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Tracking Study on Solids Motion in Vertically Vibrated Granular Beds

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Abstract

The dynamics of granular motion have been studied in a vertically vibrated bed using Positron Emission Particle Tracking (PEPT), which allows the motion of a single tracer particle to be followed in a non-invasive way. Features of the solids motion such as cycle frequency and dispersion index were investigated. The particle circulation frequency was found to increase linearly with increase in the vibration amplitude. Particle dispersion also increased strongly with vibration amplitude. Horizontal dispersion is stronger than vertical dispersion at larger vibration amplitudes.

Introduction

Granular materials are of great interest to researchers in both engineering and science communities and to industry. The importance of their study derives from the complex rheological character of granular materials and from their wide applications in industry. Granular material subjected to vertical vibration demonstrates unusual flow behaviour (Das and Blair, 1998; and Umbanhower, 1997), and this has led to applications in particle drying, mixing and separation processes. When the dimensionless acceleration exceeds unity, the free surface of a vertically vibrated bed becomes unstable and exhibits a variety of complex phenomena such as formation of heaps (Clément et al. 1992; and Evesque and Rajchenbach, 1989), fluidisation (Warr et al., 1995), formation of standing wave patterns (including square, stripe and hexagon) (Pak and Behringer, 1993; and Clément et al. 1996) and arching (Hsiau et al., 1998). These kinds of instability have attracted the interest of many researchers using both experimental and numerical approaches. In order to design and operate vibrated bed devices, an in-depth understanding of their solids behaviour is essential. This paper therefore aims to investigate the solids motion in a vertically vibrated bed at the level of single particle motion using the state-of-the-art motion-following technique--Positron Emission Particle Tracking (PEPT). PEPT is a non-invasive technique which enables a single tracer particle to be located in milliseconds and in 3D movement. It has been developed at the Positron Imaging Centre at the University of Birmingham since 1987. A detailed description of this technique can be found in the literature (Parker et al., 1993; and Parker et al., 1997).

Experimental

The vibration test system in this paper has four major components: a Perspex vessel, a LDS Ling V408 vibrator, LDS 100E Power Amplifier and Lodestar function generator. The experimental set-up is shown schematically in Figure 1. The vessel used in this paper has a square base with dimensions of 13.7 cm x 13.7 cm and is of 95 cm height. The whole vessel was made from Perspex of 5 mm thickness to permit direct observation. It was directly mounted on the vibrator (Ling Dynamic Systems Ltd., Royston, Herts, UK), and was subjected to vertical oscillation driven by sinusoidal signals created by the function generator through a Power Amplifier (Ling Dynamic Systems Ltd., Royston, Herts, UK). The present experiments used spherical glass beads with density of 2500 kg/m^3 and with diameter of 0.8 mm (standard deviation of 5%) as the granular material. The vessel was filled with 400 g of glass beads and vibrated at 18 Hz with an amplitude range 1.8-3.9 mm.

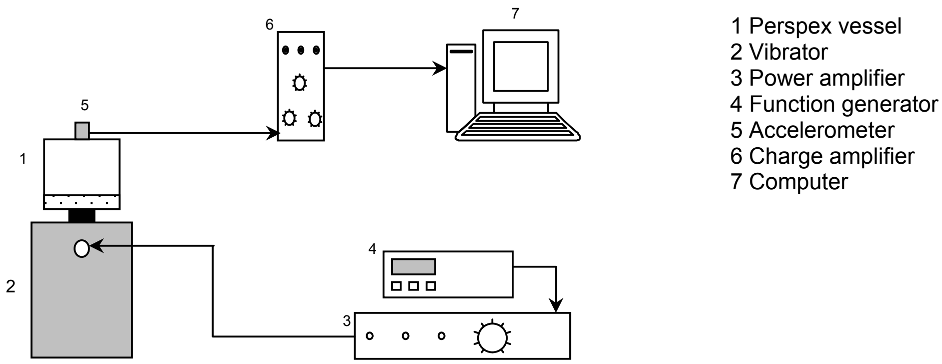


Figure 1 Schematic diagram of the experimental apparatus.

Before each PEPT experiment, a particle randomly taken from the bulk was irradiated to produce a positron-emitting isotope, ^{18}F. The vessel, which contains both bulk material and a single tracer particle, is placed between two planar detectors (Adac Laboratories, California, USA). As each positron is emitted from the tracer surface, it rapidly annihilates with a neighboring electron, producing two "back-to-back" γ-rays. This pair of γ-rays is very penetrating and can be easily detected by the positron camera, resulting in the possibility of non-invasive tracking inside a wide range of processing units, including those with metal walls. The tracer trajectory (*x*, *y* and *z* co-ordinates) as a function of time was then recorded for further computational analysis, where *x* and *y* are parallel to the plane of the positron camera in horizontal and vertical directions respectively; and *z* is perpendicular to the planar camera; as presented in Figure 2a. In order to ease the visualization of the PEPT data, the tracer trajectory is displayed in three orthogonal views (i.e. end view, side view and plan view) in this paper; as defined in Figure 2b-d.

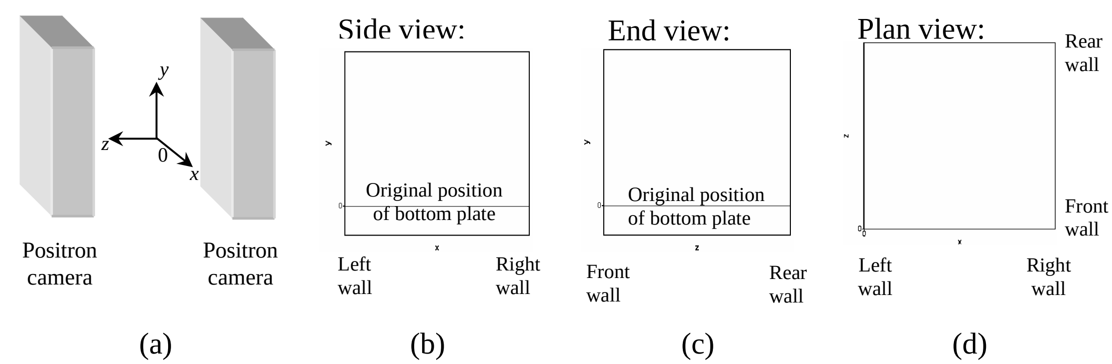


Figure 2 (a) Tracer Cartesian co-ordinates with respect to the PEPT camera; (b) side view of the bed; (c) end view of the bed; and (d) plan view of the bed.

Results and Discussion

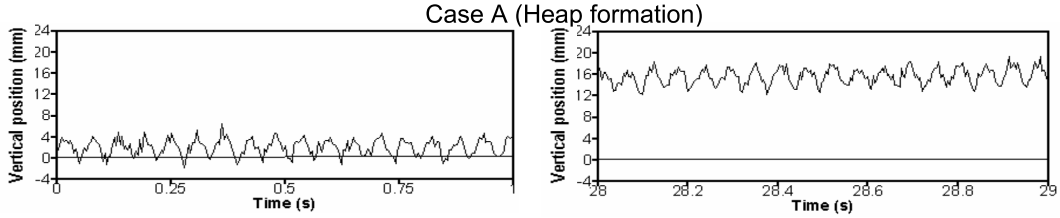
Typically, three kinds of surface behaviour can be observed during experiments: 1) formation of heaps, where particles were avalanching against one of the sidewalls or one corner of the container; 2) surface waves, where planar stripes were formed on the bed surface; and 3) double kink, where arching can be clearly seen from both sidewalls; as shown in Figure 3. The motion in vibrated beds is usually characterized by a dimensionless acceleration, Γ, which is the ratio of the vibration acceleration to the gravitational acceleration or $\Gamma = 4\pi^2 f^2 A/g$, where f is the vibration frequency, A is the vibration amplitude and g is the acceleration due to gravity. In this paper, the dominant motion depends on the vibration amplitude. Four vibration amplitudes were investigated: case A: 1.8 mm, in which heap formation was observed; case B: 2.8 mm, which showed a surface wave pattern; case C: 3.5 mm, which also showed a surface wave pattern; case D: 3.9 mm, which was in the arching state.

(a) (b) (c) (d)

Figure 3 Surface behavior: (a) Heap formation as in vertical plane; (b) Surface waves as in horizontal plane; (c) Double kink as in horizontal plane; and (d) Arching state as in vertical plane.

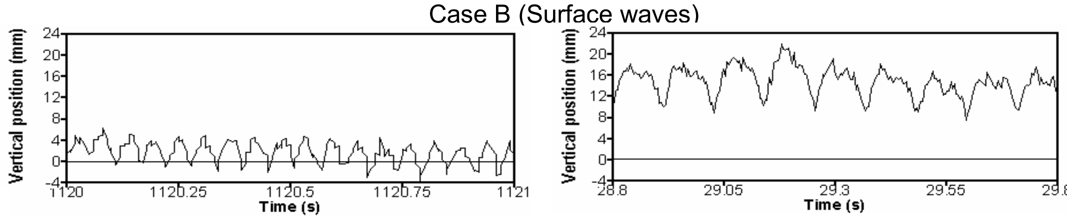
Figure 4 shows plots of tracer vertical co-ordinates over a time period of 1 s for cases A (heap formation) and B (surface waves). In both cases, in the region close to the bottom plate of the container, the tracer moved at a frequency which is the same as that of the system, i.e. 18 Hz; as shown in Figures 4a and 4c. In case A, the frequency of movement is the same at the surface (as shown in Figure 4b), but in case B movement at the bed surface is at half the frequency of the system, i.e. 9 Hz (as shown in Figure 4d). Particle movement at the frequency of the system in the bottom plate region and at half this frequency at the surface was also observed for cases C (surface waves) and D (arching). In summary, only if the bed shows heap formation, its the motion frequency is the same as the excitation frequency; otherwise, if the bed shows surface waves or arches, the motion at the surface is at half the excitation frequency.

Case A (Heap formation)



(a) In the region close to the bottom plate (b) In the region close to the bed surface

Case B (Surface waves)



(c) In the region close to the bottom plate (d) In the region close to the bed surface

Figure 4 Plots of tracer vertical co-ordinates in regions close to the bottom plate and the bed surface for cases A (heap formation) and B (surface waves).

When the dimensionless acceleration, Γ, exceeds about 1.2, the granular material will form heaps which avalanche against one of the bed sidewalls or one corner of the bed. However, the reasons for the heap formation are still not well understood. Figure 5 shows samples of tracer trajectory over certain periods of time for case A (heap formation, where particles were avalanching against the rear wall; as in end view): a) t = 667-786 s; b) t = 930-1100 s; and c) t = 150-290 s; and d) t = 2124-2366 s. A cycle begins when the tracer is traveling upward parallel to the heap surface ($P_1 \rightarrow P_2$), and then slumps down the bed ($P_3 \rightarrow P_4$). When it approaches the rear wall region, it quickly moves downward to the bottom plate ($P_4 \rightarrow P_5$) and starts another cycle again. Several successive avalanches can be observed along the heap surface ($P_3 \rightarrow P_4$). Figure 6 shows the occurrence of successive avalanches along the heap surface over a time period 25-55 s, where *i* is the upward movement region, *ii* is the avalanching region and *iii* is the downward movement region. Apparently, the tracer is carried from the top region to the bottom region of the bed surface by six successive avalanches. These experimental phenomena agree very well with Evesque and Rajchenbach's work (1989). They have reported that the instability of the heap formation is attributed by two different granular mechanisms: 1) convective upward transport; and 2) flow of avalanches on the free surface.

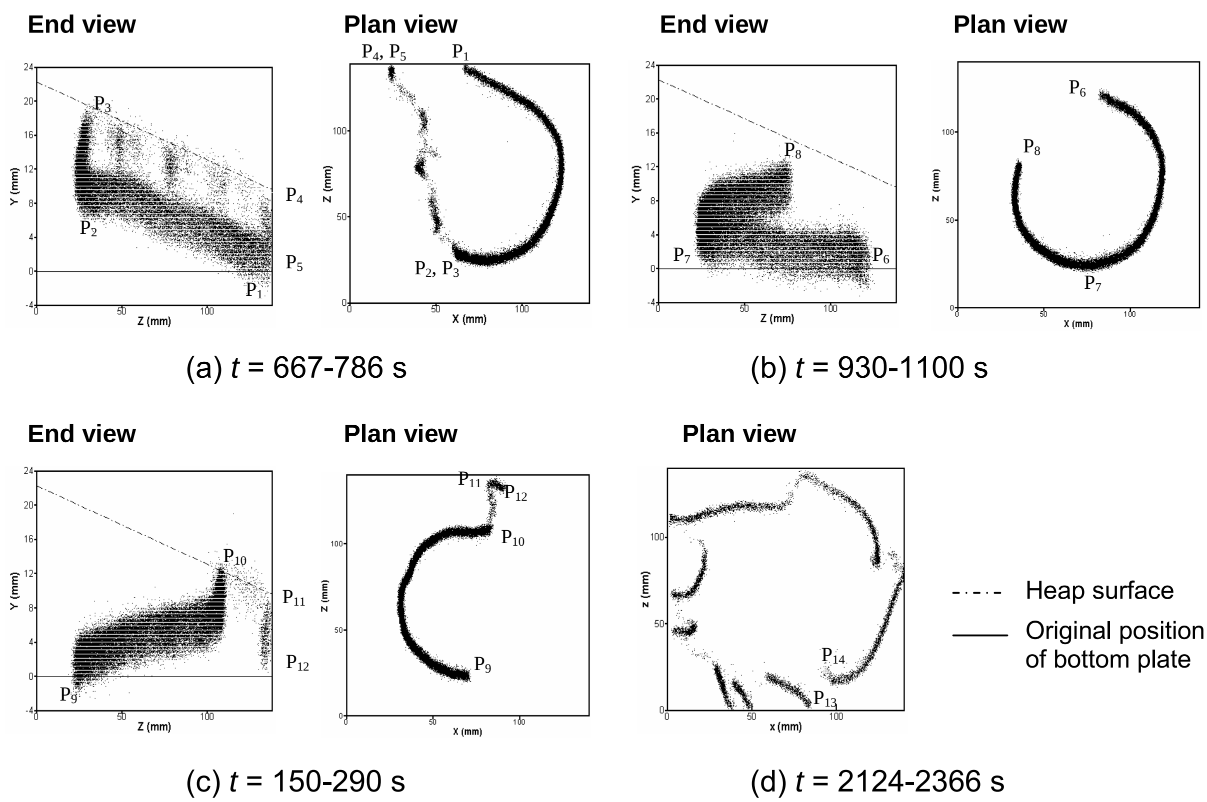


Figure 5 Tracer trajectory over certain time periods for case A (heap formation): (a) t = 667-786 s; (b) t = 930-1100 s; (c) t = 150-290 s; and (d) t = 2124-2366 s.

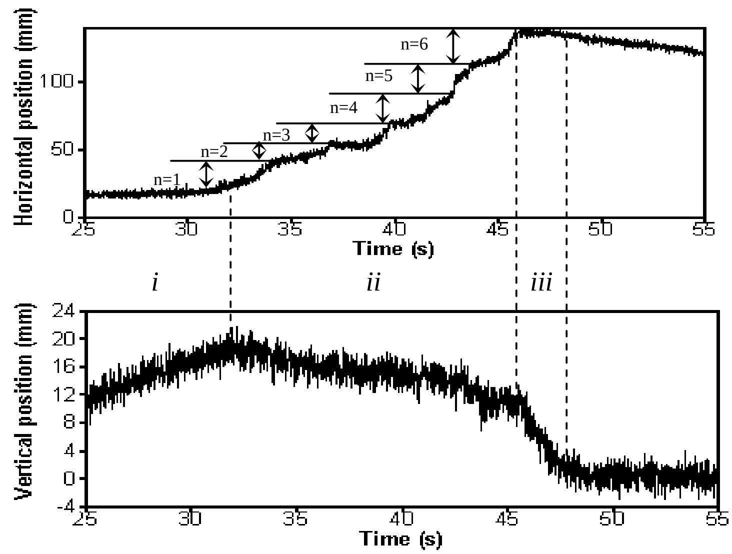


Figure 6 Occurrence of successive avalanches over a time period of 25-55s in case A (heap formation).

However, there are times when the tracer upward movement is not exactly parallel to the heap surface ($P_6 \rightarrow P_7$). When approaching the near front wall region, the tracer travels upward again, but in the direction opposite to the heap surface ($P_7 \rightarrow P_8$). The tracer is then captured in the slumping down region when it approaches the heap surface region ($P_{10} \rightarrow P_{11}$). Apart from that, it is interesting to note that the tracer always exhibits rotational movement in a circular trajectory in plan view when traveling from the bottom region to the top region of the bed in the direction either parallel ($P_1 \rightarrow P_2$) or non-parallel ($P_6 \rightarrow P_8$ and $P_9 \rightarrow P_{10}$) to the heap surface. On the other hand, it is observed that the tracer does not rotate in a circular trajectory when it is in the near wall regions ($P_{13} \rightarrow P_{14}$); as in Figure 5d. It rather travels up and down randomly in the near wall regions. The occurrence of this non-circular rotational movement suggests that the fluctuation induced by the sidewalls (through vertical vibration) has significant influence on the particle movement in the near sidewall regions.

To summarize, the tracer particle in bed with heap formation can travel from the bottom region to the top region of the bed in three ways as follows:

1) It travels upward parallel to the heap surface and slumps down the surface by successive avalanches (end view in Figure 5a);
2) It travels upward in the direction non-parallel to the heap surface and slumps down the surface when approaching the heap surface (end views in Figures 5b and 5c); and
3) It travels up and down randomly in the near sidewall region (Figure 5d).

Unlike heap formation, it is rather difficult to follow the tracer trajectory with respect to the exact location of surface waves (cases B and C) and arches (case D). In these cases, further PEPT experiments are suggested to be performed combined with the high-speed camera recording. In general, beds with surface waves and arching were found to travel up and down the bed in rotational movement in non-circular trajectories (as in plan view) throughout the system. Small departures of the bed from the vertical plane could be the reason attributed to such a rotational movement. In order to justify the main reason behind, further experiments are crucial to be carried out with more precautions.

The cycle frequency is a useful indicator in assessing solids motion in any equipment of interest (Wong, 2003). In this paper, the cycle time is defined as the time during which the tracer travels from the lower part of the bed (25% of expanded bed height) to the upper part of the bed (75% of expanded bed height), and eventually goes back to the lower part of the bed again. Figure 7 presents the effect of vibration amplitude on cycle frequency. From this figure, it is apparent that the cycle frequency increases linearly with the vibration amplitude, though no generality is claimed for this relationship. This is most likely particles receive more vibration energy to travel up and down the vessel at higher amplitudes.

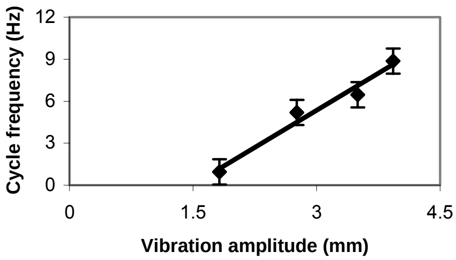


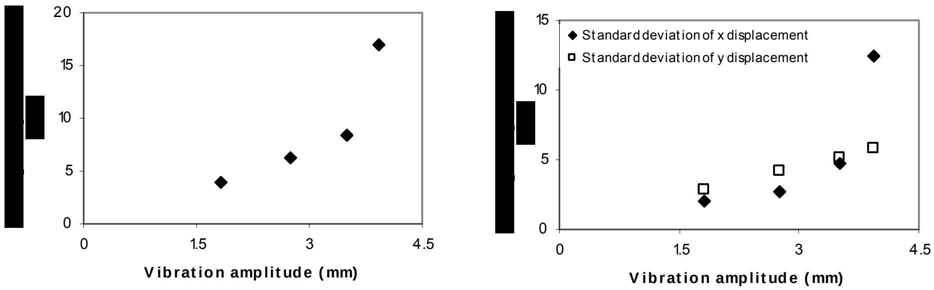
Figure 7 The variation of particle cycle frequency with vibration amplitude.

Another useful indicator of granular mixing behavior is dispersion. Here, the dispersion is measured using the approach of Martin (1999). Briefly, every time the tracer

$$\sigma = \sqrt{\frac{\sum (x-\bar{x})^2 + (y-\bar{y})^2 + (z-\bar{z})^2}{n}}$$

particle passes through a given volume element, its subsequent position is found after a short predetermined time interval. For a set of such short sections of trajectory, with all starting near the same point, the whole set of end points (*x*, *y*, *z*) can be determined and their dispersion from an average end position ($\bar{x}$, $\bar{y}$, $\bar{z}$) can be found. A dispersion index, σ, can be obtained as:

where σ is the position standard deviation (mm), n is the total number of traces, x, y and z are the end point locations (mm) and $\bar{x}$, $\bar{y}$ and $\bar{z}$ are the mean final point co-ordinates. The process can be repeated for each volume element. The time period is set for 773 ms in this study, which allows the tracer to travel 4.7 mm (i.e. 1/3 of the bed height filled with the granular material to a depth of 14 mm). The average dispersion index can be determined by averaging the total dispersion index for all volume elements over the entire system. The effect of vibration amplitude on the average dispersion index is shown in Figure 8a. The average dispersion index increases strongly with increase in vibration amplitude. When this dispersion is separated into vertical and horizontal components (as in shown Figure 8b), it is clear that the horizontal dispersion exceeds vertical dispersion at higher amplitudes.



(a) (b)

Figure 8 (a) Effect of vibration amplitude on average dispersion index; and (b) Average dispersion index in horizontal and vertical axes.

Conclusions

Positron Emission Particle Tracking has been used to investigate the solids mixing behaviour in vertically vibrated beds. Beds with surface waves and arching show the particle motion at the system frequency in the region near to the bottom plate and at half the excitation frequency at the surface. However, for beds with heap formation, the motion frequency is the same as the system frequency over the entire bed. For beds which exhibit heap formation, successive avalanches can be found along the heap surface, carrying particles from the top region to the bottom region of the bed surface. Regardless of the surface behavior, particles tend to show rotational movement in plan view. The vibration amplitude was found to have significant influence on both the particle cycle frequency and the average dispersion index. Horizontal dispersion becomes more significant than vertical dispersion at higher amplitude.

Acknowledgements

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