The Levitation Mass Method: A Precision Mass and Force Measurement Technique

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The present status and future prospects of the levitation mass method (LMM), a technique for precision mass and force measurement, 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 being tested, such as force transducers, materials, or structures. The inertial force of the levitated mass is measured using an optical interferometer. We have modified this technique for dynamic force calibration of impact, oscillation, and step loads. We have also applied the LMM to material testing, providing methods for evaluating material viscoelasticity under an oscillating or impact load, evaluating material friction, evaluating the biomechanics of a human hand, and generating and measuring micro-Newton-level forces.

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1. Introduction

Although a force is one of the most basic mechanical quantities and is usually measured using force transducers, a suitable dynamic calibration method for force transducers has yet to be established. The lack of dynamic force calibration methods results in two major problems in material testing: it is difficult to evaluate the uncertainty in the measured value of the varying force, and it is difficult to evaluate the uncertainty in the time at which the varying force is measured.

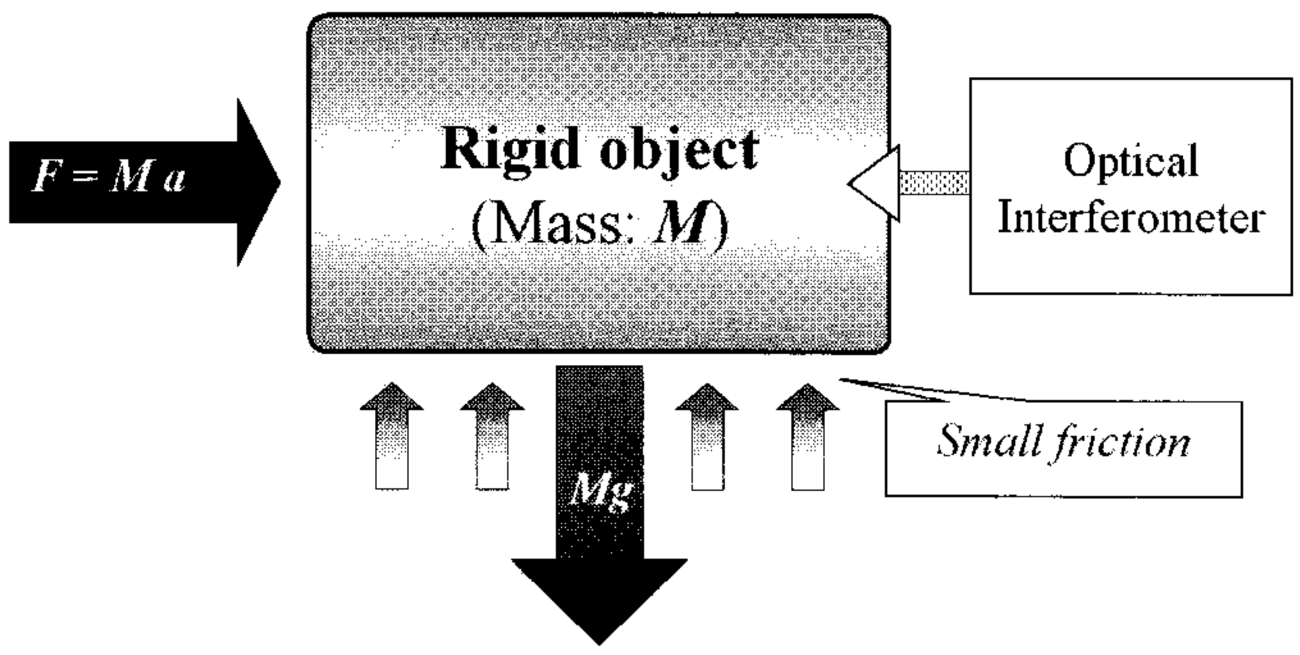

Fig. 1 Principle of the LMM

In previous studies, we proposed a levitation mass method (LMM),[1-10] in which the inertial force of a mass levitated by a pneumatic linear bearing is used as the reference force applied to the objects being tested, such as force transducers, materials, and structures. Figure 1 illustrates the principle of the LMM. The inertial force of the levitated mass is measured using an optical interferometer. Only the motion-induced time-varying beat frequency is measured; all the other quantities, such as velocity, position, acceleration, and force, are subsequently evaluated numerically. This results in good synchronization between the obtained quantities. The force is calculated directly according to its definition, *i.e.*, the product of mass and acceleration.

In this paper, the present status and possible applications of the LMM are discussed.

2. Dynamic force calibration using the LMM

Application of the LMM to the dynamic calibration of force transducers is discussed in this section. Figure 2 shows the experimental setup for measuring the electrical and mechanical responses of a force transducer against an impact load.[7] A conventional S-shaped strain-gauge force transducer with a nominal force of 200 N is attached to the base.

The velocity of the mass v_1 is measured by Interferometer 1; then the position x_1, acceleration a_1, and force acting on the mass F_{mass} are calculated. The velocity of the sensing element of the force transducer v_2 is measured by Interferometer 2; then the position x_2 and acceleration a_2 are calculated. The electrical response of the transducer is measured using a digital voltmeter (DVM). The electrical and mechanical responses of force transducers against impact loads can be evaluated simultaneously using this technique.

Figure 3 shows the force measured by the force transducer and that obtained using the proposed method. Recently, we found that the error in dynamic force measurements was almost proportional to the acceleration at the sensing point of the transducer. This can be explained as the effect of the inertial force of part of the transducer itself.[9]

From the relationship between the acceleration of the sensing point a_2 and the difference between the values measured by the

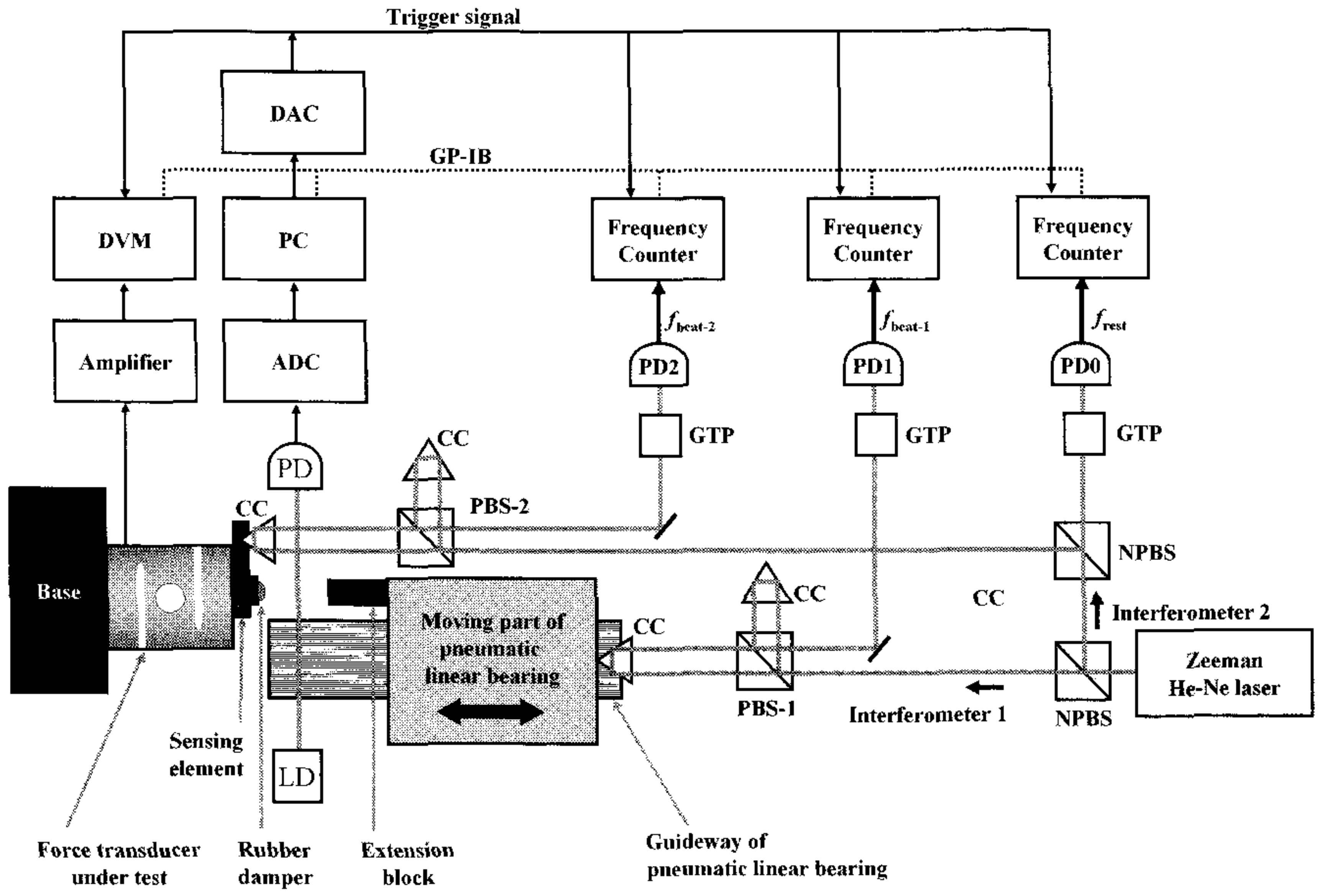

Fig. 2 Experimental setup. Code: CC = cube corner prism, PBS = polarizing beam splitter, NPBS = non-polarizing beam splitter, GTP = Glan-Thompson prism, PD = photo diode, LD = laser diode, ADC = analog-to-digital converter, DAC = digital-to-analog converter

transducer and those measured by the proposed method, $F_{diff} = F_{trans} - F_{mass}$, the regression line $F_{reg} = F_{trans} - F_{mass} = 0.325\ a_2$ can be estimated. The inclination of the line, 0.325, is the estimated effective inertial mass of the transducer, $M_{estimated}$.

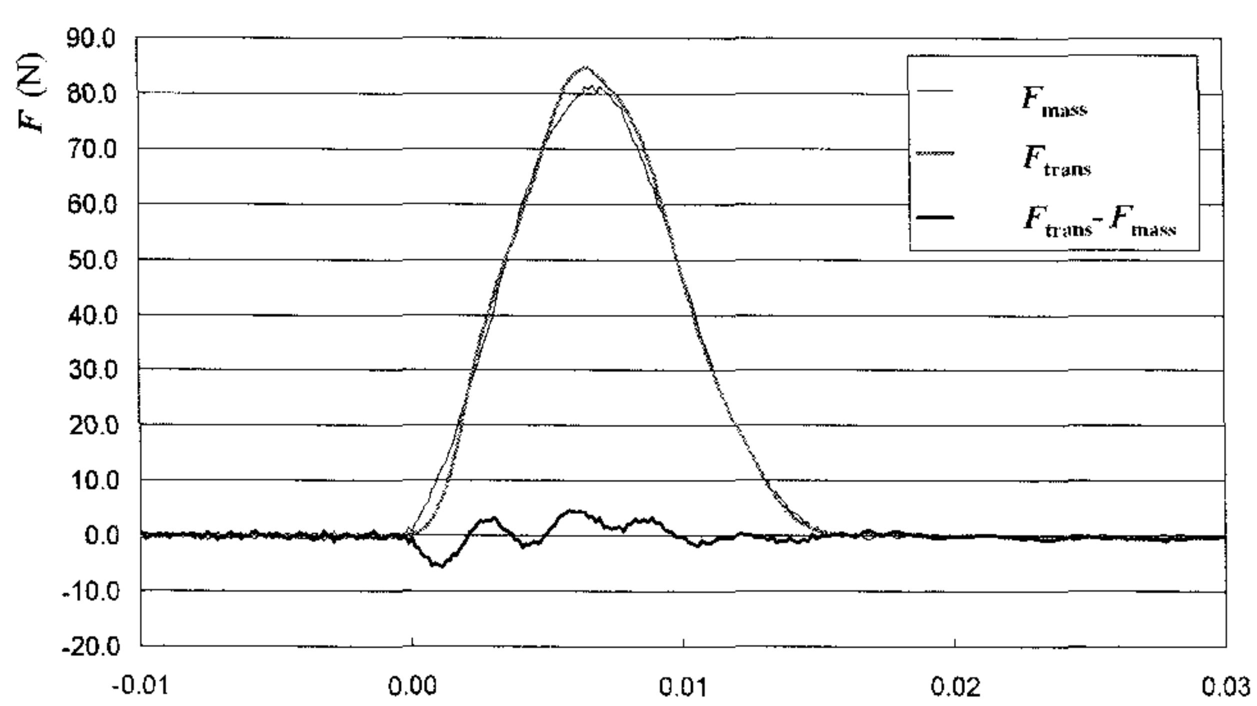

Fig. 3 Force measured by the force transducer and that obtained using the proposed method

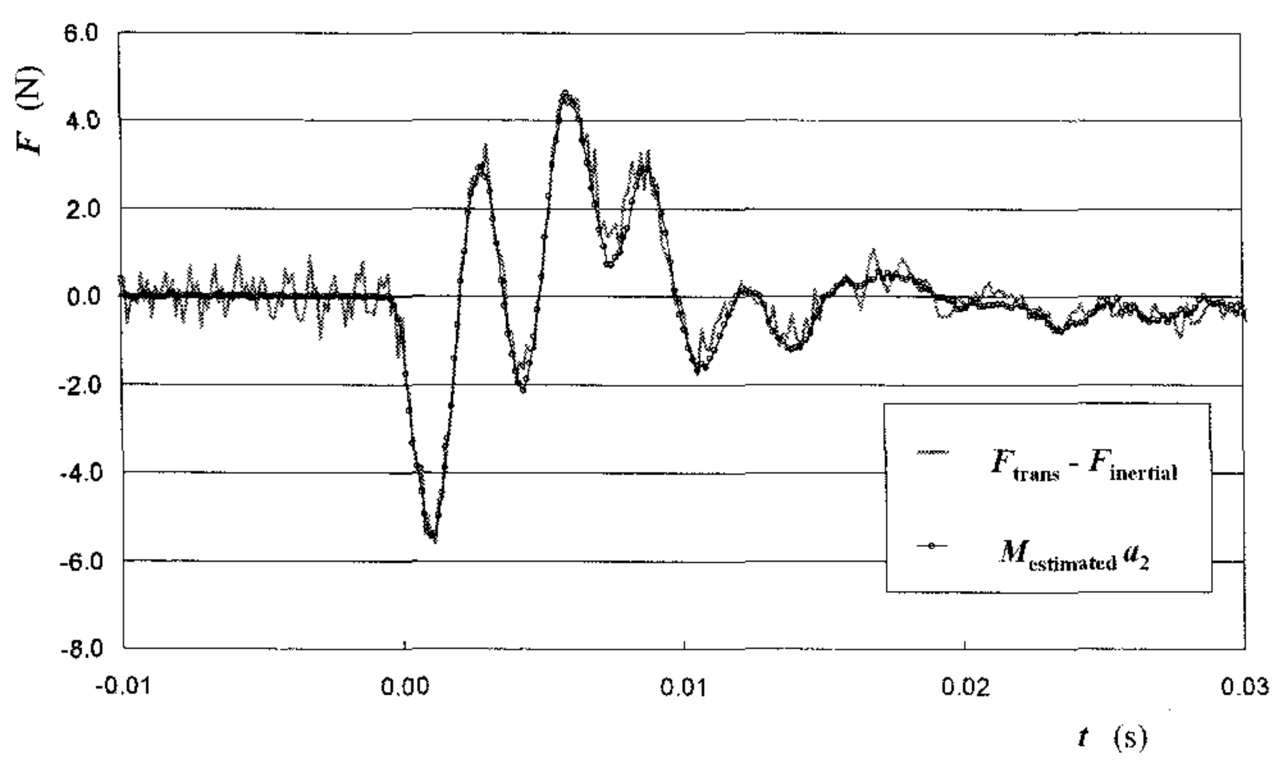

Fig. 4 Difference between the values measured by the transducer and those measured by the proposed method, and the estimated inertial force of the sensor element

Figure 4 shows the difference between the values measured by the force transducer and those obtained using the proposed method, and the estimated inertial force of the sensor element. The two curves, $F_{diff} = F_{trans} - F_{mass}$ and $F_{reg} = 0.325\ a_2$, showed a good degree of correspondence.

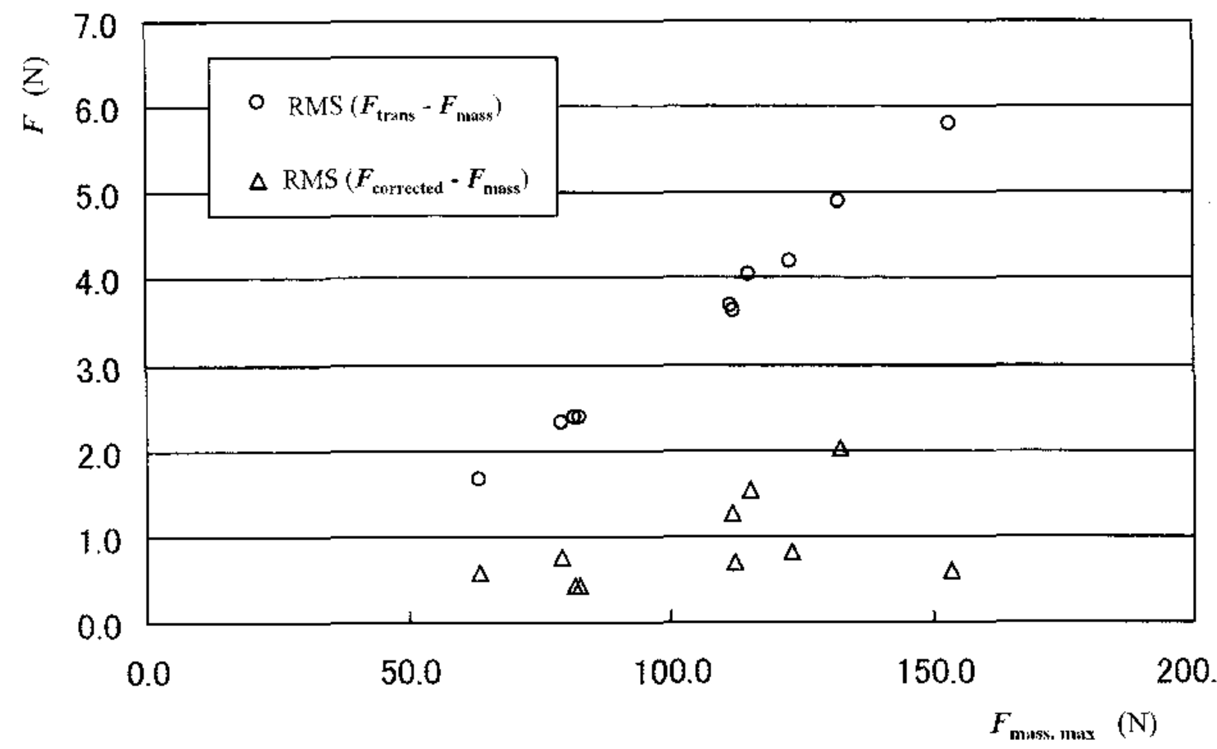

Fig. 5 RMS values of the errors of the measured forces with and without the inertial force correction

Figure 5 shows the root mean square (RMS) values of the errors of the measured forces with and without the inertial force correction. The coefficient of the regression line obtained from the previous single collision measurement was used for the correction. A significant improvement in the measurement error was obtained by using the correction.

3. Material testing using the LMM

This section presents a discussion of application of the LMM to material testing. A novel practical method of characterizing the mechanical response of viscoelastic materials against impact loading is proposed. The mechanical quantities of the material during the impact were measured accurately using the LMM and formulated by the least squares method.

Figure 6 shows a schematic diagram of the experimental setup used to characterize the mechanical responses of viscoelastic materials against impact forces. The material being tested is attached to the base. An aerostatic linear bearing is used to obtain linear motion, with negligible friction acting on the mass (*i.e.*, the moving part of the bearing). An impact force is generated and applied to the material by inducing a collision with the moving mass. An initial velocity is manually applied to the moving part. A corner cube prism, CC, and a metal block with a rounded tip (curvature radius: 10 mm) are attached to the moving part; the total mass, M, is approximately 3.98 kg. The inertial force acting on the mass is measured accurately using an optical interferometer. In this example, a rubber block (16 mm in diameter and 3 mm in thickness) is tested. The rubber block is attached to the base using an adhesive.

The total force acting on the moving part, F_{mass}, is calculated as the product of its mass, M, and its acceleration, a. The acceleration is calculated from the velocity of the mass. The velocity is calculated from the measured value of the Doppler shift frequency of the signal beam of a laser interferometer, $f_{Doppler}$, which can be expressed as:

$$v = l_{air}\,(f_{Doppler})\,/\,2,$$
$$f_{Doppler} = -\,(f_{beat} - f_{rest}), \quad (1)$$

where l_{air} is the wavelength of the signal beam under the experimental conditions, f_{beat} is the beat frequency, *i.e.*, the frequency difference between the signal beam and the reference beam, and f_{rest} is the rest frequency, which is the value of f_{beat} when the moving part is at rest. The direction of the coordinate system for the velocity, position, acceleration, and force is toward the right in Fig. 6.

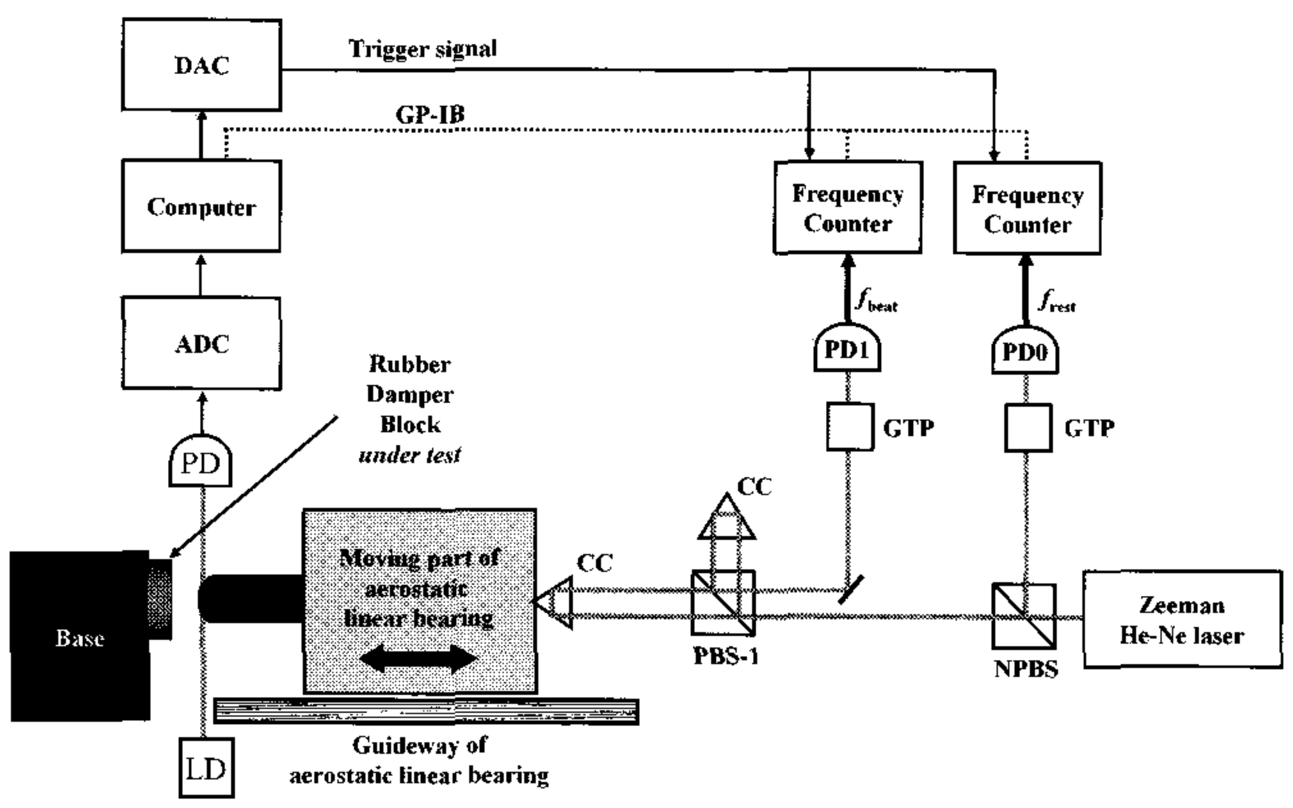

Fig. 6 Experimental setup. Code: CC = cube corner prism, PBS = polarizing beam splitter, NPBS = non-polarizing beam splitter, GTP = Glan-Thompson prism, PD = photo diode, LD = laser diode, ADC = analog-to-digital converter, DAC = digital-to-analog converter, PC = computer

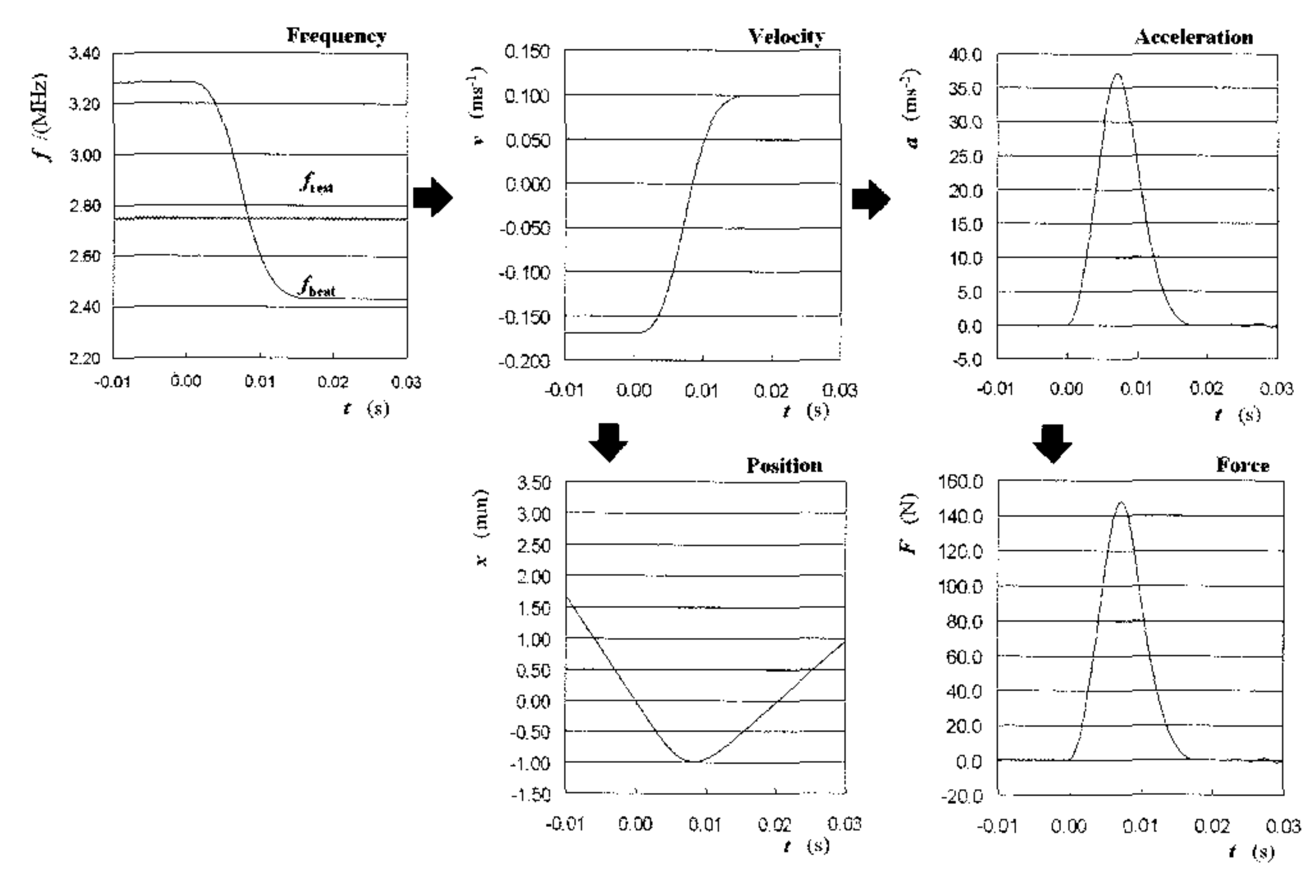

Fig. 7 Data processing procedure of the LMM: calculation of the velocity, position, acceleration, and force from the frequency

A Zeeman two-frequency He-Ne laser was used as the light source. The frequency difference between the signal beam and the reference beam, *i.e.*, the beat frequency, f_{beat}, was measured based on the interference fringe that appeared at the output port of the interferometer; it varied around f_{rest}, approximately 2.75 MHz, depending on the velocity of movement. An electronic frequency counter (model R5363; Advantest Corp., Japan) continuously measured and recorded the beat frequency, f_{beat}, 6000 times per sampling interval of $T = 400\ /\ f_{beat}$, and stored the values in its memory. This counter continuously measured the interval time every 400 periods without dead time. The sampling period of the counter was approximately 0.15 ms at a frequency of 2.75 MHz. Another electronic counter of the same model measured the rest frequency, f_{rest}, using the electrical signal supplied by a photodiode embedded inside the He-Ne laser.

Measurements using the two electronic counters were triggered by a sharp trigger signal generated using a digital-to-analog converter. This signal was initiated by a light switch, a combination of a laser diode and a photodiode. The origins of the time and position axes were set to the time and position at which the reaction force from the material being tested was detected. Ten sets of collision measurements were obtained.

Figure 7 shows the data processing procedure in the collision experiment. Only the time-varying beat frequency, f_{beat}, and the rest frequency, f_{rest}, were measured with a high degree of accuracy using an optical interferometer. The Doppler frequency shift was measured as the difference between the beat frequency and the rest frequency. The velocity, position, acceleration, and inertial force of the mass were calculated from the measured motion-induced time-varying beat frequency; this resulted in good synchronization between the obtained quantities.

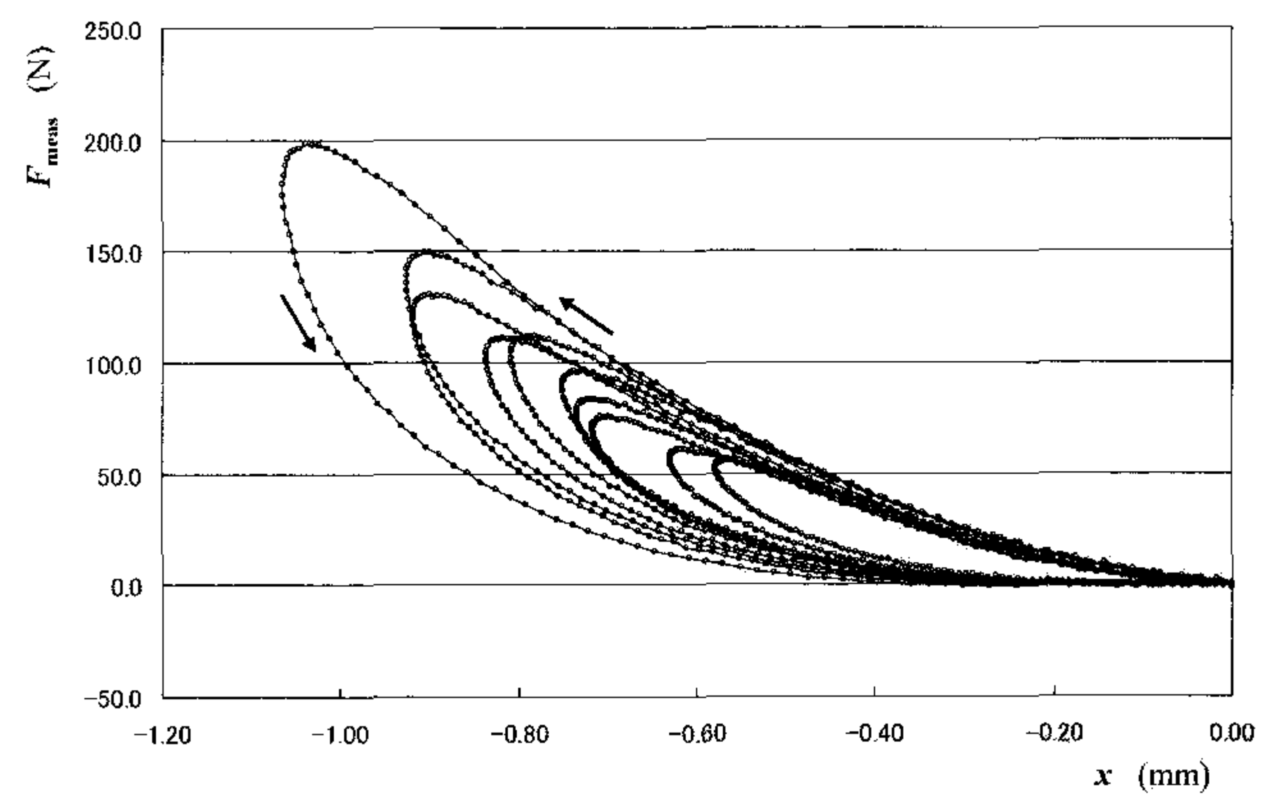

Fig. 8 Change in force measured using the optical interferometer against position

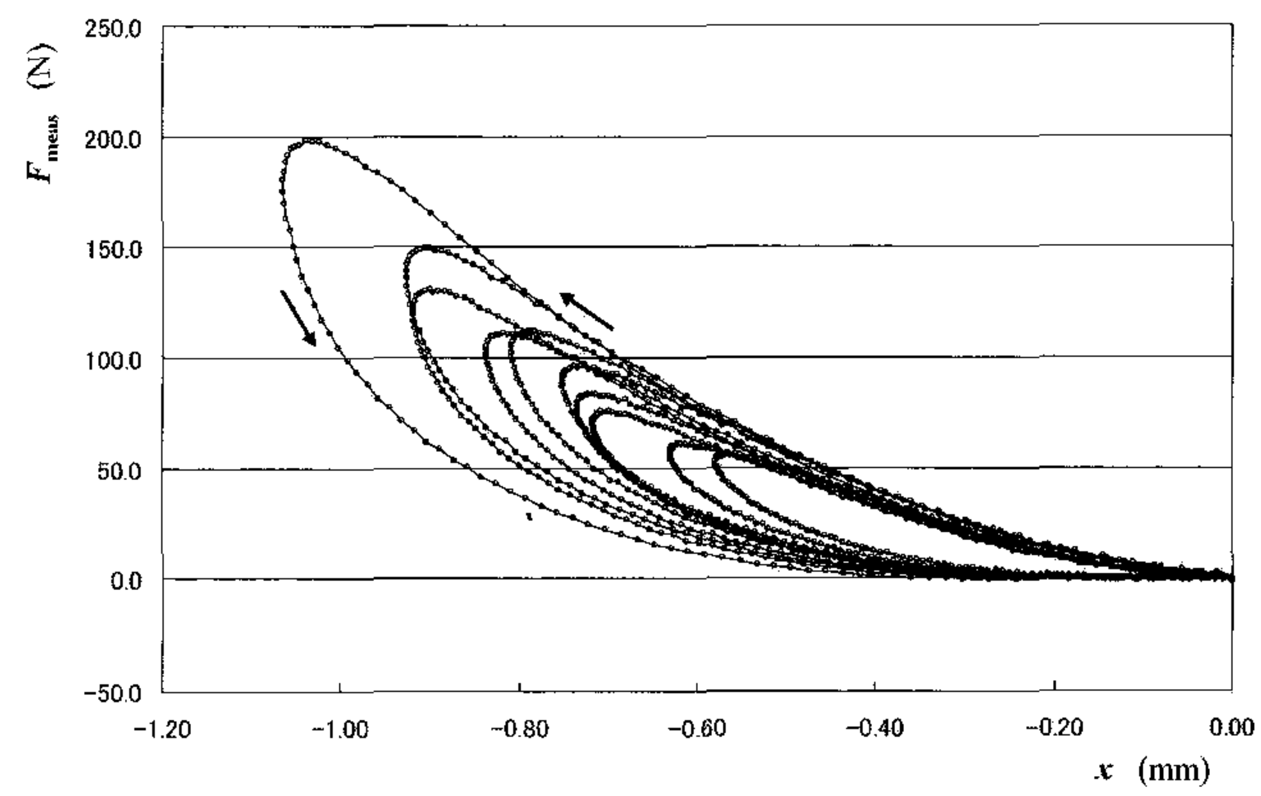

Fig. 9 Change in force calculated using the regression equation against position

Figure 8 shows the change in the force F_{mass} against the displacement x for all ten collision measurements. A total of 1490 plots are shown in the figure. Each plotted point represents a data set comprised of the time t, position x, velocity v, and force F_{mass} calculated from the corresponding data set comprised of the time t and frequency f. Elastic hysteresis, which is caused by the viscosity of the material, was clearly observed.

The coefficients of the following equation were determined by the least squares method:

$$\begin{aligned} F &= (ax + bx^3)(cv + d) + e \\ &= acxv + adx + bcx^3v + bdx^3 + e \\ &= Axv + Bx + Cx^3v + Dx^3 + E. \end{aligned} \quad (2)$$

The form of the equation was chosen by considering the velocity dependence and the non-linearity of the spring ratio observed from Fig. 3.

The results of regression analysis were as follows:

$$F_{regression} = (3.17\times10^2)\,xv + (-4.14\times10^1)\,x + (3.12\times10^2)\,x^3v + (-1.14\times10^2)\,x^3 + (-3.61\times10^0), \quad (3)$$

where the units of $F_{regression}$, x, and v are N, mm, and ms^{-1}, respectively.

Figure 9 shows the change in the force $F_{regression}$, calculated using the regression equation against the displacement x for all ten collision measurements.

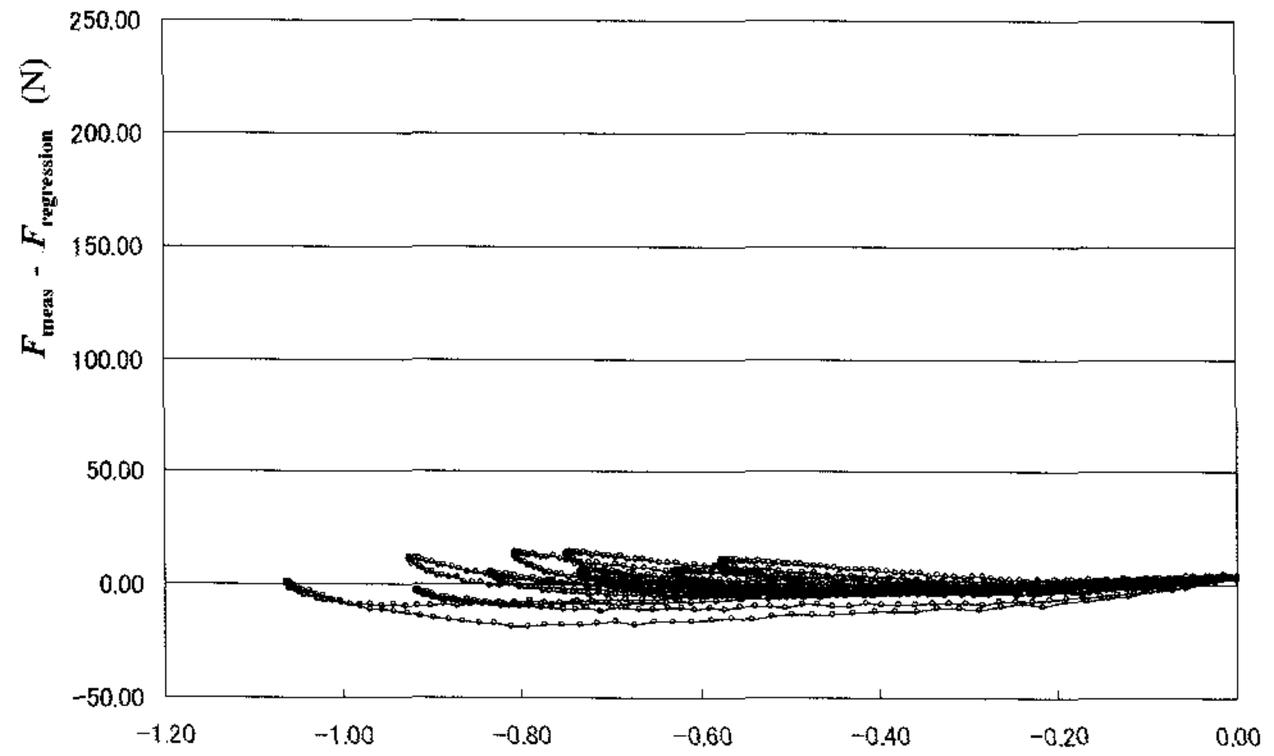

Fig. 10 Change in the residual force $F_{meas} - F_{regression}$ against position

Figure 10 shows the change in the residual force, $F_{mass} - F_{regression}$, against the position x. The RMS value of the residual force, $F_{mass} - F_{regression}$, was approximately 5.4 N, which corresponds to 0.5% of the maximum force, $F_{mass,\ max}$, of approximately 197.9 N shown in Fig. 8.

As a clear relationship between the residual force, $F_{mass} - F_{regression}$, against position x can be observed in Fig. 10, the supposed form of the regression equation for $F_{regression}$ is not perfectly appropriate. If a more appropriate regression equation for $F_{regression}$ is adopted, the RMS value of the residual force will be significantly reduced. In the experiment, the impact response of the rubber damper at the time of the collision with the rounded metal tip was determined. Using the proposed method, it is possible to characterize the impact response between any two objects, such as the collision of a rubber damper with a human body or the collision of a metal object with a plastic object, as long as one of these objects can be attached to the base and the other to the moving part of the bearing. In various industrial applications, the equation that macroscopically defines the impact response of the two objects involved can be obtained very efficiently. Such equations can be used directly to design industrial products.

4. Discussion

The following technologies can be used to improve the efficiency of the LMM and expand its applications.

(1) *Dynamic metrology,*[11,12] Recent dynamic metrology technology can be used to evaluate the uncertainty of the LMM effectively. To establish a dynamic force calibration method, the integration of some calibration methods using typical impact, oscillation, and step forces is required.

(2) *Numerical simulations for Hard Disk Drive (HDD) technology.*[13-16] The LMM provides a good technique for evaluating the dynamic properties of small mechanical parts, such as HDD. Such precision experimental data will contribute toward improving the efficiencies of the numerical simulation code and the product design.

(3) *Finite element method for modal analysis.*[17-19] A modal analysis of the mechanical parts of the experimental setup would be useful for evaluating the uncertainty of the LMM. At the same time, the data measured using the LMM would contribute to improving the finite element method for modal analyses.

(4) Biomechanics.[20,21] The LMM can measure the dynamic responses of the human body effectively, including the force controllability of human fingers and the viscoelasticity of human skin.

(5) Precision control technology,[5,22-26] Control technology of the levitated mass is essential for making automatic instruments based on the LMM, such as dynamic force calibration instruments and material testers. To apply a force of arbitrary size or a deformation of arbitrary shape to a material, the reference voltage signal supplied to the amplifier of the actuator must be properly controlled. Thus, *in situ* identification of the frequency transfer function of the entire electrical-mechanical system, including the material being tested, is required.

(6) Space medicine.[27-32] The LMM was very effective for developing an instrument to measure the body mass of astronauts under microgravity conditions.

(7) Coordinate measuring machine (CMM) technology. The LMM can accurately measure the force and position of a CMM sensing probe.

There have also been studies of dynamic calibration methods for force transducers.[30-32] Kumme proposed a method for calibrating transducers against oscillation forces.[33,34] In this method, both the mass and transducer are shaken at a single frequency using a shaker, and the inertial force of the mass is applied to the transducer. Park *et al.* used this method for dynamic investigation of multi-component force-moment sensors.[35] However, it has yet to be established how to apply the results of such dynamic calibration methods, including those proposed by our group, to actual wave profiles of varying forces.

5. Conclusions

The present status and future prospects of a method for precision mass and force measurement, the LMM, were reviewed. We expect that the LMM to become a key technique that can be used to improve and expand the technology of precision mass and force measurements in the near future due to the efforts and collaborations of many researchers in various fields.

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