Impact force measurement of a plastic sheet using drop ball test by the Levitation Mass Method (LMM)

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Abstract. Drop ball test by the Levitation Mass Method (LMM) was carried out on a plastic sheet made of PMMA. Impact response of PMMA was measured with high accuracy and accurately evaluated. In this test, the velocity of the center of gravity of a metal spherical body is accurately measured using an optical interferometer. The acceleration, displacement, and inertial force of the spherical body are calculated from the velocity. In other words, the impact response of a plastic sheet is calculated from the velocity of a sphere dropped onto a plastic sheet. The uncertainty in this measurement is estimated to be 7.4 mN. This corresponds to 0.03% of the maximum force of approximately 27 N. However, the result has an uncertainly point which is a period to receive a constant impact force. Change of the boundary condition during the test is the components of an uncertainly point.

1. Introduction

Most impact testers for plastic sheet defined by JIS K7211 uses force transducers. However, force transducers can’t measure dynamic force with high accuracy because it is difficult to evaluate the uncertainty of dynamic force measured by the transducer. Therefore, impact testers for plastic sheet without transducer is needed.

We have previously developed a method for precision mechanical measurement known as the Levitation Mass Method (LMM). In the LMM, inertial force of a mass levitated using an aerostatic linear bearing is used as the reference force applied to the objects under the test, such as force transducers, materials, or structures [1−3]. The inertial force of the levitated mass is measured using an optical interferometer. In the LMM, only the motion-induced time-varying beat frequency is measured during the experiment, and all other quantities, such as velocity, position, acceleration, and force, are numerically calculated from the frequency. This results in good synchronization between the obtained quantities. In addition, the force is directly calculated according to its definition, that is, the product of mass and acceleration. Impact force of a spherical body dropping onto a water surface is also measured using a drop ball tester by the LMM [4, 5].

In this paper, we developed a method for measuring the impact force of a spherical body dropping onto a plastic sheet by modifying the LMM. As an example, drop ball tests by the LMM for PMMA was carried out. The validity of this impact force measurement method is experimentally demonstrated.

2. Experiment

Fig. 1 shows the experimental setup of a drop ball tester using the Levitation Mass Method (LMM). A spherical body with cube corner prism is used in this tester instead of rigid body in the LMM. Fig. 2 shows the photographs of the spherical body. Fig. 3 shows the details of the spherical body. The spherical body is made of SUS440 stainless steel. The total mass of the spherical body M, is approximately 93.88 g. A cube corner prism (CC), 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 whole body.

The spherical body is held by a hollow circular electromagnet. By turning off the power of the electromagnet, the spherical body gently falls down by gravity force. Measurement is started when the optical switch is interrupted by the spherical body. Drop distance is approximately 24 mm in this test. A high-speed camera (Nikon 1 V2) is used to capture the images of the impact test with a resolution of 320×120 pixels and a frame rate of 1200 fps. The time of the photograph taken by this camera is decided by the LED which emits light when the optical switch is turned on. Measurement is stopped when the spherical body falls on the test piece and the CC embedded in the spherical body deviates from the optical axis.

The direction of the coordinate system for the velocity, the acceleration, and the force acting on the body is upward in Fig. 1. The total force acting on the spherical body is equivalent to the product of its mass and acceleration as

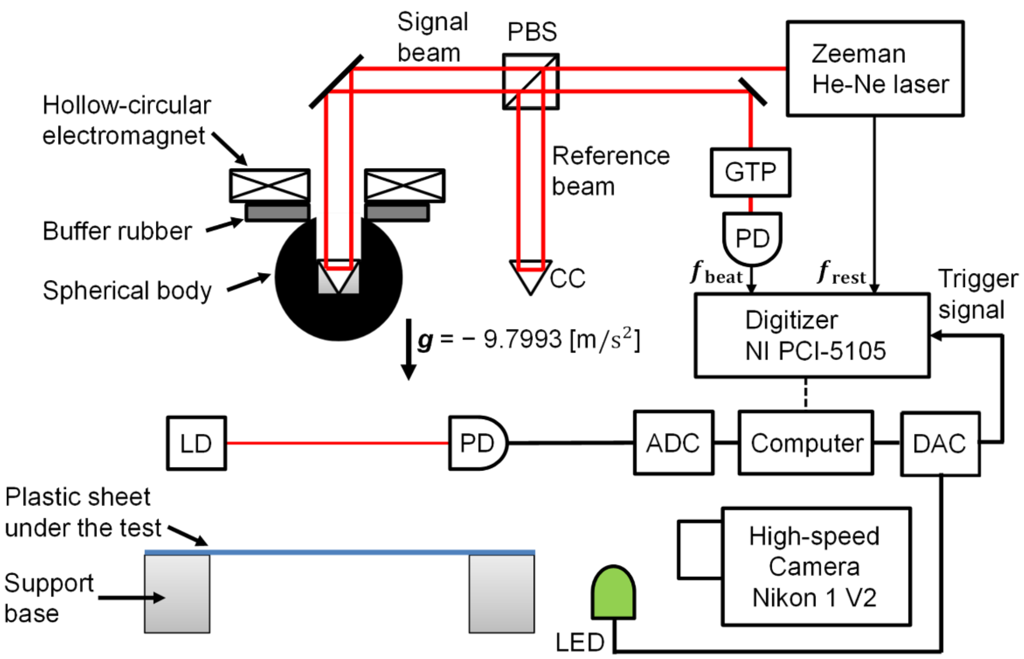
$$\boldsymbol{F}_{\mathbf{mass}} = \boldsymbol{Ma}. \tag{1}$$

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 signal beam of interferometer $\boldsymbol{f}_{\mathbf{Doppler}}$, which can be expressed as

$$\boldsymbol{v} = \boldsymbol{\lambda}_{\mathbf{air}} \left(\boldsymbol{f}_{\mathbf{doppler}} \right) / 2, \tag{2}$$

$$\boldsymbol{f}_{\mathbf{doppler}} = - \left(\boldsymbol{f}_{\mathbf{beat}} - \boldsymbol{f}_{\mathbf{rest}} \right), \tag{3}$$

where $\boldsymbol{\lambda}_{\mathbf{air}}$ is the wavelength of the signal beam, $\boldsymbol{f}_{\mathbf{beat}}$ is the beat frequency, and $\boldsymbol{f}_{\mathbf{rest}}$ is the rest frequency. The beat frequency $\boldsymbol{f}_{\mathbf{beat}}$ is the frequency difference between the signal beam and the reference beam. The rest frequency $\boldsymbol{f}_{\mathbf{rest}}$ is equivalent to the beat frequency $\boldsymbol{f}_{\mathbf{beat}}$ when the spherical body is at rest and no Doppler shift is added to the signal beam. Frequencies $\boldsymbol{f}_{\mathbf{beat}}$ and $\boldsymbol{f}_{\mathbf{rest}}$ are measured by interferometer, converted into a voltage signal by a digitizer, and recorded in a computer. Zero-crossing Fitting Method (ZFM) is a method for obtaining frequency from electric signal data [6, 7]. In ZFM, all zero-crossing times inside each sampling interval are used to determine the frequency. In our analysis, the sampling interval is defined by N = 500 periods of the signal waveform.



PBS : Polarizing beam splitter, LD : Laser diode, PD : Photo diode,
CC : Cube corner prism, GTP : Gland-Thompson prism,
ADC : Analog to digital converter, DAC : Digital to analog converter.

Fig. 1 Experimental setup

The total force, $\boldsymbol{F}_{\mathbf{mass}}$, consists of the gravitational force acting upon the body, $-\boldsymbol{Mg}$, and the impact force acting from the water, $\boldsymbol{F}$, if other forces, such as the air drag and the magnetic force, are negligible. Then, the total force is

$$\boldsymbol{F}_{\mathbf{mass}} = -\boldsymbol{Mg} + \boldsymbol{F}, \tag{4}$$

where $\boldsymbol{g}$ is the acceleration of gravity, approximately 9.799 m/s^2 at the experimental room. Therefore, the impact force acting from the water can be calculated as

$$\boldsymbol{F} = \boldsymbol{F}_{\mathbf{mass}} + \boldsymbol{Mg}. \tag{5}$$

A Zeeman-type two-wavelength He-Ne laser, the two frequencies of which have orthogonal polarization, is used as the light source. The difference between the two frequencies; i.e., the rest frequency $\boldsymbol{f}_{\mathbf{rest}}$, is approximately 2.8 MHz.

A plastic sheet which is the specimen of this test is put on a support base made of SUS304 stainless steel. Each experimental condition such as test piece shape and support base shape was decided with reference to JIS K 7211.

This experiment was conducted on PMMA plates as typical plastic material, and its impact response was measured. Experiments were carried out on three specimens, measurements were carried out five times on the same specimen. The specimen shape is square like JIS K7211, and its thickness is 0.5 mm.

Fig. 4 shows Photographs of the support base used in this tester. Fig. 5 shows details of the support base used in this tester. Table 1 shows the dimensions of each part. The dimensions of each part were determined according to the ratio of the diameter of the falling part, the inner diameter of the supporting base, the outer diameter of the supporting base and the length of one side of the test piece of JIS K7211. Chamfering of the inner circumference of the support base was set to R1 so that the contact portion between the test piece and the support stand was not worn out while the experiment was repeated.

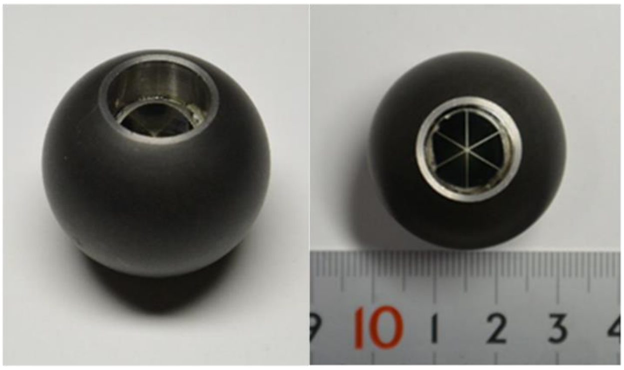


Fig. 2 Photographs of the spherical body

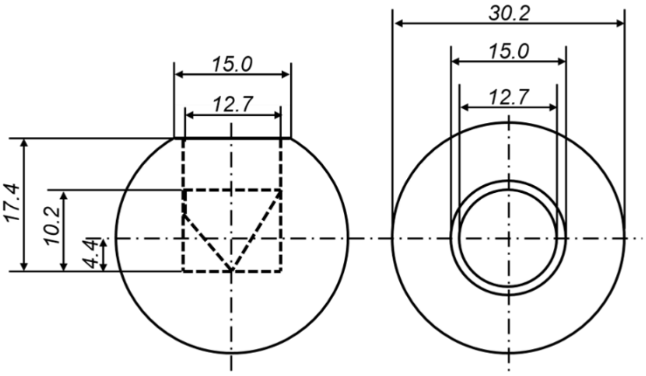


Fig. 3 Details of the spherical body

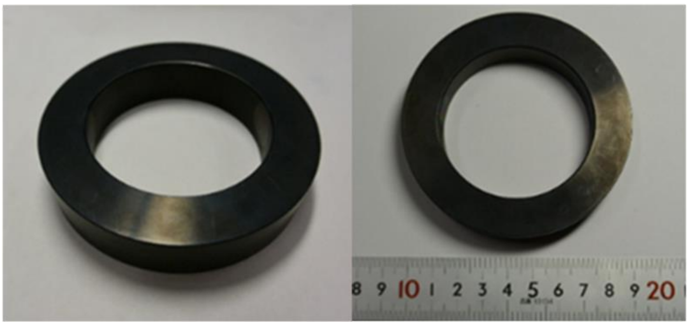


Fig. 4 Photographs of the support base

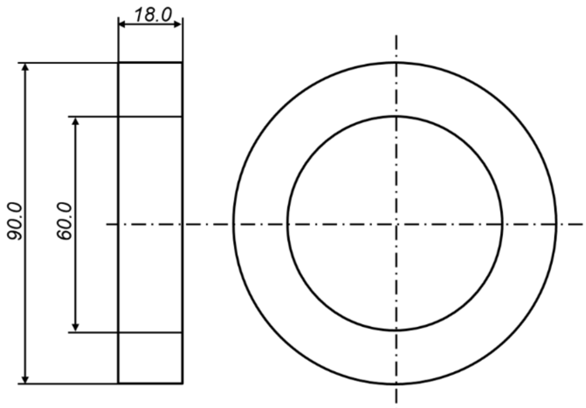


Fig. 5 Details of the support base

Table 1 Experiment condition: dimensions

Standard	Height [m]	Diameter [mm]	Inner diameter [mm]	Outside diameter [mm]	Specimen [mm]
JIS K7211	0.3−2	20	40	60	60
Drop ball test	0.024	30	60	90	90

3. Result

Fig. 6 shows the data processing procedure. The velocity, $\boldsymbol{v}$, is calculated from the frequencies $\boldsymbol{f}_{\mathbf{beat}}$ and $\boldsymbol{f}_{\mathbf{rest}}$. The acceleration, $\boldsymbol{a}$, is calculated by time differential of the velocity. The inertial force acting upon the spherical body, $\boldsymbol{F}_{\mathbf{mass}}$, is calculated from eq. (1). And the impact force acting upon the spherical body from the plastic seat, $\boldsymbol{F}$, is calculated by eq. (5).

The origins of the time and position axes are set to be the time and the position at which the impact force is detected in this test.

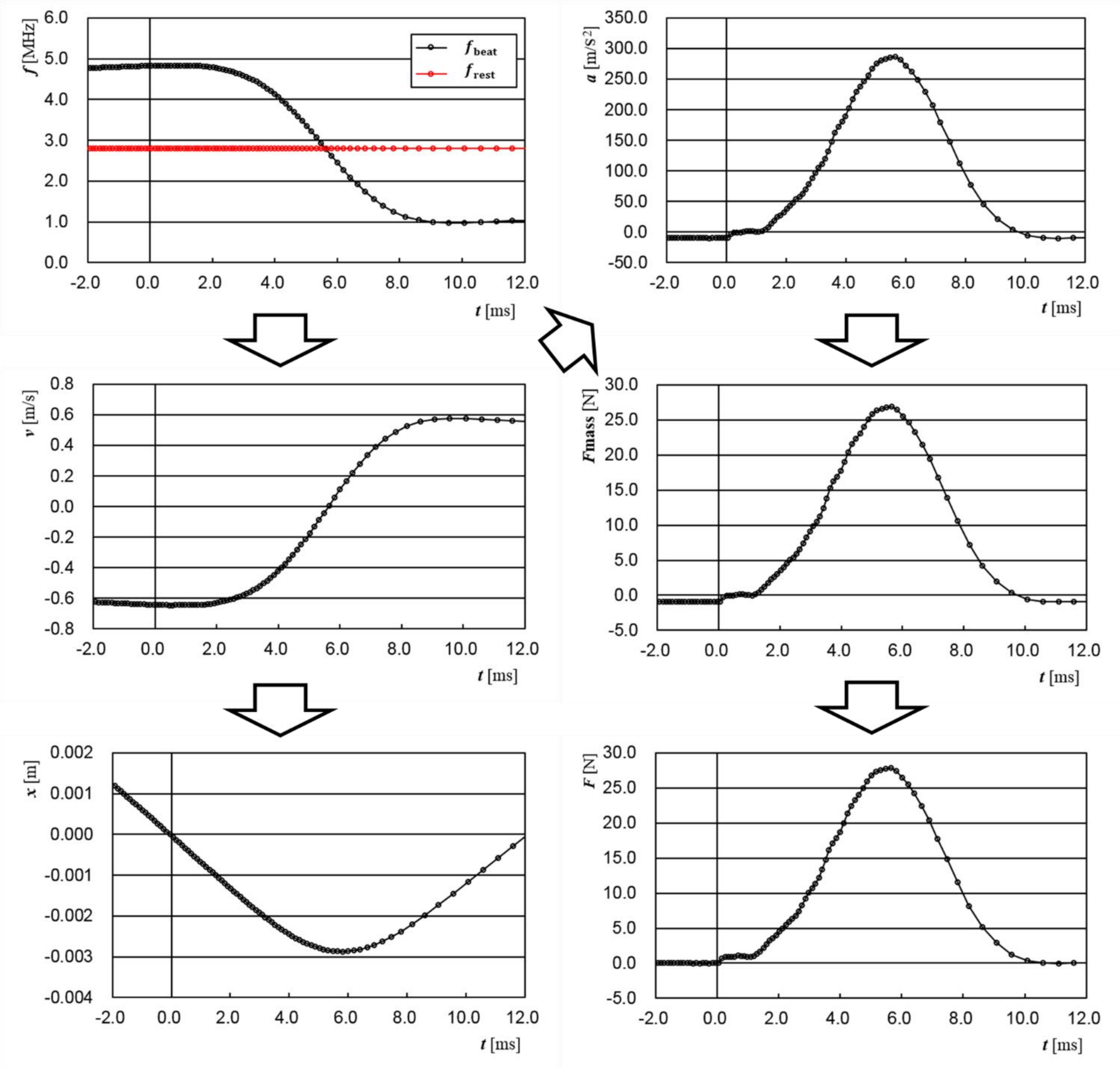


Fig. 6 Data processing procedure

Fig. 7 shows the impact force, ***F***, and the velocity, ***v***, against the time, ***t***, and images of the spherical body taken by the high-speed camera.

Fig. 7(a) shows the spherical body which touched the specimen. When the spherical body impacts the plastic seat, ***F*** increased to a constant value 1.0 N until ***t*** = 1.23 ms. Fig. 7(b) shows the spherical body which was received constant impact force.

After that, ***F*** increased steeply to a maximum value of approximately 27.8 N at ***t*** = 5.65 ms and ***x*** = − 0.0028 m. Fig. 7(c) shows the spherical body which was received large impact force at ***t*** = 5.83 ms. Fig. 7(d) shows the spherical body which leaved the specimen at ***t*** = 11.67 ms.

Fig. 8 shows the ***F*** against time for the 5 drop measurements in the same test piece. The results of the 5 drop measurements in the same test piece coincide well, indicating a high reproducibility of the measurements.

Fig. 9 shows the ***F*** against time for the drop measurements in the different 3 test pieces. The results of the drop measurements in the different 3 test pieces coincide well, indicating a high reproducibility of the measurements.

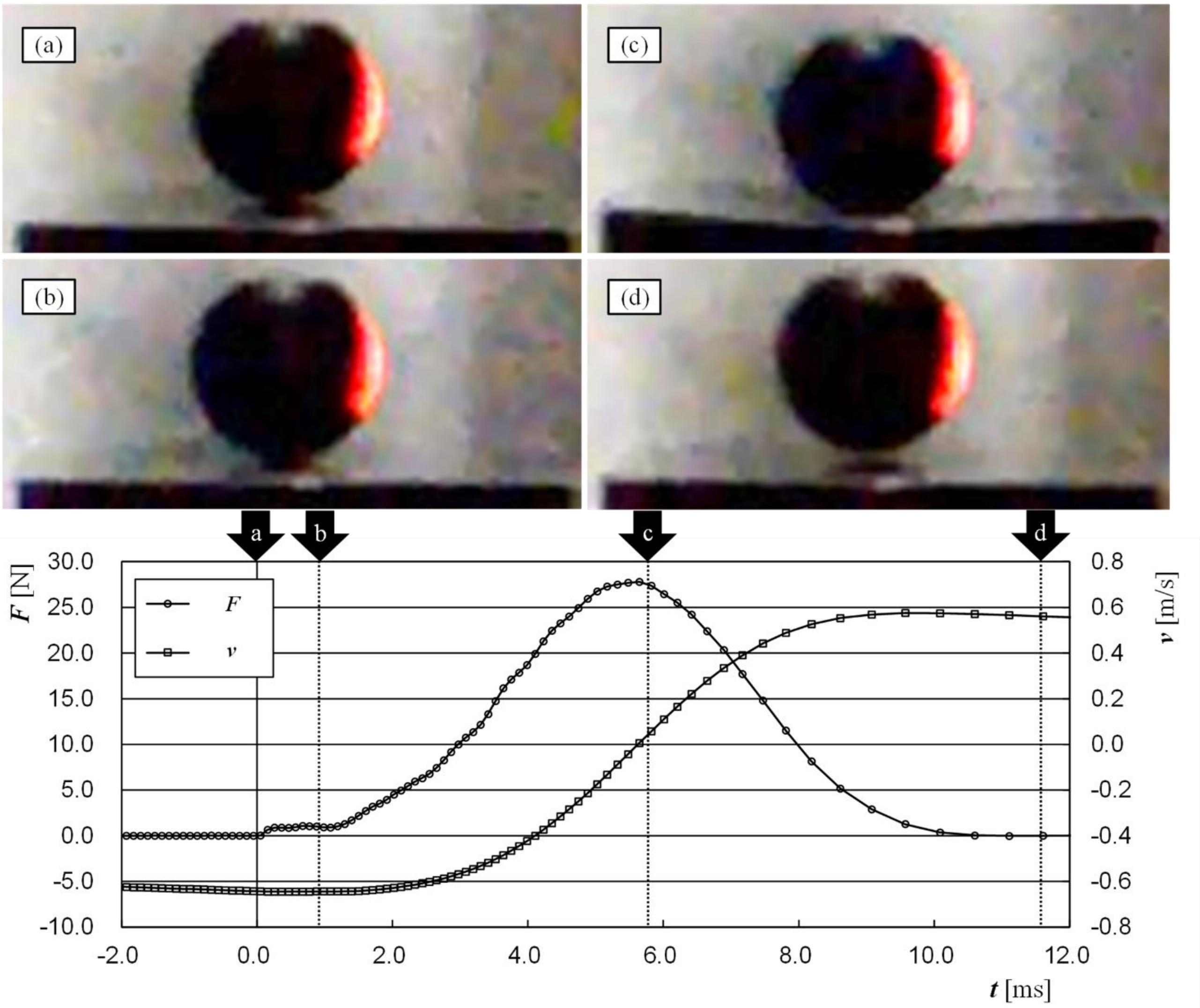


Fig. 7 Result: Impact response of PMMA

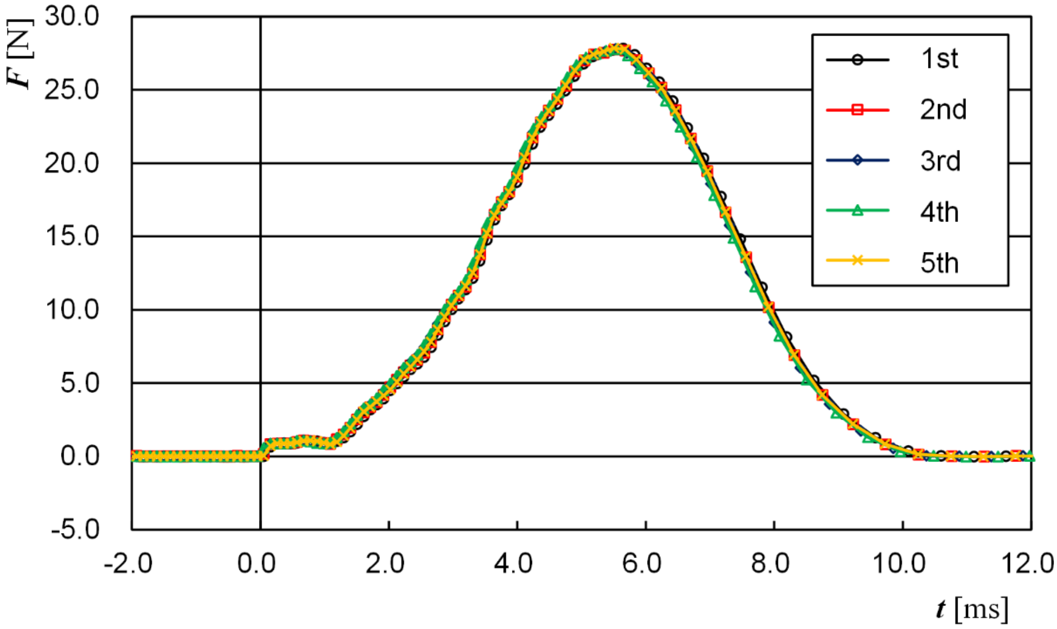


Fig. 8 5 Drop measurements in the PMMA-1

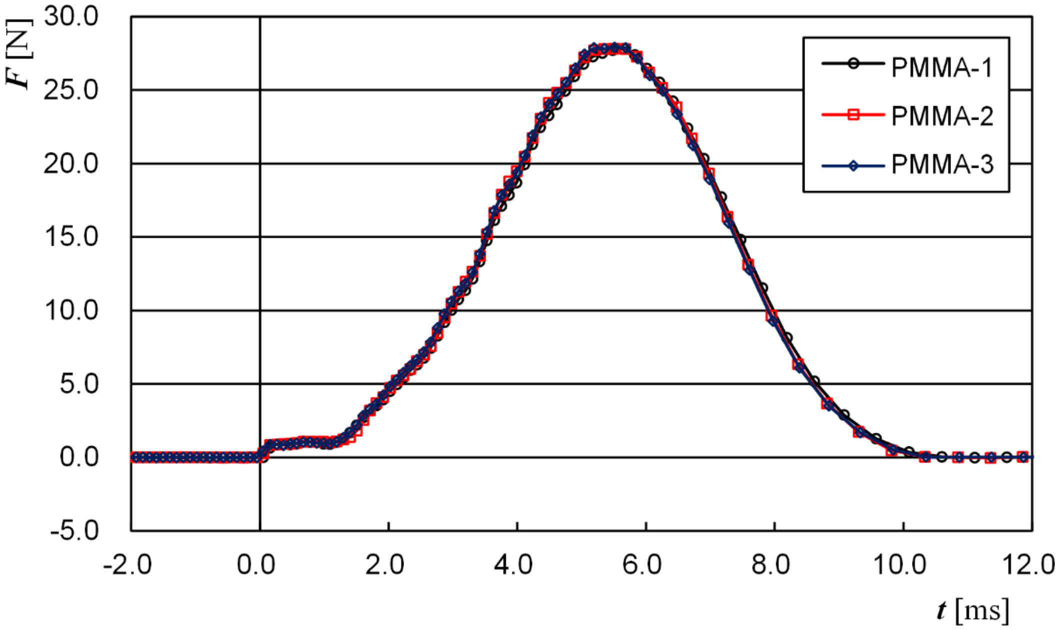


Fig. 9 Drop measurements in the 3 specimens

4. Discussion

An uncertainly point which is a period to receive a constant impact force during 0.0–1.23 ms is observed in the all results. The components of an uncertainly point is thought as follows. The contact portion between the specimen and the support base shifts from the upper surface of the support base to the circumference of the inner circumference of the support base as the specimen deforms. So the boundary condition is not constant at the start of the test.

The elements of uncertainty in this experiment are considered as follows.

[U.1] Optical alignment

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

[U.2] Mass calibration

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 moving part. This corresponds to 0.1 mN when the applied force reaches its maximum value $\boldsymbol{F}_{\mathbf{mass}}$, max = 1.0 N, which is negligible.

[U.3] Acceleration of gravity

The acceleration due to gravity g is estimated to be 9.799 m/s^2 with an uncertainty of 0.01%, which is negligible.

[U.4] Air drag

The uncertainty due to the influence of air drag was calculated from the maximum speed of the sphere in this test. The air drag force is estimated to be 0.08 mN, which is negligible.

[U.5] Noise of the optical interferometer

[U.6] Frequency estimation by ZFM

[U.7] Numerical calculation of force from the frequency

The sources of uncertainty [U.5]–[U.7] are difficult to estimate separately. However, the uncertainty from each component is assumed to be similar between when in free-fall motion before the collision and during the collision with plastic sheet.

The mean and standard deviation of $\boldsymbol{F}$ (= $\boldsymbol{F}_{\mathbf{mass}} + \boldsymbol{Mg}$) during free-fall motion before the collision, at height above the plastic sheet 0−10 mm, is approximately 0.4 mN and 7.4 mN, respectively, for the drop measurements. Therefore, the combined uncertainty of [U.5]–[U.7] is estimated to be approximately this standard deviation, 7.4 mN. Since only [U.5]–[U.7] have a significant contribution, the total uncertainty when determining the instantaneous value of the force $\boldsymbol{F}_{\mathbf{mass}}$ acting on the plastic sheet under test is estimated to be 7.4 mN. This corresponds to 0.03% of the maximum force of approximately 27 N.

5. Conclusion

Drop ball test by the Levitation Mass Method (LMM) was carried out on plastic sheets made of PMMA. In this experiment, impact response of PMMA was measured with high accuracy and accurately evaluated. But an uncertainly point at immediately after the increase time of $\boldsymbol{F}$ in the test result. Therefore investigating factors by numerical analysis such as Finite Element Method (FEM) and Computer Aided Engineering (CAE) is required to clarify this uncertainly point. And the mechanical properties of plastic materials will be investigated by this method.

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