Convection, Shearbanding and Experiments in Driven Granular Matter

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(with Dr. Priyanka Shukla and Mr. Istafaul Ansari)

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Outline of Talk

- Introduction
- Granular Hydrodynamics
- Nonlinear Stability and Stuart-Landau Eqn
- Results: ‘Bounded’ granular convection
- ‘Semi-bounded’ granular convection
- Gradient and Vorticity Banding
- Experiments on Vibrated Binary Mixtures
- Conclusions
Granular Fluid?

- Athermal system
- Inelastic dissipation → Microscopic Irreversibility
- Lack of Scale Separation
- Extended Set of Hydrodynamic Fields?
Oscillons and Faraday Waves (Swinney et al. 1996)

FIG. 2 Diagram showing the stability regions for different states, as a function of \( f \) and \( \Gamma \), for increasing \( \Gamma \) (squares) and decreasing \( \Gamma \) (triangles and circles). The transitions from the flat layer to squares and stripes are hysteretic, but the hysteresis is much smaller for stripes. Oscillons are observed for layers greater than 13 particles deep in a range of \( f \) which increases with increasing depth. For thinner layers, the phase diagram is similar but without the oscillon region.
Oscillons (f/2)
Umbanhower et al. 1996

Subharmonic (f/2, f/4, …)

Subharmonic + ???
Alam & Ansari (2012)

Vibration Driven
Granular Matter

Leidenfrost
Eshuis et al. 2005

Convection
Eshuis et al. 2007
Order parameter models for granular Faraday patterns

Patterns can be predicted by the complex Ginzburg-Landau Eqn (Tsimring and Aranson 1997)

\[
\frac{\partial \psi}{\partial t} = \gamma \psi^* - (1 - i\omega)\psi + (1 + ib)\nabla^2\psi - |\psi|^2\psi - \rho \psi
\]

\(\psi\): complex amplitude of subharmonic pattern (order parameter)
\(\rho\): thickness of the granular layer
\(\gamma \psi^*\): parametric driving
\(\gamma\): normalized amplitude
\(\omega\): frequency of driving
\(b\): ratio of dispersion to diffusion

“Phenomenological model”

Swift-Hohenberg equation describes primary pattern forming bifurcation: square, strips and oscillons (Crawford and Riecke 1999)

\[
\frac{\partial \psi}{\partial t} = R\psi - (\nabla^2 + 1)^2\psi + N(\psi)
\]

\[N(\psi) = b_1\psi^3 - b_2\psi^5 + \epsilon \nabla.(\nabla \psi)^3 - \beta_3 (\nabla \psi)^2 - \beta_2\psi^2 \nabla^2 \psi\]

Landau-type order parameter model for granular patterns?
Granular Hydrodynamic Equations
(Savage, Jenkins, Goldhirsch, …)

**Balance Equations**

\[
\frac{D\rho}{Dt} = -\rho \nabla \cdot \mathbf{u}
\]

\[
\rho \frac{D\mathbf{u}}{Dt} = -\nabla \cdot \mathbf{\Sigma}
\]

\[
\frac{3}{2} \rho \frac{DT}{Dt} = -\nabla \cdot \mathbf{q} - \mathbf{\Sigma} : \nabla \mathbf{u} - \mathcal{D}
\]

- \(\rho = \rho_p \phi\): Bulk density
- \(\rho_p\): Particle density
- \(\phi\): Volume fraction

- \(\mathbf{u}\): Bulk velocity
- \(T\): Granular temperature

**Navier-Stokes-order Constitutive Model**

**Stress Tensor**

\[
\mathbf{\Sigma} = [p(\phi, T) - \zeta(\phi, T) \nabla \cdot \mathbf{u}] \mathbf{I} - 2\mu(\phi, T)\mathbf{S}
\]

\[
\mathbf{S} = \frac{1}{2} (\nabla \mathbf{u} + \nabla \mathbf{u}^T) - \frac{1}{3} (\nabla \cdot \mathbf{u}) \mathbf{I}
\]

**Granular Heat Flux**

\[
\mathbf{q} = -\kappa(\phi, T) \nabla T
\]

**Dissipation term or sink of energy**

\[
\mathcal{D} = \frac{\rho_p}{d} f_5(\phi, e)T^{3/2} \sim (1 - e^2)
\]
`Bounded’ Convection

**Reference Scales**
- **Length:** Gap between two walls
- **Number Density:** Average number density
- **Temperature:** Base temperature

**Dimensionless Parameters**

- **Froude Number**
  \[ Fr = \frac{T_{base}}{mgH} \]

- **Knudsen Number**
  \[ K = \frac{2}{\sqrt{\pi\langle n \rangle \bar{H}}} \]

- **Heat Loss Parameter**
  \[ R = 4(1 - e)K^{-2} \]

Khain & Meerson 2003
Steady State + No Flow

**Base Flow:** steady, fully developed flow

\[
\frac{dp^0}{dy} + n^0 / Fr = 0, \quad \frac{d}{dy}\left(\kappa^0 \frac{dT^0}{dy}\right) = D^0
\]

**Boundary Conditions**

- **Thermal lower wall** \( T^{(0)}(y = 0) = 1 \),
- **Adiabatic upper wall** \( dT^0(y = 1) / dy = 0 \),
- **Integral relation** \( \int_0^1 n^0(y) \, dy = 1 \)

Image shows a graph with curves indicating the temperature distribution for different values of \( Fr = 10, R = 0.5 \) and \( K = 0.02 \).
Linear Stability

\[ \frac{\partial X'}{\partial t} = LX' + N_2 + N_3 + \ldots \quad \text{where} \quad X = X_{\text{base}} + X' \]

Boundary Conditions

\[ \frac{\partial u'}{\partial y} = 0, v' = 0 \quad \text{at} \quad y = 0, 1 \]
\[ \frac{\partial T'}{\partial y} = 0 \quad \text{at} \quad y = 1 \quad \text{and} \quad T' = 0 \quad \text{at} \quad y = 0 \]

Khain & Meerson 2003

\[ R = 4(1 - e)K^{-2} \]
\[ Fr = \frac{T_{\text{base}}}{mgH} \]

New Modes
(Shukla and Alam 2013)
Nonlinear Stability: Center Manifold Reduction *(Carr 1981; Shukla & Alam, PRL 2009)*

Dynamics close to critical situation is dominated by finitely many “critical” modes.

\[
X' = \phi + \psi
\]

\[
\phi = Z X^{[1:1]} + \tilde{Z} \tilde{X}^{[1:1]}
\]

\[
\left(\frac{\partial}{\partial t} - \omega\right) Z X^{[1:1]} = N_2 + N_3
\]

\[
\left(\frac{\partial}{\partial t} - \omega\right) \psi = N_2 + N_3
\]

\[
\left(\frac{\partial}{\partial t} - \omega\right) Z X_{11} = N_2 + N_3
\]

\[
\frac{dZ}{dt} = c^{(0)} Z + c^{(2)} |Z|^2 + c^{(4)} |Z|^4 + \ldots
\]

\[
c^{(0)} = a^{(0)} + ib^{(0)} = \omega
\]

\[
c^{(2)} = a^{(2)} + ib^{(2)}
\]

\[
c^{(4)} = a^{(4)} + ib^{(4)}
\]

Taking the inner product of slow mode equation with adjoint eigenfunction of the linear problem and separating the like-power terms in amplitude, we get an amplitude equation.
Other perturbation methods can be used:

- e.g. Amplitude expansion method (Shukla & Alam, 2011a, JFM)
- Multiple scale analysis, (TDGL eqn., Saitoh & Hayakawa 2011)

Caution: Ignoring ‘Slaved’ Equations will lead to qualitatively wrong result!
Equilibrium Amplitude and Bifurcation

Cubic Landau Eqn

\[ Z = A e^{i\theta} \]

\[ \frac{dZ}{dt} = c^{(0)} Z + c^{(2)} \left| Z \right|^2 \]

Real amplitude eqn.

\[ \frac{dA}{dt} = a^{(0)} A + a^{(2)} A^3, \]

\[ \frac{d\theta}{dt} = b^{(0)} + b^{(2)} A^2 \]

Phase eqn.

Cubic Solution

\[ A = 0, \quad A = \pm \sqrt{-\frac{a^{(0)}}{a^{(2)}}} \]

Supercritical Bifurcation \quad a^{(0)} > 0, \quad a^{(2)} < 0

Subcritical Bifurcation \quad a^{(0)} < 0, \quad a^{(2)} > 0

\[ b^{(0)} = 0 \]

\[ b^{(0)} \neq 0 \]

Pitchfork (stationary) bifurcation

Hopf (oscillatory) bifurcation
Results: Nonlinear Convection

(Shukla and Alam, 2013)

Supercritical

\[ R = 1.0, Fr = 10 \]

\[ k_x = 2 \]

Unstable

\[ R = 4(1 - e)K^{-2} \]

\[ Fr = \frac{T_{base}}{mgH} \]
Elastic and quasi-elastic collisions \( (R \approx 0) \)

\[
\begin{align*}
R &= 4(1-e)K^{-2} \\
Fr &= \frac{T_{\text{base}}}{mgH}
\end{align*}
\]

“Subcritical” and “supercritical” bifurcations in “elastic” limit

⇒ Classical Rayleigh-Benard Convection
``Leidenfrost State” to ``Convection”
Comparison of density patterns from **Experiment**, **Simulation** and **Nonlinear Theory**

\[ F = 6.2, L = 164, a = 4.0\text{mm}, \]
\[ f = 52\text{Hz or } (S = 174) \]

**Phase diagram: Linear Stability**

Convection rolls are **subcritical** or **supercritical**?

*Shukla, van der Meer, Lohse and Alam, (2013, Preprint)*

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(References: Eshuis et al 2010)
Conclusions

- "Double" roll (subcritical solution) convection
  (needs verification from simulation)

- New solutions in the quasi-elastic limit
  (related to classical Rayleigh-Benard convection)

- For semibounded convection, theory agrees with experiment
  and simulation (qualitatively)

References

Shukla & Alam (2013) Preprint
Shukla, van der Meer, Lohse & Alam (2013), Preprint

Thank you
Gradient and Vorticity-Banding Phenomena in a Sheared Granular Fluid

Meheboob Alam
(with Priyanka Shukla)
Outline of Talk

• Shear-Banding?

• Granular Hydrodynamic Equations

• Sturat-Landau Equation

• Results for Gradient Banding

• Results for Vorticity Banding

• Summary
Shear-banding: A misnomer?

Homogeneous/uniform shear flow is unstable above some critical applied shear-rate or shear stress (Hoffman 1972, Olmsted 2008).

Flow becomes inhomogeneous/non-uniform characterized by coexisting-bands of different shear-rate or shear stress (rheological properties).

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Gradient Banding

Vorticity Banding

high shear-stress
low shear-stress

high shear-rate
low shear-rate
Shear-Cell Experiments

Shear-Banding in ‘Dense’ Granular Flow
(Savage & Sayed 1984; Mueth et.al. 2000)

- Granular material does not flow homogeneously like a fluid, but usually forms solid-regions that are separated by ``narrow” bands where material yields and flow.

- Shear-bands are narrow and localized near moving boundary.

Velocity profile of shear-banded state

Fast particles (yellow) near the inner wall appear to move smoothly while the orange and red particles display more irregular and intermittent motion.
Rheological Signature of Banded States

- Multiple(*) Branches of flow-curve

- Gradient Banding: Shear-rate > critical shear-rate

* Banding also occurs for monotonic flow-curves (Olmsted 2008)
Rheological Signature....

Multiple Branches in flow curve

Vorticity Banding  
shear stress > critical shear stress

Non-monotonic flow curve

Homogeneous flow is unstable

Low shear stress band “AB”

High shear stress band “FG”

Unstable “CE”

Negative Slope
(Steady shear rate decreases with increasing shear stress)

Selected shear-rate $\dot{\gamma}_{sel}$
Particle Simulations

Gradient banding
in 2-dimensional granular shear flow at low density

\[ \phi^0 = 0.05 \]

Tan & Goldhirsch 1997

Vorticity banding
in 3-dimensional granular shear flows at low density

\[ \phi^0 = 0.05 \]

Conway & Glasser 2004
Gradient Banding in Granular Shear Flow

Order-Parameter Description Of gradient-banding?

\[ \frac{dA}{dt} = f(A,t) \]
\[ \frac{\partial A}{\partial t} + a_1 \frac{\partial A}{\partial x} + a_2 \nabla^2 A = g(A,t,x,\cdots) \]
Order-parameter description of gradient-banding?

Uniform Shear Flow (homogeneous state)

- **Uniform flow**: Steady, Fully developed.
- **Boundary condition**: No-slip, zero heat flux

Uniform Shear Solution

- **Reference Length**: $\bar{h}$
- **Reference Velocity**: $\bar{U}$
- **Reference Time**: $\bar{h}/\bar{U}$

\[
\frac{\partial}{\partial y} \left( \mu \frac{\partial u}{\partial y} \right) = 0, \quad \frac{\partial p}{\partial y} = 0
\]

\[
\frac{1}{H^2} \frac{\partial}{\partial y} \left( \kappa \frac{\partial T}{\partial y} \right) + \mu \left( \frac{\partial u}{\partial y} \right)^2 - D = 0
\]

**Control Parameters**

- $H = \bar{h}/d$
- $\phi^0$
- $e$

$d$ : diameter
Linear Stability Analysis

- \( \phi(y) = \phi^0 = \text{const.} \)
- \( u(y) = y \)
- \( T(y) = T^0 = \text{const.} \)

Finite-size Perturbation (\( X' \))

\[
\frac{\partial X'}{\partial t} = LX',
\]

Linear Problem

Normal Mode

\[
L \hat{X} = \omega \hat{X},
\]

Eigenvalue Problem

If the disturbances are infinitesimal ‘nonlinear terms’ of the perturbation eqns. can be ‘neglected’.

Gradient Banding

\[
\frac{\partial}{\partial x} (.) = 0, \frac{\partial}{\partial z} (.) = 0, \frac{\partial}{\partial y} (.) \neq 0
\]

Vorticity Banding

\[
\frac{\partial}{\partial x} (.) = 0, \frac{\partial}{\partial y} (.) = 0, \frac{\partial}{\partial z} (.) \neq 0
\]
Linear stability theory fails in `dilute’ limit!

**Linear Theory**

Flow remains ‘uniform’ in dilute limit

Density segregated solutions are not possible in dilute limit

**Particle Simulation**

Flow is ‘non-uniform’ in dilute limit

Density Segregated solutions are possible in dilute limit

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* Tan & Goldhirsch 1997 Phys. Fluids, 9
**Nonlinear Analysis:**

**Center Manifold Reduction** *(Carr 1981; Shukla & Alam, PRL 2009)*

Dynamics close to critical situation is dominated by finitely many “critical” modes.

\[ Z(t) : \text{complex amplitude of finite-size perturbation} \]

\[
\begin{align*}
X' &= \phi + \psi \\
\phi &= ZX^{[1;1]} + \tilde{Z}\tilde{X}^{[1;1]} \\
(\frac{\partial}{\partial t} - \omega)\phi &= N_2 + N_3 \\
(\frac{\partial}{\partial t} - L)\psi &= N_2 + N_3 \\
\end{align*}
\]

Taking the inner product of slow mode equation with adjoint eigenfunction of the linear problem and separating the like-power terms in amplitude, we get an amplitude equation

\[
\begin{align*}
(\frac{\partial}{\partial t} - \omega)ZX_{11} &= N_2 + N_3 \\
\frac{dZ}{dt} &= c^{(0)}Z + c^{(2)}Z|Z|^2 + c^{(4)}Z|Z|^4 + ... \\
\end{align*}
\]

First Landau Coefficient

\[ c^{(2)} = a^{(2)} + ib^{(2)} \]

Second Landau Coefficient

\[ c^{(4)} = a^{(4)} + ib^{(4)} \]

First Landau Coefficient

\[ c^{(0)} = a^{(0)} + ib^{(0)} = \omega \]
Analytical Method

Linear Problem
\[ LX^{[1;1]} = c^{(0)} X^{[1;1]} \]

Second Harmonic
\[ L_{22} X^{[2;2]} = G_{22} \]

Distortion to mean flow
\[ L_{02} X^{[0;2]} = G_{02} \]

Distortion to fundamental
\[ L_{13} X^{[1;3]} = c^{(2)} X^{[1;1]} + G_{13} \]

Expression for first Landau coefficient
\[
    c^{(2)} = \frac{\phi^a G_{13}^1 + u^a G_{13}^2 + v^a G_{13}^3 + T^a G_{13}^4}{\phi^a \phi^{[1;1]} + u^a u^{[1;1]} + v^a v^{[1;1]} + T^a T^{[1;1]}}
\]

Analytical solution exists at any order!

We have developed a spectral based numerical code to calculate Landau coefficients.
Equilibrium Amplitude and Bifurcation

Cubic Landau Eqn

\[ Z = Ae^{i\theta} \]

\[ \frac{dZ}{dt} = c^{(0)}Z + c^{(2)}Z|Z|^2 \]

\[ \frac{dA}{dt} = a^{(0)}A + a^{(2)}A^3 \]

\[ \frac{d\theta}{dt} = b^{(0)} + b^{(2)}A^2 \]

Real amplitude eqn.

Phase eqn.

\[ \frac{dA}{dt} = 0 \]

Cubic Solution

\[ A = 0, \quad A = \pm \sqrt{-\frac{a^{(0)}}{a^{(2)}}} \]

Supercritical Bifurcation \( a^{(0)} > 0, a^{(2)} < 0 \)

Subcritical Bifurcation \( a^{(0)} < 0, a^{(2)} > 0 \)

Pitchfork (stationary) bifurcation

Hopf (oscillatory) bifurcation

\[ b^{(0)} = 0 \]

\[ b^{(0)} \neq 0 \]
Phase Diagram


Nonlinear Stability theory and MD simulations both support gradient banding in 2D-GPCF (PRL 2009)

"Density Segregation and Shear Localization" in dilute flows too! (Tan & Goldhirsch 1997)
Paradigm of Pitchfork Bifurcations

- **Supercritical:**
  \( \phi^0 > \phi^s_c \)

- **Subcritical:**
  \( \phi^{s1} < \phi^0 < \phi^{s2}_c \approx 0.559 \)

- **Supercritical:**
  \( \phi^s < \phi^0 < \phi^{s1}_c \approx 0.467 \)

- **Subcritical:**
  \( \phi^l < \phi^0 < \phi^{s1}_c \approx 0.196 \)

- **Bifurcation from infinity:**
  \( \phi^0 < \phi^l_c \approx 0.174 \)

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*Khain, PRE, 2007*

*Tan & Goldhirsch, 1997*

Conclusions from nonlinear gradient banding

- Problem is analytically solvable

- Landau coefficients suggest that there is a “sub-critical” (bifurcation from infinity) finite amplitude instability for “dilute” flows even though the dilute flow is stable according to linear theory.

- This result agrees with previous MD-simulation of granular plane Couette flow

- GCF serves as a paradigm of pitchfork bifurcations.

- Gradient banding corresponds to shear localization and density segregation

- Origin of gradient banding is tied to lower dynamic friction ($\mu/p$)
Vorticity Banding

Conway & Glasser, 2004, Phys. Fluids

\[ \frac{\partial}{\partial x} (.) = 0, \frac{\partial}{\partial y} (.) = 0, \frac{\partial}{\partial z} (.) \neq 0 \]

\[ \frac{dA}{dt} = c^{(0)}A + c^{(2)}A|A|^2 + c^{(4)}A|A|^4 + \ldots \]

Alam & Shukla, J. Fluid Mech. (2013a) vol 716
Vorticity banding instability (linear)

\[
\frac{\partial}{\partial x} (.) = 0, \quad \frac{\partial}{\partial y} (.) = 0, \quad \frac{\partial}{\partial z} (.) \neq 0
\]

\[
\phi^0 = \phi^{vb} \approx 0.1
\]

\[
k^*_{zc} = \frac{k^{vb}_{zc}}{H} \approx 0.15
\]

Gradient-banding modes stationary modes in all the flow density regime.

Vorticity banding modes stationary in dilute density limits & traveling in moderately dense density limit.
Vorticity.... (nonlinear)

Dilute limit

\[ \phi^0 \leq \phi^{vb} \approx 0.1 \]

\[ A_e = \pm \sqrt{-a^{(2)} \pm \sqrt{(a^{(2)})^2 - 4a^{(0)}a^{(4)}}} \]

Shear Stress Localization

\[ \mu = \mu^0 + \mu_0^0 \phi' + \mu_1^0 T' \]
Vorticity Banding in Dense 3D Granular Flow
(Grebenkov, Ciamarra, Nicodemi, Coniglio, PRL 2008, vol 100)

\[ \phi = 0.608 \]

Disordered \rightarrow Ordered

\[ V_{\text{shear}} \]

Time

\[ t = 400 \]
Disordered

\[ t = 800 \]
Ordered

Length (x)

Width (z)

Depth (y)
Vorticity Banding in Dense 3D Granular Flow
(Grebenkov, Ciamarra, Nicodemi, Coniglio, PRL 2008, vol 100)

φ = 0.608

Time

V_{shear}

φ^{-1}

Disordered state

Ordered state

'Higher' viscosity

'Lower' viscosity

Disordered state

Ordered

Metastable

Disordered

Viscosity

φ = 0.608

Time

V_{shear}

φ = 0.608

Time

V_{shear}

φ = 0.608

Time

V_{shear}
Oscillatory Hopf bifurcation occurs for pure vorticity (spanwise) modes for \( \phi^0 \geq \phi^{vb} \approx 0.1 \)

- Stationary pitchfork bifurcation for all densities
- Two bicritical points exist for gradient banding
Conclusions from nonlinear vorticity banding

- Quintic-order Landau Equation is derived for vorticity banding instability
- Analytical solutions for first and second Landau coefficients have been obtained.
- Bistable nature of nonlinear vorticity banding (stationary & oscillatory) states has been confirmed.
- Localization of shear stress (viscosity) and pressure along the spanwise direction.

Overall Conclusions

- Hydrodynamic justification for gradient and vorticity banding in a sheared granular fluid using nonlinear stability theory.
- Unified description of gradient and vorticity banding in terms of shear and viscosity localization, respectively.

References:
Alam & Shukla (2013a), J. Fluid Mech., vol. 716, 131-180
Shukla & Alam (2011a), J. Fluid Mech., vol. 666, 204-253
Shukla & Alam (2013c) Phys Fluid (submitted)
Segregation-driven Patterns, Controlled Convection and Kuramoto’s Equation (?)

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Physics of Glassy and Granular Materials (Satellite Meeting of STATPHYS 25)
@YITP, 16-19 July 2013
Outline of talk

• Introduction

• Experimental Setup and Procedure

• Particle Image Velocimetry

• Phase Diagram and Patterns

• Conclusions and Outlook
Details of Experimental Setup

Sketch of experimental setup.

Experimental Setup

Quasi-two dimensional box

\[ D \sim 5d \]

\[ L \sim 100d \]
**Experimental Procedure**

**Dimensionless Control Parameters:**

- **Shaking acceleration:** \( \Gamma = A \omega^2 / g \)
  - \( A \) is the shaking amplitude
  - \( \omega = 2\pi / \tau \), where \( \tau \) is the time period.
  - \( g \) is the acceleration due to gravity.

- **Number of particle layers at rest**
  \( F = F_{\downarrow g} + F_{\downarrow s} = h_0 / d \)
  \( F \in (2.5, 10) \)
“Adaptive PIV” iteratively optimizes the size and shape of each interrogation area (IA).

Interrogation window is chosen iteratively until desired particle density is reached.
Undulation Waves

\[ \lambda = \frac{n \lambda}{2}, \quad n = 1, 2, 3, \ldots, \] (mode number)

\[ n=5 \text{ mode} \]

\[ n=2 \text{ mode} \Rightarrow \lambda = \lambda \]
Maxima (peak) exchanges with Minima (valley) after each cycle.

Undulation Waves \([f/2 \text{ Waves}]\)

- \(F_{\downarrow g} = 2.5, \; F_{\downarrow s} = 2.5\)
- \(A/d = 3\)
- \(\Gamma = 8.16 \; (f = 26 \; Hz)\)
- \(n = 5 \; \text{ mode}\)

Well-mixed? No Segregation?

Maxima (peak) exchanges with Minima (valley) after each cycle.

\(f/2\)-waves
Undulation Wave (UW) + Gas

Alam & Ansari (2012)
(APS DFD Meeting, San Diego, Nov. 2012)

Synchronous (period-2) + Disordered (gas) states

Alam & Ansari (2012)
(APS DFD Meeting, San Diego, Nov. 2012)
Convection + Leidenfrost

Alam & Ansari (2012)
(APS DFD Meeting, San Diego, Nov. 2012)
Particle Simulations?

- Only ‘qualitative’ agreement with MD simulation

- All phase-coexisting patterns are found in simulations, but (i) the life-time of ‘UW+Gas’ from simulations is found to be orders-of-magnitude lower than that from experiments (ii) vertical segregation is not well reproduced by present simulation, (iii) ….

§ Simulation help from Mr. Rivas N.

¶ Simulations (impact model, etc) are currently being improved

Ansari, Rivas & Alam (June 2013, submitted)
Conclusions

- We discovered novel phase-coexisting patterns (Alam & Ansari 2012) in vibrated binary granular mixtures:
  - Bouncing bed + Granular gas
  - Undulations + Granular gas
  - Leidenfrost + Granular gas
  - Leidenfrost + Convection
  - Leidenfrost + Horizontal segregation
  - Bouncing Bed + Vertical Segregation

- In all phase-coexisting states, steel balls are in gaseous phase and the glass balls are in a Leidenfrost/Bouncing Bed/Undulation state.

- Segregation is due to non-equipartition of granular energy between heavier and lighter particles.

- Convection can be controlled in a binary mixture.

- Alam & Ansari (2012, APS’s DFD Meeting, San Diego)

- Ansari, Rivas & Alam (2013, submitted)
Thank You