Dynamics of Sheared Granular Materials

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ABSTRACT

This work focuses on the properties of sheared granular materials near the jamming transition. The project currently involves two aspects. The first of these is an experiment that is a prototype for a planned ISS flight. The second is discrete element simulations (DES) that can give insight into the behavior one might expect in a reduced-g environment.

The experimental arrangement consists of an annular channel that contains the granular material. One surface, say the upper surface, rotates so as to shear the material contained in the annulus. The lower surface controls the mean density/mean stress on the sample through an actuator or other control system. A novel feature under development is the ability to 'thermalize' the layer—i.e., create a larger amount of random motion in the material, by using the actuating system to provide vibrations as well control the mean volume of the annulus. The stress states of the system are determined by transducers on the non-rotating wall. These measure both shear and normal components of the stress on different size scales. Here, the idea is to characterize the system as the density varies through values spanning dense almost solid to relatively mobile granular states. This transition regime encompasses the regime usually thought of as the glass transition, and/or the jamming transition.

Motivation for this experiment springs from ideas of a granular glass transition, a related jamming transition, and from recent experiments. In particular, we note recent experiments carried out by our group to characterize this type of transition (Howell et al. Phys. Rev. Lett. 82, 5241 (1999)) and also to demonstrate/characterize fluctuations in slowly sheared systems (Miller et al. Phys. Rev. Lett. 77, 3110 (1996)). These experiments give key insights into what one might expect in near-zero g. In particular, they show that the compressibility of granular systems diverges at a transition or critical point. It is this divergence, coupled to gravity, that makes it extremely difficult if not impossible to characterize the transition region in an earth-bound experiment.

In the DE modeling, we analyze dynamics of a sheared granular system in Couette geometry in two (2D) and three (3D) space dimensions. Here, the idea is to both better understand what we might encounter in a reduced-g environment, and at a deeper level to deduce the physics of sheared systems in a density regime that has not been addressed by past experiments or simulations.

One aspect of the simulations addresses sheared 2D system in zero-g environment. For low volume fractions, the expected dynamics of this type of system is relatively well understood. However, as the volume fraction is increased, the system undergoes a phase transition, as explained above. The DES concentrate on the evolution of the system as the solid volume fraction is slowly increased, and in particular on the behavior of very dense systems. For these configurations, the simulations show that polydispersity of the sheared particles is a crucial factor that determines the system response. Figures 1 and 2 below, that present the total force on each grain, show that even relatively small (10%) nonuniformity of the size
of the grains (expected in typical experiments) may lead to significant modifications of the system properties, such as velocity profiles, temperature, force propagation, and formation of shear bands.

The simulations are extended in a few other directions, in order to provide additional insight to the experimental system analyzed above. In one direction, both gravity, and driving due to vibrations are included. These simulations allow for predictions on the driving regime that is required in the experiments in order to analyze the jamming transition. Furthermore, direct comparison of experiments and DES will allow for verification of the modeling assumptions. We have also extended our modeling efforts to 3D. The (preliminary) results of these simulations of an annular system in zero-g environment will conclude the presentation.

Figure 1: The (instantaneous) force experienced by the variable size particles; the volume fraction at the instant shown is approximately 0.9. The flow is driven by constant velocity motion of the upper wall in the $+x$ direction (left to right).

Figure 2: The force in the case of uniform size particles; all the other quantities are the same as in Fig. 1. Note formation of a shear band at $y \approx -0.1$; it should be mentioned that this particular shear band is just one of possible configurations characterizing the flow, and the manner in which the force propagates.
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Main goal

Understand the dynamics of a granular system as the volume fraction $\gamma$ is modified between gas-like and solid-like
Analyze the phase transition which may occur in 3D zero-\textit{g} experiment
Analogy to 2D? - see Howell et al. PRL (1999)
Discuss the parameters defining the system, in particular distribution of particle sizes

Techniques

Experimental
Computational (discrete element simulations)

This talk: Simulations

Discuss expected behavior in zero \textit{g}
Analyze force propagation
Also: can we thermalize the system in non-zero \textit{g} and expect to reach uniform states?
(from Howell et al, PRL (1999) )
Experiment:

2D: Second-order phase transition as the volume fraction is decreased
2D: gravitational effects are reduced by using a horizontal system
3D (annular geometry): gravitational compaction does not allow to analyze dynamics close to $\gamma_c$
Sheared Granular System with Gravity

- volume fraction: 70 %
- variable size particles

![Graph showing shear forces over time](image)

(time = 0)

(time > 0)

(an example of gravitational compaction)

Goal of Simulations

Analyze open (channel) (2D) Couette geometry to understand the basics of dynamics in 3D experiment in annular geometry and zero-g environment
Switch on gravity as well as excitation

Sheared system with slowly varying

This talk: periodic boundaries, rough walls

PRL (1999)

tolerable disks, e.g. Howell and Behringer.
Parameters chosen appropriately for (soft) pro-

Coulomb coefficient

\[ u + s : s \]

\[ s \left( u \cdot f_\Lambda \right) \gamma \right) \mu \eta = f_\mu P \]

Tangential force

\[ u \left[ (u \cdot f_\Lambda) \mu \eta \right] - (f_\mu \mu - p) \eta = f_\mu P \]

Tangential directions

Linear force model with damping in normal and

Discrete element techniques
uniform size

variable size

column 1

uniform size

variable size

column 2
Plain Couette Flow

volume fraction: 63% - 94%

variable size (range 0.1)

increased vol. frac.

volume fraction: 63% - 94%

uniform size

increased vol. frac.
Savage, JFM, 98
Hopkins, Louise, Phys. Fluids, 91
Campbell, Annual. Rev. Fluid Mech., 90
Walton, Braun, J. Rheol., 86
Jenkins, Richman, Phys. Fluids, 85

Related works
(nearly imposed excitations?)
(can this shearing band be removed by external
as in radial Couette geometry
Shearing band formation for lower ζ similarly
Rate-independent system behavior
the shearing wall
Higher temperature and elastic energy close to
Energy shared between Kinetic and elastic
System dilated next to the shearing wall
and polydisperse materials
No significant difference between monodisperse
and multimodal wall

Low volume fractions: Gas-like regime
High volume fractions

From exponential to linear velocity profiles (note: linear profiles are not observed in annular geometry!)
From gas-like to solid-like behavior: jamming
Significant differences between monodisperse and polydisperse systems:
Fracture occurs for monodisperse systems
Monodisperse systems are compressed easier (crystallization) → large difference in the stored elastic energy
Rate-dependent behavior for large volume fractions
Elastic energy

uniform size particles
shear. vel. 0.1

t euth. ener. / vel. shear^2

increased vol. frac.

Temperature

uniform size particles
shear. vel. 0.1

t euth. ener. / vel. shear^2

increased vol. frac.
Gravity plus excitations

If gravity is included, compaction results in possible phase transition cannot be observed. Question: Can we excite (thermalize) the system so to reach uniformly sheared states? (Analogy: glasses, colloids, ...)

Consider:

Sheared system + gravity
Excitations through vibrated lower boundary

Analyze:

different modes of excitations
different $\Gamma$'s
different ratios of shearing and thermalizing energy input
different volume ratios
Plain Couette Flow

volume fraction: 80%
variable size particles

(last 5 averages shown)

Zero Gravity

Velocity (shearing direction)

Earth Gravity

Velocity (shearing direction)

vibrating lower wall: Gamma = 4.0

Zero Gravity

Volume fraction

Earth Gravity

Volume fraction

vibrating lower wall Gamma= 4.0
Answer: It is not easy to fight Gravity!

Difficult to produce uniform and dense granular system which responds to shearing (there are also large forces resulting from excitations)

Suggestion of this study: will need to perform experiments (and simulations) in zero $g$ to fully understand the problem.
Current and Future Work

Analyze the stress distribution in space and time.
Understand the effect of geometry on the na-
ture of the flow.
Understand better the influence of initial con-
tions (multiple solutions?).
Also include elastic energy?
How relevant is the granular temperature?

Extend to 3D and analyze the influence of ma-
ternal parameters.

Analyze in more detail the role of external ex-
Plain Couette Flow

Volume fraction variable: 63% - 94%
Variable size (range 0.1)

Increased vol. frac.

Volume fraction variable: 63% - 94%
Uniform size
Elastic energy

variable size particles
shear. vel. 0.1

Temperature

variable size particles
shear. vel. 0.1

elast. ener. / vel. shear^2

increased vol. frac.

temperature / vel. shear^2

increased vol. frac.
Elastic energy
variable size particles
shear, vel. 0.1

Temperature

Generalized temperature
Flow under gravity, shearing and excitations

variable size particles
Gamma = 4
amplitude = d

Force

0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
0
0.1
0.2
0.3
0.4
0.5

1.0E+00
9.2E-01
8.5E-01
7.7E-01
6.9E-01
6.2E-01
5.4E-01
4.6E-01
3.8E-01
3.1E-01
2.3E-01
1.5E-01
7.7E-02
2.0E-04