Hysteretical behavior of a jam-packed granular monolayer

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Summary

We are examining a granular (sub-)monolayer subjected to horizontal vibrations in gravity. Depending on the excitation parameters A and ω one can find three different dynamical states:
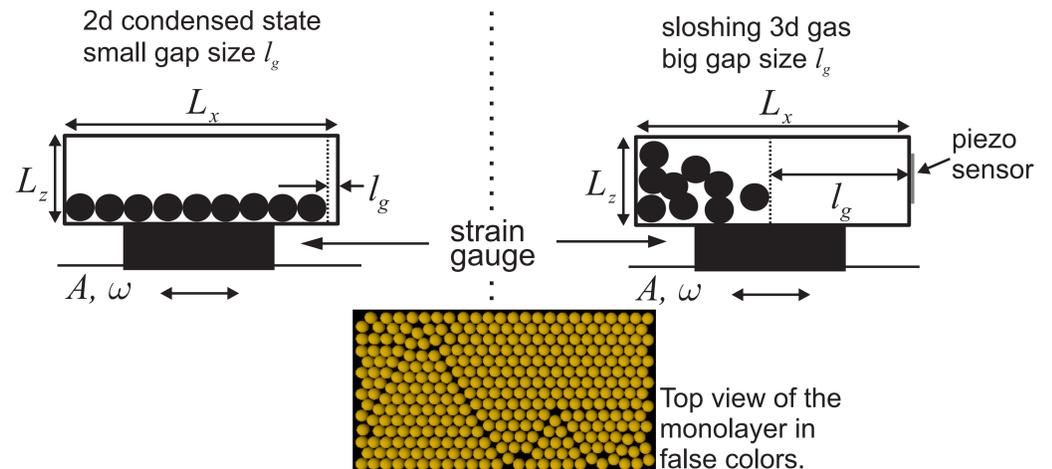
1. a 2d gas-like state;
2. a 2d condensed (often crystalline) state;
3. a 3d granular gas.

Here we consider only the transition 2 ⟷ 3.
For fixed frequency and slowly varying amplitude of the oscillation, we observe an abrupt change of the systems's dynamical state, where the system expands to the vertical dimension. This transition leaves its fingerprint in several measurable quantities, such as energy dissipation rate, sound emission characteristics and a gap size which quantifies the sloshing motion of the granulate. The well defined hysteresis of the transition can be understood by considering the ernergy of the collective motion of the particles relative to the container. Both transition forward and backwards occur at critical energies.

Setup

For monodisperse granulate we use 4 mm steel spheres in a polycarbonate box of dimension L_x, L_y, and L_z. The angular frequency ω is fixed at 18.85 s^{-1}. The power of the excitation is adjusted by the driving amplitude A.

2d condensed state
small gap size l_g

sloshing 3d gas
big gap size l_g

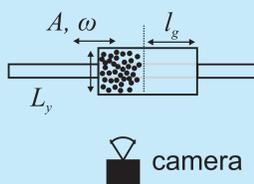Top view of the monolayer in false colors.

Measurement methods

We are collecting information about the systems behavior using 3 different methods:

Camera:
Observing the system via a high speed camera in front of the box. Analyzing the maximum free space to the wall, i.e. gap size l_g

Strain gauge:
Measuring the force $F(t)$ needed to drive the system via a strain gauge between the box and the linear gear. Calculating the energy dissipation rate η

$$\eta \equiv \frac{\int_T \dot{x}(t) F(t)\,\mathrm{d}t}{4 N m A^2 \omega^2}$$

Piezo sensor:
Recording the sound emission via a piezo sensor attached to the side wall of the box. Calculating a quotient S of the power spectrum P

$$S \equiv \frac{\int_{1\mathrm{kHz}}^{5\mathrm{kHz}} P(f)\,\mathrm{d}f}{\int_0^{1\mathrm{kHz}} P(f)\,\mathrm{d}f}$$

Model

Energy equipartition: $\dfrac{1}{2} m v^2 = m g d$

The velocity corresponding to the energy needed to lift a particle by its diameter equates to $v \approx 0.28$ m/s. If 24 particles (one row) are pushing the last particle this velocity is reduced to $v \approx 0.06$ m/s.
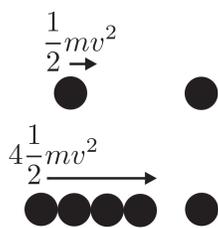
The collision time t_c of the granulate with the wall is given by:

$$\omega t_c = \sin(\omega t_c) + \frac{l_g}{A}$$

Expanding for t_c the velocity between wall and granulate equates to:

$$v = A\omega \left(1 - \cos\left[\left(\frac{6 l_g}{A}\right)^{\frac{1}{3}}\right]\right)$$

which results in $v \approx 0.066$ m/s for $A_{2\to3} \approx 17$ mm and $l_g \approx 0.8$ mm (experimental values).
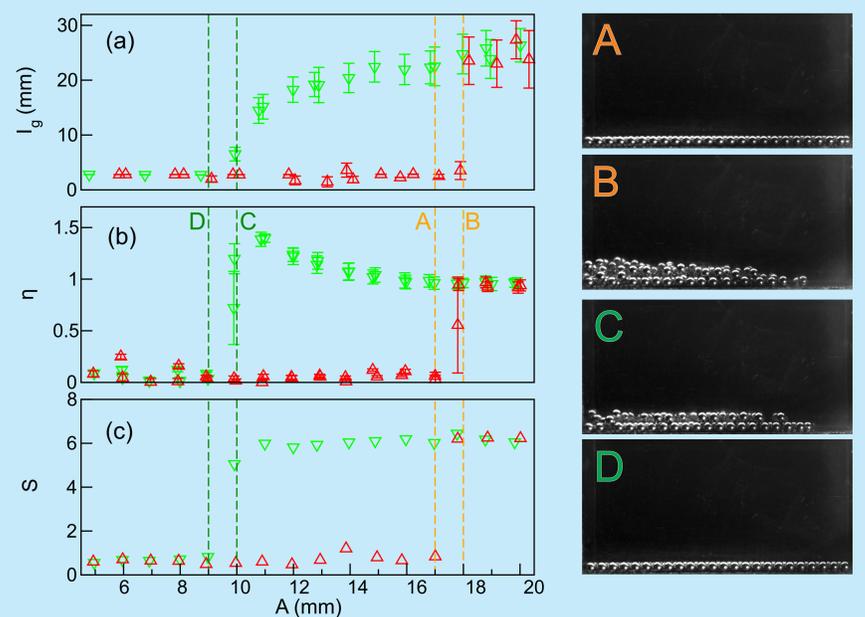
After the first particle left the first layer, the gap size is increased rapidly and the full layer breaks up.

Lower boundary for the solid state ($A_{3\to2}$):
Maximum relative velocity is $2 A \omega$, which results in

$A_{3\to2} > \dfrac{1}{\omega}\sqrt{\dfrac{g d}{2}} \approx 7.4$ mm (experiment: $A_{3\to2} \approx 9$ mm)

Results

Left: Characterization of the solid ⟷ 3d gas transition (2 ⟷ 3), using a) the gap size, l_g, b) the dissipation rate, η, and c) the sound emission, S. Red symbols indicate increasing amplitude, green symbols decreasing amplitude. Vertical dashed lines labeled A-D corresponds to the transition points.
Right: Snapshots at the transition points A-D.
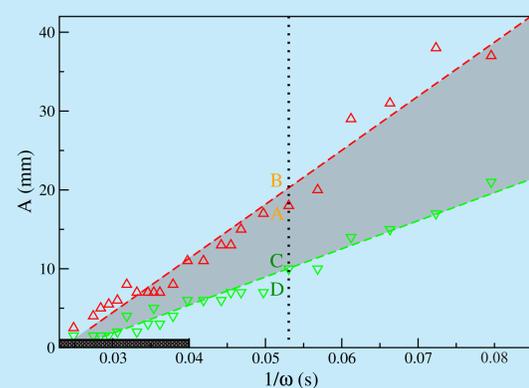
Both transitions, forward and backward, take place where $A \sim 1/\omega$. This is what is expected from our model.
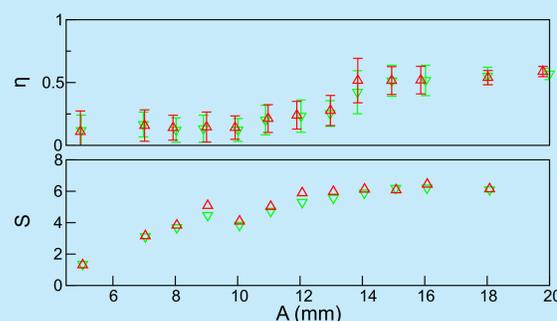
For a submonolayer no hysteresis is noticable which is also in agreement with our model.

Acknowledgment

References

C. Krülle and A. Sanchez, AIP Conf. Proc. **1542**, 803 (2013)
M. Heckel, A. Sack, J. E. Kollmer, and T. Pöschel, *Fluidization of a horizontally driven granular monolayer*, submitted (2014)
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