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Analysis of Behavior of Small Agglomerated Particles on Two-dimensional Vibrating Plate

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Abstract. The movement of particles in the range from 0.5 to 500 μm in mass median diameter on a two-dimensional vibrating plate is observed through a high-speed digital camera with a zoom lens. The results show that larger particles saltate higher, while smaller particles easily agglomerate and slightly saltate because of the low restitution of their loosely packed structure. The salation heights are in good agreement with the results calculated by a model based on gravity, adhesion, drag force, and restitution.

Keywords: vibration, fine particles, agglomerate, particle movement, restitution.
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INTRODUCTION

For smaller particles, interaction forces between particle-particle and particle-substrate are stronger than gravity; thus fine particles easily agglomerate and cannot flow under gravity. To overcome the interaction forces, vibration is often used for powder handling processes in industry. There are many studies on the behavior of particles on a vibrating substrate; however, most studies have been carried out using noncohesive particles with diameters larger than several hundred micrometers[1-5]. There are few reports on the behavior of fine particles.

In this paper, four different particles in the range from 0.5 to 500 μm in mass median diameter are examined. The behavior of the particles on a two-dimensional vibrating plate is observed through a high-speed digital camera with a zoom lens. Furthermore, the vertical motion of the particles is studied by a model based on gravity, adhesion, drag force and restitution.

THEORY

The x and y coordinates are defined, where the x axis and y axis are tangential and vertical, upward, to the substrate, respectively. The displacement y_s, velocity v_{ys} and acceleration α_{ys} of the substrate are given by the following equations[2, 5]:

$$y_s = A_y \sin \omega t \qquad (1)$$

$$v_{ys} = \frac{dy_s}{dt} = A_y \omega \cos \omega t \qquad (2)$$

$$\alpha_{ys} = \frac{d^2 y_s}{dt^2} = -A_y \omega^2 \sin \omega t \qquad (3)$$

where A_y is the vertical vibration amplitude, ω is the angular velocity, and t is the time. When the force caused by the vertical vibration acceleration, upward, is larger than the sum of gravity and adhesive force, particles can flight from the substrate.

$$m_p A_y \omega^2 \sin \omega t_0 > F_g + F_a \qquad (4)$$

where m_p is the mass of particle, t_0 is the time at start of flight, F_g is the gravity, F_a is the adhesive force. The motion equation of particles during flight is represented by

$$m_p \frac{d^2 y_p}{dt^2} = -F_g - F_d \qquad (5)$$

where v_p is the vertical velocity of particle. F_d is the drag force. For larger particles, F_d can be neglected compared to F_g. The coefficient of restitution of particle–wall collisions e is defined by the relative velocities before and after collision, i.e.

$$e = -\frac{v_{p2} - v_{s2}}{v_{p1} - v_{s1}} \qquad (6)$$

The vertical motions of particles and the substrate can be calculated using Eqs (1)–(6).

EXPERIMENTAL

Figure 1 shows a schematic diagram of the experimental setup. A metal plate (15×15 mm^2), made of stainless steel (SUS304), was vibrated horizontally

TABLE 1. Test particles.

No.	Material	D_{p50} (μm)	ρ_p (kg/m³)	Manufacturer
1	Alumina (spherical)	500	4000	Taimei Chemicals Co., Ltd.
2	Alumina (spherical)	50	4000	Showa Denko K.K.
3	Alumina (spherical)	5	4000	Showa Denko K.K.
4	Alumina (irregular)	0.5	4000	Fujimi Incorporated

and vertically by two piezoelectric vibrators. The frequency, amplitude and phase of vibrations were controlled with a vibration control system (VST-01, IMP. Co., Ltd.).
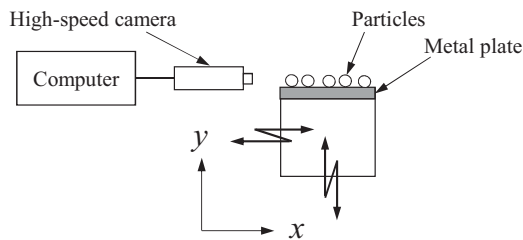

FIGURE 1. Schematic diagram of experimental setup.

Table 1 shows the properties of four different particles used. These particles were dried at 120 °C over 24 h and cooled down to room temperature in a desiccator. The behaviors of the particles on the vibrating plate were observed by a high-speed digital camera with a zoom lens (Fastcam-Max, Photron, Inc.). The height of particles during flight was obtained from images captured by the camera. The restitution coefficients of particle–wall collisions needed for the numerical calculation were determined from the results of the preliminary impact tests.

RESULTS AND DISCUSSION

Figure 2 shows the horizontal and vertical displacements of the plate obtained from the images. The signals applied to the piezoelectric vibrators were sine waves, where the frequency is 280 Hz and phase difference between two waves is zero. The experimental results showed that the plate can be stably vibrated and the vibrations in two directions are synchronized. Although this figure shows the 20 μm in amplitude of vibration, the amplitude can be easily changed.
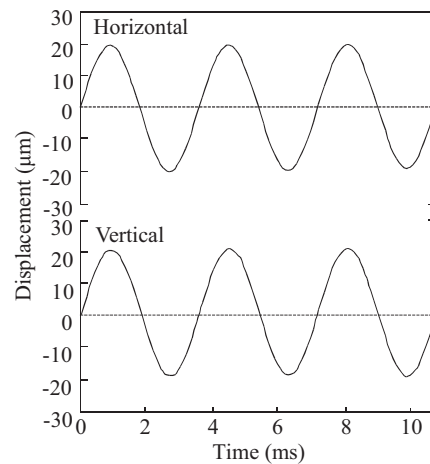

FIGURE 2. Displacement of vibrating substrate (f = 280 Hz, $A_x = A_y$ = 20 μm).

Table 2 shows the ranges of the particle heights of the four different particles. The plate was vibrated at f = 280 Hz, A_y = 35 μm. For D_{p50} = 500 μm and 50 μm, all the particles saltate on the vibrating plate. For D_{p50} = 5 μm, particles adhered to the plate owing to the adhesive forces. As for D_{p50} = 0.5 μm, particles formed small agglomerated particles (D_{ag50} = 230 μm), which slightly saltate on the vibrating plate. These results show that smaller particles generally have lower saltation heights.

TABLE 2. Height of particles during flight (vibrating plate: f = 280 Hz, A_y = 35 μm).

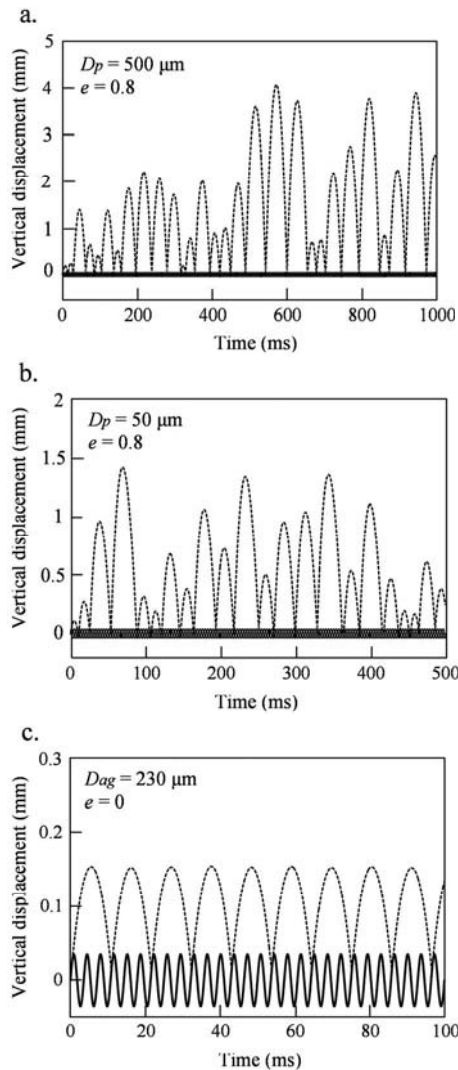| D_{p50} (μm)	Height (mm)
500	0 – 4.0
50	0 – 1.5
5	0
0.5	0 – 0.2

a.

b.

c.

FIGURE 3. Vertical trajectory of particle and vibrating substrate (vibrating substrate: $f = 280$ Hz, $A_y = 35$ μm).

Figure 3 (a) –(c) shows the vertical trajectory of the particles obtained from the numerical calculations. Restitution coefficients for the calculations are 0.8, 0.8 and 0 for $D_{p50} = 500$ μm, 50 μm and $D_{ag50} = 230$ μm, respectively. The saltation heights of the particles calculated by the model are in good agreement with the results shown in Table 2. A comparison between Figure 3 (a) and (b) shows that the smaller particle saltates in a lower height range owing to the effect of the drag force during flight. Figure 3 (c) shows that the small agglomerated particle saltates in the lowest height range. This is because the agglomerated particle adheres to the substrate at the collision. As a result, the

flight is controlled by the velocity and acceleration of the vibrating substrate after the collision.

CONCLUSION

The observation by the high-speed digital camera shows that larger particles saltate higher, while smaller particles form small agglomerated particles, which slightly saltate. The saltation height ranges of the particles obtained experimentally is in good agreement with the results calculated by the model based on gravity, adhesion, drag force, and restitution. The model shows that the saltation heights of the agglomerated particles are determined by the velocity and acceleration of the vibrating substrate.

NOMENCLATURE

A_x	horizontal vibration amplitude	(m)
A_y	vertical vibration amplitude	(m)
D_p	diameter of primary particle	(m)
D_{p50}	mass median diameter of primary particle	(m)
D_{ag}	diameter of agglomerated particle	(m)
D_{ag50}	mass median diameter of agglomerated particle	
		(m)
e	coefficient of restitution between particle and substrate	(-)
F_a	adhesive force between particle and substrate	
		(N)
F_g	gravity force	(N)
F_d	fluid resistance force	(N)
f	vibration frequency	(Hz)
m_p	mass of particle	(kg)
t	time	(s)
t_0	time at start of flight	(s)
v_{ys}	vertical velocity of substrate	(m/s)
v_p	vertical velocity of particle	(m/s)
y_s	vertical displacement of substrate	(m)
α_{ys}	vertical acceleration of substrate	(m/s^2)
ω	vibration angular velocity (=$2\pi f$)	(rad/s)
ρ_p	particle density	(kg/m^3)

Subscripts
1   before collision
2   after collision

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