Measuring the Impact Force Acting on the Clay by the Drop-ball test method based on the Levitation Mass Method (LMM)

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Abstract. The impact force acting on a clay is measured by the Drop-ball test method based on the Levitation Mass Method (LMM). In the measurement, a spherical body containing a cube corner prism which is arranged so that its optical center coincides with the center of gravity of the whole body is dropped from an initial height to the clay under test. The velocity of the center of gravity of the whole body is measured using an optical interferometer as the function of the Doppler shift frequency. The position and acceleration is calculated by differentiating and integrating the velocity, respectively. Force acting on the spherical body is calculated as the product of the mass and the acceleration. Impact force acting on the clay is calculated as summation of gravitational force and force acting on the spherical body, if other forces, such as the air drag of the free fall motion and the magnetic force form the hollow circular electromagnetic which used to hold the spherical body, are negligible. In the experiment, the measured of maximum force acting on the clay is approximately 34.5 N with estimated uncertainty of 50.9 mN. This corresponds to 0.2 % of the maximum force acting on the clay.

1. Introduction

Plasticity is one of important properties of clay-water systems. It is defined as a property that shows shape changes without crack when a clay body with added water is submitted to an external force. Furthermore, when the force is removed or reduced below to a value corresponding to the yield stress, the shape is maintained. The evaluation of clay plasticity can be distinguished in two groups: indirect or direct measurements [1]. In the indirect measurement, the plasticity is not determined itself, but rather the properties related to it. Examples: in the Atterberg method, the plasticity is expressed as the range of the water content within which clay achieves its plastic state. In Pfefferkorn method, the plasticity is determined based on the effect of moisture content to the reduction height of a sample with a defined diameter and height deformed by a free falling plate with a given mass [2]. Otherwise, in the direct measurement, the plasticity is determined by evaluating the effect moisture content of the clay body on the relationship between an applied force and the resulting deformation. The dynamic force is applied to the clay and measured using a force sensor which calibrates using static calibration method. The deformation is measured using a meter scale or a caliper [3-7]. Examples of direct measurement are indentation method [4-5], capillary rheometer [6] and tension versus deformation [7]. In indentation method, the plasticity of the clay is expressed in terms of a measured reaction force of the clay against the indentation force applied on it with a given volume. The reaction force of a clay is measured using a force sensor. However, at the present, the accuracy of the measured dynamic force using a force sensor is difficult to achieve because only the static calibration of the force sensor is available. So, it is very difficult to evaluate the uncertainty of the measured dynamic force.

In order to achieve the accuracy of the measured dynamic force, we have been developed the Levitation Mass Method (LMM). In this method, a mass is made to collide with the object under tests, such as force transducers, materials, or structures [8-10]. The mass is supported by an aerostatic linear bearing to realize sufficiently small friction which can be negligible. The force acting on the mass is measured using an optical interferometer and defined as the force acting from the material under test based on the law of action-reaction (Newton's third law). In the LMM, only the motion-induce time-varying beat frequency is measured during the experiment. The velocity, position, acceleration and force are numerically calculated from the frequency. This makes a good synchronization between the calculated quantities. In addition, the force is directly calculated according to its definition, that is, the product of the mass and acceleration. We have been modified the LMM by replacing the aerostatic linear bearing with a spherical body that dropped onto the object under tests. This test is named the Drop-ball test [11].

In this paper, we propose a method for measuring the impact force acting on the clay by the Drop-ball test method based on the LMM, and the validity and reproducibility of the proposed method are experimentally demonstrated. In the proposed method, there is a possibility to establish new indication of a plasticity of a clay by dividing maximum impact force acting on the clay with the maximum volume of clay deformation. The proposed method can be classified to a direct method to measure the plasticity of a clay.

2. Experiment

Fig. 1 shows the schematic diagram of the experimental setup for measuring the impact force acting on the clay by the Drop-ball test method based on the LMM. In the experiment, a clay for handicrafts (composition: shirasu balloon, talc, synthetic binder, pulp fiber powder, preservative, moisture retaining, whitening agent and water, Manufacturer: Moritoku. Ltd., Japan) is used as the object to be tested. The clay is shaped in the block shape with length 60.0 mm, width 60.0 mm and height 10.0 mm. The density of the clay is approximately 1.7 g/cm^3. The clay is placed on the rigid base. The spherical body is dropped onto the clay from the initial height. The initial height approximately 30 mm. The spherical body is made from the SUS440 stainless steel 30.2 mm in diameter and containing a cube corner prism 12.7 mm in diameter, which arranged so that its optical center of a cube corner prism coincides with the center of gravity of the whole body *i.e.* the spherical body and the cube corner prism. The photographs and schematic diagram of the whole body is shown by Fig.2. The total mass of the whole body, $\boldsymbol{M}$, is approximately 93.88 g.

In the initial stage the whole body is held by a hollow-circular electromagnetic. When the test is started, the power of the electromagnetic is turn off then the whole body will fall freely by gravity. The velocity at the center of mass of the whole body is measured using an optical interferometer. A Zeeman-type two-wavelength He-Ne laser is used as the optical interferometer light source, which have two frequencies with orthogonal polarization. The difference between two frequencies is approximately 2.8 MHz.

A digitizer (NI PCI-5105, National Instruments Corp., USA) is used to record the output signals of photodiode (PD_1) with sampling number of 15 M, sampling rate of 30 M samples per second, and a resolution of 8 bit. The period of measurement of the digitizer is approximately 0.5 s.

The developed Zero-Crossing Fitting method (ZFM) [12] is employed to determine the beat frequencies, $\boldsymbol{f_{beat}}$, and the rest frequencies, $\boldsymbol{f_{rest}}$, from the waveforms signals which recorded by the digitizer. In this ZFM, the sampling interval is defined by $N = 200$ periods of the signal waveform, which corresponds to 0.032 ms when $\boldsymbol{f_{beat}}$ is approximately 6.3 MHz.

The velocity of the spherical body is calculated from the measured value of the Doppler shift frequency of the signal beam of an optical interferometer, $\boldsymbol{f_{Doppler}}$, which can be expressed as

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

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

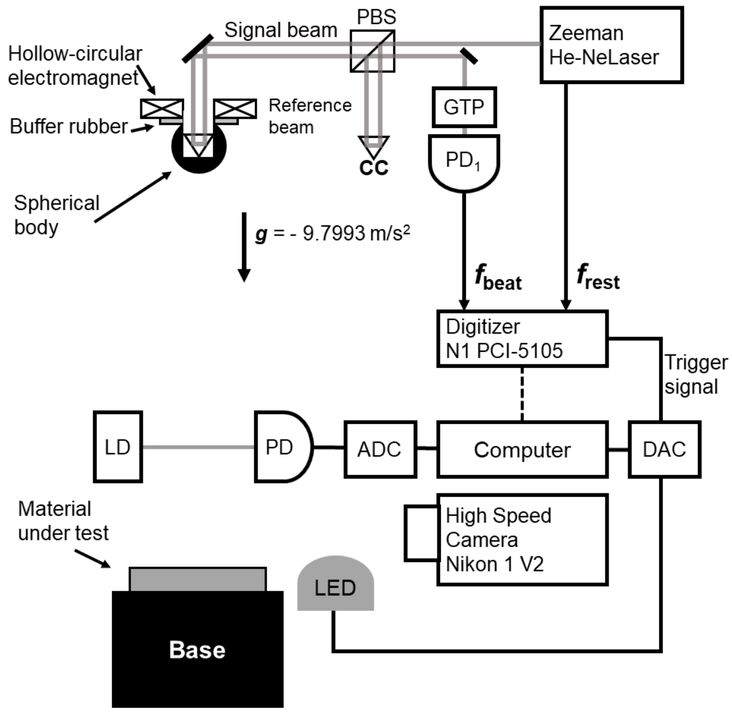
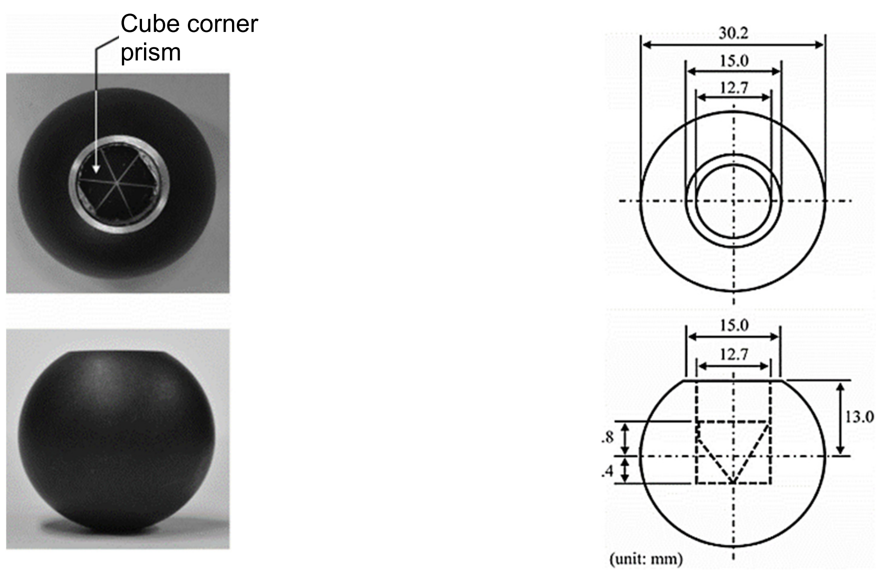


Fig. 1. Experimental Setup, CC= cube corner prism, PBS= polarizing beam splitter, ADC= analog digital converter, DAC= digital analog converter, LD= laser diode, PD= photo diode.



(a) Photographs of the whole body (b) Schematic diagram of whole body

Fig. 2. Photographs and schematic diagram of whole body.

where λ_{air} is the wavelength of the signal beam, f_{beat} is the beat frequency that defined as the frequency difference between signal beam and reference beam, and f_{rest} is the rest frequency, which is equivalent to the beat frequency, f_{beat} when the spherical body at the rest position. The direction of the coordinate system for the velocity, the acceleration, and the force acting on the spherical body is upward in Fig. 1, which is opposite direction of gravity. The acceleration and displacement are calculated by differentiating and integrating the velocity of the spherical body, respectively.

The total force acting on the spherical body, F_{mass}, is calculated as the product of the mass and acceleration. If the other force such as the air drag and the magnetic force, are negligible. Then at the point of impact between the body and the material under test, the total force acting on the body, F_{mass}, can be expressed as

$$F_{mass} = -Mg + F_{clay}, \tag{3}$$

where $-Mg$ is the gravitational force acting upon the spherical body, and F_{clay} is the impact force acting on the clay. Then the impact force acting on the clay can be expressed as:

$$F_{clay} = F_{mass} + Mg, \tag{4}$$

Otherwise, if the other force, such as air drag, cannot be negligible. Then F_{clay} is assumed to include those other forces.

An optical switch, which is the combination of a laser diode and the photodiode is employed to initiate the digitized and LED. During the measurement, a high-speed camera with a resolution of 320×120 pixels and a frame rate of 1200 fps (Nikon 1 V2) is employed to record the images of the dropping body. Five Drop-ball tests are conducted to show the reproducibility of the proposed method. In the experiment, five of the Drop-ball test with the same initial height is conducted.

3. Result

Fig. 3 shows the data processing procedure of measuring the impact force acting from the clay by the Drop-ball test method based on the Levitation Mass Method (LMM). In the processing procedure, the velocity, v, is calculated from the frequencies f_{beat} and f_{rest}. The displacement, x, and the acceleration, a, are determined by differentiating and integrating the velocity, respectively. The total force acting on the spherical body, F_{mass}, is calculated as the product of the mass and acceleration. The impact force acting from the clay, F_{clay} is calculated using equation (4). The origin of the time and position axes are set to be the time and the position at the impact force acting from the clay, F_{clay}, is begin to occur. The maximum value of total force acting on the spherical body, F_{mass_max}, is approximately 33.5 N. The maximum impact force acting from the clay, F_{clay_max}, is approximately 34.5 N. The period of full width at half-maximum (FWHM) of the impact force, T_{FWHM}, is approximately 2.5 ms.

Fig. 4 shows the relationship between velocity and displacement. The velocity before collision, v_1, is approximately - 0.7 m/s and the velocity after collision, v_2, is approximately 0.2 m/s. The kinetic energy dissipation, ΔKE is approximately 2.3×10^{-2} J. The energy dissipation ratio, which is the ratio between the kinetic dissipation and the initial kinetic energy, $\Delta KE/KE_1$, is approximately 0.93 (93%).

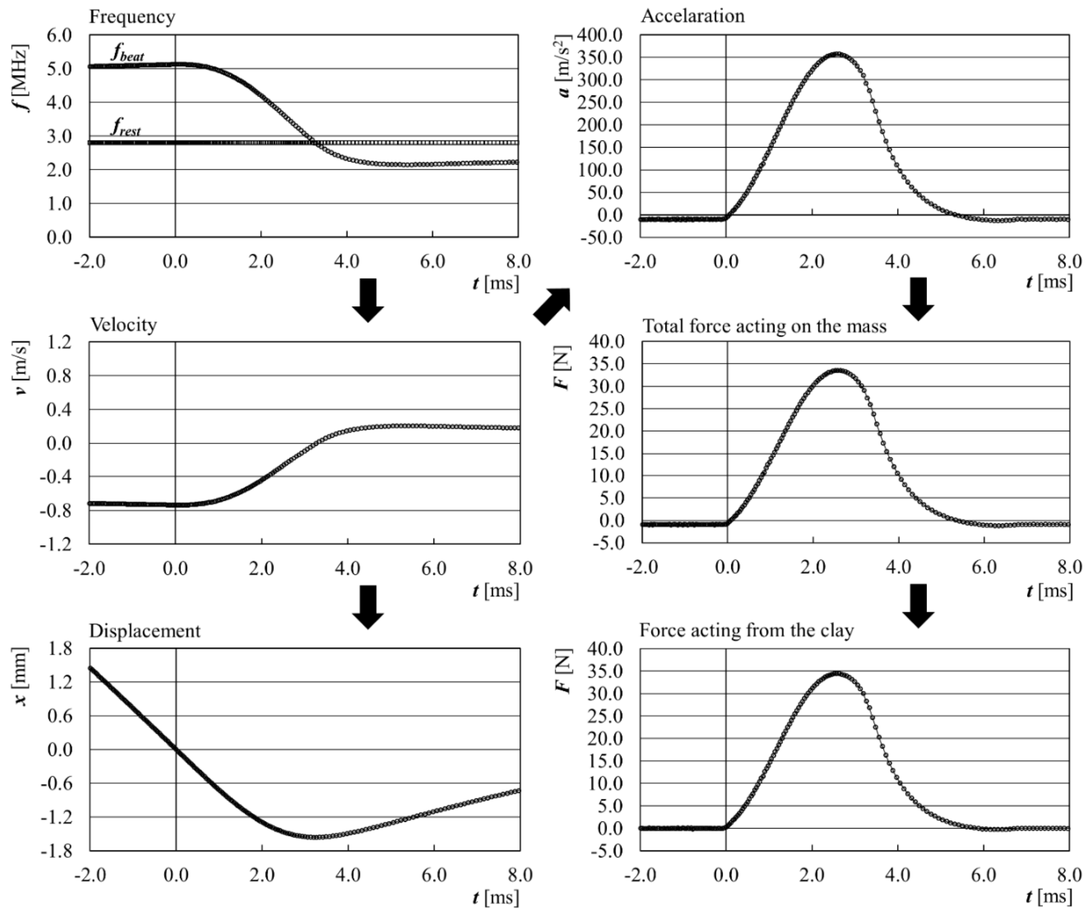


Fig. 3. Data processing procedure of measuring the impact force acting from the Clay by the Drop-ball test using the Levitation Mass Method (LMM).

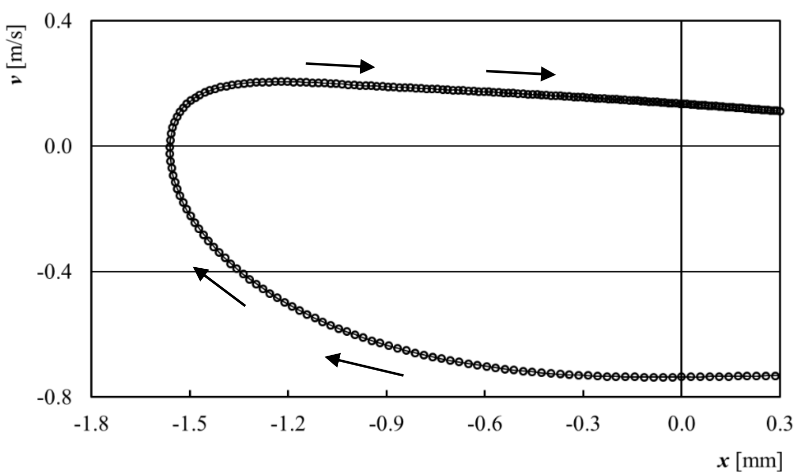


Fig. 4. Change in velocity against displacement.

Fig. 5 shows the relationship between force and displacement. The hysteresis curve is obtained. The work done by the mass is calculated by integration the force along the path of displacement, which is approximately 2.4 × 10^{-2} J. This value is match up to the kinetic energy dissipation, which calculated from the velocity before and after the collision.

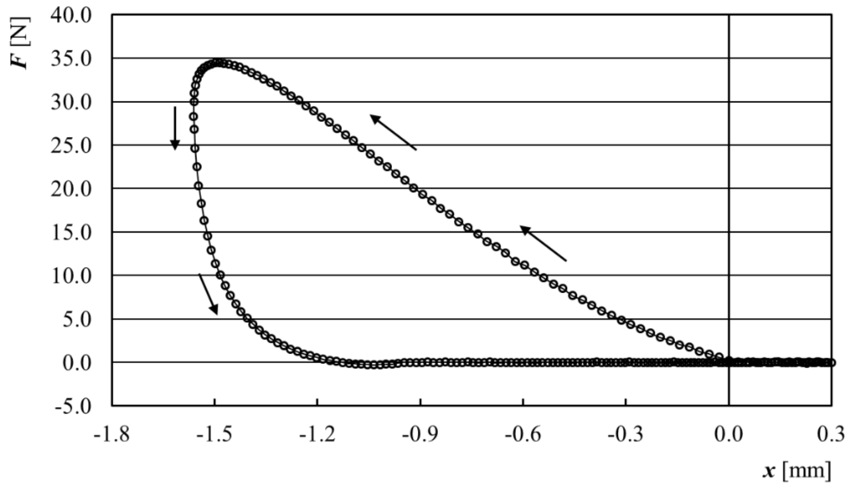


Fig. 5. Change in force against displacement.

Fig. 6 shows the relationship between force and velocity. The reduction of the velocity after collision is shown. The velocity when the force has a maximum value is determined by averaging the value of eleven nearest neighbors of every point since the difficulty to determine the peak of the curve shown by Fig.6. The velocity when the force has a maximum value is approximately -2.4 × 10^{-1} m/s.

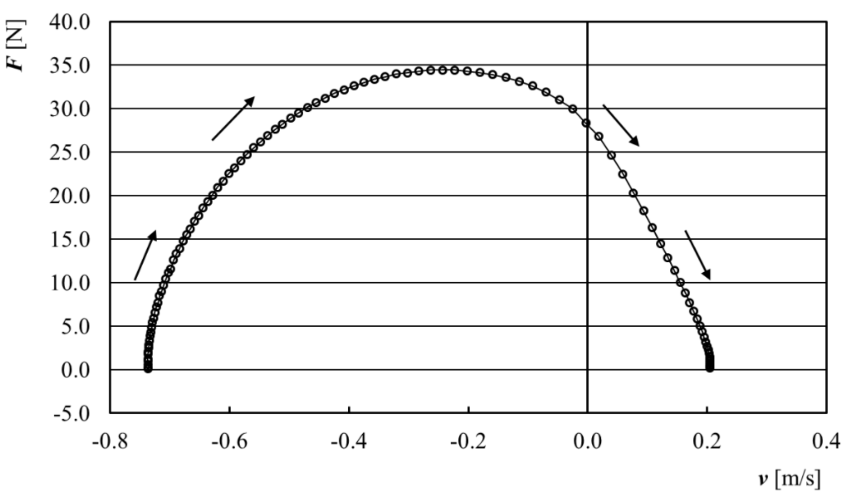


Fig. 6. Change in force against velocity.

Fig.7 shows changes in the impact force acting from the clay, $\boldsymbol{F_{clay}}$, and the velocity, $\boldsymbol{v}$, against the time, $\boldsymbol{t}$, synchronized with images taken by the high-speed camera. The maximum indentation on the clay from the spherical body is approximately 1.6 mm when the force acting from the clay is approximately 28.3 N. The velocity is approximately -2.9 × 10^{-3} m/s. The maximum volume of clay deformation is approximately 2.2 × 10^{2} mm^3 and the plasticity of a clay is approximately 1.5 × 10^{-1} N/mm^3.

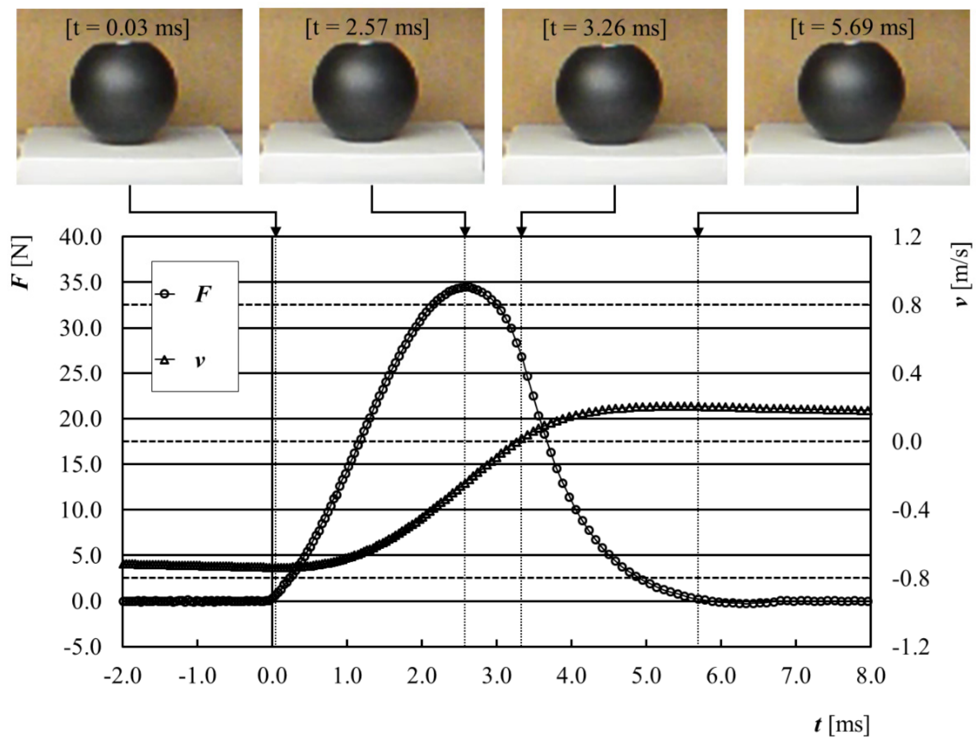


Fig. 7. Change in the impact force acting on the clay and the velocity against the time synchronized with images taken by high-speed camera.

Fig. 8 shows the relationship between force and time in 5 measurements with a same initial height. The coincide curve is obtained. The reproducibility of the proposed method is shown.

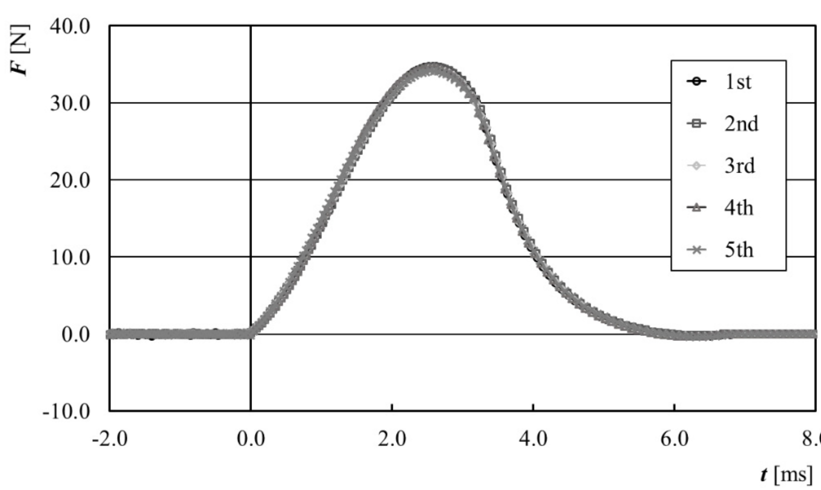


Fig. 8. Change in force against time in 5 measurements.

4. Uncetainty evaluation

In the measurement of the impact force acting from the clay, the uncertainty components are defined as follows:

4.1 Uncertainty components from determination the total force acting on the spherical body

[U 1] Optical alignment
The uncertainty from the optical alignment is determined from the inclination of the signal beam of 1 mrad results in a relative uncertainty in the initial force approximately 5×10^{-7}, which is negligible.

[U 2] Mass
Mass of the whole body is measured by the electric balance with a standard uncertainty of 0.01 g, which correspond to 0.01% of total mas of the body. This corresponds to 3.4 mN when the maximum force is 34.5 N, which is negligible.

[U 3] The acceleration caused by gravity
The gravity of earth, $\boldsymbol{g}$, is approximately 9.799 m/s^2 with the relative uncertainty of 0.01%. This corresponds to 3.4 mN when the maximum force is 34.5 N, which is negligible.

[U 4] Noise of the optical interferometer.

[U 5] Frequency estimation using ZFM.

[U 6] Numerical calculation of the force acting from the clay.

The uncertainty contributed from [U 4] – [U 6] are estimated simultaneously since it is very difficult to estimate separately. The combining uncertainty from [U 4] – [U 6] are estimated by analyzing the mean and standard deviation of force acting from the clay, $\boldsymbol{F_{clay}}$, during the free-fall motion before the collision at 30 mm above the clay. The calculated mean and standard deviation of $\boldsymbol{F_{clay}}$ are approximately 2.6 mN and 50.9 mN, respectively. The combination uncertainty from [U 4] – [U 6] is estimated to be approximately 50.9 mN.

4.2 Uncertainty components from the external force

Air drag, $\boldsymbol{F_{air}}$, is calculated at the maximum velocity $\boldsymbol{v}$ = - 0.7 m/s to be approximately 0.2 mN with an air drag coefficient of the spherical body, $\mathbf{C_d}$ = 0.5, which is negligible.

In the measurement, the standard uncertainty in determined the force acting form the clay when dropped by spherical body is estimated to be 50.9 mN. This corresponds to 0.2×10^{-3} (0.2 %) of the maximum force acting from the clay of approximately 34.5 N.

5. Discussion

In the other experiment which use a penetrometer to measure the plasticity of a clay, force is measured using the force sensor which usually calibrate using static method [4]. The uncertainty of the force measurement is approximately 2.5%. In the proposed method, the impact force acting from the clay is measured as the summation of the force and gravitational force acting on the whole body. The force acting on the whole body is measured using an interferometer. The uncertainty of the force measurement is approximately 0.2%. The improvement of accuracy in the force measurement is obtained using the proposed method. In this experiment, the possibility of a new indication of the plasticity of a clay is proposed. The plasticity of a clay is indicated by dividing maximum impact force acting on the clay with the maximum volume of clay deformation. However, in this experiment, only one kind of composition of clay is used. The force measurement from a variation of the clay composition is needed to validate the possibility of new indication of plasticity of a clay. The measurements will be conducted in the future work.

6. Conclusion

The impact force acting on the clay is measured by the drop ball test method based on the Levitation Mass Method (LMM). The measured maximum force acting on the clay is approximately 34.5 N with estimated uncertainty of 50.9 mN. This corresponds to 0.2 % of the maximum force acting on the clay. A good synchronous between mechanical properties such as velocity, acceleration, displacement, and force, are obtained since only the time-varying beat frequency is measured during the experiment. In addition, the high-speed camera images give a detail information about the impact process.

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