DOE/PC/95203--T2
M96030251

Experimental Investigation of Vibration-Induced Bulk Solids Transport and Segregation

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Technical Report

Period Ending: 3/31/96
Contract No: DE-FG22-95PC95203

During this quarter, substantial progress was made on the experiment. The results of these experiments will be presented at the AIChE World Congress this summer. Attached is a copy of the paper which will be published in the Congress proceedings.

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Experimental Observations of a Rise of a Single Large Sphere in a Bed of Granular Material Subjected to Vertical Vibration

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ABSTRACT

An experimental investigation of the motion of a single large sphere in a bed of dry granular material subjected to vertical vibration is presented. We have studied the rise time of the sphere as a function of vibration parameters, frequency and amplitude. While previous results report a decreasing rise time with increasing relative acceleration, we evidence the existence of a critical frequency where the rise time jumps to greater values before decreasing again. We also show that the rise time scales with the velocity amplitude of vibration and the transition corresponds approximately to a doubling of rise time. The results reported are over a rather narrow range of input accelerations, and generally involve gross phenomena of heaping and fluidization. Observations of the dynamic trajectory of the rising particle are also reported through the use of a novel non-intrusive particle tracking system.

INTRODUCTION

The use of particulates is widespread in industries such as chemical, pharmaceutical, ceramics, and agricultural. In these industries, vibration is often used for handling and processing of granular materials. The response of granular material placed in a container subjected to vibration is in general quite complicated, and a rich variety of resulting phenomena, such as convection, segregation, fluidization, densification, heaping, arching, and surface waves occur. In this paper, we report ongoing experimental observations made on a vibrated bed of granular material placed in a container. The experiments reported here consist of the transport of a single large sphere in a vertically vibrated bed of granular material. It is generally known that when bulk solids are vibrated, size segregation may occur, and it is well accepted that the principal cause of segregation is the discrepancy in particle size. There exists a growing body of literature on such experiments as well as simulations[1-9]. According to Knight *etal.* [1-2], segregation is driven by convection, while Rosato *etal.* [4] and Duran *etal.* [7] argue on geometrical effects. It is also argued that high friction with the wall is a necessary condition for the upward motion of the larger particle [1-2,6,7]. Most reported experiments (and theories to explain segregation) are in general involved with only qualitative observations (and analysis) of the phenomena and some may involve only two dimensional geometries. Lack of theoretical analysis may be attributed to poor understanding of actual motion during each vibration cycle.

The configuration used in our experiments is somewhat different from the usual setups reported in the literature [1-3]. Unlike the whole cylinder vibrating in the usual experimental setups, in our experiment, only the piston, i.e. the bottom of the cylinder moves, while the walls of the cylinder are fixed. This creates shear near the wall even at the lowest acceleration. The trajectory measurements

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reported are made in actual dynamic experiments using a tracer particle that contains miniature transmitters. This allows for tracking a single particle within a mass of many particles in a three dimensional flow configuration. The general experimental configuration is described in the next section, followed by a brief description of the non-intrusive tracking system. The experimental results are presented next and the paper is concluded with the discussion of results.

EXPERIMENTAL APPARATUS

The granular medium utilized in this experiment consists of 0.125" diameter acrylic spheres. These are placed in a fixed 4.5" diameter acrylic cylinder. There is a piston at the bottom of this cylinder, such that it can move freely within the cylinder. The vibrations to the material inside the cylinder are induced by the sinusoidal motion, $X(t) = a \sin(\omega t)$, of the piston, which is connected to a Bruell & Kjaer electromagnetic shaker. Fabric softener is used on the cylinder wall as well as spheres to reduce static electricity. The vibration exciter is controlled through power amplifier and an accelerometer mounted on the piston to get the feedback for the controller. The "intruder" or the large sphere is a 1" diameter polyethylene ball that contains miniature high-frequency transmitters. Thus the size ratio (intruder size divide by the medium size) in all the experiments reported here is 8. The cylindrical container is surrounded by an antennae cage, which is used to collect signals from the transmitters inside the intruder. A schematic diagram of this apparatus is given in Fig. 1.

Direction of Vibration

Figure 1. Schematic of vibration apparatus

The particle-tracking system consists of a sphere which includes three miniature high-frequency transmitters, a power source, and a set of receiving loop antennae surrounding the experimental device along with associated receiver electronics, data acquisition system, and elaborate software that allows for computing the position as well as orientation of the tracked sphere [10-12]. The unique feature of this system is that it allows us to measure three-dimensional translation as well as rotations of the intruder, which could be fully immersed in the mass of other granular material, and may be invisible to optical instruments. In that sense, it is non-intrusive, and is the only system known to directly allow for such detailed instantaneous measurements at over 900 samples per second. While some time averaged measurements inside the flow may be made using NMR instruments [2], our device, at a fraction of the cost of MRI, can provide very detailed results for a single sphere. For instance, it would be extremely difficult to measure rotations using MRI. The relative average tracking accuracy in this apparatus is $\pm 0.03''$ for translation and $\pm 2.0^\circ$ for rotation. Some individual trajectories measured using this device are presented in the next section along with other experimental results.

EXPERIMENTAL RESULTS

First, in a series of observations, we report the rise time of the intruder. The group of experimental results presented in Fig. 2 are for a fixed amplitude of 0.225", the range of frequency from 6 to 15 Hz, and two different bed heights of 2" and 4". As can be seen from this figure, a very

Figure 2. Rise time of the intruder as a function of acceleration

Figure 3. Vertical rise of the intruder for lower acceleration

Figure 4. Vertical rise of the intruder for higher acceleration

Figure 5. Rise time of the intruder as a function of frequency

interesting behavior is found. In this figure, the segregation time (time for the intruder to reach the maximum height) for different experiments is plotted versus the input acceleration ($\Gamma = a\omega^2 / g$, where a is the amplitude, ω is the frequency, and g is the gravitational acceleration). Γ is the natural nondimensional control parameter [2,3,5]. Till about $\Gamma = 1.8$, the segregation time decreases with increasing acceleration. However, beyond that, the behavior is counter-intuitive, as the segregation time actually increases with the acceleration. Gross motion of the bed reveals that the changing behavior may be attributed to the change in flow regime. Below $1.8g$, the flow regime is heaping type, while above $1.8g$, the flow regime is surface fluidization with apparently random motion. Looking at the trajectory of the intruder we observe a bifurcation (the acceleration threshold for bifurcation is different from the one for the change in flow regime). As shown in Fig. 3, the intruder trajectory for $\Gamma < 2.5$ shows same periodicity as the piston, while as shown in Fig. 4, for $\Gamma > 2.5$, the motion shows the phenomena of period doubling as the intruder is rising. Such bifurcation has been observed before, see for example

Figure 6. Rise time as a function of velocity amplitude ($a\omega$)

amplitude. In this figure, for all the amplitudes, the rise time curves show a jump between 12 Hz and 13 Hz. Above 13 Hz, the rise time again decreases. In Fig. 6, the same data of Fig. 5 is plotted as a function of the piston velocity amplitude (equivalently square root of kinetic energy). The velocity amplitude is simply $a\omega$. We see that the data collapses into two sets. As seen, the points for frequencies at or above 13 Hz are separated from the points for frequencies at or below 12 Hz. It seems that the gross motion of the bulk material is different for these two sets of data. At or below 12 Hz, you can clearly observe either heaping at low Γ or surface fluidization at higher Γ . At or above 13 Hz, even at low Γ , the top surface is flat indicating that heaping may not be present. The two sets of data in Fig. 6 collapse together when the rise time for points above transition is divided by 2 as shown in the inset. The transition could be interpreted as a period doubling in the segregation mechanism above the transition, and hence doubling of the rise time. The detailed motion of the intruder for these series of experiments are not included here due to the space constraint, but will be reported in a forthcoming paper.

DISCUSSION AND CONCLUSIONS

A series of results for the rise of a single intruder sphere in a three-dimensional bed of smaller spheres are presented. These preliminary results represent a part of ongoing experimental investigation of vibrated beds and in particular, study of size segregation. The results presented here corroborate some of the results previously reported by others, but they also indicate some departure from the usual conclusions made by others. The main observation is that the velocity amplitude (or the kinetic energy amplitude) may be a good parameter for such studies, as indicated by the lumping of curves plotted as a function of $a\omega$ in Fig. 6. Another main observation is that as seen in Fig. 5, the frequency of about 12 Hz for this experimental configuration is seen as a threshold. Usually, only relative acceleration Γ is used to describe transitions in granular material behavior [15]. We show here that frequency also is a transition parameter. As for granular waves [16], we find a typical time through this frequency threshold. An interesting observation from Fig. 2, is that even for $\Gamma < 1g$, the rise of the intruder could occur. We did observe segregation for even lower Γ than actually shown. More investigation of this

[13,14]. However, a careful scrutiny of the literature reveals that in comparing results with each other, the researchers do not always keep in mind the possibility of being in entirely different regimes from one set of experiments to another.

Another set of experiments are carried out by varying the amplitude as well as frequency. The amplitudes ranged from 0.125" to 0.225", and the frequency ranged from about 5 Hz to 15 Hz. In Fig. 5, these results are plotted as a series of curves, depicting the segregation time versus frequency. Each curve corresponds to a fixed value of the

Figure 7. The actual trajectory of the intruder and offset motion of the piston

motion may be worthwhile. The specific configuration of our apparatus (i.e. pushing the piston/plunger in and out) is probably responsible for this behavior.

It is expected that the trajectory measurements made through the use of magnetic induction-based non-intrusive tracking system [10-12] will prove to be very useful in performing the detailed analysis of motion. As an example, In Fig. 7, we show approximately one period of motion from Fig. 3, superimposed by the offset motion of the piston. One can see that the intruder appears to be traveling with the piston for the beginning part, then develops a free flight, and then eventually hits the piston, and then bounces off again. From our detailed observations, we find that the effecting coefficient of restitution between the intruder and

the granular medium below it changes along the height of the bed. The amplitude of motion during the flight of the intruder increases as the intruder rises. Also, the motion during a given cycle is not always sinusoidal, thus just sampling the motion at one or less samples per cycle (as done in [3] for many plots) may preclude one from observing nuances of the motion. For instance, one obtains rise curves which are quite different from one another if a single sample per cycle is taken from Fig. 4 at fixed value of phase angle. We have also observed that almost all the detailed trajectories that were obtained for various operating conditions exhibited a linear rise of the particle (except some curved motion at the beginning and end of the rise), thus corroborating the general trend observed in [3], while somewhat contradicting the observations in [1,2]. It is noted, however, that in [1,2], the trajectories plotted are not dynamic, and are synthesized through a series of careful experiments where the initial position of the intruder is different for each experiment. Another difference in [1,2] versus our experiment (also [3]) is that the vibrations are simply a series of taps.

In closing, even the simple experiments reported here indicate a rich variety of behavior for the motion of an intruder in a vertically vibrated bed. More detailed results along with the analysis of individual trajectories will be forthcoming.

ACKNOWLEDGMENTS

Support for this work was provided from U.S. Department of Energy contracts DE-AC22-91PC90181 and DE-FG22-95PC95203.

REFERENCES

1. Knight, J. B., H. M. Jaeger and S. R. Nagel, "Vibration-Induced Size Separation in Granular Media: the Convection Connection," *Phys. Rev. Lett.*, **70**, 3728 (1993).
2. Knight, J. B., E. E. Ehrichs, V. Y. Kuperman, J. K. Flint, H. M. Jaeger and S. R. Nagel, "An Experimental Study of Granular Convection," *Phys. Rev. E*, submitted.

3. Cooke, W., S. Warr, J. M. Huntley and R. C. Ball, "Particle Size Segregation in a Two-dimensional Bed Undergoing Vertical Vibration," *Phys. Rev. E*, to appear.
4. Rosato, A. D., K. J. Strandburg, F. Prinz, R. H. Swendsen, "Why the Brazil Nuts Are On Top: Size Segregation of Particulate Matter by Shaking," *Phys. Rev. Lett.* **58**, 1038-1042 (1987).
5. Rosato, A. D., R. N. Dave and E. Mosch, "Experimental Study of Vibrational Size Segregation," *Proceedings of the AIChE Particle Technology Forum, Symposium on Solids Transport, Separation and Classification*, p. 325-330, Aug. 17-19, 1994, Denver, American Institute of Chemical Engineers, NY (1994).
6. Rosato, A. D. and Y. Lan, "Granular Dynamics Modeling of Vibration-Induced Convection of Rough In-elastic Spheres," *Proceedings of the First International Particle Technology Forum, Symposium on Solids Transport, Separation and Classification*, p. 446-453, Aug. 17-19, 1994, Denver, American Institute of Chemical Engineers, NY (1994).
7. Duran, J., Mazozi, T., Clement, E., and Rajchenbach, J., "Size Segregation in A Two-Dimensional Sandpile: Convection and Arching Effects," *Physical ReviewE*, **50**, 5138-5141 (1994).
8. Gallas, A. C., Herrmann, H. J., and Sokolowski, S., "Convection Cells in Vibrating Granular Media," *Phys. Rev. Lett.*, **69**, 1371 (1992).
9. Julien, R., Meakin, P., and Pavlovich, A., "Three-Dimensional Model for Particle Size Segregation by Shaking," *Letters*, **69**, 640 (1992).
10. Dave, R. N., Ashok, A. S., and Bukiet, B. G., on development of a three dimensional particle motion tracking system, *1992 ASME Winter Annual Meeting*, 92-WA/DSC-5 (1992), 1-8.
11. Dave, R. N. and Bukiet, B. G., Non-intrusive rigid body tracking technique for dry particulate flows, Part I: Theoretical aspects, in review, *Review of Scientific Instruments*, (1995).
12. Dave, R. N., Non-intrusive rigid body tracking technique for dry particulate flows, part II: Practical aspects, *Review of Scientific Instruments*, to be submitted, (1996).
13. Wassgren, C. R., C. E. Brennen and M. L. Hunt, "Vertical Vibration of a Deep Bed of Granular Material in A Container," *J. of Applied Mechanics*, to appear.
14. C. E. Brennen, S. Ghosh, and C. R. Wassgren, "Vertical Oscillation of a Bed of Granular Material," *J. of Applied Mechanics*, to appear.
15. F. Melo, P. B. Umbanhowar and H. L. Swinney, "Hexagons, Kinks and Disorder in Oscillated Granular Layers", , to appear.
16. E. Clement, L. Vanel, J. Rajchenbach, J. Duran, "Pattern Formation In a Vibrated 2D Granular Layer", *Physical ReviewE*, to appear.