test by collision with the mass. An initial velocity is manually given to the
moving part. A corner-cube prism (CC), that forms part of the interferometer, and a metal block with a round-shaped tip are attached to the moving part (made in aluminum with square pole shape); its total mass $M$ is approximately 21.18 g. The inertial force acting on the mass is measured highly accurately using an optical interferometer. The arm under test is attached to the movable metallic base.

The total force acting on the moving part $F$ is the product of its mass $M$ and its acceleration $a$,

$$F = Ma.$$ 

The acceleration is calculated from the time-varying velocity of the moving part.

An optical interferometer was used to accurately measure the velocity. The light source used was a Zeeman-type two-wavelength He-Ne laser in which the two wavelengths had orthogonal polarization. The interfering beams were incident on a detector PD1 and resulted in a beat signal, since the beams had slightly different wavelengths. The rest frequency, $f_{\text{rest}}$, was measured with detector PD2. When the object was at rest, then $f_{\text{beat}} = f_{\text{rest}}$ was approximately 2.7 MHz.

The mass velocity was obtained by measuring the induced Doppler shift in the signal beam of the laser interferometer and by using the following equations,

$$v = \frac{\lambda_{\text{air}} f_{\text{Doppler}}}{2},$$

$$f_{\text{Doppler}} = f_{\text{beat}} - f_{\text{rest}},$$

where $f_{\text{Doppler}}$ is the Doppler shift, $\lambda_{\text{air}}$ is the wavelength of the signal beam in the air, $f_{\text{beat}}$ is the beat frequency, $f_{\text{rest}}$ is the rest frequency defined above.

The aerostatic linear bearing, “GLS08A50/25-2571” (NSK Co., Ltd., Japan), was attached to an adjustable tilt stage. The tilt angle of the tilt stage can be adjusted by adjusting three compression and three tension bolts. The mechanism of the tilt stage is not shown in Figure 1.

Figure 2 shows the data processing procedure in a collision experiment. During the experiment, the beat frequency, $f_{\text{beat}}$, and the rest frequency, $f_{\text{rest}}$, are measured highly accurately using an optical interferometer. The Doppler shift frequency is taken as the difference between the beat frequency and the rest frequency. The velocity, position, acceleration and inertial force of the mass are calculated from the time-varying Doppler shift frequency.
afterward. The acceleration is obtained by differentiating the resultant velocity time history, while collision force (which is the inertial force of the mass) is calculated by $F = ma$.

Figure 3 shows the change in force acting on the mass from the arm under test, $F = Ma$, against time. In the collision experiment shown in Figure 3, the maximum value of the impact force, $F_{\text{max}}$, is approximately 15.7 mN.

Figure 4 shows the change in force acting on the mass from the arm under test, $F = Ma$, against position. The force varies roughly linearly with position.

3. Static Small Forces

In this section, methods for generating and measuring static small forces proposed based on the LMM are discussed [19].

The experimental setup is the same as shown in Figure 1. In the method, the down-slope component of gravity acting on a mass on an inclined plane is used as a static force. An aerostatic linear bearing is used to realize linear motion with a small friction acting on the mass, i.e., the moving part of the bearing. The moving part is made of aluminum and with square pole shape; its total mass, $M$, is approximately 21.03 g. The inertial force acting on the
mass is measured highly accurately using an optical interferometer. An arm of a hard-disk drive (HDD) is used as a spring element to which the generated static small-force is applied.

The tilt angle of the upper stage is roughly measured using an autocollimator with a standard uncertainty of approximately 10 seconds (50 μrad), which corresponds to the down-slope component of gravity acting on the mass of approximately 10 μN. The origin of the tilt angle is set so that the moving part of the bearing is at a standstill. As for the direction of the angle, the counterclockwise direction in Figure 1 is positive. The direction of the coordinate system for velocity, position, acceleration and force is toward the right in Figure 1.

In the experiment, tilt angle is set to be 3 min (0.87 mrad). The velocity of the mass is measured as the Doppler shift frequency of the signal beam using an optical interferometer. The measurement procedure is as follows: first, the mass is released around the right side of the guide way and then it moves leftward due to gravity, collides with
the arm of the HDD, and bounces back from it. This movement is damped oscillation. Finally the mass reaches a standstill, where the down-slope component of gravity acting on the mass balances the force generated by the spring element.

Figure 5 shows the change in position against time. 40 positive peaks of force are observed during the measurement period of 48 s. This region is indicated in Figure 5 as “Oscillation with free fall”. After “Oscillation with free fall”, the moving part does not move away from the HDD arm during the oscillation; this region is indicated in Figure 5 as “Standstill”.

Figure 6 shows the changes in force against time. When the moving part is in the free fall motion along the slope apart from the arm of the HDD, the total force $F_{\text{mass}} = F_{\text{regression}}$ is supposed to be expressed as

$$F_{\text{regression}} = F_{\text{gravity}} + F_{\text{air}} = A_1v + A_2x + A_3$$

Three coefficients $A_1$, $A_2$ and $A_3$ can be determined by the least-squares method.

4. Discussions

The proposed method of static small-force generation and measurement [19] is based on the method of dynamic small-force generation and measurement [17,18,20]. The instrument shown in Figure 1 is capable of generating and measuring both dynamic small-forces and static small-forces. In this respect, the proposed method is the only method with such capability that has been proposed.

The micro-force material tester based on the LMM described in the paper can be used not only for evaluating the mechanical properties of the materials but also for calibration force transducers against static and dynamic small forces.

The following subjects are to be developed to improve the accuracy and efficiency of the Levitation Mass Method (LMM).

Correction method of the friction acting inside the air-bearing

Evaluation and correction of the friction acting inside the air-bearing is necessary for more accurate measurement of smaller forces. The improvement of developed methods [21,22] are planed.

Introduction of single frequency laser

In the experimental setup shown in Figure 1, an expensive Zeeman type He-Ne laser are used as the light source. To realize a low cost instrument, the introduction of single frequency He-Ne laser will be effective.

Frequency estimation method

The zero-crossing averaging method (ZAM) and zero-crossing fitting method (ZFM) have recently been proposed by the author [25-27]. These methods are expected to be very effective for improving both the sampling rate and resolution of frequency measurement of the proposed method of generating and measuring static small-force. The improvement of ZAM and ZAF is the key to improve both the sampling rate and resolution of frequency measurement of the proposed method.

Introduction of linear motor

To realize the easy-to-use material tester, the introduction of liner motor (liner actuator) is essential.

Introduction of constant-temperature box

In the material testing, the temperature is important. The controlled constant-temperature box is strongly required in testing some material, such as visco-elastic materials.

Smaller linear air bearing

In the experiment, the mass of the moving part is approximately 20 g. It has a large load capacity of 1 kg, resulting in a relatively large amount of airflow. Development of a small aerostatic linear bearing with a moving mass of approximately 1 g and with a much smaller load capacity will be possible.

The authors believe that the Levitation Mass Method (LMM) will be the key to improve the accuracy and efficiency of the small force measurement in the future.

5. Conclusion

Material testers with static and dynamic micro forces based on the Levitation Mass Method (LMM) are reviewed. 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. In this paper, the previous achievement and the future prospects on the methods of generating and measuring the static and dynamic micro-Newton level forces based on the LMM are discussed.

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