Large Amplitude Oscillatory Shear (LAOS) Rheometry of wet and dry granular matter and their non-linear dynamics

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Introduction:

Dry and wet granular materials exhibit rich non-linear dynamics under confinement, causing uncanny flow behaviour when sheared at large deformation rates during industrial processing operations. In this study, we have investigated granular flow dynamics in a conventional rheometer, and with the help of MITLAOS framework, we have identified three dynamical regime for grains, namely, linear, non-linear and stick-slip. We revealed scaling relationship between non-linearity (quantified in terms of Chebyshev coefficients of higher order harmonics) and the dissipated energy.

Experimental Details :

- **Materials:**
  1. Dynoseeds (DySy) : 140 µm - 500 µm, Dry and wet (1-3 % Silicon oil))
  2. Lactosa Powder : 140 µm, Dry and wet (3 % H_2O)
- **Rheometer:**
  1. Cup-Plate gap: 10mm
  2. Frequency: 1.5 Hz
  3. Strain amplitude range: (0.001-200) s^{-1}
  4. Number of repetitions per cycle: 10

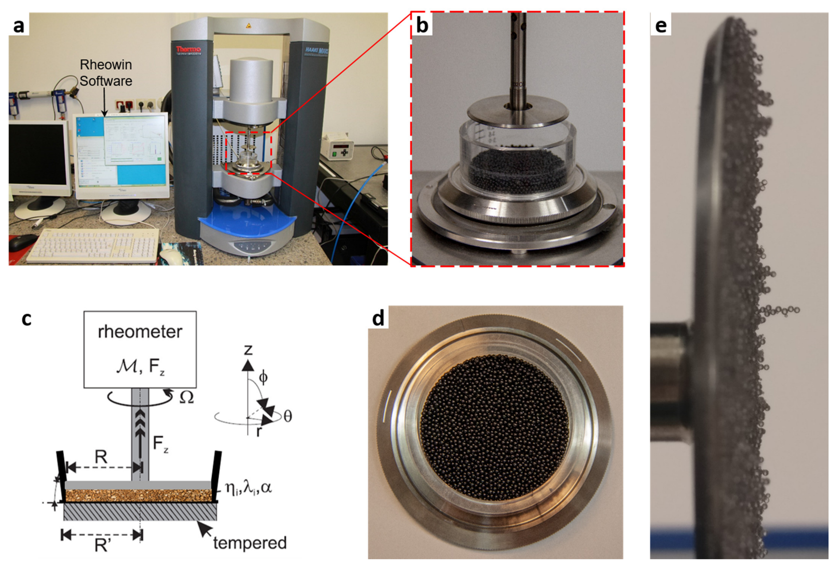
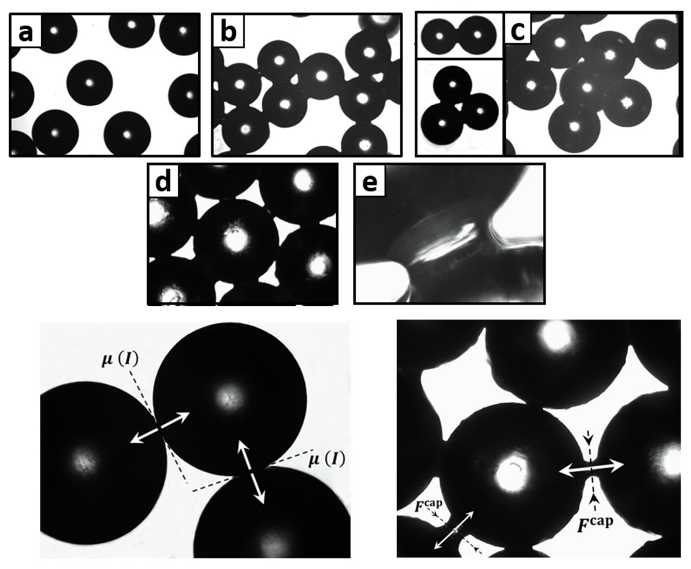


Fig. 1 Experimental system used: (a) HAAKE MARS 2 Rheometer with cup-plate geometry and the Rheowin software. (b) Zoomed-in image of cup-plate geometry, where the cup is fixed to the bottom, and upper plate shears the grains. (c) Schematic representation of cup-plate assembly. (d) Close-up image of glass beads, packed in the cup before they undergo shear stresses. and (e) Vertical view of wet Dynoseeds forming a chain-like structure, while the upper plate is going to its initial position, defying gravity.



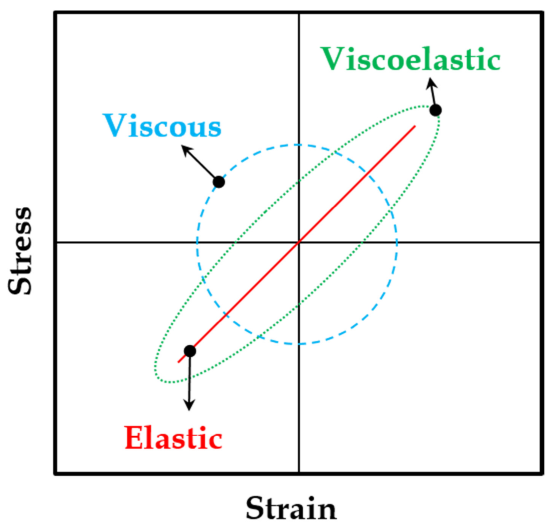
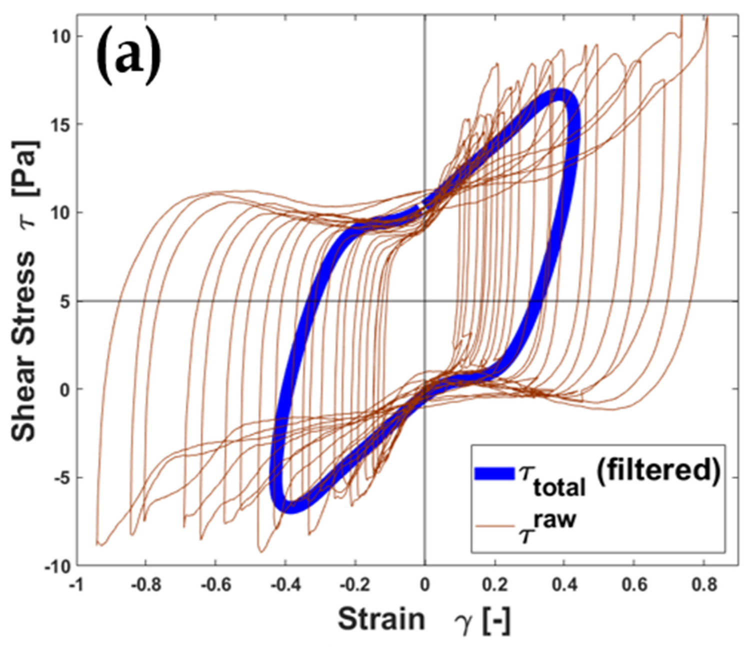


Fig. 2 Micro-graphs, displaying different states of granular media, were obtained from (Nikon Microscope) with bright field settings. (a) Dry granular media, negligible cohesion. (b) Partially saturated grains, cohesive grains. (c) Formation of dimers, trimers and pentamers. (d) Maximum number of contacts and (e) Capillary bridge between two Dynoseeds. Images were inspired from Kudrolli et. al. Images at the bottom shows dynamical action in dry and wet grains, respectively (Left to right). Plot on the right shows, Stress-Strain during a cycle for different materials.

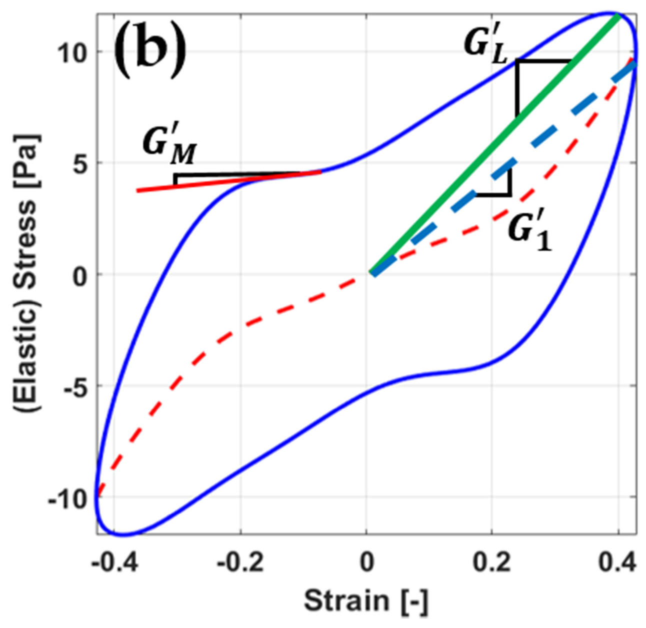
Results:



$$\sigma' \equiv \frac{\sigma(\gamma,\dot{\gamma}) - \sigma(-\gamma,\dot{\gamma})}{2} = \gamma_0 \sum_{n\,odd} G'_n(\omega,\gamma_0)\sin n\omega t$$

$$\sigma'' \equiv \frac{\sigma(\gamma,\dot{\gamma}) - \sigma(\gamma,-\dot{\gamma})}{2} = \gamma_0 \sum_{n\,odd} G''_n(\omega,\gamma_0)\cos n\omega t$$

Orthogonal stress decomposition using symmetry arguments



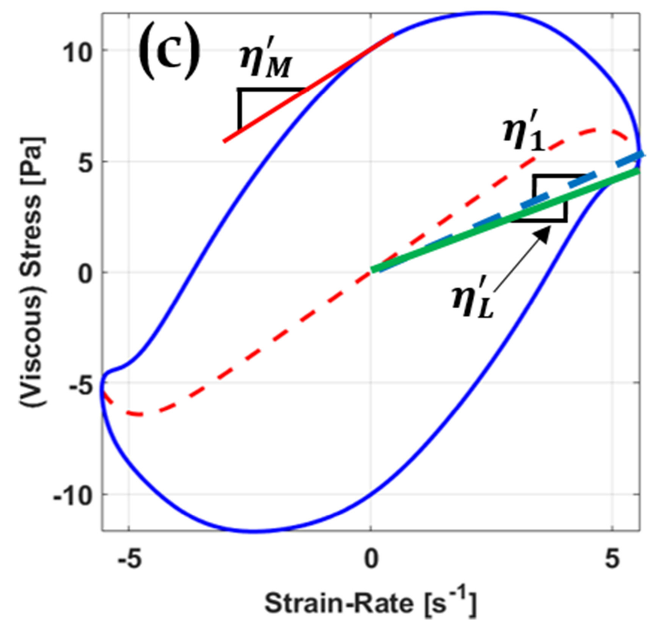
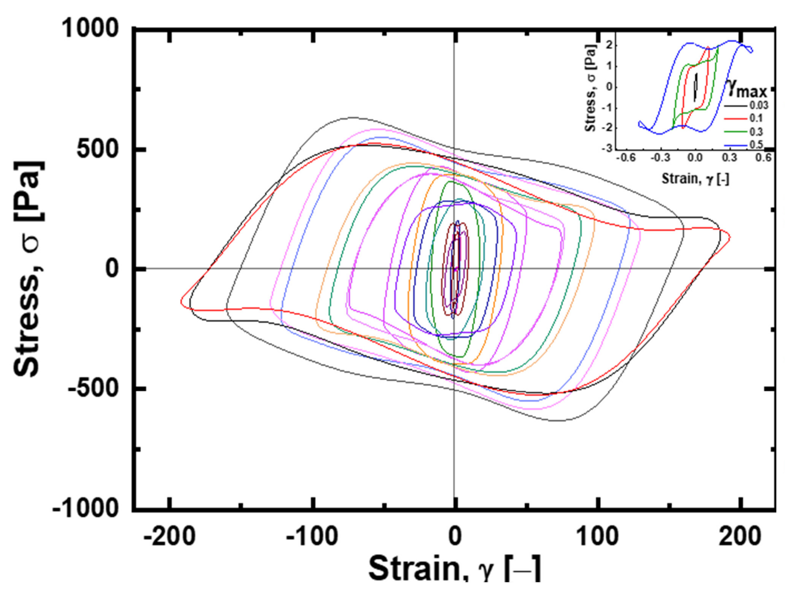


Fig. 3. (a) Typical raw Stress-Strain Lissajous loops with filtered stress response for Dynoseeds (500 µm) wet with 3 % Silicon oil. (b) and (c) Definitions of new measures for reporting non-linear viscoelastic moduli through orthogonally decomposed stress response. Where, G'_M: minimum strain modulus at γ=0, G'_L: large strain modulus at max. γ, G'_1: first harmonic modulus. Similarly, η'_M: minimum-rate dynamic viscosity, η'_L: large-rate dynamic viscosity, η'_1: first harmonic dynamic viscosity.



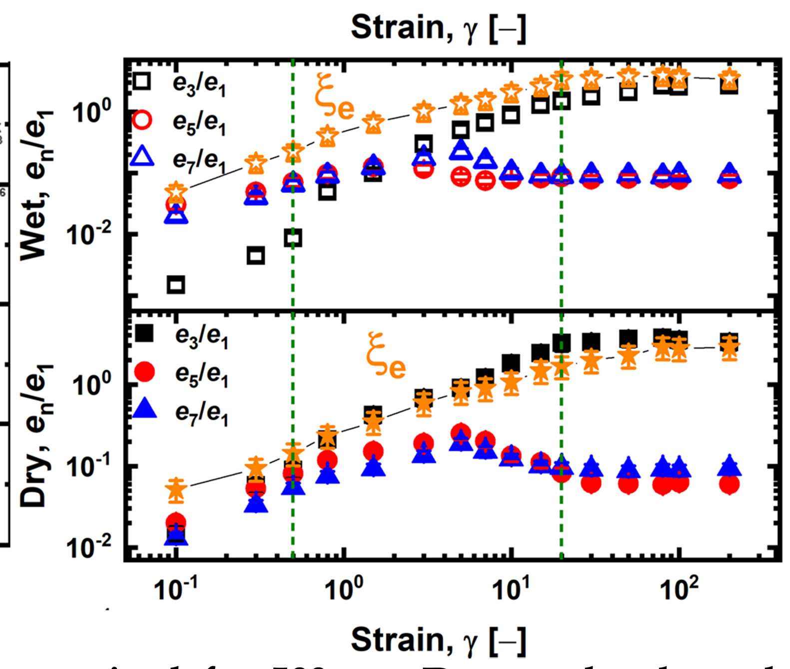
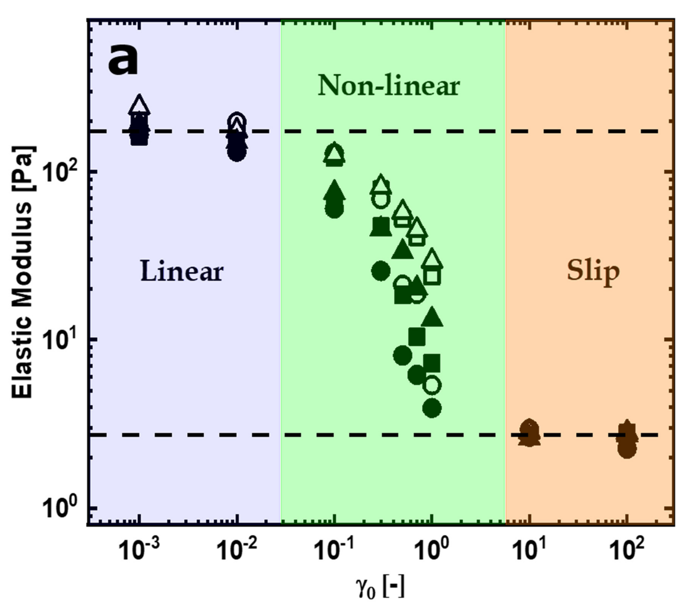


Fig. 4. *Left*: Lissajous-Bowditch loops summarized for 500 µm Dynoseeds, sheared between confining plates (F_n =0.85N) and normalized by higher order Chebyshev polynomial. Inset plot shows the zoomed in portion of the loops, not visible otherwise. *Right*: Master plot to show the quantification of non-linearity, ξ, in terms of higher order Chebyshev coefficients, for wet and dry grains, respectively.



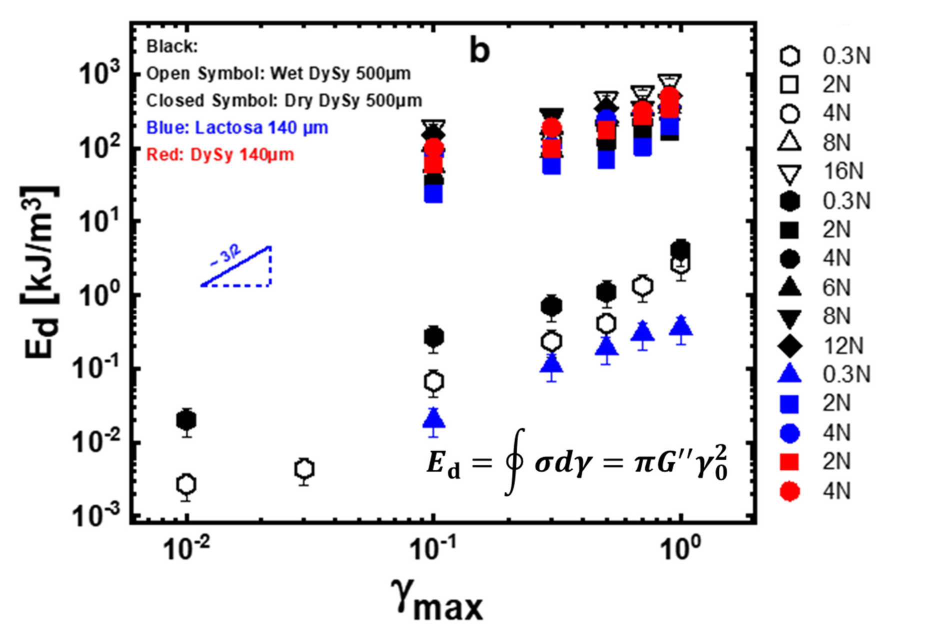
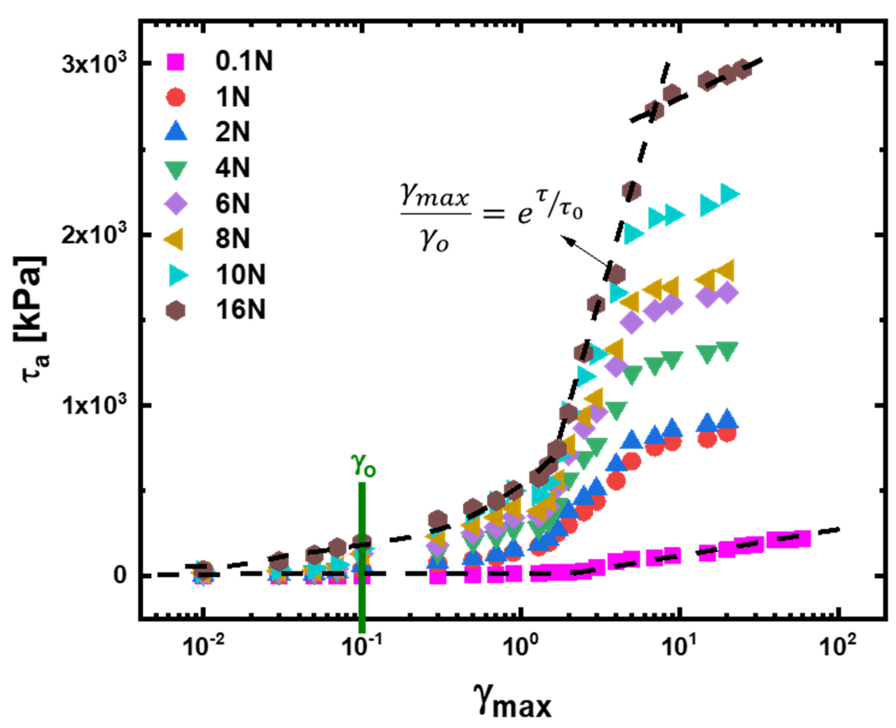


Fig. 5. Large amplitude oscillatory shear test of dry (closed symbols) and wet (open symbols) Dynoseeds, analyzed within the new MITlaos framework; (a) elastic moduli: minimum-strain (circles) and large-strain (triangles) elastic moduli compared to first harmonic (squares) elastic modulus. (b) Dissipated energy per unit volume E_d vs strain amplitude γ_{max} for dry (closed symbols) and wet (open symbols) granular materials.

Conclusion & Outlook:

- ✓ Identified three regimes on account of granular rheology, with critical strain, γ~0.1 (approx. the size of one grain) to push the system to non-linear regime.
- ✓ Utilising confinement pressure, tuned the viscosity (measure of dissipation energy) of granular materials.
- ➢ The plot on the right shows the inter-grain transitional process for granular matter under confinement, which is yet to be quantified.
- ➢ We are also working on tuning properties of grains via wetting agents of varying surface tension, to invoke phenomenal surface features.
- ➢ Also, setting up the experimental assembly for complex flow pattern formation in vibrating granular matter.



References:

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2. R. H. Ewoldt et. al. Journal of Rheology 52(6), 1427-1458 (2008).

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