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Original Research Paper

Microscopic analysis of saltation of particles on an obliquely oscillating plate

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ABSTRACT

This paper presents a microscopic analysis of the saltation of particles on an obliquely oscillating plate driven by sine waves with an amplitude on the order of tens of micrometers and a frequency on the order of hundreds of hertz. To examine the effect of the diameter of a particle on its motion, the trajectories and velocities of different-sized particles, from 0.5 to 500 μm in mass median diameter, are analyzed using images captured by a high-speed microscope camera. The results show that larger particles bounce higher, whereas smaller particles easily agglomerate and bounce only slightly, owing to the low restitution caused by their loosely packed structure. In addition, larger particles bounce forward and backward repeatedly, while the agglomerated particles always bounce forward, and consequently have the highest transport velocity among these particles. The particle motion and the transport velocity can be explained by a theoretical probability model.

1. Introduction

The energy input from an oscillating surface can induce fluidization of particles. Through experiments and simulations for non-cohesive, coarse particles under vibration, unusual particle behaviors have been observed, e.g. convection [1–3], bubbling [4–6], and segregation [7–9]. More recently, using cohesive fine particles, vigorous bubbling caused by vibration-induced air inflow was demonstrated [10]. Such particle fluidization under vibration has been used for numerous applications, such as fluidized beds [11,12], conveyors [13,14], micro-feeders [15,16], and evaluation methods for powder flowability [17–19].

As one of the simplest systems of particle fluidization under vibration, one-dimensional motion analysis of particles bouncing on a vertically oscillating surface has been conducted, both experimentally and numerically [20–23]. The fluid state of the particles is influenced by the balance between the input of vibrational energy and its dissipation due to inelastic collisions and friction. Luding et al. found that the transition from a fluidized state where the particles move individually to a condensed state where the particles move as a particle bed depends on vibration acceleration, number of particles, and the coefficient of restitution [20,21]. However, the effects of particle size on the fluid state have not been studied fully. In industry, a vibrating conveyor, i.e. an oblique oscillating trough inducing two-dimensional motion of a particle bed, is used for the transport of solid materials. In this system, the energy input through the oscillating trough sufficiently dissipates owing to friction of particles; thus, the particles behave as a perfectly inelastic bed.

Although many studies on the dynamics of particles under vibration have been conducted, there have been few reports on the two-dimensional motion of individual particles on an obliquely oscillating plate, where the plate can induce the more significant differences in the motion of the different-sized particles than one-dimensional vertical oscillating plate. In particular, there have been few studies on fine particles, because fine particles exhibit complicated behaviors owing to their adhesive and cohesive forces and fluid resistance. However, studies of fine particles are necessary, because there are many applications that use their unique size-dependent electric, magnetic, mechanical, optical, and chemical properties [24].

In this paper, the saltation of particles from 0.5 to 500 μm in mass median diameter on an obliquely oscillating plate is studied. Their trajectories and velocities are analyzed from images captured by a high-speed microscope camera, and the effect of particle diameter on the motion is discussed. Furthermore, the transport velocities of the particles are evaluated.

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2. Experimental

Fig. 1 shows a schematic diagram of the experimental setup. A metal plate (15 × 15 mm^2) made of stainless steel (SUS304) was mounted on a shock absorber. The plate was vibrated horizontally and vertically by piezoelectric vibrators. The signals applied to the vibrators were sine waves with a frequency of 280 Hz and the phase difference between the waves was zero. The vibration amplitude could be adjusted by the applied voltage. The vibrators were controlled by a vibration control system (VST-01, IMP. Co., Ltd.).

Different-sized alumina particles, with a mass median diameter D_{p50} from 0.5 to 500 μm, were used in the experiments: (1) irregularly shaped particles, D_{p50} = 0.5 μm (Fujimi Incorporated), (2) spherical particles, D_{p50} = 5 μm (Showa Denko K.K.), (3) spherical particles, D_{p50} = 50 μm (Showa Denko K.K.), and (4) spherical particles, D_{p50} = 500 μm (Taimei Chemicals Co., Ltd.). These particles were dried at 120 °C over 24 h and cooled down to room temperature in a desiccator. The particles were distributed on the metal plate through a sieve. To avoid collisions between particles, the area covered by the particles was less than 0.5% of the total surface area.

The plate and the particles were illuminated by metal halide lamps (Smita LS-M250), and observed through a high-speed microscope camera with a resolution of 1 μm (Fastcam-Max, Photron, Ltd.). The images were recorded at a rate of 3000 or 6000 frames per second (fps) and analyzed via digital image processing (Dipp-Motion 2D, Detect Co., Ltd.). All the experiments were conducted at 20 ± 2 °C, and the relative humidity was controlled at 30–40% to avoid disturbances caused by liquid bridge forces.

3. Results and discussion

3.1. Two-dimensional vibration of the plate

Fig. 2(a) and (b) shows the horizontal and vertical displacements of the oscillating plate as a function of time elapsed; these were obtained from the images captured by the high-speed microscope camera at a frame rate of 6000 fps. The experimental results indicate that the plate was sinusoidally oscillated with an amplitude of A = 35 μm. The angular velocity was 1760 s^{-1}, and the period of the cycle was 3.6 ms, which corresponded to a vibration frequency of f = 280 Hz. From the amplitude and frequency, the maximum vibration velocity was determined to be 62 mm/s. These two vibration waves were synchronized. Fig. 3 shows the Lissajous figure of the oscillating plate over ten cycles. The two synchronized sine waves formed an inclined linear vibration at a 45° angle from horizontal, showing that the repeatability was sufficiently high.

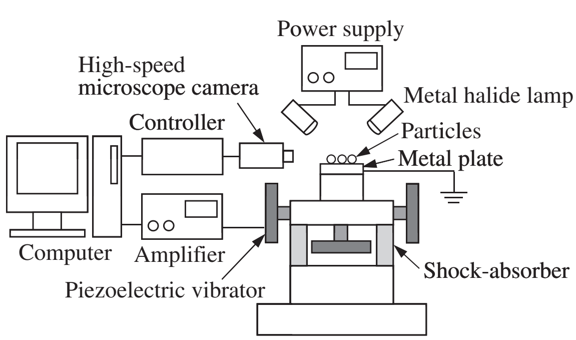

Fig. 1. Schematic diagram of the experimental setup. Particles are distributed on a metal plate. The plate is vibrated horizontally and vertically by three piezoelectric vibrators. The two-dimensional motion of the particles and the plate is observed from one side of the plate through a high-speed microscope camera.

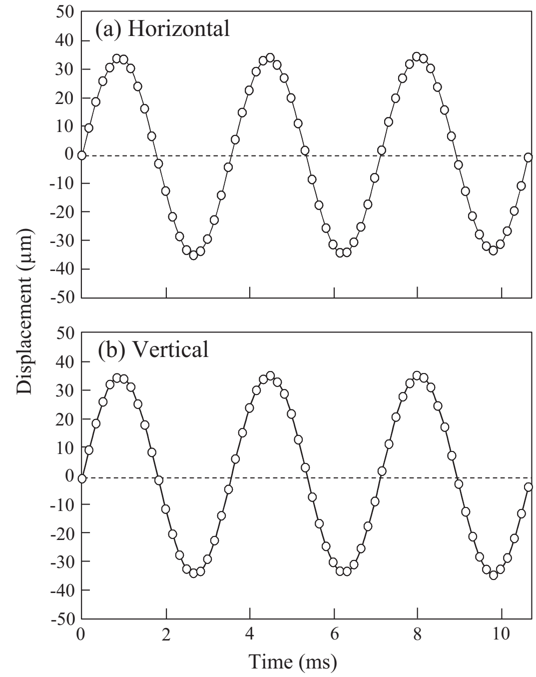

Fig. 2. Displacement of the oscillating plate as a function of time elapsed in (a) the horizontal direction and (b) the vertical direction. The data were obtained from the images captured by the high-speed microscope camera at a frame rate of 6000 fps. The signals applied to the piezoelectric vibrators were sine waves with a frequency of 280 Hz and the phase difference between the waves was zero.

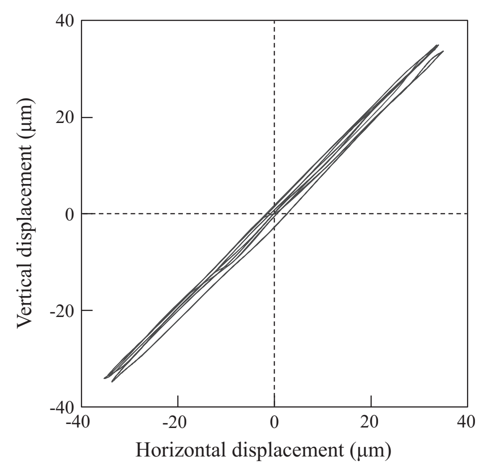

Fig. 3. A Lissajous figure of the obliquely oscillating plate. The wave data of ten cycles are shown here.

3.2. Effect of particle diameter on particle motion

For D_{p50} = 500 μm and 50 μm, the obliquely oscillating plate induced particle saltation. For D_{p50} = 5 μm, the particles adhered to the oscillating plate and did not saltate owing to their adhesive forces. The particles with D_{p50} = 0.5 μm formed agglomerated particles owing to van der Waals force after passing though the sieve. The morphology of the agglomerated particles was observed through a scanning electron microscope (VE9800, Keyence Corp.). Fig. 4(a) shows the SEM image of the agglomerated particle. The agglomerated particle was almost spherical. In addition, the magnified image is shown in Fig. 4(b). From this figure, it is observed that the agglomerated particle had a loosely packed structure consisting of the small primary particles. The volume-based size