Spontaneous rotation and slow "breathing" in a vertically vibrated dense granular monolayer

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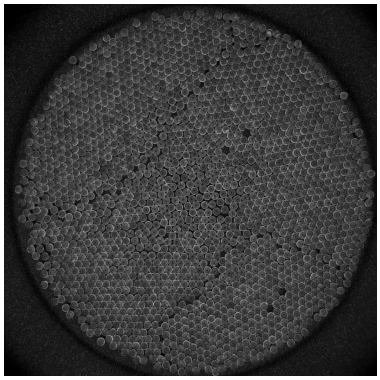

FIG. 1. An instantaneous configuration.

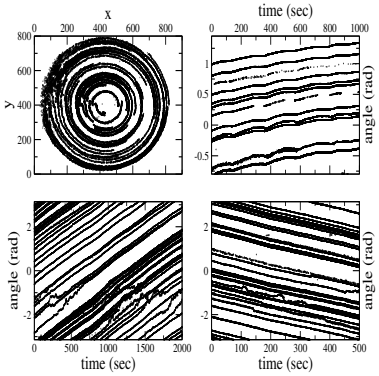

FIG. 2. From top-left, going anti-clockwise: 1) position $x(t), y(t)$ of few particles during a 2000 seconds trajectory ($f = 75$Hz, $\Gamma = 3.5$); 2) angle $\tan^{-1}(y/x)$ of the tracers as a function of time ($f = 75$Hz, $\Gamma = 3.5$); 3) the same for a different frequency ($f = 100$Hz, $\Gamma = 4$); 4) the same for $f = 125$Hz and $\Gamma = 3$, where the "breathing" mechanism can be identified.

Granular materials are athermal systems, nevertheless they can be excited by periodic or stochastic macroscopic mechanical drivings, reaching very peculiar non-equilibrium steady states. A typical setup is constituted by one or more horizontal layers of spherical grains on a vertically vibrating surface: under periodical vibration this system displays a wide variety of ordering behaviors [1–4], sensitive to covering fraction, number of layers, vibration parameters, material properties, boundary conditions, etc.

In this communication we report about recent experiments on a quasi-2D monolayer made of ~ 2000 glass beads, $4mm$ of diameters, close to the hexagonal packing, as exemplified by Fig. 1. The vibrating container is made of a horizontal teflon-covered rigid aluminum circular plate, of diameter ~ 20cm, delimited by slowly rising boundaries to prevent highly dissipating frontal collisions between beads and borders. The teflon covering provides a finely rough surface which efficiently transfers vertical energy into horizontal motion. The energy input is provided by a shaker which vibrates the system vertically with a sinusoidal law at frequency f. We focus on the range of frequencies $f \in [75, 200]$ and on amplitudes A such that $\Gamma = A(2\pi f)^2/g \in [3, 5]$. In this range a granular regime is observed, similar to a thermally vibrating crystal: most of the grains show rapidly fluctuating displacement with respect to an averagely stable hexagonal lattice, with few sparse fractures and defects due to the overall inconsistency of the boundary with the lattice. Superimposed to this thermal solid-like behavior, we observe a remarkably stable *rigid rotation* of the whole lattice at constant angular velocity Ω. The period of rotation $T = 2\pi/\Omega$ is several orders of magnitude larger than $1/f$. We find that Ω increases with the amplitude of the vibration, but changes in a *non-monotonic* fashion when f is varied from 75Hz to 200Hz [5]. In particular at least two inversions of the sign of Ω are observed, increasing f. A careful study of the container reveals small imperfections which account for the rotational symmetry breaking. The comparison with known granular ratchet models is discussed [6]. At small amplitudes, i.e. at the onset of the vibrating crystal regime, we also observe a very slow *breathing* mechanism, where energy cyclically disappears and comes back into the system, while the rigid rotation slows down and accelerates: the breathing period is much larger than $1/f$ but lower than T. This seems to be the cyclical reproduction of a front propagating "ignition" mechanism already observed in previous experiments [7].

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