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A Proposal of 3D Measurement of Velocity in the Drop-ball Experiment by the Levitation Mass Method

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Abstract. The method of 3D measurement of velocity in the Drop-ball experiment by the Levitation Mass Method is proposed. In the drop-ball experiment, the spherical body containing a cube corner prism is dropped from initial high onto the material under test. The velocity of the spherical body is measured using an optical interferometer as the function of the Doppler shift frequency. The position and acceleration of the spherical body are calculated by integrating and differentiating the velocity, respectively. The force acting on the spherical body is calculated as the product of the mass and the acceleration. The impact force generated at the contact point of the spherical body collided the material under test is measured accurately by this experiment. In order to measure the velocity of the spherical body around the contact point of a colliding material in three coordinates axes. Theoretical calculation of the proposed method is explained.

1. Introduction

Recently, the need to measure the mechanical properties of impact phenomenon around the contact point of a rigid object collided the material has increased in various industrial and research applications such as the crash testing of an automotive bumper beam [1], the ballistic impact characteristics of aramid fabrics [2] and the water impact phenomenon [3]. Special in the water impact phenomenon, many studies have been conducted; some studies related to numerical simulation and in other studies related to analyzing a record image of the water impact phenomenon by the high speed cameras. However, only the 1-dimensional measurement of mechanical properties of impact phenomenon around the contact point of a rigid object collided the material is available at the present [1-3]. It results the information of the phenomenon in the 3-dimensional coordinates are difficult to evaluated. In order to solve the problem, the theoretical calculation and the experimental design of the 3D measurement of velocity in the drop-ball experiment are proposed.

The drop-ball experiment is the experiment which conducted to measure the mechanical properties of the spherical body that dropping onto the material under test. This experiment was modified from the Levitation Mass Method which successfully evaluated the impact response of a material, microforce material tester, the electrical and mechanical responses of a force transducer, etc. [4-6]. In the drop-ball experiment, the spherical body containing a cube corner prism is dropped from initial high and the mechanical properties such as velocity, acceleration, position, and force acting on it is measured using an optical interferometer. The experiment has been successfully evaluated impact force of a spherical body dropping onto a water surface [3] and impact force of a spherical body dropping onto a plastic sheet [7]. However, the mechanical properties which measured in the drop-ball experiment until now is only 1D measurement (z-axis).

This paper is a work improvement of previous paper [8], the improvement is the detail calculation using the three-dimensional vector calculation and modification of the schematic diagram.

2. Experimental design

Fig. 1 shows the design of a schematic diagram of the experimental setup of 3D measurement of velocity in the drop-ball experiment. Three interferometers are used to measure the velocity of the spherical body around the contact point of collision. Signal beam 1 (SB_1), b_1, is from the interferometer No.1, is on the xz plane. Signal beam 2 (SB_2), b_2, is from the interferometer No.2, is on the yz plane. Signal beam 3 (SB_3), b_3, is from the interferometer No.3, is along z-axis.

The spherical body approximately 30.2 mm in diameter and made from SUS440 stainless steel body is used. A cube corner prism, 12.7 mm in diameter, is inserted with an adhesive agent so that its optical center coincides with the center of gravity of the whole body. The total mass of the body, $\boldsymbol{M}$, is approximately 93.88 g.

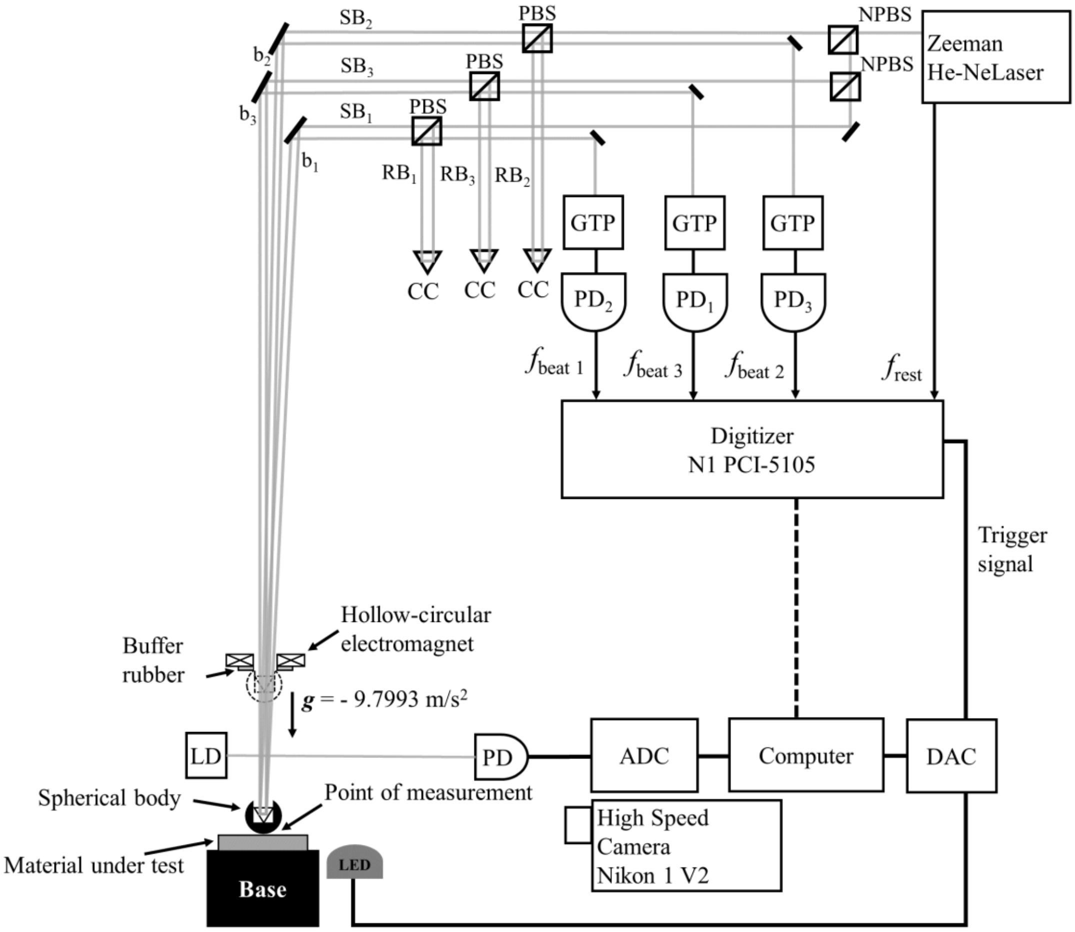

Fig. 1. The Drop-ball experimental setup using three lasers interferometer. (Code: NPBS: Non-Polarizing beam splitter, PBS: Polarizing beam splitter, LD: Laser diode, PD: Photo diode, CC: Cube corner prism, GTP: Gland-Thomson prism, ADC: Analog to digital converter, DAC: Digital to analog converter, SB: Signal Beam, RB: Reference Beam).

The motion-induced time-varying beat frequency, f_{beat}, was measured during the spherical body was dropping onto the material under test. The velocity is calculated from the measured value of the Doppler shift frequency of the signal beam of interferometer, f_{Doppler}, which expressed as follows:

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

$$f_{\mathrm{Doppler}} = -\left(f_{\mathrm{beat}} - f_{\mathrm{rest}}\right) \tag{2}$$

$$v_{\mathrm{b1}} = -\lambda_{\mathrm{air}}\left(f_{\mathrm{beat1}} - f_{\mathrm{rest}}\right)/2 \tag{3}$$

$$v_{\mathrm{b2}} = -\lambda_{\mathrm{air}}\left(f_{\mathrm{beat2}} - f_{\mathrm{rest}}\right)/2 \tag{4}$$

$$v_{\mathrm{b3}} = -\lambda_{\mathrm{air}}\left(f_{\mathrm{beat3}} - f_{\mathrm{rest}}\right)/2 \tag{5}$$

Where λ_{air} is the wavelength of the signal beam. $f_{\mathrm{beat\ 1}}$, $f_{\mathrm{beat\ 2}}$, $f_{\mathrm{beat\ 3}}$, are the beat frequency from interferometer number 1, 2, and 3, respectively. f_{rest} is the rest frequency. v_{b1}, v_{b2}, v_{b3}, are velocity measured by interferometer number 1, 2, and 3, respectively. The beat frequency, f_{beat}, is the frequency difference between the signal beam and the reference beam. The rest frequency, f_{rest}, is equivalent to the beat frequency, f_{beat}, when the spherical body is at rest and no Doppler shift is added to the signal beams.

If the other forces such as the air drag and the magnetic force from hollow-circular electromagnet are negligible. The total force acting on the mass can be express as:

$$F_{\mathrm{mass}} = -Mg + F_{\mathrm{impact}} \tag{6}$$

Where F_{mass} is total force consists of the gravitational force acting upon the body, $-Mg$ is a weight of the spherical body and F_{impact} is the impact force acting from the material under test when it collided by the spherical body. Then the impact force acting from the clay can be expressed as:

$$F_{\mathrm{impact}} = F_{\mathrm{mass}} + Mg \tag{7}$$

An optical interferometer type Michaelson interferometer is used to accurately measure the velocity of the spherical body. A Zeeman-type two-wavelength He-Ne laser that have two frequencies which have orthogonal polarization is used as the light source. The Digitizer (NI PCI-5105, National Instruments Corp., USA) is used to recording the output signal of PD_1, PD_2, and PD_3. The Zero-Crossing Fitting method (ZFM) [9] is applied to the waveform of the output signal to determining the beat frequency, f_{beat} and rest frequency, f_{rest}.

3. Discussion

Fig. 2 show the diagram of the light beams reflected from mirrors to the measurement point. Beam 1, b_1, beam 2, b_2, and beam 3, b_3, are the beam from interferometer no.1,2 and 3, respectively. d_1 is the distance between the point of light reflection on beam reflector interferometer number one to the point of light reflection on beam reflector interferometer number three. d_2 is the distance between the point of light reflection on beam reflector interferometer number two to the point of light reflection on beam reflector interferometer number three. d_3 is the distance between the point of light reflection on beam reflector interferometer number three to the measurement point.

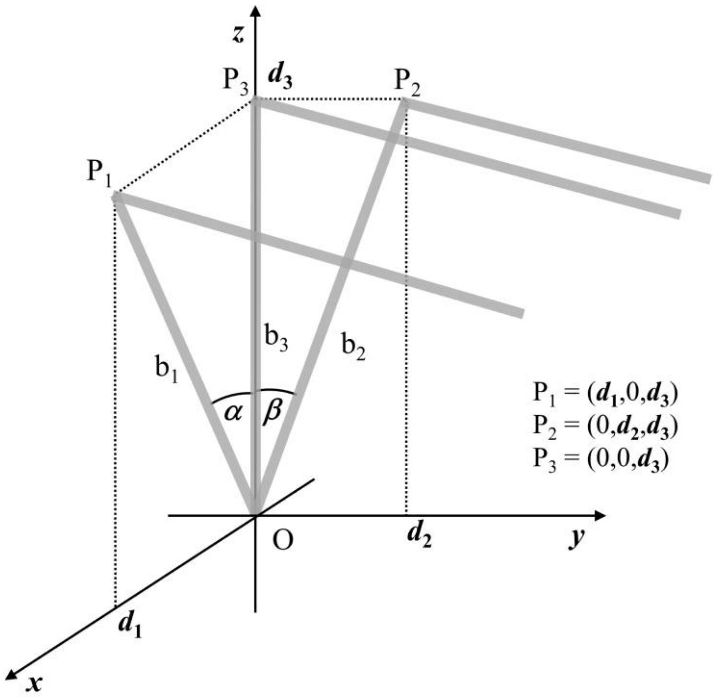

Fig. 2. The diagram beam of laser reflected from mirror to point of measurement.

$\boldsymbol{\alpha}$ is the angel between beam one, b_1, and beam three, b_3. $\boldsymbol{\beta}$ is the angel between beam two, b_2, and beam three, b_3. With defined $\boldsymbol{\alpha}$ and $\boldsymbol{\beta} << 15^{\circ}$ the value of sin $\boldsymbol{\alpha}$ or sin $\boldsymbol{\beta} \cong$ tan $\boldsymbol{\alpha}$ or tan $\boldsymbol{\beta}$. The value of $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ can calculated as:

$$\boldsymbol{\alpha} = \tan^{-1}\frac{\boldsymbol{d_1}}{\boldsymbol{d_3}} \tag{8}$$

$$\boldsymbol{\beta} = \tan^{-1}\frac{\boldsymbol{d_2}}{\boldsymbol{d_3}} \tag{9}$$

The velocity of the spherical body around the point of measurement, $\boldsymbol{v}$, is calculated as the linear combination of three unit vectors expressed as:

$$\vec{\boldsymbol{v}} = \boldsymbol{v}_x\hat{\boldsymbol{i}} + \boldsymbol{v}_y\hat{\boldsymbol{j}} + \boldsymbol{v}_z\hat{\boldsymbol{k}} \tag{10}$$

$$\boldsymbol{v} = \sqrt{\boldsymbol{v}_x^2 + \boldsymbol{v}_y^2 + \boldsymbol{v}_z^2} \tag{11}$$

Where $\vec{\boldsymbol{v}}$ is the vector of velocity, $\boldsymbol{v}_x, \boldsymbol{v}_y, \boldsymbol{v}_z$ are scalar quantities of the vectors velocity along x-axis, y-axis, and z-axis, respectively. $\hat{\boldsymbol{i}}$, $\hat{\boldsymbol{j}}$, $\hat{\boldsymbol{k}}$ are unit vectors along x-axis, y-axis, and z-axis, respectively.

3.1. Calculation of the velocity along z-axis, $\vec{v}_z$

The velocity along z-axis, $\vec{v}_z$, is measured using the interferometer number three. Beam three, b_3, is set coincide to the z-axis. Then the velocity along z-axis, $\vec{v}_z$, can be expressed as:

$$\vec{v}_z = v_z \hat{k} \tag{12}$$

$$v_z = v_{b3} \tag{13}$$

3.2. Calculation of the velocity along x-axis, $\vec{v}_x$

The velocity along x-axis, $\vec{v}_x$, is measured using two beam from the interferometer number one and number three. Beam three, b_3, coincides with the z-axis and beam one, b_1, is set on the xz plane. Fig. 3 shows the diagram of the beam three, b_3, and beam one, b_1. The velocity along x-axis, $\vec{v}_x$, is calculated using triangle proportionality theorem. It expressed as:

$$v_{b1} = v_x \sin\alpha + v_{b3} \cos\alpha \tag{14}$$

$$v_x = \frac{v_{b1} - v_{b3}\cos\alpha}{\sin\alpha} \tag{15}$$

$$\vec{v}_x = v_x \hat{i} \tag{16}$$

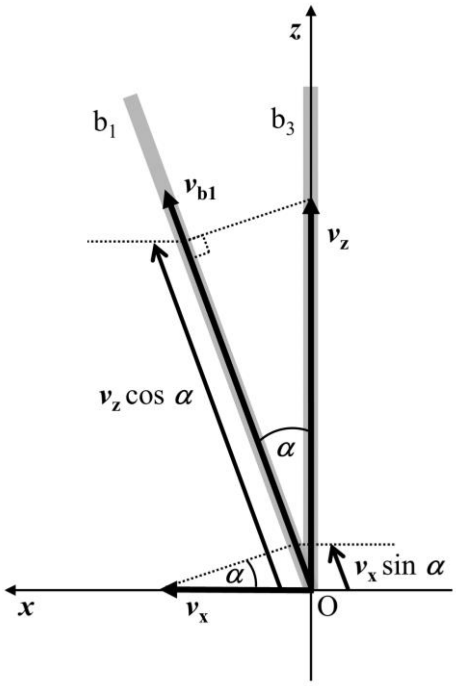

Fig. 3. The diagram of the concept measuring velocity of the dropping ball with two beam of laser which at z-axis and xz plane.

3.3. Calculation of the velocity along y-axis, $\vec{v}_y$

The velocity along y-axis, $\vec{v}_y$, is measured using two beam from the interferometer number two and number three. Beam three, b_3, coincides with the z-axis and beam two, b_2, is set on the yz plane. Fig. 4 shows the diagram of the beam three, b_3, and beam two, b_2. The velocity along y-axis, $\vec{v}_y$, is calculated using triangle proportionality theorem. It expressed as:

$$\boldsymbol{v}_{b2} = \boldsymbol{v}_y \sin\boldsymbol{\beta} + \boldsymbol{v}_{b3} \cos\boldsymbol{\beta} \tag{17}$$

$$\boldsymbol{v}_y = \frac{\boldsymbol{v}_{b2} - \boldsymbol{v}_{b3} \cos\boldsymbol{\beta}}{\sin\boldsymbol{\beta}} \tag{18}$$

$$\vec{\boldsymbol{v}}_y = \boldsymbol{v}_y \hat{\boldsymbol{j}} \tag{19}$$

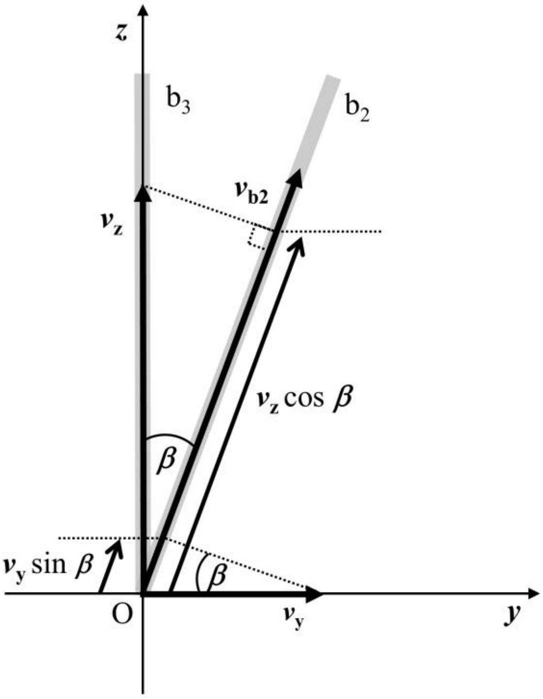

Fig. 4. The diagram of the concept measuring velocity of the dropping ball with two beam of laser which at z-axis and yz plane.

By substitute the equations (13), (15), and (18) to the equation (10), the velocity of the spherical body around the point of measurement can be expressed as:

$$\vec{\boldsymbol{v}} = \left(\frac{\boldsymbol{v}_{b1} - \boldsymbol{v}_{b3}\cos\boldsymbol{\alpha}}{\sin\boldsymbol{\alpha}}\right)\hat{\boldsymbol{i}} + \left(\frac{\boldsymbol{v}_{b2} - \boldsymbol{v}_{b3}\cos\boldsymbol{\beta}}{\sin\boldsymbol{\beta}}\right)\hat{\boldsymbol{j}} + \left(\boldsymbol{v}_{b3}\right)\hat{\boldsymbol{k}} \tag{20}$$

$$\boldsymbol{v} = \sqrt{\left(\frac{\boldsymbol{v}_{b1} - \boldsymbol{v}_{b3}\cos\boldsymbol{\alpha}}{\sin\boldsymbol{\alpha}}\right)^2 + \left(\frac{\boldsymbol{v}_{b2} - \boldsymbol{v}_{b3}\cos\boldsymbol{\beta}}{\sin\boldsymbol{\beta}}\right)^2 + \left(\boldsymbol{v}_{b3}\right)^2} \tag{21}$$

The above calculation can be applied in velocity measurements on the drop-ball experiment to measure the velocity of a spherical object dropped from a certain height. The proposed method can be applied to accurately measure the velocity in the drop-ball experiment in three coordinates axes. A theoretical calculation of the proposed is explained. In the near future, the experiment will be conducted.

4. Conclusion

The method of 3D measurement of velocity in the Drop-ball experiment using the Levitation Mass Method is proposed. The triangle proportionality theorem is used to calculate the velocity along x-axis and y-axis. The velocity along x-axis is calculated as a function of the velocity along z-axis and the velocity calculated by interferometer number one, $\boldsymbol{v}_{\mathbf{b1}}$. The velocity along y-axis is calculated as a function of the velocity along z-axis and the velocity calculated by interferometer number two, $\boldsymbol{v}_{\mathbf{b2}}$. Theoretical calculation and the experimental design of the 3D measurement velocity in the drop-ball experiment are explained.

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