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Experimental study on the packing of uniform spheres under three-dimensional vibration

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ABSTRACT

Densification of mono-sized sphere packings under three-dimensional (3D) vibration is experimentally studied. The effects of an operational condition, such as vibration amplitude and frequency and feeding method, on packing density are systematically investigated. The results indicate that the dense packings can be achieved by proper control of both vibration amplitude and frequency. The feeding method plays an important role in densification. Higher packing densities can be obtained when the number of particles fed per batch is less than one layer. Packing density decreases with increasing number of particles fed per batch, but keeps constant when the number of particles per batch is larger than three layers. Through the extrapolation on packing density obtained from different sized containers, the maximum packing density is 0.69 for the total feeding method and 0.74 for the batch-wise feeding under the present experimental condition. The formation of ordered structure is discussed based on the particle interlayer diffusion.

1. Introduction

Particle packing is an important subject in scientific research and industrial applications [1–7]. Three reproducible states can be identified in terms of packing density [2,9–12]: random loose packing (RLP, $\rho \le 0.60$), random close packing (RCP, $\rho = 0.64$) and ordered FCC (face-centered cubic) or HCP (hexagonal closed packed) packings ($\rho = 0.7405$). These states and their correlation (transition), as indicated in a phase diagram [13], attract increasing interests. Vibration is a common method to achieve the transition from loose to dense packings, and many efforts have been spent in this area [2,8–11,14–24]. We recently carried out a systematic study of the densification of mono-sized spheres under vibration in the vertical direction. The effects of vibration condition and feeding method were investigated. The maximum packing density can reach 0.636 in the total feeding method and 0.663 using the batch-wise feeding method, indicating different densification mechanisms.

Previous studies, however, largely focused on one-dimensional (1D) vibration, and the maximum packing density obtained is still relatively low (0.64–0.66 depending on the feeding method). How to achieve physically the transition from a disordered (random) to an ordered (regular) structure is still an open question [25,26]. Earlier work conducted by Owe Berg et al. [15] on packings of mono-sized steel ball-bearings indicated that 3D vibrations can produce a nearly perfect HCP structure. While their vibration conditions are not quite clear, their results indicated that 3D mechanical vibration is an effective way to obtain much higher packing density. Some studies have also claimed to achieve ordered packings [12,15,27–33]; nearly all of them were on the numerical basis or under special packing conditions in physical experiments (e.g., packing spheres manually). Systematic analysis of vibrated densification of equal spheres under 3D vibration in physical experiments has not been carried out.

This paper is to systematically study the densification of sphere packing under 3D vibration. The roles of vibration parameters such as amplitude A and frequency ω, container size and feeding method will be investigated. The focuses of this work are to reproduce physically the transition from a disordered to an ordered state and to identify the formed ordered structure and densification mechanism.

2. Experimental method and conditions

The physical experiments were carried out using a 3D vibration device as shown in Fig. 1. This setup is able to vibrate independently in three directions with different amplitudes and frequencies. The vibrations in three directions are driven by three motors whose amplitudes and frequencies can be controlled independently by cams and transducers. In this work, we employed the same A and ω in the three vibration directions, so the phase difference is zero in three components and the movement is in a straight line. Under this condition, it is considered that the phase angle of vibration has no effect. The experimental procedure was as follows: first, glass beads of diameter $d = 5.02$ mm $\pm$ 0.065 and containers made of PMMA material were cleaned using distilled water and dried in an oven at 60 °C. Then

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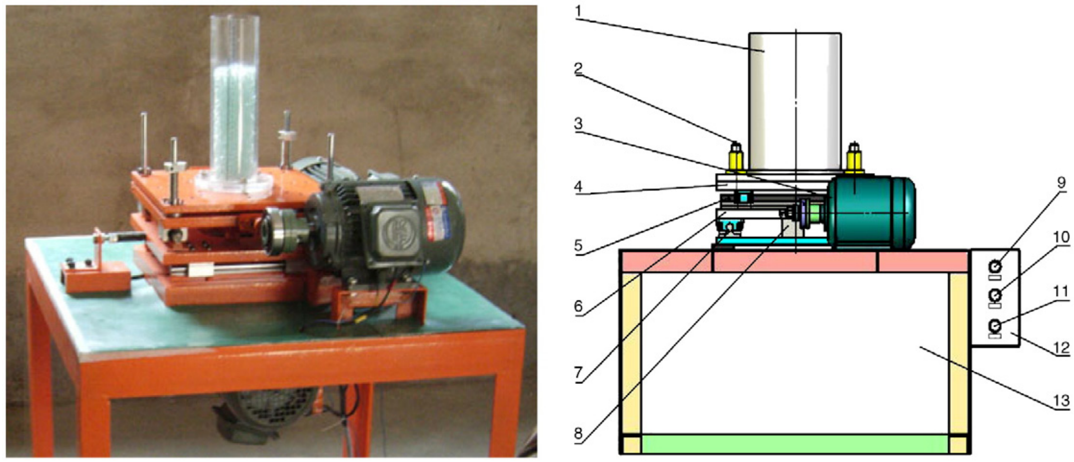

Fig. 1. (a) Physical setup; and (b) schematic view of the vibration setup. 1, container; 2, 5 and 7, guide rail at three directions; 3, electromotor; 4 and 6, vibrating desk along X and Y directions; 8, shaft along the Z axis; 9–11, frequency control of vibration at three directions; 12, transducer; and 13, transmission and amplitude control device.

the container was fixed in the vibration device and the particles were poured down gently into the container to form an initial packing. The packing density was then calculated by averaging the packing heights measured at different positions. The packing was then vibrated concurrently in 3 directions at a given condition for a period of time and stopped, and the packing density was re-measured. Vibration amplitude A, frequency ω, and feeding method were varied to study their effects on the packing structure. In this work, we employed the same A and ω in the three vibration directions. In order to eliminate the wall effect, the experiments in five different sized containers (D = 79.42 mm, 109.90 mm, 140.38 mm, 185.77 mm, and 229.70 mm in inner diameter) were carried out. Two feeding methods were considered: total feeding (i.e. all particles were poured into the container together at the beginning) and batch-wise feeding (i.e. particles were fed batch by batch during vibration at certain time interval when the height of particles in the container did not change with time).

3. Results and discussions

Fig. 2 shows the variation of packing density with time under different vibration conditions. For all cases, packing density first increases exponentially with time and then saturates after a certain time. Here, in the whole 3D vibrated experiments with total feeding, the maximum vibration time is set to t = 35 min. Also the results under each condition in Fig. 2 exhibit a desirable exponential fit between packing density and vibration time t, given by $\rho_t = \rho - K^{*}\exp(-t/\tau)$, where ρ is the final packing density, and K and τ are constants. The present work is mainly concerned with the final packing density. The solid lines in Fig. 2 are the fitting results; clearly they match the measurements well. Fig. 2 also indicates that different packing densities can be obtained under different vibration conditions such as different A and ω. Such dependence will be analyzed in detail in the following sections.

3.1. Vibration with total feeding

3.1.1. Effect of vibration condition

Fig. 3 shows the effect of ω on packing density ρ with different amplitudes. The ρ–ω curves have similar trends, i.e. ρ first increases with ω to a maximum value and then decreases. There is an optimum value for ω to achieve the maximum packing density in each case, and the peak position of each ρ–ω curve shifts to the left with the increase in amplitude. In addition, at smaller A, higher ρ can be obtained in a wider range of ω. On the contrary, vibration at larger A requires relatively a narrower range of ω to produce higher ρ. All these variations are in good agreement with our previous numerical and physical results [10,11,33].

Fig. 4 indicates that the effect of A on ρ has similar trends as ω, i.e. for a fixed ω, ρ first increases with A to a maximum value and then decreases. Meanwhile, small ω needs a broader range of A than larger

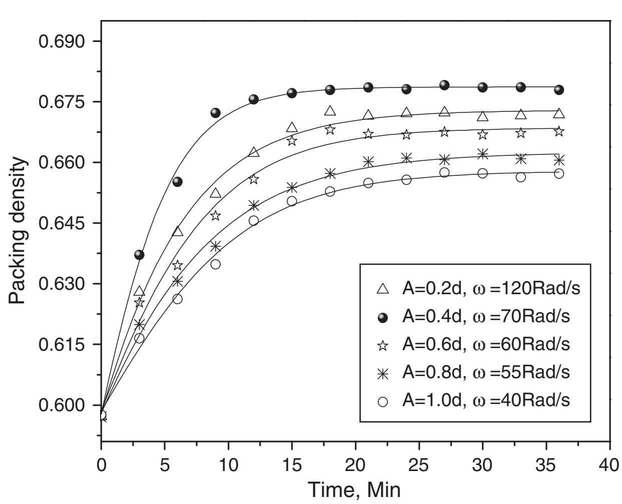

Fig. 2. Packing density as a function of vibration time, where D = 229.70 mm.

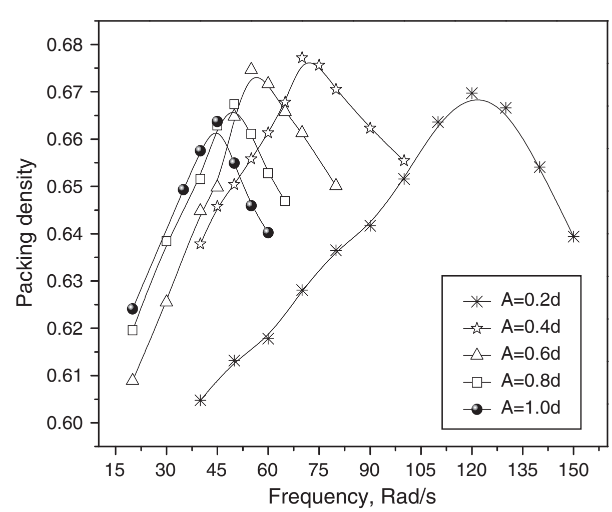

Fig. 3. Frequency effects on packing density with each fixed amplitude A, where D = 229.70 mm.