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Dynamics and avalanches in a system exhibiting granular collapse

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HIGHLIGHTS

- The dynamics of quasi-2D polydisperse granular particles is characterized.
- Evidence is found that aging in glass-like systems is dominated by avalanches.
- Relaxation resembles that of some 3D colloidal monodisperse hard sphere glasses.
- Avalanches may play a role in the dynamics of a wide variety glassy systems.

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ABSTRACT

The dynamics of an experimental driven quasi-2D system of polydisperse particles in a cluster formed by granular collapse is characterized via the self-intermediate scattering function and the mean-squared displacement and is compared with monodisperse experimental and computational systems. The dynamics, despite the difference in dimensionality, is shown to resemble that of de-vitrification in certain simulations of 3D colloidal monodisperse hard sphere glasses in that avalanches are a key feature.

1. Introduction

The dynamics of systems exhibiting granular collapse, defined as the constituent particles losing nearly all of their kinetic energy due to inelastic collisions and forming a dense cluster [1], is comparatively poorly understood, particularly in polydisperse systems. Quasi-2D systems are those in which 3D constituents are constrained to move in such a manner that two particles cannot simultaneously have the same 2D coordinates. Quasi-2D granular dynamics has been studied experimentally before [2–4] but, with relatively few exceptions, previous work has focused on near-monodisperse particles with no granular collapse. An important exception is the seminal work of Olafsen and Urbach [5], who report clustering and granular collapse for a granular monolayer with uniform agitation. Experimentally, inhomogeneities in thermal systems in non-equilibrium states have been observed, for example, in supercooled liquids, which can develop fragile solid-like networks, which exhibit aging, enclosing "liquid pockets" [6].

In the present work we present primarily experimental results regarding the dynamics of quasi-2D systems subject to granular collapse. There is evidence supporting that the dynamics of systems without granular collapse are, except for a ballistic regime at short times, diffusive or subdiffusive [3], and that entropy-like arguments can be applied to them [7–9]. We present evidence that, in the presence of granular collapse arising due to inhomogeneous agitation, the dynamics of slow relaxation, i.e. aging [10], is dominated by "avalanches", i.e. some particles participating in large, sudden, stochastic

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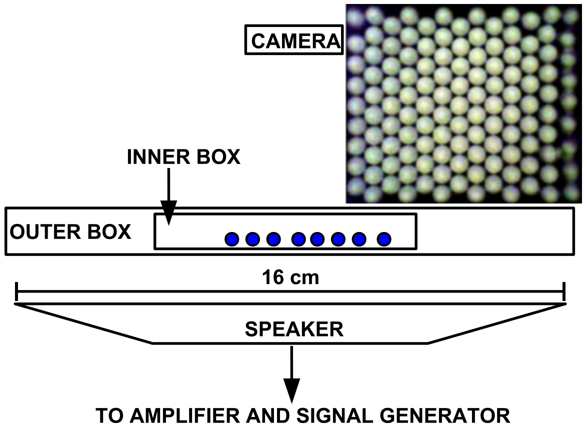

Fig. 1. The experimental setup used is shown schematically. The filled circles depict the particles used (not shown to scale). The diagram is reproduced, with modifications, from Sánchez and Huerta [13]. The inset shows a still from a video of 123 near-monodisperse particles, with enhanced contrast for visual clarity.

motions [11]. This situation is reminiscent of that predicted by simulation for certain non-equilibrium colloidal glasses [11], i.e. glasses of thermal particles with classical dynamics [12], where we define glasses as arrested, dense systems with no long-range order.

2. Materials and methods

A level plastic box containing the particles, itself placed within another plastic box to reduce, but not eliminate, inhomogeneities in agitation, was made to vibrate by a speaker (Sony, 190 W peak output, 16 cm diameter) driven by a 150 Hz sinusoidal wave from a signal generator (Phillips PM5132) and an amplifier (Steren AMP-010, 35 W rms) (see Fig. 1). Laterally, the particles are confined by rectangular hard walls; for the polydisperse particles, these walls have approximate dimensions of 22×26 mean diameters. The vibrations were transmitted via air under normal atmospheric conditions. The inhomogeneities arise from curved wavefronts impinging on a flat surface (the maximum induced amplitude in the box containing the particles is estimated as $\sim$1%) and decrease approximately linearly with squared distance from the cell center.

Images were captured by a Microsoft LifeCam VX-800 webcam at a rate of 5 frames per second; using a rate over an order of magnitude slower than the driving frequency ensures non-negligible agitation between frames. The setup is described in detail elsewhere [14,13]. Fundamentally, this system is reminiscent of that used by Gradenigo et al. [15]. Near-monodisperse ($\sim$1% polydispersity) 0.77 cm mean diameter plastic spheres, and 6.76% polydispersity 0.35 mm mean diameter Styrofoam spheres were used. For the polydisperse spheres, the number of particles per frame (i.e. the number of particles in the system) is $\sim$500, depending on the exact packing fraction η, defined as the fractional area occupied by the particles, taking them as circles. For the near-monodisperse spheres, $\sim$100 were used.

The particle positions as a function of frame number were obtained using an ImageJ plugin developed by Sbalzarini and Koumoutsakos [16]. All further analysis was carried out using software written in-house. $F_s(\mathbf{k}, t)$ was calculated using all trajectories obtained from a given image sequence.

Event-driven molecular dynamics (MD) simulations of strictly 2-dimensional, non-dissipative, monodisperse hard disks with periodic boundary conditions were carried out. We fixed the temperature $k_B T = 1$ by appropriately scaling the magnitudes of the velocities of each particle, and the diameter $\sigma = 1$, such that the kinetic energy agrees with the equipartition theorem. The velocities' initial directions were chosen randomly. In order to get equally time-sampled positions of the particles, i.e. the trajectories, we interpolated the position of each particle between a collisional event. Otherwise, standard event-driven MD was used. The algorithm treated the discontinuous hard disk potential by using elastic collisions (conserving energy and momentum) during each event (collision) [17]. We recorded the trajectories of 400 and 2500 particles for 60 000 time steps with a fixed time interval of 0.01. The 400 and 2500 particles were located inside a square box whose size was assigned to match the appropriate packing fraction. We started from a random configuration obtained from a previous NVT Monte Carlo simulation. Before recording trajectories we also ran a MD simulation with velocities assigned as described before, in order to equilibrate the system, and checking also that the mean-squared displacement reaches diffusive behavior at each packing fraction. Non-dissipative dynamics were used for the simulations in order to better isolate the effect of non-equilibrium effects, including dissipative dynamics, in the experiments.

To characterize the dynamics of both the experimental systems and the simulations, we define the 2D self-intermediate scattering function as follows [18]:

$$F_s(\mathbf{k}, t) = \frac{1}{N} \left\langle \sum_{j=1}^{N} \exp\{-\mathrm{i}\mathbf{k} \cdot [\mathbf{r}_j(t) - \mathbf{r}_j(0)]\} \right\rangle, \quad (1)$$