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Resonant and non-linear behaviour in vibrationally fluidised beds

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Abstract

This paper presents an experimental examination of the behaviour of vibrationally fluidised granular materials. This work was principally focused on examining the resonant behaviour of these systems. The harmonic response of a column of various granular materials (Geldart type A and B) was measured using a small apparatus. These materials displayed several non-linear effects such as; a normalised response that was dependent on excitation level, multiple harmonic components in the response to a single excitation frequency, and odd behaviour in terms of the motion of the emulsion.

Two resonant peaks were found for each material. The relative magnitudes of these two peaks were heavily dependent on excitation level, so much so that at high levels of excitation only the higher resonant frequency was present. In each case, some correlation was found between this resonant peak and a prediction based on a "granular-gas" estimate of the speed of sound in the fluidised emulsion. This correlation was further examined by studying the resonant of the system under various levels of partial vacuum. The prediction followed the trend correctly.

Keywords: Granular materials; Vibrational fluidisation; Non-linear vibration

1. Introduction

Cohesionless granular materials are unique in the sense that they can have properties that resemble solids, liquids and gases depending on the rate of deformation or energy introduced into the system. At higher energy levels granular materials often become fluidised, a phenomenon that is exploited in a vast number of handling systems and industrial processes (e.g., air slides, vibrational flow promotion and gas–solid contact). In most industrial applications (e.g., pneumatic transportation, catalytic reactions etc.) fluidised states are achieved by passing air through a material bed. However, in general fluidised states can be achieved in any number of ways. For example, during an avalanche the rapid deformation that is experienced provides sufficient energy for the material (snow/ice, grain, sand etc.) to flow in a fluid like manner.

There is a vast amount of phenomenological wealth in the behaviour of vibrated powders. It is now well known that vibrated beds of granular materials can show various self-organised patterns known as "Faraday waves" or "Faraday crispations" [1], as originally observed in vibrated liquids. In addition to these phenomena, vibrated granular materials also demonstrate more unique behaviour, such as the formation of "oscillons" and convection rolls ([2], and [3]). While these results are easily repeatable, there are currently substantial difficulties in describing the origins of these peculiar behaviours.

This paper is focused on the fluidisation of granular materials due to vibration, and in particular, resonant behaviour of vibrationally fluidised systems. We will attempt to understand the resonant behaviour of these systems in terms of a granular-gas description of the fluidised material. This approach revolves around an observation made by Roy et al. [4], that the speed of sound in a fluidised emulsion is governed by the properties of the pore fluid (e.g., air) and the bulk density of the emulsion;

$$c_{\mathrm{em}} = c_{\mathrm{air}}\sqrt{\frac{\rho_{\mathrm{air}}}{\rho_{\mathrm{em}}}} \qquad (1)$$

The central assumption of this model is that the emulsion has the same compressibility as the pore fluid and the particles serve

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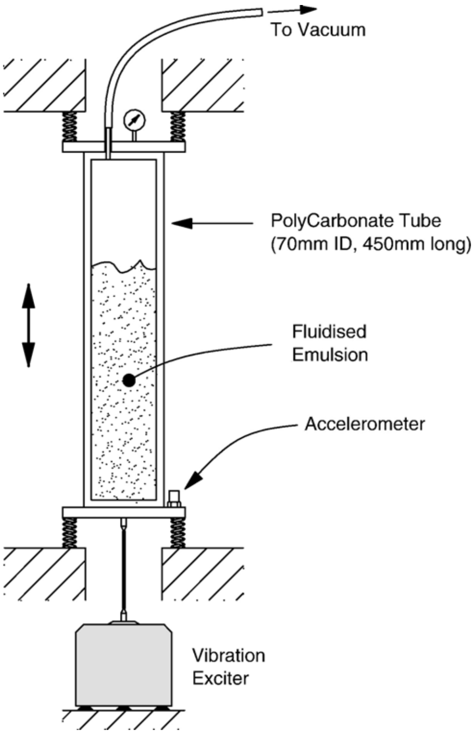

Fig. 1. The experimental apparatus.

only to increase the density. The excitation provides particles with sufficient energy to undergo Brownian motion, and the system is treated as a quasi-granular-gas. It is important to note that this description does not consider inter-particle interactions or the interaction of the particles with the boundary to be significant. These interactions provide a continual loss of energy which is assumed to be replaced by the fluid flow or vibrational excitation.

This paper aims to investigate the validity of this approach using a small experimental system. Results from several different granular materials will be presented in addition to results at various air densities. Some particularly interesting behaviour at reduced air pressures will also be presented without explanation.

2. Experimental approach

A small system was designed and built in order to examine resonant behaviour in fluidised systems (Fig. 1). This piece of equipment consists of a small polycarbonate tube (70 mm ID, 450 mm long) with sealed end caps, fitted to a moving frame. The frame is suspended by linear bearings and four preloaded springs. A 100 N 4824 Bruel and Kjaer vibration exciter is fixed to the frame by a 200 mm long “stinger”. The chamber formed by the tube can be evacuated using a vacuum pump via a pressure fitting mounted to the upper end cap. Instrumentation consists of a pressure transducer (Barksdale 423H3-01-A) mounted to the upper end-cap via a flexible tube, and an accelerometer (MONITRAN MTN/1100HC) fitted to the moving frame. The four springs are mounted so that they apply only compressive forces; however they were each preloaded with 5 mm of static deformation to allow this amount of movement before the springs leave their seats. The completed apparatus was mounted to a firm foundation in the form of a large structural column in a laboratory building. The empty tube and the sliding frame has a mass of 2.1 kg, and the stiffness of the completed apparatus was measured at 118 N/mm (120 N/mm design). These parameters provide an empty resonant frequency of 37.7 Hz (theoretically).

By varying the frequency and magnitude of the excitation it is possible to measure the harmonic response of the complete system (including the fluidised bed and apparatus). Practically this was achieved using a 16-bit Data Translations PCI data acquisition board equipped with an analogue output. This board was used in conjunction with a program written in HP-VEE (now Agilent-VEE) which automated the testing procedure. This program measures the response to a series of harmonic excitations (of increasing frequency) provided by the D/A system. The system was driven at each individual frequency for a period of 6 s, and to avoid transient effects, only the final 3 s of data was used to determine the response. The 3 s delay before recording data was chosen by observing the behaviour of the output over the whole time period. It was observed that the response settled to a steady magnitude within 1–2 s of each change of frequency. This approach ensures that the initial conditions of the bed do not affect the measured response. The response is calculated as the ratio of the amplitude of the vibration to the amplitude of the current passing through the voice coil (proportional to the forcing function). Fourier transforms of these two signals were used to calculate their magnitudes. Measurements were sampled at 1 kHz.

A range of materials were examined to gain an insight into the effect of material properties. Table 1 shows selected properties for the materials tested in this study. These materials cover a range of densities and particle sizes, and give examples of group A and B powders in the Geldart classification [5].

3. Characteristic behaviour

It is unreasonable to consider the behaviour of the fluidised emulsion separate to the motion of the experimental apparatus. Dynamically, each of these components has an intimate influence on the other. To model the system we view the apparatus, and in particular the container, as

Table 1
Properties of the materials investigated in this study

Material	Bulk density (kg/m^3)	Solid density (kg/m^3)	d_{50} (μm)	Geldart classification (Fig. 2)
PVC powder	650	990	187	A
Alumina	1120	3600	89	B
Sand	1600	2620	322	B

Bulk density was estimated during testing by dividing the known mass by the volume (calculated from the observed bed depth).