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Improvement of analysis method for drop ball tester based on the Levitation Mass Method (LMM)

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Abstract. Drop ball test based on the Levitation Mass Method (LMM) is carried out on EPS board. In our previous method, it became a problem that the accuracy of force calculated from the obtained data decreases as the object's speed approaches 0 [m/s]. There are two causes for this problem one is correcting program of wave data, and the other is referenced time width of fitting calculation. The center point correcting program for waveform data must refer to a large amount of waveform data. But, this does not satisfy the condition when the velocity is near 0 [m/s]. Because the referenced time width for calculating position, velocity, and acceleration is always constant, there is very few number of waves in the time width at low velocity condition. Therefore, we changed the number of data referenced by the correction program according to the frequency. And the number of data to be referred to in the fitting calculation was changed according to the velocity of the ball.

1. Introduction

Our laboratory performs dynamic force measurement based on the Levitation Mass Method (LMM). As an application of the LMM, a drop ball tester using an optical interferometer was developed. The LMM is a method which measures dynamic force precisely [1]. In the LMM, a mass with known mass is levitated and collided with the test target. The force acting on the mass is calculated from a product of the mass and acceleration measured by an optical interferometer. Instead of using an air bearing, this drop ball tester drops metal balls built-in corner cube prism (CC) onto the test target. And the impact force applied to the ball is measured by measuring the position using an optical interferometer [2]. The impact test was performed on the expanded polystyrene (EPS) board using this tester. Our previous experimental system used two-frequency laser to measure the velocity of the dropped ball. Recently, we develop new experimental system which uses inexpensive single-frequency laser. However, when a single-frequency interferometer is used, there is a problem that the force can’t be accurately calculated when the ball velocity approaches 0 [m/s].

In this paper, the problem is solved by improving the analysis method.

2. Experimental setup and analysis method

2.1 Experimental setup

A schematic of the experimental device used in this experiment is shown in Fig.1. This experimental device is a drop ball tester that applies the levitation mass method. The drop ball is made by drilling a hole in a 30.2 [mm] diameter ball made of SUS440 stainless steel and embedding a 12.7 mm diameter cube corner prism (CC). The mass of the whole sphere is 93.86 [g]. In this experiment, the ball was dropped 15 times at the same position from the height of 33 [mm] to the surface of the sample. The sample EPS board was placed on a rigid steel base, and a circular metal fixture was placed to prevent displacement during the test. Thickness of EPS board is 10 [mm]. The cube corner prism (CC) is used to measure the position of the ball.

In this device, as a light source of the interferometer, a single frequency He-Ne laser is used. The wavelength of the laser is 632.8 [nm]. The laser with polarization components in the 45°direction is split into vertical and horizontal components by passing it through a polarizing beam splitter (PBS). One is incident on CC on the ball side and the other is incident on CC on the fixed side. After that, the reflected light from each CC is split into two through a non-polarizing beam splitter (NPBS), and one of them is passed through a quarter-wave plate to give a quarter-phase difference. Each interference light is then passed through a Glan-Thomson prism (GTP) and the polarization components are cut off to only 45 degree components to cause interference, and the light intensity of the interference light is converted to a voltage signal by a photodiode (PD). This signal is recorded by the digitizer (NI PCI-5105 National Instruments). The digitizer measures 5 M samples of the voltage signal output from the PD with 12 bit resolution and a sample rate of 30 [MHz].

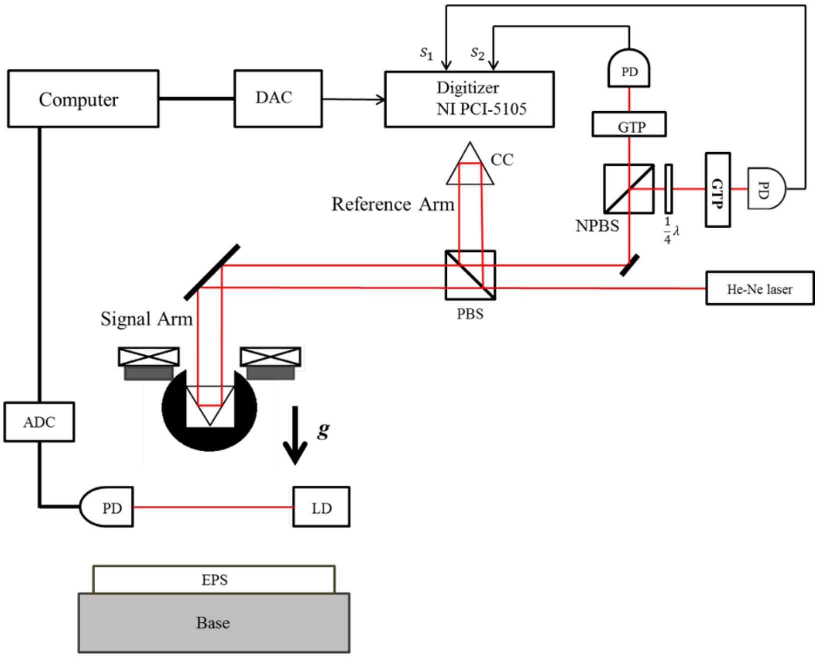

Fig.1 Experimental Setup Code: PBS = Polarizing beam splitter, NPBS = Non-polarizing beam splitter, CC = Cube corner prism, GTP = Gland-Thompson prism, PD = Photo diode, LD = Laser diode, ADC = Analog to digital converter, DAC = Digital to analog converter

2.2 Analysis method

Next, I explain the relationship between the change of light intensity and the position of CC.

Assuming that the optical path lengths are $\boldsymbol{L_1}$ and $\boldsymbol{L_2}$, respectively, the electric fields $\boldsymbol{E_1}$ and $\boldsymbol{E_2}$ of two light beams different in phase can be expressed as follows.

$$E_1(t) = U_1 exp\left\{i\left[2\pi f t + \frac{L_1}{\lambda} + \varphi_0\right]\right\} \tag{1}$$

$$\boldsymbol{E_2(t) = U_2 exp\left\{i\left[2\pi f t + \frac{L_2}{\lambda} + \varphi_0\right]\right\}} \tag{2}$$

The light intensity of this interference light can be expressed as follows.

$$I(t) = \langle|E_1(t) + E_2(t)|^2\rangle$$

$$= U_1^2 + U_2^2 + 2U_1U_2 cos\left[\frac{L_1}{\lambda} - \frac{L_2}{\lambda}\right] \tag{3}$$

In this experiment, one optical path length changes twice as much as the position x of CC, so it can be expressed as follows.

$$L_2 = L_1 + 2x \tag{4}$$

$$I(t) = \langle |E_1(t) + E_2(t)|^2 \rangle$$
$$= U_1^2 + U_2^2 + 2U_1U_2 cos\left[\frac{2x}{\lambda}\right] \tag{5}$$

The graph in Fig. 2 shows the change in light intensity s1, s2 obtained from two PDs. When the voltage signal oscillates for one cycle, the optical path length changes by one wavelength. Since the optical path length is twice the position, the amount of movement of the CC corresponding to the oscillation of one period of the voltage signal is 1/2 wavelength. Since two voltage signals are obtained with a 1/4 wavelength shift, as shown in Fig. 2, it is possible to calculate the amount of movement of CC with 1/8 wavelength resolution for each point of positive and negative switching. Since the wavelength of the He-Ne laser is λ = 632.8 [nm], it can be said that this one count is 79.1 [nm]. If the velocity changes in polarity, it can be determined from the context of the two voltage signals. We can calculate the position of CC by signal to count conversion table like Table 1.

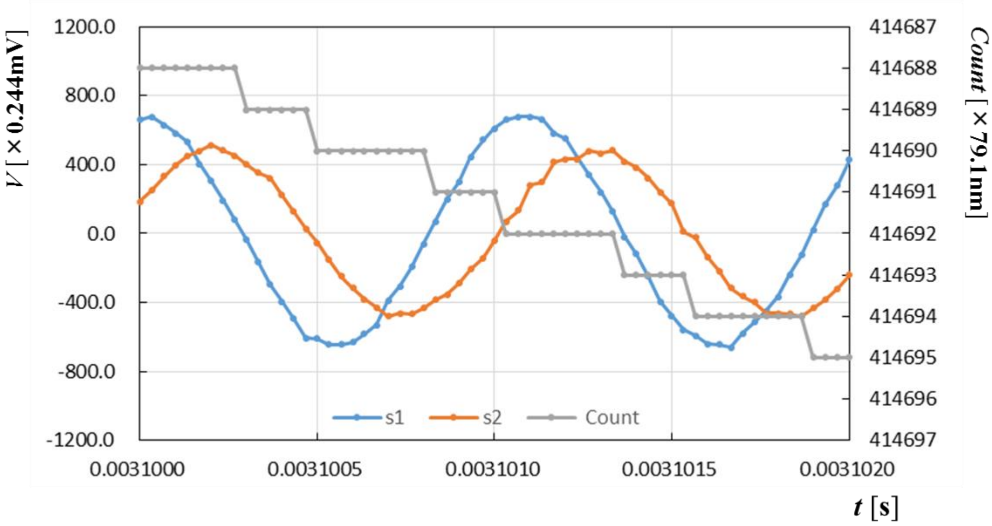

Fig.2 Voltage signal output from the PD and count of position

Condition1	Condition2	Result	Condition1	Condition2	Result
s_1: N→P	s_2>0	Count-1	s_2: N→P	s_1>0	Count+1
	s_2<0	Count+1		s_1<0	Count-1
s_1: P→N	s_2>0	Count+1	s_2: P→N	s_1>0	Count-1
	s_2<0	Count-1		s_1<0	Count+1

Table.1 Signal to count conversion table. Code: N->P = Negative to Positive, P->N = Negative to Positive.

To calculate the velocity and acceleration of the ball, the relations between time and position during certain period are fitted into a cubic function by a least square method. By substituting coefficients calculated by the fitting into the derivative of cubic function, it is possible to derive velocity and acceleration as follows.

$$x_n(t) = b_n t^3 + c_n t^2 + d_n t + e_n \tag{6}$$
$$v_n(t) = 3b_n t^2 + 2c_n t + d_n \tag{7}$$
$$a_n(t) = 6b_n t + 2c_n \tag{8}$$

3. Problems and improvements

3.1 Problems

The transition of the impact force was calculated from the data obtained by the experiment using the analysis method as shown in Section 2.2. However, as shown in Fig. 3, discontinuous values are obtained only certain sections where the ball velocity was close to 0 [m/s]. It seems that the cause was noise that became dominant only at low speeds. An analysis method to reduce the influence of noise has become necessary.

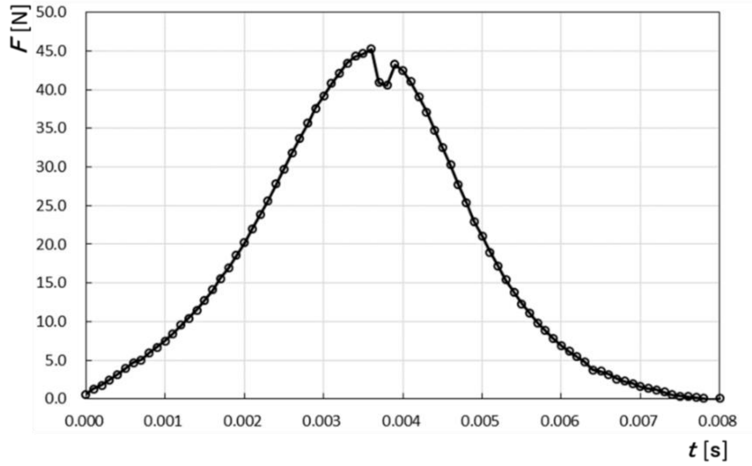

Fig.3 Calculation result of force by the previous method

3.2 Voltage signal and moving average

When investigating the cause, it was found that when the velocity is close to 0 [m/s], the voltage signal representing the light intensity becomes close to 0 [mV] as shown in Fig.4.

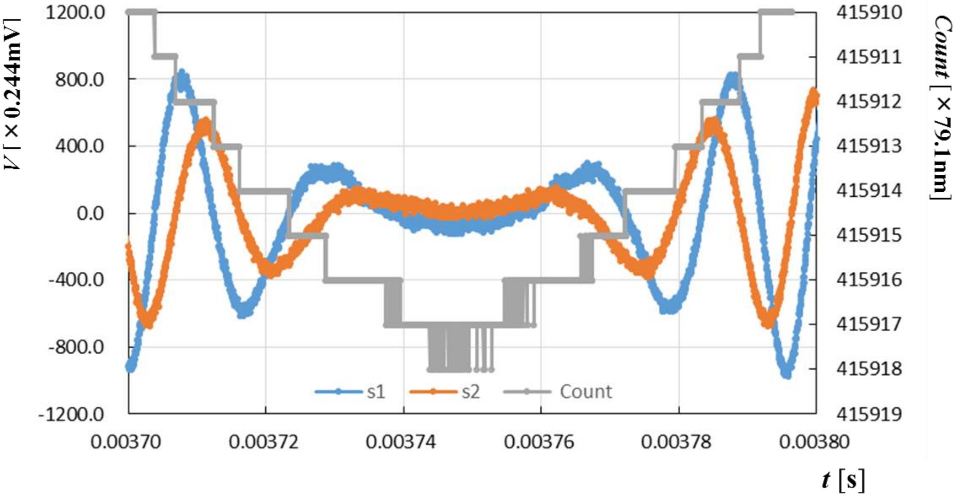

Fig.4 Calculation result of Voltage signal by the previous method

The previous analysis uses the moving average of waveform data to find the center point of vibration. Since the number of data referenced by this moving average is always constant, when the frequency of interference signal is low as shown in Fig. 4, the number of data is insufficient. In order to solve this problem, we changed the number of data to be referred to when calculating the moving average according to the frequency. The averaging width, the number of data used to averaging, is variable and is set so that a certain number of waves are included in the range. In this experiment, 50 waves are used to the averaging.

3.3 Fitting to cubic functions

In the previous fitting method, only the points at which the count changed were used for fitting. However, this is a factor that is strongly influenced by noise. Therefore, all the value of the count was used for fitting without distinction.

Additionally, fitting to cubic functions has been performed using count values in a specific constant time width. In the new method, when the velocity is small, the fitting will refer to longer time width. The time width of the fitting is set so that a certain number of waves are included in the width. This improvement has reduced the effect of noise on the fitting functions.

4. Result

Figure 5 shows voltage signal and count values calculated by improved method. It is clear that the noise on the count value generated when the velocity was close to 0 [m / s] was reduced.

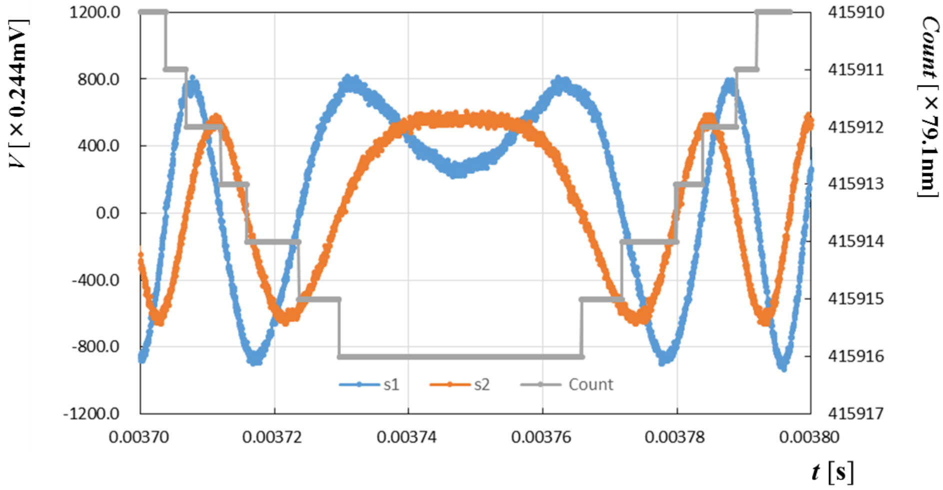

Fig.5 Calculation result of Voltage signal by the new method

Figure 6 shows force calculated by the improved method. The discontinuous values were disappear.

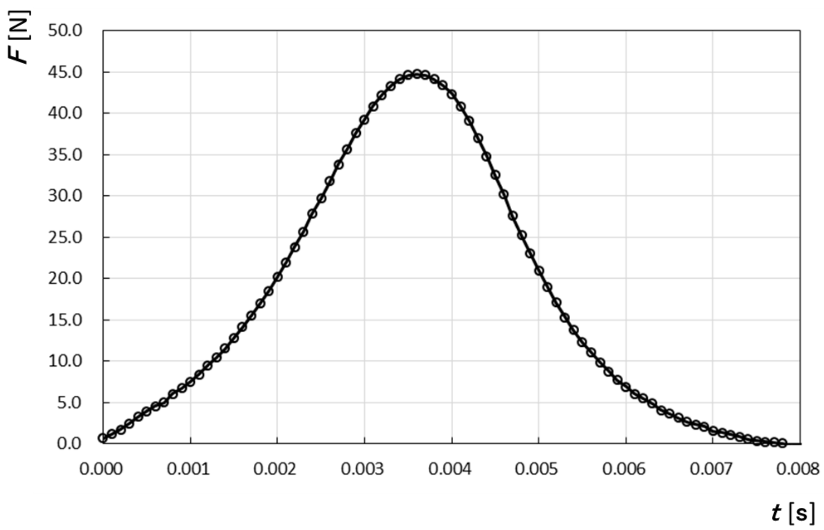

Fig.6 Calculation result of force by the new method

5 Discussion

The noise corrected by this improvement is due to the noise of the voltage signal obtained from PD. A further improvement in accuracy is expected by reducing the noise of this voltage signal. The fact that the waveform signal is not exactly shifted by 1⁄4 wavelength is also a factor of uncertainty. There is also a need for a method to correct this non-uniform wavelength shift

6 Conclusion

Drop ball test by the Levitation Mass Method (LMM) was carried out on EPS board. To solve the problem causing around the low velocity condition, time widths of wave data correction and least squares fitting were adjusted according to frequency of wave data. Discontinuous values in the force calculated by previous analysis method is disappeared by the improved method.
From the above, it became possible to calculate the transition of the repulsive force of the material continuously.

References

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