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Dynamic response of sand particles impacted by a rigid spherical object

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ABSTRACT

A method for measuring the dynamic impact responses that acting on a spherical object while dropping and colliding with dried sand, such as the velocity, displacement, acceleration, and resultant force, is presented and discussed. In the experiment, a Michelson-type laser interferometer is employed to obtain the velocity of the spherical stainless steel object. Then the obtained time velocity profile is used to calculate the acceleration, the displacement, and the inertial force acting on the observed sand particles. Furthermore, a high-speed camera is employed to observe the behavior of the sand during the collision. From the experimental results with the sampling interval for frequencies calculation of 1 ms, the combined standard uncertainty in the instantaneous value of the impact force acts on the observed object is obtained and approximated to 0.49 N, which is related to a corresponding 4.07% of the maximum value at 12.05 N of the impact force.

Introduction

The mechanical behavior of soil, sand, dust and the other associated composite materials is receiving intensive attention and widely investigated by a variety of research methods, where there are many of relevant studies proposed, for an instant, an attempt to investigate mechanical behavior of geological materials in any considered conditions [1–3], where the lunar soil simulant with a geochemical reproduction of lunar regolith is examined to compare with the returned samples from the Moon, which aim to support the landing missions or facility constructions on the lunar surface [4–6]. The impact cratering process on brittle materials, such as borosilicate glass and a mixture of geophysical materials is investigated as well for improving parts of industrial products [7] and understanding impact craters on the Moon [8]. Furthermore, the dynamic behavior of an object impacts onto any material is received intensive attention [9–12]. One of the most important groups of the materials in both the geography and construction industry is sand [13,14], in which some studies employ the numerical simulations to evaluate the impact responses from testing materials [15–17]. However, it is still difficult to measure the dynamic mechanical quantities acting on an object during the collision, such as the impact force on and from the material, which is under tested.

Several authors have previously developed methods based on the law of momentum conservation for precision mechanical measurement, known as the Levitation Mass Method (LMM). In this method, the force due to a moving mass, levitated by a linear motion air bearing so that its velocity is at an almost constant, which is employed to be a reference force made to collide with testing objects. The LMM experiment has been conducted to evaluate mechanical quantities for some investigations such as the strength test for a general industrial product [18]. Measuring response calibration in dynamic conditions for a force transducer [19,20] and impact force measurement for a hard drive actuator arm have been reported [21]. In addition, the dynamic response of an object impacts onto a surface such as the water entry event can also be evaluated using the modified LMM [22]. By using the LMM, all necessary mechanical quantities during the collision of the observed object, such as the velocity, the displacement, and the acceleration, can be evaluated by an optical interferometer. The results were obtained in a good synchronization using numerical calculations of the motion-induced time-varying beat frequency of the optical interferometer. Finally, the resultant force acts on the observed object will be calculated directly according to the force definition as multiplying the mass of the whole object's body by its acceleration.

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In this paper, the LMM method has been modified for evaluating the dynamic responses of a mass in the vertical movement, which is suitable for impact measurement under the gravity and found in nature. In the experiment, by modifying the LMM, a method for evaluating the dynamic impact responses of a spherical object dropped onto the dried sand surface is presented. The experimental validity is demonstrated and discussed as well.

Experimental setup

The interference-based experiment, of which the schematic diagram of apparatus setup illustrated in Fig. 1, is employed to evaluate the dynamic response that a rigid object drops impact onto the sand particles surface. In the experiment, the object is free to fall under the gravity before the collision. Therefore, the shape of the object that can provide the symmetry orientation of the laser beam is considered, where the spherical shape is suitable. Additionally, the simple drag force formula can be applied. Thus, the spherical object with a tempered surface of 30.2 mm in diameter is made up by machining a spherical stainless steel SUS440. A cube corner prism with a diameter of 12.7 mm has been firmly inserted into the object's body afterwards so that the center of gravity of the object coincides with the optical center of the laser beam. The total mass of which, including the cube corner prism, is $m = 93.88g$. Fig. 2 details the photographs and dimensions of the spherical object. In operation, the time and the displacement, at the moment of the impact force is detected, will define to be the origin of each the time and displacement axis.

Fig. 3 shows the photographs of the sand under test, which is a standard sand of JIS R 5201 provided for a cement strength test. It is employed for the experiment in order to keep the major properties and moisture content in the sand under test with the less possible contamination. The sand is specified by the Japanese Industrial Standard (JIS) and provided by the Japan Cement Association (JCA), a trade organization comprises all 17 cement manufacturers in Japan (as of April 2015). It is natural dried sand of which the criterions are less than 0.2% of moisture content, screened and preferably prepared to contain at least 98% of a silicon dioxide content. The density is 2640 kg/m^3 (specific gravity of 2.64). The composition and particle size distribution of the sand are given in Table 1.

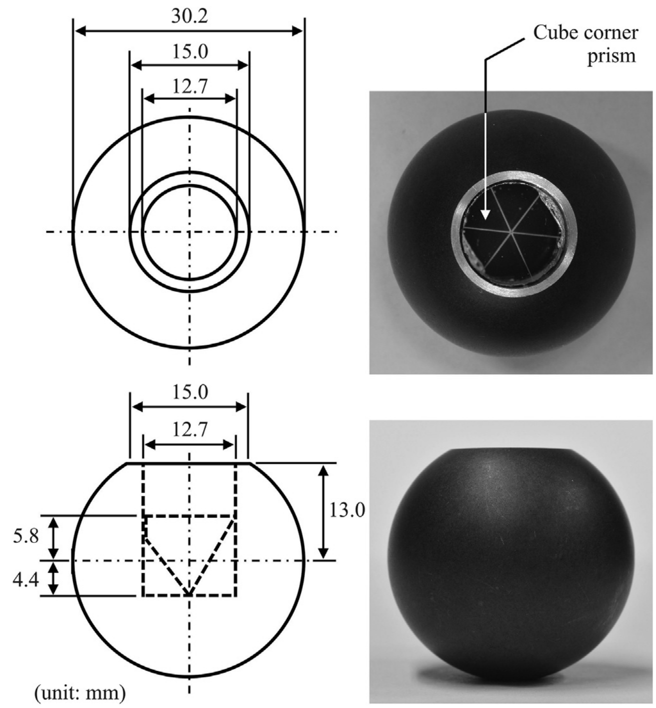

Fig. 2. Photographs and dimensions of the spherical object.

During the free fall motion and collision event, the total force that acts on the spherical object is considered a combination by three forces. The first is the force due to gravity that acts on the object, $-mg$, the second is the reaction force acts on the object due to colliding with the sand, F_{sand}, and the last is the other negligible forces (air drag force and magnetic force that used to hold and release the spherical object). Therefore, the resultant force acts on the spherical object, F_{object}, can be expressed as:

$$F_{object} = -mg + F_{sand} \quad (1)$$

where g is the acceleration due to gravity of the Earth, which is estimated to be 9.799 m/s^2 at the altitude of the experiment room. By

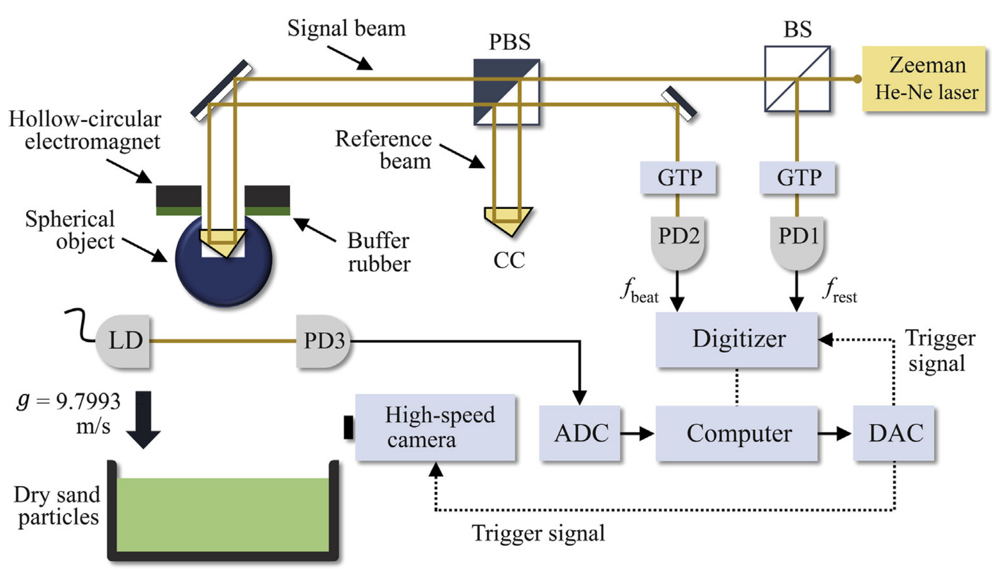

Fig. 1. The experimental setup for the proposed method, where BS is a beam splitter, PBS is a polarization beam splitter, CC is a cube-corner prism, GTP is a Glan-Thompson prism, PD is a photodiode, LD is a laser diode, ADC is an analog to digital converter, and DAC is a digital to analog converter.