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Impact Response Measurement of Poly-Urethane Sheet Using an Optical Interferometer

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A method for measuring the impact response of a polyurethane sheet is proposed. In the method, the velocity, acceleration, force, and displacement of a spherical body dropping onto the polyurethane sheet is measured using an optical interferometer. Only the velocity is measured from the Doppler shift of the laser light reflected on the cube corner prism embedded inside the spherical body. The optical center of the cube corner prism is made to coincide with the center of gravity of the whole spherical body to minimize the effect of the attitude change of the body. The acceleration, displacement, and inertial force of the body are calculated from the velocity. The dropping body is also observed using a high-speed camera. The uncertainty in measuring the instantaneous value of the impact force with a sampling interval of approximately 0.1 ms is estimated to be 0.23 N, which corresponds to 0.14% of the maximum force of approximately 1.60×10^2 N. In the experiment, 10 drop measurements are conducted and show good reproducibility of this method.

Keywords: impact absorption, optical interferometer, force measurement

1. Introduction

In recent years some methods for measuring impact response of structures were proposed by several researches [1–10], such as, the force is measured highly accurately as inertial force acting on a mass using an optical interferometer [11–18]. Furthermore, there also have been proposed the impact force and impact energy absorption tests for mouth-guards using a steel ball as a collision object [19, 20] and a method for measuring the impact force of a spherical body dropping onto a water surface [21], whose method is referred and modified to the method described in this paper.

Impact is a complex event involving several phenomena. Furthermore, the nature of impact response influences the type of damage and the extent of structural degradation. Extensive researches have been carried out concerning the impact behavior of composite materials [22]. Dynamic behavior of materials is focused on the analysis and design of energy absorbing materials and structures. The work presented that the inertia of the composite material plays a very important role in absorbing energy, which can be reduced significantly due to impact damage. Thus, there have been several of experimental investigations concerning the energy-absorption materials [23–25], whose interesting point is to reduce impact pressure and other unexpected damage [26–28].

The focus of this research is to evaluate a drop ball tester using an optical interferometer by measuring the force acting of a spherical body onto polyurethane sheet. The acceleration, displacement, and inertial of the sphere are calculated from the velocity of the center of gravity of a spherical body. A high-speed camera is used to capture the images during the impact test.

In this paper, we investigate the impact response measurement of a polyurethane sheet using an optical interferometer, and its validity is experimentally shown (**Figs. 2–4** in Section 3). The uncertainty of proposed method is estimated.

2. Experiment

Figure 1 shows the principle of measurement and experimental devices. We investigated the impact response of a spherical body dropped from 155 mm height onto a polyurethane sheet, which is in 3 mm thickness and in 100×100 mm size. The spherical body is made of stainless (SUS440) which has magnetism. The total mass, M, and diameter of the spherical body are 0.09388 kg, and 30.2 mm, respectively. A cube corner prism (CC) with 12.7 mm in diameter is inserted into the spherical body with an adhesive agent so that its optical center coincides with the center of gravity of the spherical body. An optical interferometer is used to accurately measure the velocity. A Zeeman type two-frequency laser is used for light source. The laser irradiates orthogonally polarized two-frequency laser light whose frequency difference is

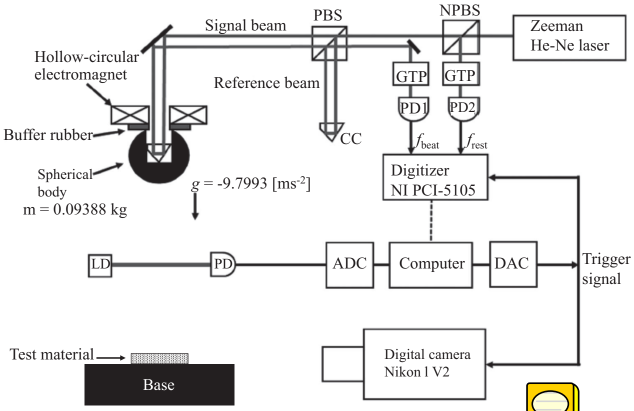


Fig. 1. A schematic diagram of the experimental setup (NPBS = Non-polarized beam splitter, PBS = Polarized beam splitter, CC = Cube corner prism, GTP = Glan-Thompson prism, PD = Photo detector, LD = Laser diode, ADC = Analog-to-digital converter, DAC = Digital-to-analog converter).

approximately 3.1 MHz. The original frequency difference of the laser and a frequency difference modulated by Doppler Effect are measured by a photo detectors (PD2 and 1) with a Glan–Thompson prism (GTP) as f_{rest} and f_{beat}, respectively. The images of impacts were recorded using a digital camera with a width of 320 pixels, a height of 120 pixels and a frame rate of 1,200 fps.

The digitizer records the output signals of PD1 and PD2 with a sample number of 5 Msamples for each channel, a sampling rate of 30 Msamples per second, and a resolution of 12 bit. The measurement duration of the digitizer is approximately 0.167 s. The frequencies of interference signal of the optical interferometer f_{beat} and f_{rest} are accurately determined from the digitized waveforms of the output signals appearing at PD1 and PD2, respectively, using the recently developed Zero-crossing Fitting Method (ZFM) [29]. In our analysis, the sampling interval is defined by $N = 200$ periods of the signal waveform, which corresponds to 0.25 ms when f_{beat} is approximately 8 MHz, therefore the interval of data points are not constant in **Figs. 2–4**.

The total force acting on the spherical body is equivalent to the product of its mass and acceleration; i.e., $F_{mass} = Ma$. The acceleration is calculated from the velocity of spherical body, and the velocity is calculated from the measured value of the Doppler shift frequency of the interference signals $f_{Doppler}$, which can be expressed as

$$v = \frac{\lambda_{air}(f_{Doppler})}{2}, \quad (1)$$

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

where λ_{air} is the wavelength of the signal beam, f_{beat} and f_{rest} are the frequencies of interference signals.

The total force, F_{mass}, consists of the gravitational force acting upon the spherical body, $-Mg$, and the impact force acting from the polyurethane sheet, F_{impact}, if other forces, such as the air drag and the magnetic force, are negligible. Then, the total force is

$$F_{mass} = -Mg + F_{impact}, \quad (3)$$

where g is the acceleration of gravity, approximately 9.799 m/s^2 at the experimental environment.

Therefore, the impact force acting from the polyurethane sheet can be calculated as

$$F_{impact} = F_{mass} + Mg. \quad (4)$$

If other forces, such as air drag, cannot be ignored, then F_{impact} is assumed to include those other forces.

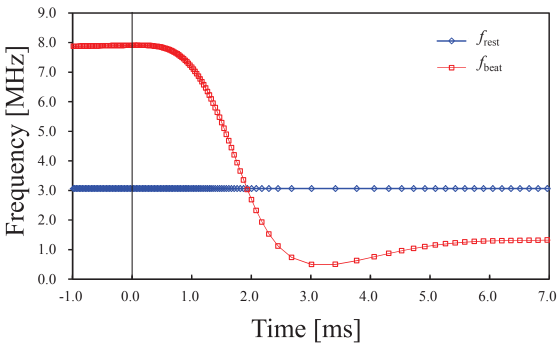
In the experiment, 10 sets of impact test were performed. In each of the test, the spherical body was fixed onto the hollow-circular electromagnet that was held and released by turned on/off manually. The digitizer is initiated by a trigger signal generated using digital-to-analog converter (DAC). This signal is activated by means of a light switch, which is a combination of laser diode (LD) and photo detector.

3. Results

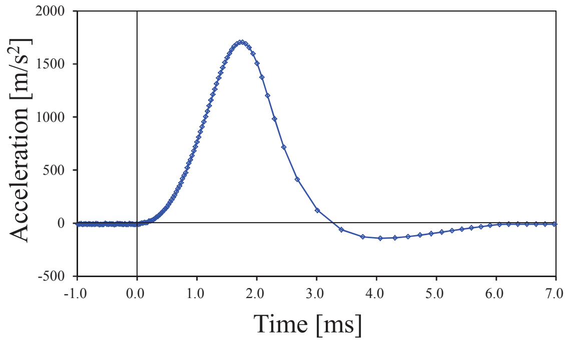
Figure 2 shows the data processing procedure and measurement results, which are calculated from the frequencies f_{beat} and f_{rest} that is properly measured by the beat frequency, for the velocity v; the position x; the acceleration a; the total force acting upon the spherical body F_{mass}; and the impact force acting onto the spherical body from the urethane sheet, F_{impact}. **Fig. 2(a)**: frequencies of f_{beat} and f_{rest} shows the frequencies of f_{beat} and f_{rest} calculated from digitized waveform of interference signal by means of ZFM. The time at which the spherical body seems to hit the urethane sheet is set to 0. **Fig. 2(b)**: calculated velocity shows the velocity calculated by Eq. (1). The positive velocity after 1.9 ms shows that the spherical body was rebounded after collide with the polyurethane sheet. **Fig. 2(c)**: calculated displacement shows the displacement of the spherical body calculated by integrating the velocity. The position when the sphere seems to hit the urethane sheet is set to 0. **Fig. 2(d)**: calculated acceleration, shows the acceleration of the spherical body calculated by differentiating the velocity. **Fig. 2(e)**: calculated impact force shows the impact force calculated by Eq. (4). During the spherical body bounded on the polyurethane sheet, the adhesivity was observed from 3.4 ms to 6.2 ms.

Figure 2(f): displacement VS impact force shows the relation between displacement and impact force. Arrows indicate the flow of data points by time. The area of this plot is equivalent of the energy loss during the impact.

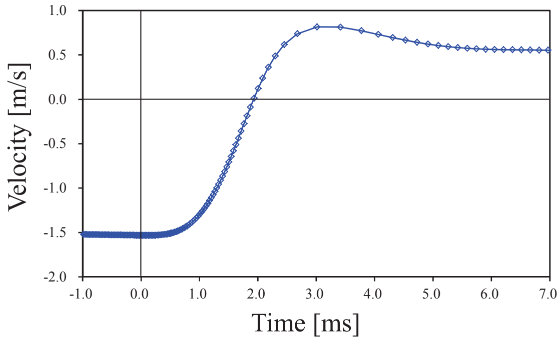
In these results, the contact time (the period during which the impact force is acting on the spherical body) is 6.2 ms, the velocity before the collision, v_0, is -1.53 m/s, the velocity after the collision, v_1, is 0.56 m/s, the coefficient of restitution, $e = -v_1/v_0$, is 0.36, and energy loss (the kinetic energy lost during the collision) calculated using the velocity before/after the impact is 9.5×10^2 J (87% of initial kinetic energy).



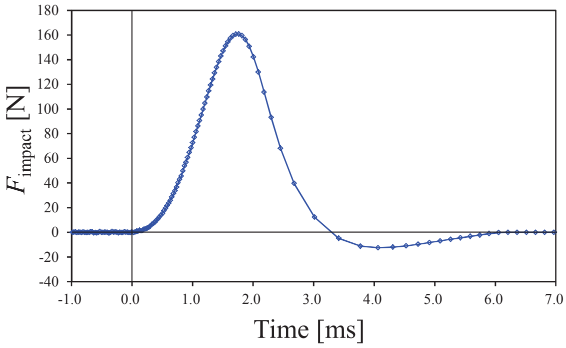
(a) Frequencies of f_{beat} and f_{rets}.



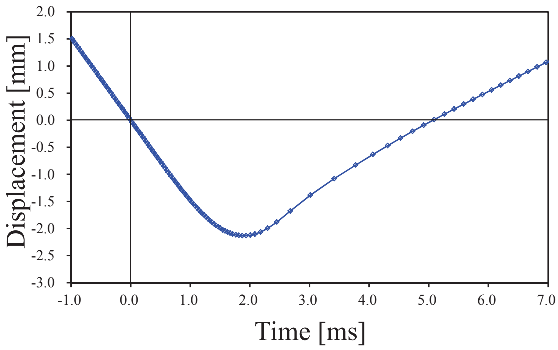
(d) Calculated acceleration.



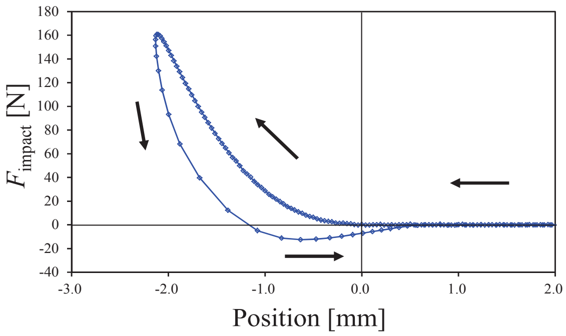
(b) Calculated velocity.



(e) Calculated impact force.



(c) Calculated displacement.



(f) Displacement VS impact force.

Fig. 2. (a)–(f) Data processing procedure: calculation of velocity, position, acceleration, and force from frequency which the details are as follows: maximum impact force: 1.60×102 N, contact time: 6.2 ms, velocity before impact: -1.53 m/s, velocity after impact: 0.56 m/s, coefficient of restitution: 0.36, and energy loss: 9.5×102 J (87%).

Figure 3 shows the changes in F_{impact} against time for all the 10 drop measurements. The results of the 10 drop measurements coincide well, and indicate a high reproducibility of this measurement method.

Figure 4 shows the changes in impact force and displacement against time, with corresponding images taken by the high-speed camera. When the spherical body impacts the urethane sheet, the spherical body sinks in the polyurethane sheet maximally 2.1 mm with a maximum value of F_{impact} of 1.60×10^2 N at $t = 1.7$ ms. The spherical body separated from the urethane sheet at $t = 6.2$ ms. From the image, it is clear that the spherical body completely leaved from the polyurethane sheet at $t = 7.5$ ms.

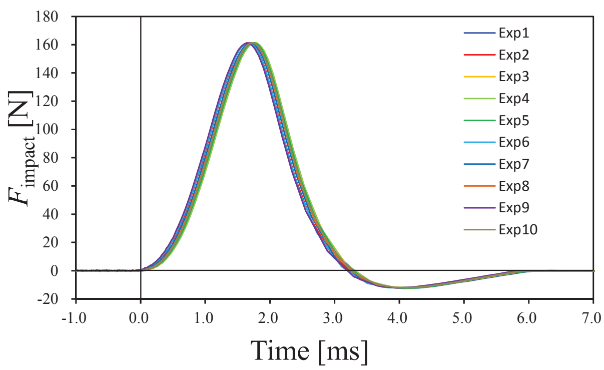


Fig. 3. Changes in impact force and velocity against time.

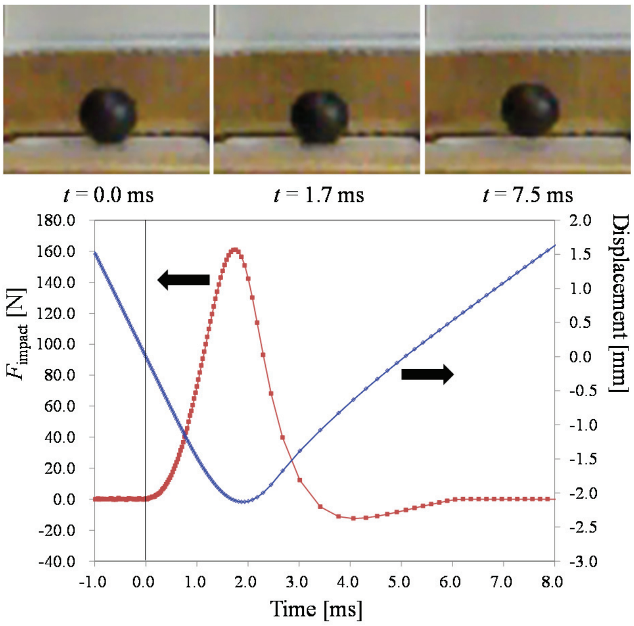


Fig. 4. Changes in impact force and displacement against time.

4. Uncertainty of Measurement

The sources of uncertainty in determining the instantaneous value of F_{impact} against time for all the 10 drop measurements are considered as follows:

[U.1] Uncertainty from optical miss-alignment: The major source of uncertainty in the optical alignment was the inclination of the laser beam, and is expected to be less than 1 mrad; this resulted in a relative uncertainty in the inertial force of approximately $5 \times 10^{-5}\%$, which is negligible.

[U.2] Uncertainty of mass measurement: The uncertainty in the mass measurement when using the electric balance was approximately 0.01 g, which corresponds to 0.01% of the total mass of the impact force. This corresponds to 0.1 mN when the maximum impact force is applied, which is negligible.

[U.3] Uncertainty of gravitational acceleration measurement: The acceleration due to gravity g is estimated to be 9.799 m/s with an uncertainty of 0.01%, which is negligible.

[U.4] Uncertainty from optical noise.

[U.5] Uncertainty of frequency estimation.

[U.6] Uncertainty of numerical operation.

In terms of uncertainty of U.4–U.6, each uncertainty cannot be estimated individually. Therefore, the total amount of uncertainty is estimated by calculating measurement error of the F_{impact} during free fall motion of the spherical body, which is U_{4-6}: 0.23 N, (0.14% of maximum F_{impact}).

Table 1. Uncertainty estimation.

<table>
<tr><th>No.</th><th>Source</th><th>Relative uncertainty</th></tr>
<tr><td>U.1</td><td>Optical alignment</td><td>$5 \times 10^{-5}\%$</td></tr>
<tr><td>U.2</td><td>Mass measurement</td><td>0.01%</td></tr>
<tr><td>U.3</td><td>Gravitational acceleration measurement</td><td>0.01%</td></tr>
<tr><td>U.4</td><td>Optical noise</td><td rowspan="3">0.14%</td></tr>
<tr><td>U.5</td><td>Frequency estimation</td></tr>
<tr><td>U.6</td><td>Numerical operation</td></tr>
</table>

Finally, the total uncertainty of proposed method, U_{total}, was estimated to be $U_{total} = (U_1^2 + U_2^2 + U_3^2 + U_{4-6}^2)^{0.5} = 0.14\%$. **Table 1** shows a summary of uncertainty estimation.

5. Discussion

In this method, the relationship between the instantaneous values of the impact force, position, velocities, acceleration of the spherical body are accurately evaluated. Usual force sensor can be calibrated to only the static force; in contrast, this method can measure dynamic (time-varying) force and evaluate the uncertainty of measured force. Therefore, this method can be used for various applications. One expected application is to calibrate a drop ball tester using a force transducer.

6. Conclusions

A method for measuring the impact response of a sheet material was proposed. The velocity, acceleration, displacement, and inertial force of a spherical body were measured and calculated with an optical interferometer. The uncertainty of measurement of the impact force was estimated to be 0.23 N, which corresponds to 0.14% of the maximum impact force. In the experiment, 10 drop measurements were conducted and the results shows good reproducibility.

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