A preview of 3D measurement velocity in Drop-Ball experiment by Levitation Mass Method

Hadi Nasbey[1, a], Akihiro Takita [1,b], Agus Setyo Budi[2, c], Eko Satria[3,d] , Mitra Djamal[3,e] and Yusaku Fujii[1,f]

[1]Division of Mechanical Science and Technology, Faculty of Science and Technology, Gunma University, 1-5-1 Tenjin-cho, Gunma, 376-8515, JAPAN

[2]State University of Jakarta, Jalan Rawamangun muka no.1, Jakarta, INDONESIA

[3]High Theoretical Energy Physics and Instrumentation, Department of Physics, Bandung Institute of Technology, Bandung, INDONESIA

[a]<t15806008@gunma-u.ac.jp>, [b]<takita@gmail.com>, [c]<abihuda123@yahoo,com>
[d]<ekosatria004@gmail.com>, [e]< mitra@fi.itb.ac.id>, [e]<fujii@gunma-u.ac.jp>

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Abstract. A preview 3D measurement of velocity in Drop-ball experiment using the Levitation Mass Method is proposed. In drop-ball experiment, the impact force of a spherical body which dropped onto a surface of material under test was measured. The impact force acting on the spherical body is calculated from the value of measured velocity of the dropping ball using an optical interferometer. In this preview, the three optical interferometers were used to measure the velocity of dropping ball at the impact point of the ball and the surface of material under test. $\boldsymbol{v}_x$, $\boldsymbol{v}_y$, $\boldsymbol{v}_z$ are measured using three optical interferometer.

1. Introduction

The drop-ball experiment is an experiment to evaluate the impact response of a spherical body that falls from a high hits a surface of things such as water or materials [1]. This experiment was modified from Levitation Mass Method which success evaluated impact response of a material, microforce material tester, the electrical and mechanical responses of a force transducers, etc [2-4]. In the LMM, the initial force of a mass that levitated using a pneumatic linear bearing is used as the reference force. This force applied to the object under test, such as a force transducer, a material or a structure. An optical interferometer is used to measuring the motion-induced time-varying beat frequency that produced by a moving of levitated mass. The quantities, such as velocity, acceleration, positions, and forces, are numerically calculated from the frequency based on the laws of physics and the good synchronization between the quantities is obtained. In addition, the force is calculated as the product of the acceleration and the mass of a levitated mass. Recently, a spherical body that dropped from initial high is used to evaluate an impact response the surface of things as the modification of the LMM. This experiment called drop-ball experiment. In the drop-ball experiment, a spherical body is dropped from initial high and the total force acting on it is measured using an optical interferometer. The experiment has successfully evaluated impact force of a spherical body dropping onto a water surface [1] and impact force of a plastic sheet [5].

In this paper, we propose a concept to measure the impact force of a spherical body using the drop-ball experiment in three coordinate systems. This concept is proposed to measure of the effect of Von Karman vortex street at the dropp-ball experiment.

2. Research Methodology

Figure 1 shows the design of a schematic diagram of the experimental setup of drop-ball experiment measured the velocity using three optical interferometers. The spherical body is fabricated by machining a spherical SUS440 stainless steel body approximately 30.2 mm in diameter, the surface of which is tempered. 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.

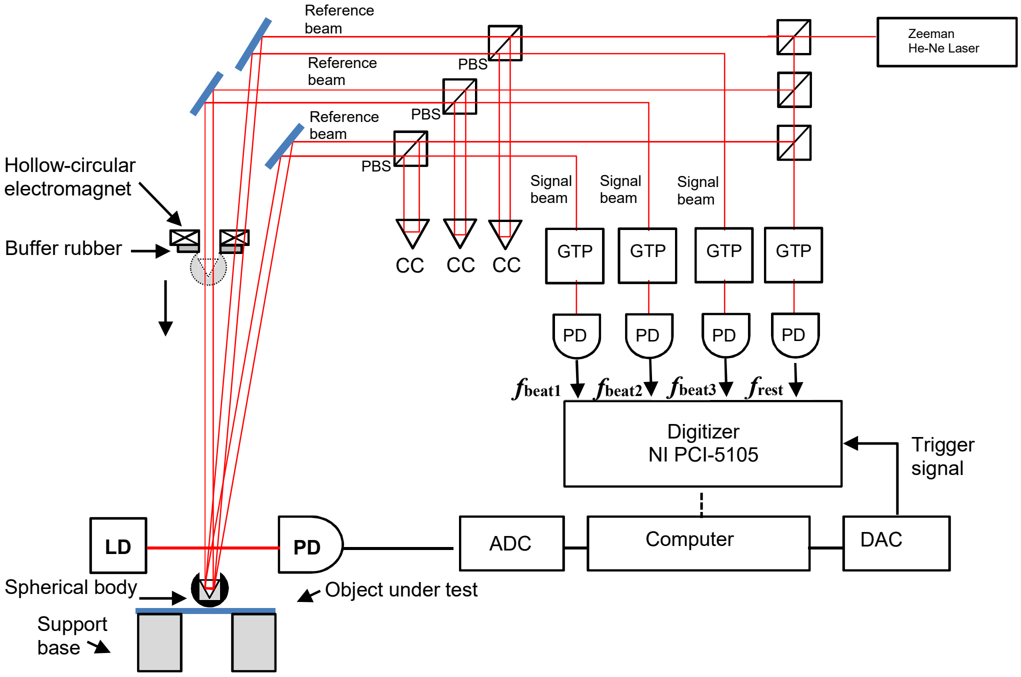

Figure 1. Drop-ball experimental setup using three laser interferometer. (PBS: Polarizing beam splitter, LD : Laser diode, PD : Photo diode, CC : Cube corner prism, GTP : Gland-Thomson prism, ADC : Analog to digital converter, DAC : Digital to analog converter).

The motion-induced time-varying beat frequency, $f_{\mathbf{beat}}$, is measured during the spherical body was dropping to the object under test. The velocity is calculated from the measured value of the Doppler shift frequency of the signal beam of interferometer, $f_{\mathbf{Doppler}}$, which can be expressed as;

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

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

where $\lambda_{\mathbf{air}}$ is the wavelength of the signal beam, $f_{\mathbf{beat}}$ is the beat frequency, and $f_{\mathbf{rest}}$ is the rest frequency. The beat frequency $f_{\mathbf{beat}}$ is the frequency difference between the signal beam and the reference beam. The rest frequency $f_{\mathbf{rest}}$ is equivalent to the beat frequency $f_{\mathbf{beat}}$ when the spherical body is at rest and no Doppler shift is added to the signal beam. 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

$$F_{\mathrm{mass}} = -Mg + \; F_{\mathrm{impact}} \tag{3}$$

Where $F_{\mathbf{mass}}$ is total force consists of the gravitational force acting upon the body, **-Mg** is a weight of the spherical body and $F_{\mathbf{impact}}$ is the impact force acting from the surface when it slammed by the spherical body. An optical interferometer type Michaelson interferometer is used to accurately measure the velocity of the dropping ball. A Zeeman-type two-wavelength He-Ne laser that have two frequency 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 PD1 and PD2 with a sample number of 5 M for each channel, a sampling rate 30 M samples per second, and resolution of 8 bit. The Zero-Crossing Fitting method (ZFM) is applied to the waveform of the output signal to determining the beat frequency, $\boldsymbol{f}_{\mathbf{beat}}$ and rest frequency, $\boldsymbol{f}_{\mathbf{rest}}$.

3. Discussion

In this paper, the concept of three system coordinate is introduced to calculating the velocity of the dropping ball. The idea is using three optical interferometer to measuring the velocity of the dropping ball at the point of impact of surface object under test. The figure 2 shows the diagram of the concept measuring velocity of the dropping ball with two beam of laser which along z-axis and xz plane. Three optical interferometer are used to measuring the velocity at the time of the spherical ball hit the surface of the object under test.

Calculation of three-dimensional measurement of drop-ball experiment.

The ball only have one velocity, $\boldsymbol{v}$, that will measure on three axis (x-y-z) using three beam ($\boldsymbol{b}_1$,$\boldsymbol{b}_2$,$\boldsymbol{b}_3$). Beam one, $\boldsymbol{b}_1$ is beam on the xz plane, beam two, $\boldsymbol{b}_2$ is beam on the yz plane, beam three, $\boldsymbol{b}_3$ is beam along z-axis. Velocity can express as:

$$\boldsymbol{v} = \sqrt{\boldsymbol{v}_{\mathrm{x}}^2 + \boldsymbol{v}_{\mathrm{y}}^2 + \boldsymbol{v}_{\mathrm{z}}^2} \tag{4}$$

[1] velocity along z-axis direction ($\boldsymbol{v}_{\mathbf{z}}$)

$$\boldsymbol{v}_{\boldsymbol{z}} = \boldsymbol{v}_{\mathbf{b3}} \tag{5}$$

[2] velocity along x-axis direction ($\boldsymbol{v}_{\mathbf{x}}$)

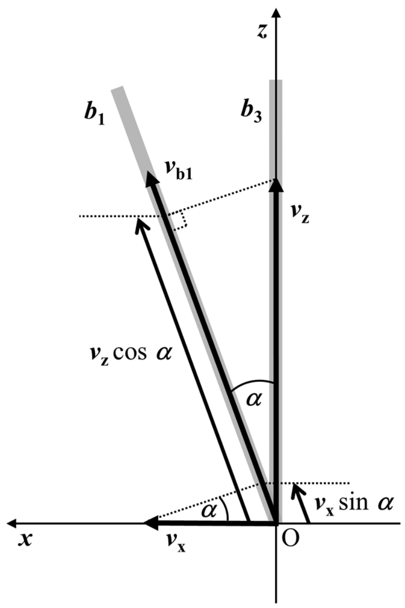

Figure 2. The diagram of the concept measuring velocity of the dropping ball with two beam of laser which along z-axis and xz plane.

The velocity along x-axis, $\boldsymbol{v}_{\mathbf{x}}$, is calculated using triangle proportionality theorem.
Velocity along x-axis, $\boldsymbol{v}_{\mathbf{x}}$, can express as:

$$\boldsymbol{v}_{\mathbf{b1}} = \boldsymbol{v}_{\mathbf{x}} \sin \boldsymbol{\alpha} + \boldsymbol{v}_{\mathbf{z}} \cos \boldsymbol{\alpha}$$

$$\boldsymbol{v}_{\mathbf{x}} = \frac{\boldsymbol{v}_{\mathbf{b1}} - \boldsymbol{v}_{\mathbf{z}} \cos \boldsymbol{\alpha}}{\sin \boldsymbol{\alpha}} \tag{6}$$

[3] Applied calculation on $\boldsymbol{v}_{\mathrm{x}}$ to calculated $\boldsymbol{v}_{\mathrm{y}}$.
velocity along y-axis, $\boldsymbol{v}_{\mathrm{y}}$, can express as:

$$\boldsymbol{v}_{\mathbf{b2}} = \boldsymbol{v}_{\mathbf{y}} \sin \boldsymbol{\beta} + \boldsymbol{v}_{\mathbf{z}} \cos \boldsymbol{\beta}$$

$$\boldsymbol{v}_{\mathrm{y}} = \frac{\boldsymbol{v}_{\mathbf{b2}} - \boldsymbol{v}_{\mathbf{z}} \cos \boldsymbol{\beta}}{\sin \boldsymbol{\beta}} \tag{7}$$

The velocity can express as;

$$\boldsymbol{v} = \sqrt{\left(\frac{\boldsymbol{v}_{\mathbf{b1}} - \boldsymbol{v}_{\mathbf{z}} \cos \boldsymbol{\alpha}}{\sin \alpha}\right)^2 + \left(\frac{\boldsymbol{v}_{\mathbf{b2}} - \boldsymbol{v}_{\mathbf{z}} \cos \boldsymbol{\beta}}{\sin \boldsymbol{\beta}}\right)^2 + (\boldsymbol{v}_{\mathrm{z}})^2} \tag{8}$$

With defined $\boldsymbol{\alpha}$ and $\boldsymbol{\beta} << 15^{\circ}$ the value of $\sin \boldsymbol{\alpha}$ and $\sin \boldsymbol{\beta} \cong \tan \boldsymbol{\alpha}$ and $\tan \boldsymbol{\beta}$.
The value of $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ can calculated as

$$\boldsymbol{\alpha} = \tan^{-1} \frac{\boldsymbol{x_1}}{\boldsymbol{x_3}}$$

$$\boldsymbol{\beta} = \tan^{-1} \frac{\boldsymbol{x_2}}{\boldsymbol{x_3}} \tag{9}$$

$\boldsymbol{x_1}$ is distance between point of beam reflector interferometer which beam on the xz plane to the measurement point. $\boldsymbol{x_2}$ is distance between point of beam reflector interferometer which beam on the yz plane to the measurement point. $\boldsymbol{x_3}$ is distance between point of beam reflector interferometer which beam along z-axis to the measurement point. Same calculation is used to calculate the acceleration.

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