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Particle dynamics in a dense vibrated fluidized bed as revealed by diffusing wave spectroscopy

V. Zivkovic, M.J. Biggs *, D.H. Glass, P. Pagliai, A. Buts

Institute for Materials and Processes, University of Edinburgh, King's Buildings, Mayfield Road, Edinburgh, United Kingdom, EH9 3JL

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Abstract

We report granular temperature data and long-time dynamics of mono-disperse glass particles in a three-dimensional dense bed subject to vertical sinusoidal vibrations over a wide range of conditions. The granular temperature of the particles was found to scale with the square of the peak vibrational velocity. The mean time of flight between the collisions was found to scale with the inverse of the square of the peak vibrational velocity, whilst the mean free path of the particles was observed to scale with the inverse of this velocity. The movement of the particles throughout the bed, which was observed to be sub-diffusive over macroscopic timescales for all conditions considered here, appears to be governed by collective motion of particles between cavities defined by their neighbours.

Keywords: Granular temperature; Vibro-fluidized bed; Sub-diffusive; Jamming; Glassy dynamics; Caged dynamics

1. Introduction

Vibrated granular materials have received much attention over many years because they are a simple example of dissipative non-equilibrium systems that demonstrate rich and complex behaviour [1,2]. They are, however, also of wide interest across industry. For example, flow of bulk solids from hoppers and silos is often controlled through the application of vibration [3], whilst more recent work has shown that vibration can also improve the fluidization of fine powders [4]. Vibration has long been known to cause segregation in mixtures of different sized particles [5] as well as compaction, whether desired as in the manufacture of sintered products [6] or otherwise [7]. Squires [8] has recently highlighted how vibrated granular systems may lead to improved operation of reactors, combustors and heat exchangers. Finally, vibration of granular materials is important in the construction industry including, for example, in the manufacture of building materials [9], soil improvement [10] and soil response to seismic events [11].

A key quantity in granular systems is the ‘granular temperature’, which is defined as the mean of the square of the velocity fluctuations about the mean velocity [12,13]. The granular temperature underpins the kinetic theory of granular flows [14,15], which has been widely used to model various non-equilibrium granular systems [16–19], as well as theories for heat transfer in granular materials [20], erosion in fluidized beds [21] and granulation [22]. The validation of these theories demands the experimental elucidation of the particle dynamics in general and determination of granular temperature in particular.

Much understanding of the dynamics of particles in vertically vibrated fluidized beds (vibro-FBs) and associated granular temperature data has been accumulated over the past decade or more using high-speed video imaging [23–31], nuclear magnetic resonance [32,33], and positron emission particle tracking (PEPT) [34–37]. Various constraints inherent to these methods – multiple light scattering for video methods, small bed-to-particle diameter ratios in NMR, and limited spatial and temporal resolutions – mean they have all been restricted to one particle thick [23–28], relatively shallow [29–31], confined [32,33] or dilute three-dimensional (3D) [34–37] beds.

A few methods have been (or in principle can be) applied to dense systems not accessible to video-based methods, NMR and PEPT including solids pressure-data inversion [38], mechanical spectroscopy [39,40], which involves using the Langevin equation to interpret the random angular motion of a torsional pendulum immersed in the granular material, and the light

* Corresponding author. Tel.: +44 131 650 5891; fax: +44 131 650 6551.
E-mail address: M.Biggs@ed.ac.uk (M.J. Biggs).

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scattering based techniques of diffusing wave spectroscopy (DWS) [41] and speckle visibility spectroscopy (SVS) [42]. The pressure-data based approach is, however, limited to the wall region, whilst mechanical spectroscopy is an intrusive method that appears to give results that depend on the nature of the probe used [40]. Both DWS and SVS, on the other hand, are neither intrusive nor restricted to the wall region, yet they are able to probe length and timescales well below those accessible to NMR, their nearest rival in this regard.

The single DWS-based study to date of dense 3D vibro-FBs [41] was very limited in scope, focussing on a single frequency and short-time dynamics of the particles. The SVS study [42] was similarly limited, focusing on describing a new method rather than the phenomena observed. We, therefore, undertook a far more detailed study of the dynamics of particles in a dense 3D vibro-FB using DWS in which we considered both the short and long-time behaviour of the particles across a wide range of conditions and at various point in the bed — this study is reported here. We first outline the experimental details, including an overview of DWS and details pertaining to the apparatus and the particulate material, and the experimental procedures used. This is followed by presentation of the results obtained, which include the particle dynamic regimes observed and the variation of the granular temperature with process conditions and height above the base of the bed, and their discussion.

2. Experimental details

2.1. Overview of diffusing wave spectroscopy

Diffusing wave spectroscopy (DWS), which is described in detail by Weitz and Pine [43], is a light-scattering technique that can be used to determine the dynamics of dense dispersed phase media such as turbid colloids and fluidized beds. Light-scattering techniques involve irradiating the medium of interest with light and then measuring the temporal intensity fluctuations of the scattered light arising from the motion of the scatterers (which are the particles in the case here). These intensity fluctuations can be characterised by a temporal autocorrelation function whose behaviour can be related quantitatively to the motion of the scatterers through mathematical models. In traditional dynamic light scattering, this model assumes the photons are scattered at most once — the method is, therefore, limited to dilute systems. Diffusing wave spectroscopy, on the other hand, is valid in the opposite limit: dense systems where the light is scattered so many times, Fig. 1, that it may be assumed that the photons are undergoing a random walk through the medium. Unbiased random walks can be described by a purely diffusive process, which is exploited in DWS to relate the dynamics of the scatterers to the temporal autocorrelation function of the intensity.

2.2. Experimental setup

The experimental apparatus is illustrated in Fig. 2. The granular material was held in a rigidly fixed rectangular column constructed from two 500 mm high and 196 mm wide borosilicate glass plates separated by two aluminium edges 14.5 mm thick. The granular material was subject to vertical vibrations at the base of the column by a piston fixed to an air-cooled electromagnetic driven shaker (V721, LDS Ltd., Hertfordshire, UK) controlled by a Dactron COMET USB controller (LDS Ltd.) with feedback from two integrated circuit piezoelectric accelerometers (model 353B03, PCB Piezotronics Inc., NY, US) attached to the piston. The shaker was capable of delivering a range of different vibrational modes at frequencies in the range of 5–4000 Hz, accelerations up to 70 g, and amplitudes as large as 12.7 mm.

The dynamics of the particles in the vibro-FB were studied using DWS in transmission mode [43–47]. This method involves illuminating one side of the bed at the point of interest with a ~2 mm diameter laser beam and collecting the scattered light from the opposite side of the bed over time, t, with a single mode optical fibre (OZ Optics Ltd., Ottawa, Canada). A

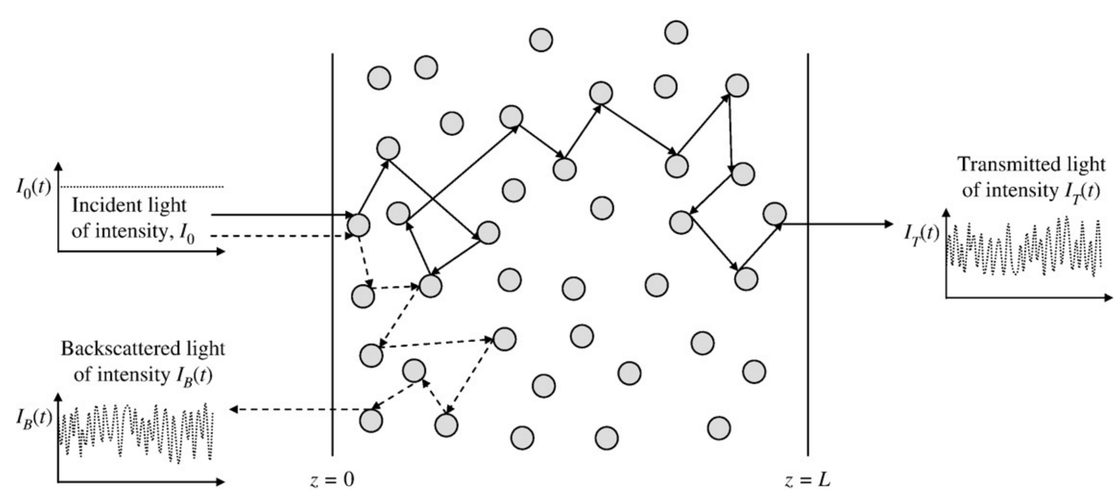

Fig. 1. Schematic of the process that underpins diffusing wave spectroscopy (DWS). A beam of light incident on the dispersed phase medium is multiply scattered by the moving particles (shown as grey circles) before exiting the medium to be picked up by light intensity detectors. The light that exits from the face on which the incident beam enters is said to be backscattered, whilst that which leaves through the opposite face is said to be transmitted — the fluctuations in the transmitted and backscattered beams, which can be characterised in terms of temporal autocorrelation functions (see details in Section 2.4.2 and Fig. 4), can both be analysed to determine the dynamics of the light-scattering particles of the medium.