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Proposal for material viscoelasticity evaluation method under impact load

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A novel practical method for evaluating the viscoelasticity of materials under impact load is proposed. The method is characterized by the fact that preparation of the test specimen is very easy and the testing time is very short. In the method, a mass that is levitated with a pneumatic linear bearing, and hence encounters negligible friction, is made to collide with a material under test. During the collision the Doppler frequency shift of a laser beam reflecting from the mass is accurately measured using an optical interferometer. The velocity, position, acceleration and inertial force of the mass are calculated from the measured time-varying Doppler shift. To demonstrate the high performance of the proposed method, the impact response of a gel block is highly accurately determined by means of the proposed method. *© 2005 Springer Science + Business Media, Inc.*

1. Introduction

Recently, the need for evaluating the mechanical properties of materials and structures under varying load have arisen in various industrial and research applications such as material testing, motion control and crash testing. In such evaluations, the force acting on the material under test is measured using a force transducer and the position of the point at which the force is acting on it is measured using a position transducer. However, force transducers are typically calibrated with standard static methods using static weights and under static conditions. At present there are no standard methods for evaluating the dynamic characteristics of force transducers. This results in the two major problems concerning material testing. One is that it is difficult to evaluate the uncertainty in the measured value of the varying force. The other is that it is difficult to evaluate the uncertainty in the time at which the varying force is measured.

Force is one of the most basic mechanical quantities and is defined as the product of mass and acceleration as:

$$F = Ma$$

where F is the force acting on an object, M is the mass of the object, and a is the acceleration of the center of the gravity of the object. This implies that a well-defined acceleration is required to obtain force accurately and to calibrate force transducers accurately.

Acceleration due to gravity, g, is conveniently used for generating and/or measuring constant force. Constant force can be accurately compared using a conventional balance with a knife-edge or a hinge.

Although methods for the dynamic calibration of force transducers are not yet well established, there have been several attempts to develop these [1–7]. These attempts can be divided into three categories: methods for calibrating transducers using an impact force [1, 2], methods for calibrating transducers against a step force [3] and methods for calibrating transducers against an oscillation force [4–7].

The first author has proposed calibration methods for all three categories [1, 3, 7]. In the methods, the inertial force of a mass levitated using a pneumatic linear bearing is used as the reference force applied to the force transducers. The inertial force of the levitated mass is measured using an optical interferometer. The first author has also proposed methods for investigating the frictional characteristics of pneumatic linear bearings [8].

The authors have also proposed methods for material testing, such as a method for dynamic three-point bending test [9] and a method for evaluating material viscoelasticity under an oscillating load [10]. In the latter method [10], metal parts must be glued to the two opposing sides of the test specimen for attaching the material to the base and the mass. The performance of the experimental setup based on this method was very high. However, this method presents a disadvantage in

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the requirement of the preparation of the test specimen, i.e. the two sides of the test specimen must be glued to the base and the levitated mass.

This paper proposes a novel practical method for evaluating the viscoelasticity of materials under impact load, in which the preparation of the test specimen is very easy and the testing time is very short.

2. Experimental setup

Fig. 1 shows a schematic diagram of the experimental setup for evaluating the viscoelastic response of materials against impact force. The material under test is attached to the base. A pneumatic 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 given to the moving part. A corner-cube prism CC (for the interferometer) and a metal block for adjusting the collision position are attached to the moving part; its total mass, M, is approximately 4.5014 kg. The inertial force acting on the mass is accurately measured using an optical interferometer. A gel block (model: COSMOGEL; manufactured by Cosmo Instruments Corp., Japan) is used as the material for test. The gel is comprised of hydrocarbon and is colorless, transparent and adhesive. The material has viscoelasticity and thermo-plasticity. The density of the gel is 1.05 g/cm^3. The gel block is attached to the base by its adhesion, and a thin plastic sheet is attached to the other side to prevent the gel block from adhering to the moving part at the time of collision.

The law of inertia states that the force acting on the material from the moving part is equal to the inertial force of the moving part, $F_{\mathrm{inertial}} = -Ma,$ if other forces, such as the frictional force inside the bearing, can be ignored. For this case, the force acting on the moving part from the material is the product of mass and acceleration of the moving part, i.e. $F = Ma$. The acceleration is obtained from the time-varying velocity of the moving part.

An optical interferometer was used to accurately measure the velocity. It consisted of a Michelson interferometer in which the mirrors were replaced with corner-cube prisms. One corner-cube was firmly attached to the moving mass and defined the signal arm of the interferometer. The other corner-cube was at rest and defined the reference arm. The light source used was a Zeeman-type two-wavelength He-Ne laser in which the two wavelengths had orthogonal polarization. The light from the He-Ne laser was incident on a polarization beam splitter PBS. One wavelength was transmitted to the signal arm and then reflected from the corner-cube attached to the moving mass. The other wavelength was reflected from the beam splitter and into the reference arm. After propagation in the Michelson interferometer the two beams were transmitted through a polarizer (a Glann-Thompson prism at 45 degrees to the polarization of the beams), and hence interfered. The interfering beams were then incident on a detector and resulted in a beat signal, since the beams had slightly different wavelengths. The frequency difference between the signal and reference beams (i.e., the beat freqeuency), f_{beat}, was measured with a frequency counter. When the object was at rest, then $f_{\mathrm{beat}} = f_{\mathrm{rest}}$ was approximately 2.8 MHz. However, object motion resulted in a Doppler shift in the signal beam which in turn resulted in a variation of f_{beat}.

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,

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

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

where f_{Doppler} is the Doppler shift, λ_{air} is the wavelength of the signal beam, f_{beat} is the beat frequency, (i.e., the frequency difference between the signal beam and

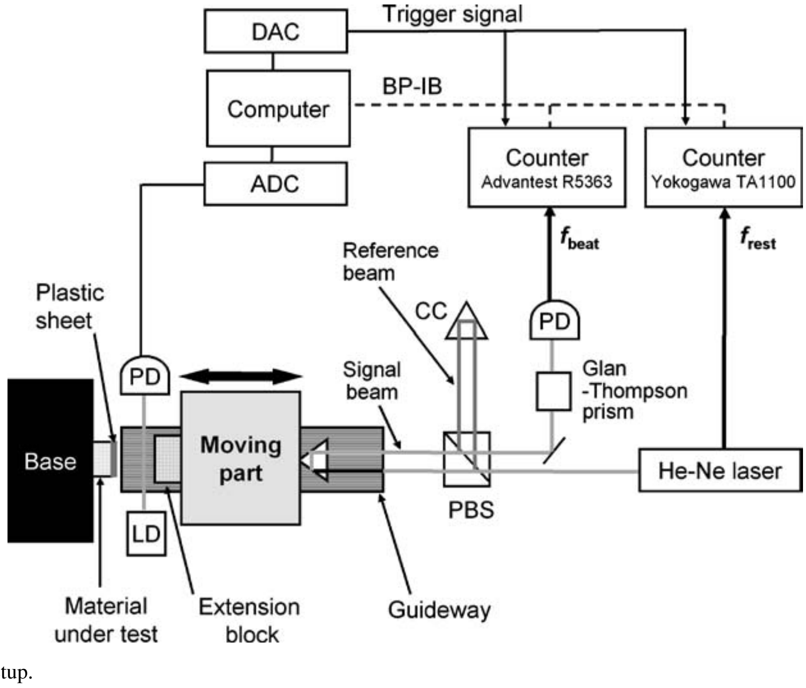

Figure 1 Experimental setup.

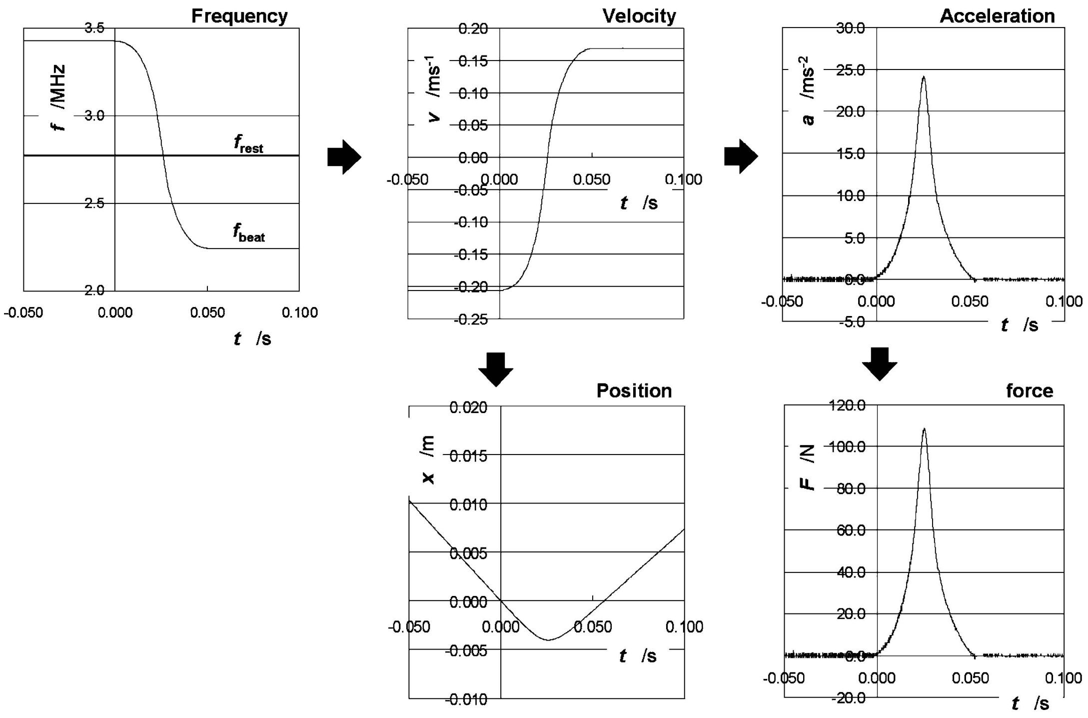

Figure 2 Data processing procedure: Calculation of velocity, position, acceleration and force from frequency.

the reference beam), f_{rest} is the rest frequency defined above. The positive direction for the velocity, acceleration and force acting on the moving part is towards the right in Fig. 1.

An electronic frequency counter (model: R5363; manufactured by Advantest Corp., Japan) continuously measures and records the beat frequency, f_{beat}, until 14000 samples are stored (with a sampling interval of $T = 400/f_{\mathrm{beat}}$). This counter continuously measures the interval time of every 400 periods without dead time. The sampling period of the counter is approximately 0.15 ms at a frequency of 2.8 MHz. Another electronic counter (model: TA-1100; manufactured by Yokogawa Electric Corp., Japan) measures the rest frequency, f_{rest}, using the electric signal supplied by a photodiode embedded inside the He-Ne laser.

The pneumatic linear bearing, "Air-Slide TAAG10A-02" (NTN Co., Ltd., Japan), is attached to an adjustable tilting stage. The maximum weight that can be tolerated by the moving part is approximately 30 kg, the thickness of the air film is approximately 8 μm, the stiffness of the air film is more than 70 N/μm, and the straightness of the guideway is better than 0.3 μm/100 mm. The frictional characteristics are determined in detail by means of the developed method [9].

Measurements using the two electronic frequency counters (R5363 and TA1100) are triggered by means of a sharp trigger signal generated using a digital to analog converter. This signal is initiated when the moving mass blocks a light switch (a combination of a laser-diode and a photodiode). In the experiment, 20 sets of collision measurements are conducted by manually changing the initial velocity of the moving part of the pneumatic linear bearing.

3. Results

Fig. 2 shows the data processing procedure in a collision experiment. During the collision experiment, only the time-varying beat frequency, f_{beat}, and the rest frequency, f_{rest}, are measured highly accurately using an optical interferometer. The Doppler frequency shift is measured 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 measured motion-induced time-varying beat frequency. In the collision experiment shown in Fig. 2, the maximum value of the impact force, F_{max}, is approximately 108.9 N, and the temporal full width at half-maximum (FWHM) of the impulse, W_{hv}, is approximately 12 ms. The origin of the time and position axes are set to be the time and the position where the reaction force from the material under test is detected, respectively.

Figs 3, 4 and 5 show the same collision experiment as Fig. 2 but in different manners. Fig. 3 shows

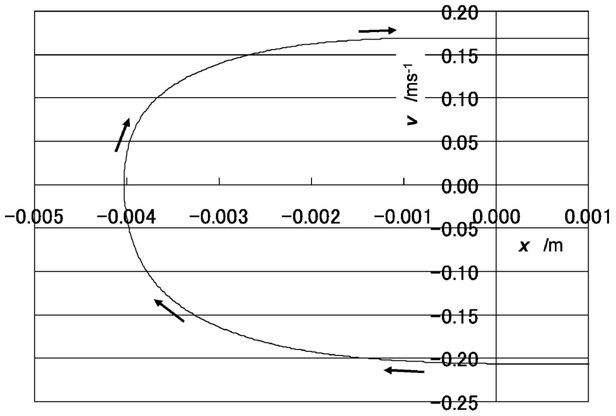

Figure 3 Change in velocity against position.

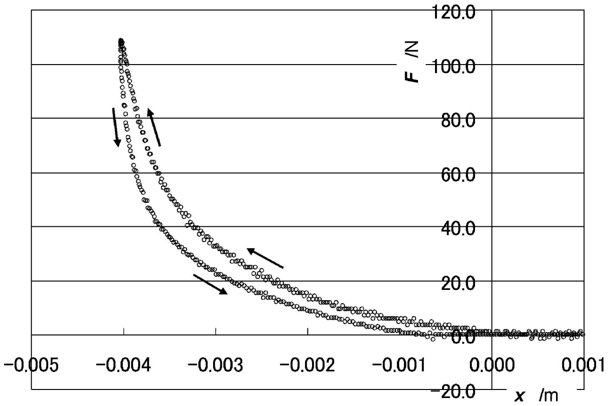

Figure 4 Change in force against position.

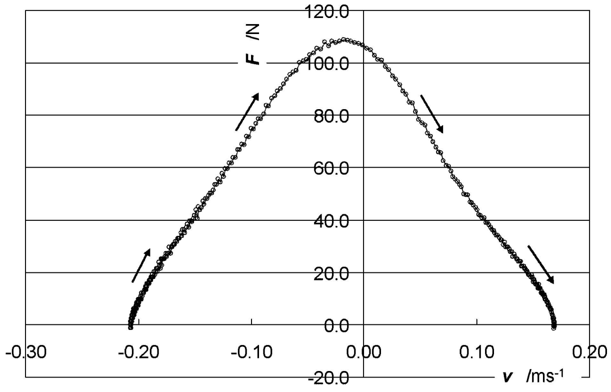

Figure 5 Change in force against velocity.

the change in velocity against position. The velocity before and after the collision are approximately, $v_1 = -0.2064\ \mathrm{ms}^{-1}$, and $v_2 = 0.1688\ \mathrm{ms}^{-1}$, respectively. The reduction of the kinetic energy is approximately 0.03181 J. This loss of the kinetic energy is believed to disperse as heat inside the material under test.

Fig. 4 shows the change in force acting on the mass from the material, $F = Ma$, against position. The spring constant, or slope of the curve, increases according to the increase of the displacement. The force acting on the material from the mass is expressed as $-F$ according to the law of action and reaction. The elastic hysteresis, which is caused by the viscocity of the material, is clearly observed. The work done by the moving part is expressed as the integral along the trajectory of motion, $W\ (= \int(-F)dx)$, and is calculated to be approximately 0.03179 J. The absolute value of this work is equal to the area bounded by the curve shown in Fig. 4. This value agrees well with the reduction of the kinetic energy of approximately 0.03181 J calculated using the velocity before and after the collision, v_1 and v_2 The energy dissipation ratio, $\frac{W}{E_1} = W/[\frac{1}{2}mv_1^2]$, is approximately 0.33 (33%).

Fig. 5 shows the change in force against velocity. The lead of force against the velocity, which is caused by the viscocity of the material, is observed. The velocity where the force has its maximum value of approximately 108.9 N, $V_{F\max}$, is approximately $-0.018\ \mathrm{ms}^{-1}$.

Fig. 6 shows the change in force against velocity in all the 20 collision measurements. The lead of force against the velocity, is observed in all the collision measurements. The shape of the curves can be divided into two types, and the boundary between the types seems to occur around the maximum value of the force of approximately 50 N.

Fig. 7 shows the relationship between the FWHM of the impulse, W_{hv}, and the maximum value of the impact force, $F_{\max}$ The FWHM of the impulse, W_{hv}, decreases with an increase in the maximum value of the impact force, $F_{\max}$. This indicates that the spring constant of the gel block increases with the increase of the displacement.

Fig. 8 shows the relationship between the energy dissipation ratio, $\frac{W}{E_1} = W/[\frac{1}{2}mv_1^2]$, and the initial kinetic energy of the moving part, $E_1 = \frac{1}{2}mv_1^2$. The energy dissipation ratio increases with the increase in the initial kinetic energy. The form of the relationship seems to change around the energy dissipation ratio of approximately 0.3. This is thought to correspond to the mode change observed in Fig. 6.

Fig. 9 shows the velocity where the force has its maximum value, $V_{F\max}$, against the maximum value of the impact force, $F_{\max}$ The velocity where the force has its maximum value, $V_{F\max}$, decreases with the increase of the maximum value of the force, $F_{\max}$ In the determination of $V_{F\max}$, the value at every point was obtained by averaging the value of the eleven nearest neighbors, because the noise superimposed to the curve shown in the Fig. 6 is too large to numerically detect the peak.

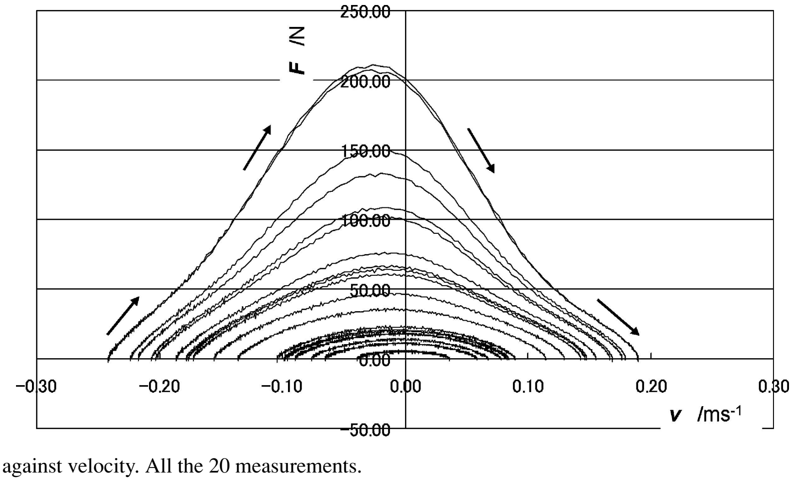

Figure 6 Change in force against velocity. All the 20 measurements.

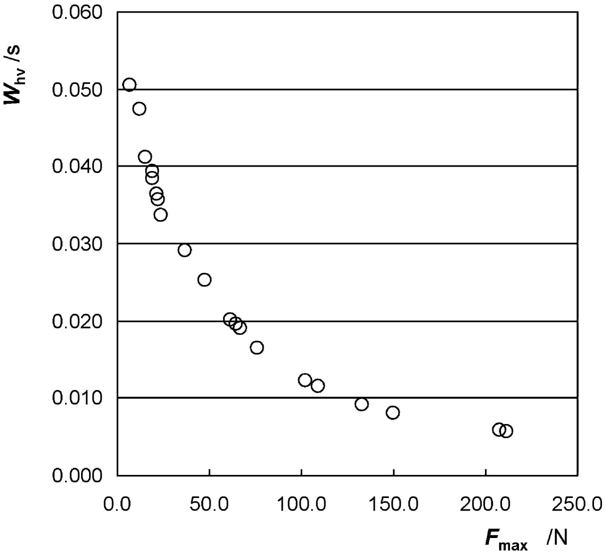

Figure 7 The half value width of the impulse, W_{hv}, against the maximum value of the impact force, $F_{\max}$.

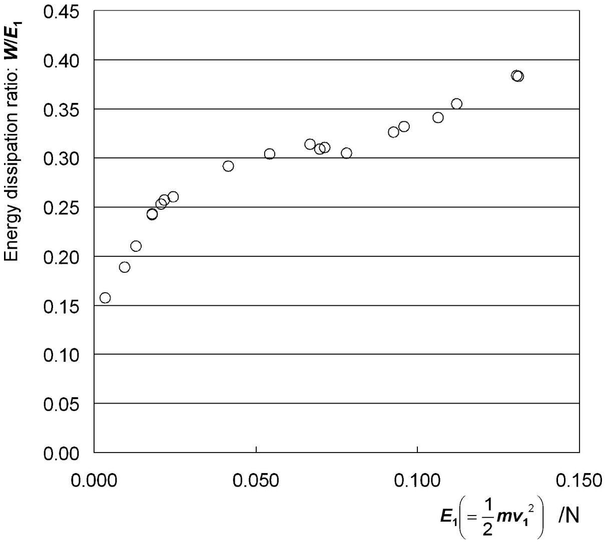

Figure 8 Relationship between the energy dissipation ratio, W/E_1, and the initial kinetic energy of the moving part, $(1/2)mv_1{}^2$.

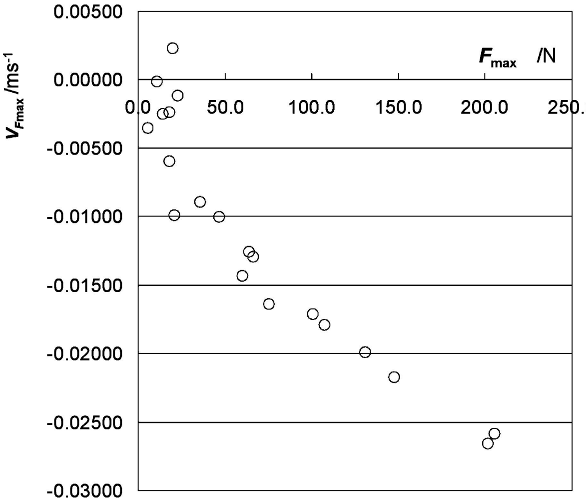

Figure 9 Change in the velocity where the force has its maximum, $V_{F\max}$, against the maximum value of the impact force, $F_{\max}$.

4. Uncertainty evaluation

The uncertainty components, in the determination of the instantaneous value of the impact force acting on the material under test, are as follows.

(A) Determination of the inertial force of the moving part

(A1) Mechanical vibration

The mechanical vibration of the optical interferometer should be carefully considered. The root mean square values of the standard deviation of the velocity before and after the collision, $\sigma_{\mathrm{v\_before}}$ and $\sigma_{\mathrm{v\_after}}$, are approximately 1.5×10^{-5} m/s and 2.3×10^{-5} m/s, respectively. In this calculation, 20 measured values of the velocity just before and after the collision are used for all the 20 collision measurements. The reason that $\sigma_{\mathrm{v\_after}}$ is larger than $\sigma_{\mathrm{v\_before}}$, is the vibration of the optics of the optical interferometer initiated by the shock of the collision. The oscillation of velocity of approximately 2.3×10^{-5} m/s corresponds to the oscillation of the acceleration and force of approximately 2×10^{-1} ms^{-2} and 1.0 N, respectively

(A2) Electronic frequency counter (R5363)

The uncertainty originating from the frequency counter R5363 with the sampling interval of $dt = 400/f_{\mathrm{beat}}$ (s) is estimated to be approximately 100 Hz. This uncertainty of the beat frequency corresponds to an uncertainty of the velocity of the moving part of approximately 3×10^{-5} m/s, according to the relational expression, $\vee = -\lambda_{\mathrm{air}}(f_{\mathrm{beat}} - f_{\mathrm{rest}})/2$. This corresponds to an uncertainty of the acceleration and force of approximately 3×10^{-1} ms^{-2} and 1.3 N, respectively.

(A3) Mass

The mass of the moving part is measured with a standard uncertainty of approximately 0.1 g, which correspond the relative standard uncertainty in force determination of approximately 2×10^{-5}. This is negligible.

(A4) Frequency stability

The uncertainty in the rest frequency emitted from the He-Ne laser is estimated to be 10 Hz. This corresponds to the uncertainty of the velocity of the moving part of approximately 3×10^{-6} m/s and the corresponding uncertainty of the force of approximately 0.13 N. This is negligible.

(A5) Optical alignment

The major source of uncertainty in the optical alignment is the inclination of the signal beam of 1 mrad, and it results in a relative uncertainty in the velocity of approximately 5×10^{-7}, which is negligible.

(B) Determination of the external force

For the external force acting on the moving part, the frictional force acting inside the pneumatic linear bearing is dominant under the condition that the air film of approximately 8 μm thickness inside the bearing is not perturbed. The frictional characteristics of the air bearing are determined using the developed method

[9]. The dynamic frictional force acting on the moving part, F_{df}, is estimated by

$$F_{\mathrm{df}} = Av,$$
$$A = 8 \times 10^{-2}/\mathrm{kg\,s^{-1}}.$$

This corresponds to approximately 0.02 N at a velocity of approximately 0.2 $\mathrm{ms^{-1}}$, which is negligible.

Therefore, the standard uncertainty in the determination of the force acting on the transducer is estimated to be 1.6 N. This corresponds to 0.8×10^{-2} (0.8%) of the maximum applied force of approximately 2.1×10^{2} N in the experiments.

5. Discussion

Since all the measurement is done in a single shot of collision, thus the testing time is very short. This aspect is very important especially in measuring the viscoelasticity of high molecular weight materials, which largely depends on the temperature.

The setup procedure for a new test is very easy in the proposed method. Any object, such as a viscoelastic material or a specimen with complicated structure, can be attached to the base using an appropriate adhesive material or a mechanical holder. Only one side of the material must be fixed to the base with an appropriate bonding agent. Then its dynamic response against impact force is evaluated highly accurately by measuring the time-varying beat frequency of the laser light reflected from the moving object.

In the proposed method, only the motion-induced time-varying beat frequency is measured during the collision experiment, and all the other quantities, such as velocity, position, acceleration and force, are numerically calculated afterwards. This results in the good synchronization between the obtained quantities. In addition, force is directly calculated according to its definition, that is, the product of mass and acceleration. The authors consider that this simplicity is the most significant advantage of the proposed method compared with other conventional methods using a force transducer and a position sensor.

If the material under test is put in a constant temperature box, the temperature dependency of the material characteristics, which is especially important for high molecular weight materials materials, can be evaluated using the proposed method. In this case, if the extension block is long enough and made of a material, such as a ceramic, which has insignificant heat conductivity and large stiffness, the rest of the apparatus including the pneumatic linear bearing can be placed outside the constant temperature box.

If the interferometer is miniaturized by using a stabilized laser diode instead of the He-Ne laser, the whole system could be portable. In addition, if the application is clearly defined, a simple mechanical linear guide, such as a parallel flat-spring mechanism, could be used instead of the pneumatic linear bearing.

6. Conclusions

A novel practical method for evaluating the viscoelasticity of materials under impact load, in which the preparation of the test specimen is very easy and the testing time is very short, is proposed. In the method, a mass is levitated using a pneumatic linear bearing and gives rise to a moving mass with negligible friction that is made to collide with a material under test. During the collision measurement, only the Doppler frequency shift of a laser light beam reflecting from the mass is accurately measured using an optical interferometer. The velocity, position, acceleration and inertial force of the mass are calculated from the time-varying beat frequency. The impact response of the gel block is highly accurately determined by means of the proposed method. Any object, such as a viscoelastic material or a specimen with complicated structure, can be attached to the base using an appropriate adhesive material or a mechanical holder. Only one side of the test specimen must be fixed to the base with an appropriate bonding agent. The advantages and future prospects of the proposed method were discussed.

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