International Journal of Innovative
Computing, Information and Control
Volume **11**, Number **3**, June **2015**

ICIC International ©2015 ISSN 1349-4198
pp. **949–954**

A METHOD FOR EVALUATING THE MECHANICAL RESPONSE OF RUBBER-LIKE MATERIAL UNDER SMALL IMPACT LOADS

Irfa Aji Prayogi[1], Kazuhide Watanabe[1], Kyohei Irisa[1], Akihiro Takita[1]
Mitra Djamal[2] and Yusaku Fujii[1]

[1]Division of Mechanical Science and Technology
Faculty of Science and Technology
Gunma University
1-5-1 Tenjincho, Kiryu 376-8515, Japan
{ t13802281; t09306070; t08306011 }@gunma-u.ac.jp
{ Takita; Fujii }@el.gunma-u.ac.jp

[2]Department of Physics
Faculty of Mathematics and Natural Sciences
Institut Teknologi Bandung
Jalan Ganesha 10, Bandung 40132, Indonesia
mitra@fi.itb.ac.id

Received June 2014; revised November 2014

Abstract. *A method for evaluating mechanical responses of rubber-like material under small impact loads has been developed. The method is characterized by the fact that preparation of sample is very easy and the testing time is very short. In this method, a small-levitated mass is made to collide with a material under test. The inertial force acting on the levitated mass is highly accurately determined by measuring the velocity of the mass using an optical interferometer. The proposed method provides information about the mechanical responses of material such as impact duration, viscoelasticity and energy dissipation. The performance of this method was demonstrated by evaluating the mechanical response of three types of rubber-like materials.*

Keywords: Mechanical responses, Rubber-like material, Levitation Mass Method, Dynamic impact force, Small impact loads

1. **Introduction.** Recently, the need for evaluating the mechanical properties of material under varying load conditions has increased in many industrial and research applications such as crash testing and motion control. The impact test is a convenient method to evaluate the mechanical responses of material such as viscoelasticity [1] and strength [2]. In such impact tests, the force acting on the material is measured using a force transducer and the deformation of material is measured using a position transducer during impact [1,3]. However, force transducers are usually calibrated with standard static method using static weights and under static conditions. According to Newton's second law, force is defined as the product of mass and acceleration. This means that an accurately measured acceleration is required to calibrate force transducers accurately. Acceleration due to gravity, g, is usually used for generating and measuring the constant force. This constant force can be accurately compared using a conventional balance. At present, there is no accepted standard method for evaluating the dynamic characteristics of the force transducers. Only static force calibration methods are widely available at present. The transducers are calibrated by static weighting under static conditions in this method.

Although the standard method for the dynamic calibration of force transducers is not yet well established, there have been several efforts to develop dynamic calibration methods for force transducers. One of the methods has developed by Kumme, which used the inertial force of the attached mass generated by shaker [4]. In this method, the dynamic force of a single frequency is generated and applied to a force transducer. Then Fujii proposed another method, which is known as Levitation Mass Method (LMM) [5-11]. This method was first proposed as an impulse response evaluation method for force transducers [5]. In this method, the levitated mass is made to collide with a force transducer. The impulse is accurately measured as a change in momentum of the levitated mass. The inertial force of the levitated mass is used as the reference force that is applied to the force transducer. The velocity of the levitated mass determines the force acting on the force transducers, which is highly accurately measured using an optical interferometer.

The LMM has also been developed to evaluate a strength test of a material [3], viscoelasticity of material under oscillation load and impact load [7,8]. In these methods [3,7,8], the levitated mass is 4.5 kg. These methods are effective for evaluating mechanical properties of strength and toughness of materials. Furthermore, the methods for generating and evaluating small-dynamic forces have also been developed for force transducer calibration [6] and material testing [9,10]. The material testing experiments [9,10] used a micro-Newton level force, which is approximately 0.1 mN [10], in its test. These methods are appropriate to evaluate mechanical response of very small and fine materials. The generating of micro-Newton level force needs long duration of measurement since it requires a low velocity of the levitated mass or small mass. This paper describes a method to evaluate the mechanical response of material under small impact loads and short-duration of measurement.

2. **Experimental Setup.**

Figure 1 shows the schematic diagram of the experimental setup for evaluating the mechanical response of a material under small impact loads. A material under test is firmly attached to the base. An impact force is applied to the material by colliding the levitated mass (i.e., Moving-part inside the air-bearing holder). The levitated mass is levitated by pneumatic air bearing in order to realize the linear motion with sufficiently small friction force. The initial force on the moving part is manually generated. A small corner-cube prism (CC) for interferometer and the metal extension block with the round-shaped tip are attached to the moving part. The total mass of moving part, $\boldsymbol{m}$ is 11.78 g. The inertial force acting on the moving part is accurately measured using an optical interferometer. Figure 2 shows images of rubber-like materials under test.

The force acting on the material from the moving part and vice versa have the same absolute value but the opposite sign $\boldsymbol{F}_{\mathbf{inertia}} = -\boldsymbol{ma}$. It is correct if the other force, such as the frictional force inside the bearing, can be ignored. In this case, the force acting on the moving part from the material is the product of mass and acceleration of its moving part, $\boldsymbol{F} = \boldsymbol{ma}$. The acceleration, $\boldsymbol{a}$ is calculated from the time-varying velocity of the moving part. The velocity is obtained by measuring the Doppler shift frequency in the signal beam of the laser interferometer, $\boldsymbol{f_{Doppler}}$, using the following equation,

$$\boldsymbol{v} = \boldsymbol{\lambda_{air}}(\boldsymbol{f_{Doppler}})/\boldsymbol{2}, \tag{1}$$

$$\boldsymbol{f_{Doppler}} = -(\boldsymbol{f_{beat}} - \boldsymbol{f_{rest}}), \tag{2}$$

where $\boldsymbol{\lambda_{air}}$ is the wavelength of the Zeeman-type two-frequency He-Ne laser 632.8 nm; $\boldsymbol{f_{beat}}$ is the beat frequency, which is the frequency difference between the signal and reference beam. The $\boldsymbol{f_{rest}}$ is the rest frequency, which has the same value with its $\boldsymbol{f_{beat}}$ when the moving part is in standstill condition. A digitizer (NI PCI-5105, National

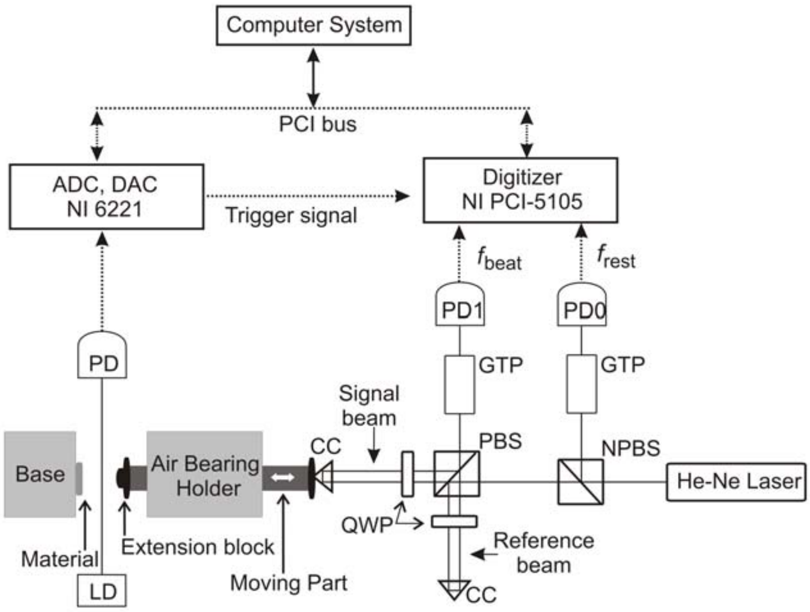
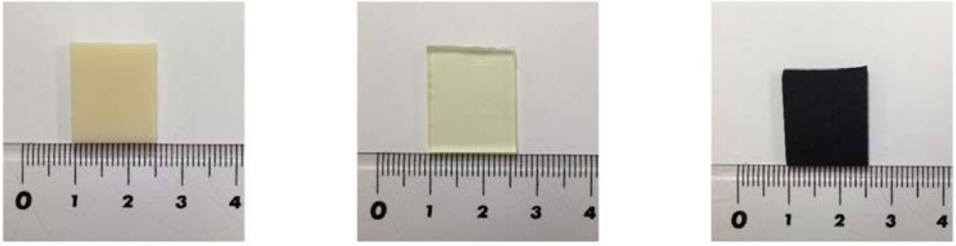


FIGURE 1. Schematic diagram of experimental setup. PD = Photodiode, LD = Laser Diode, ADC = Analog-to-Digital Converter, DAC = Digital-to-Analog Converter, CC = Corner-Cube, QWP = Quarter Wave Plate, GTP = Glan-Thompson Prism, PBS = Polarizing Beam Splitter, and NPBS = Non-Polarizing Beam Splitter.



Material-A (Silicone Rubber)

Material-B (Urethane)

Material-C (LER-Hanenaito®)

FIGURE 2. Materials under test

Instrument Corp., USA) recorded 5M samples for each gate from PD0 and PD1 at a sampling rate of 30M samples per seconds. In this case, the measurement duration of the digitizer is 0.17 s. The measurement using the digitizer is initiated by a trigger signal from a light-switch, which is installed between the moving-part and the material. The light-switch is a combination between a laser diode and a photodiode. It sends a trigger signal to DAC when the moving part covers its beam.

The frequencies f_{beat} and f_{rest} are accurately determined from digitizer waveforms of PD1 and PD0, respectively, using Zero-crossing Fitting Method (ZFM) [11]. In ZFM, all zero-crossing times are used to determine the frequency of each gate time, which is defined by 200 periods of the signal waveform. In the experiment, 25 collision measurements were taken for each material.

3. **Results and Discussion.** Figure 3 shows the data processing procedure in the experiment. Only the beat and rest frequencies are accurately measured using an optical interferometer during the collision. The beat frequency varies around its rest frequency

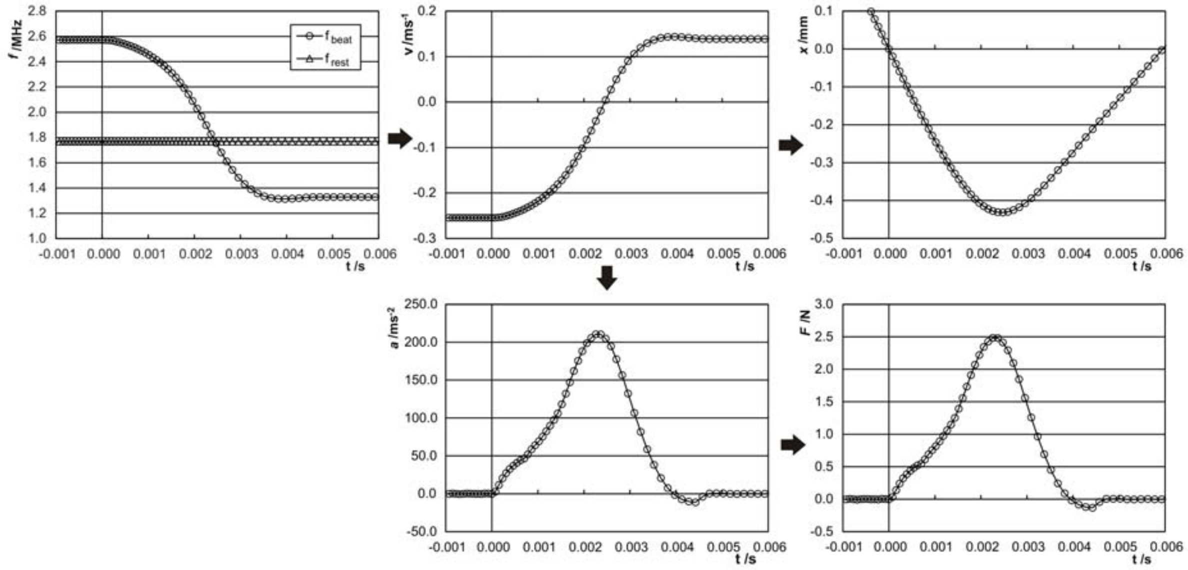
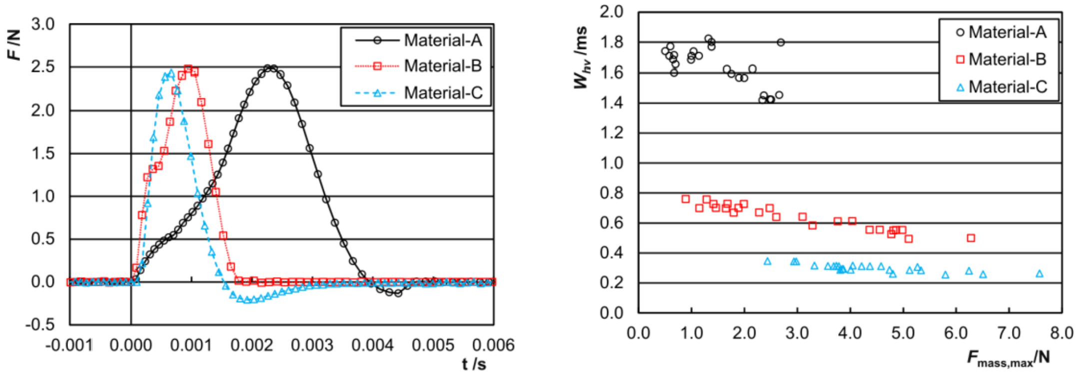


FIGURE 3. Data processing procedure (Material-A)



(a)

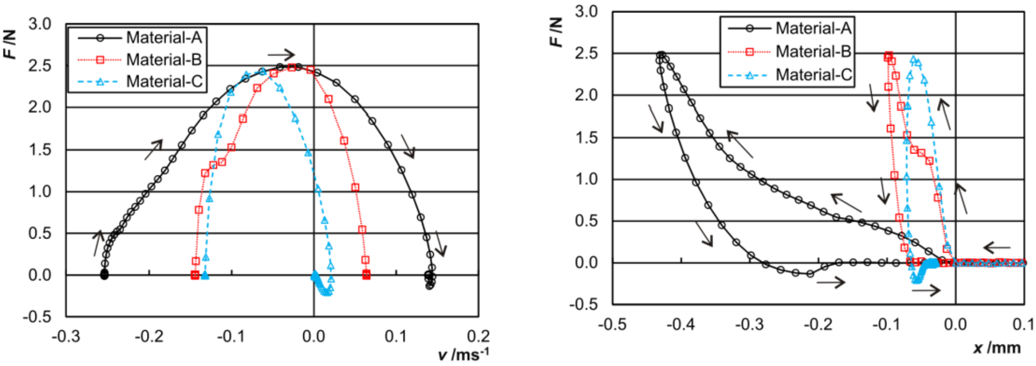
(b)

FIGURE 4. (a) Impulse of collision for each material; (b) full width at half maximum of the impulse, $\boldsymbol{W_{hv}}$, against the maximum value of the impact force, $\boldsymbol{F_{mass,max}}$

1.76 MHz, which is depending on the direction and magnitude of velocity of the moving-part. The velocity, $\boldsymbol{v}$ is calculated using Equation (1). Thus, the acceleration, $\boldsymbol{a}$, and position, $\boldsymbol{x}$, are numerically calculated by differentiating and integrating its velocity, respectively. The origins of the time and position axes are set, where the material under test gives a reaction force to the moving part.

Figure 4(a) shows the impulse of collision for each material with the maximum value of the impact force, $\boldsymbol{F_{mass,max}}$, approximately 2.5 N. The impact duration of material is represented by the full width at half maximum (FWHM) of the impulse, $\boldsymbol{W_{hv}}$, which is approximately 1.6 ms for Material-A, 1.1 ms for Material-B and 0.8 ms for Material-C. Figure 4(b) shows the relationship between the $\boldsymbol{W_{hv}}$ and $\boldsymbol{F_{mass,max}}$ in all the 75 collision measurements.

Figures 5(a) and 5(b) show the same collision experiment as Figure 4(a) but in a different manner. Figure 5(a) shows the change in force against the velocity. In the experiment, the moving part is made to collide with the material with an initial velocity



(a) (b)

FIGURE 5. (a) Relationship between force and velocity; (b) Relationship between force and position for each material

TABLE 1. Velocity before and after a collision for all materials

	v_i (ms^{-1})	v_f (ms^{-1})
Material-A	-0.254	0.143
Material-B	-0.144	0.064
Material-C	-0.132	0.020

v_i. After the collision, the velocity of moving part decelerates with the velocity after collision v_f. The velocity before and after the collision for each material is shown in Table 1. The lead of force against the velocity, which is caused by the viscoelasticity of the material, is observed.

The velocity where the force has its maximum value, $v_{F_{mass,max}}$, is -0.041 ms^{-1} for Material-A, -0.027 ms^{-1} for Material-B and -0.062 ms^{-1} for Material-C. Furthermore, the reduction of kinetic energy for each material is observed that is approximately 0.261 mJ for Material-A, 0.098 mJ for Material-B, and 0.10 mJ for Material-C. The loss of kinetic energy is believed to disperse as heat inside the material under test.

Figure 5(b) shows the change in force acting on the moving-part from the material against the position. The hysteresis curve due to the viscosity of the material is observed. The work done by the moving part is expressed as the integral along the trajectory of motion, $W(=\int -Fdx)$ for each material. The absolute value of the work for each material is equal to the area surrounded by the curve shown in Figure 5(b). It is calculated to be approximately 0.265 mJ for Material-A, 0.096 mJ for Material-B, and 0.096 mJ for Material-C. This value agrees well with the reduction of the kinetic energy of each material. The ratio energy dissipation, W/E_i, for Material-A, Material-B, and Material-C are approximately 0.6960 (69.60%), 0.7865 (78.65%), and 0.9319 (93.19%), respectively.

4. **Uncertainty Evaluation.** The uncertainty sources in determining the instantaneous value of the impact force acting on the material are as follows:

(1) Vibration of the optical interferometer

The vibration of the optical interferometer should be carefully considered. The root mean square values of the standard deviation of velocity before and after the collision in the 75 measurements, are approximately 4.76×10^{-5} ms^{-1} and 3.38×10^{-3} ms^{-1}, respectively. The oscillation of velocity of approximately 3.38×10^{-3} ms^{-1} corresponds to the oscillation of the force of approximately 7.4 mN.

(2) Mass measurement

The mass of moving part was measured using an electronic balance that has a standard uncertainty 0.01 g. It relates to 5×10^{-4} of the total mass of the moving part, which is corresponding to 3.8 mN when $\boldsymbol{F_{mass,max}} = 7.6$ N.

(3) Optical alignment

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

(4) Dynamic frictional force acting inside the bearing

The dynamic frictional characteristics of the air bearing are determined using the developed method [12]. The frictional force acting inside the moving part is 0.5 mN at a velocity 0.27 m/s.

The standard uncertainty in determining the instantaneous values of force acting on the material under test is calculated approximately 8.3 mN; it corresponds to 0.11% of the value of maximum force applied in the experiments 7.6 N.

5. **Conclusions.** The proposed method is very easy to perform and the testing time is very short. In this method, a small-levitated mass is made to collide with a material under test. The impact force acting on the mass is accurately measured using optical interferometer. The dynamic impact force was applied on the material with maximum value approximately 7.6 N. The mechanical responses of the rubber-like material such as impact duration, viscoelasticity and energy dissipation on the material, are accurately determined by means of the proposed method.

Acknowledgment. This work was supported in part by a research-aid fund of the NSK Foundation for the Advancement of Mechatronics (NSK-FAM) and the Grant-in-Aid for Scientific Research (B) 24360156 (KAKENHI 24360156).

REFERENCES

[1] V. M. Kulik, A. V. Boiko, S. P. Bardakhanov, H. Park, H. H. Chun and I. Lee, Viscoelastic properties of silicone rubber with admixture of SiO_2 nanoparticles, *Materials Science and Engineering*, vol.528, no.18, pp.5729-5732, 2011.

[2] T. Suzuki, Y. Fujii and J. D. R. Valera, Optical method for strength test for general industrial products, *Mechanical Systems and Signal Processing*, vol.06, no.5, pp.735-744, 2004.

[3] J. Hessling, Dynamic calibration of uni-axial material testing machines, *Mechanical Systems and Signal Processing*, vol.22, no.2, pp.451-466, 2008.

[4] R. Kumme, Investigation of the comparison method for the dynamic calibration of force transducers, *Measurement*, vol.23, no.4, pp.239-245, 1998.

[5] Y. Fujii and H. Fujimoto, Proposal for an impulse response evaluation method for force transducers, *Measurement Science and Technology*, vol.10, no.4, pp.N31-N33, 1999.

[6] M. Djamal, K. Watanabe, K. Irisa, I. A. Prayogi, A. Takita, T. Yamaguchi and Y. Fujii, Dynamic characteristics measurements of a force transducer against small and short-duration impact forces, *Metrology and Measurement Systems*, vol.21, no.1, pp.59-66, 2014.

[7] Y. Fujii and T. Yamaguchi, Method for evaluating material viscoelasticity, *Review of Scientific Instrument*, vol.75, no.1, pp.119-123, 2004.

[8] Y. Fujii and T. Yamaguchi, Proposal for material viscoelasticity evaluation method under impact load, *Journal of Materials Science*, vol.40, no.18, pp.4785-4790, 2005.

[9] Y. Fujii, Method for generating and measuring the micro-Newton level forces, *Mechanical Systems and Signal Processing*, vol.20, no.6, pp.1362-1371, 2006.

[10] Y. Fujii, Microforce materials tester, *Review of Scientific Instruments*, vol.76, 2005.

[11] Y. Fujii and J. P. Hessling, Frequency estimation method from digitized waveform, *Experimental Techniques*, vol.33, no.5, pp.64-69, 2008.

[12] Y. Fujii, Measurement of force acting on a moving part of a pneumatic linear bearing, *Review of Scientific Instruments*, vol.74, no.6, pp.3137-3141, 2003.