

Vibration Induced Phenomena in Granular Media in Microgravity

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Abstract. In order to study the dynamical behavior and the handling properties of granular materials under microgravity conditions, an ESA Topical Team is developing the VIP-Gran instrument whose multiple functionalities allow for the study of Vibration Induced Phenomena in Granular media in low gravity. Here, we present an overview of VIP-Gran's evolution, from the original idea to the latest encouraging and fascinating results. At first, we give a description of the instrument and the different investigated topics. Then, we present numerical simulations that we performed in order to prepare our experiments and tackle fundamental questions concerning granular gases. Finally, we give an insight on the first experimental results from parabolic flight campaigns and confront them with preliminary works and theoretical models.

1 Introduction

A granular gas is a paradigm for dissipative systems exhibiting spectacular behaviors such as inelastic collapse or clustering [1, 2]. The latter structures raise fundamental questions regarding their possible relations to thermodynamics principles [3]. Indeed, the classical kinetic theory of gases is unable to predict the behavior of such systems. The interest of the scientific community for granular gases has been strongly increased when sounding rocket experiments were performed in the late nineties by Falcon et al. [4] and confirmed for the first time the formation of clusters in microgravity. Since then, the European Space Agency formed a Topical Team (TT) of about 20 people and started the development of VIP-Gran (Vibration Induced Phenomena in Granular media) [5], an instrument designed for the study of the dynamics and the statistical mechanics of an ensemble of particles that interact through dissipative collisions. For dilute systems, the physical mechanisms and experimental conditions for the formation of clusters are deeply studied. For dense systems, phenomena such as convection [6], jamming [7] and segregation [8] are investigated. The prototype of the instrument is available and has already flown on two parabolic flight campaigns (PFC) of the European Space Agency (ESA).

In this article, we present an overview of VIP-Gran's evolution, from the original idea to the latest encouraging and fascinating results [5]. After a brief description of the instrument, we present the numerical simulations that we performed in order to prepare the experiments and give an insight on the first experimental results.

2 Setup and experimental parameters

The VIP-Gran instrument has a simple but polyvalent design. Granular media is enclosed in an exchangeable container where two opposite walls act as pistons and assure a continuous energy injection into the system. The container is exchangeable since it is connected to the kinematic chain of the instrument via magnetic joints. A bead feeding mechanism allows the injection of additional grains into the cell in order to increase the density of the granular media. Data is recorded using pressure sensors and accelerometers mounted on the pistons. Moreover, the experiments are recorded by two high speed cameras.

Currently, two container geometries have been designed for VIP-Gran. Both present a length of 60 mm and a depth of 30 mm but differ in their height h . The value of h is 30 mm in the case of the 3D container and 5 mm in the case of the quasi-2D container. Parameters such as the amplitudes A , the frequencies f and the phase shifts φ of the pistons can be tuned in order to expose the granular media to several types of driving and different acceleration levels. The average distance L between the oscillating walls can also be modified for controlling the volume of the cell.

3 Numerical simulations

Given the need for microgravity, the efficient preparation of the experiments for VIP-Gran relies strongly on predictive numerical simulations. Discrete Element Method (DEM) algorithms are a good candidate for such task. Indeed, this numerical model is broadly used for the simulation of granular materials [9, 10] and has been validated through the two last decades. All following simulations were realized thanks to a homemade soft sphere DEM

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software in which normal forces F_n are evaluated via a linear spring-dashpot model using a restitution coefficient $\varepsilon = 0.9$ and a viscosity constant η . Tangential forces F_t are proportional to the relative tangent velocities at contact while being bounded as follows: $\|F_t\| \leq \mu F_n$, where $\mu > 0$ is the friction coefficient. For further information on our numerical model see previous works [11].

3.1 Defining the gas cluster transition

For a better understanding of the different dynamics of granular gases, it is of great interest to be able to anticipate the occurrence of density inhomogeneities [12]. Indeed, being a consequence of the dissipative collisions within a granular gas, clustering is expected once the density of the system exceeds some threshold value. In order to link this threshold to the geometry of the container we realized a first series of simulations modifying the filling number of the system for different values of L , h and A . The granular media is composed of N beads of radius R that are excited with a frequency $f = 10$ Hz.

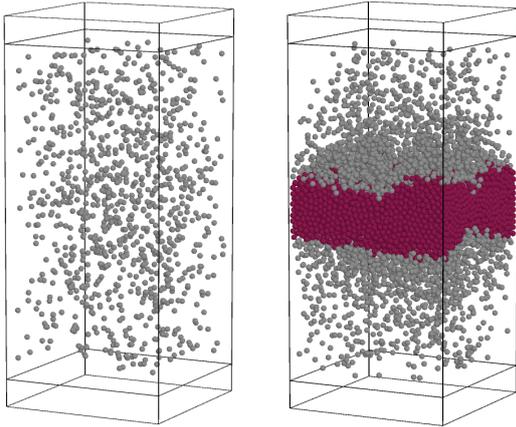
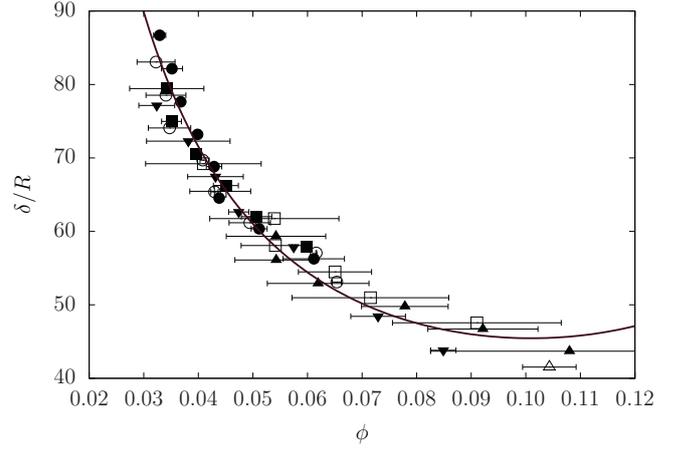


Figure 1. Simulation of clustering within in the 3D container with $R = 0.5$ mm and $\delta/R = 80$. (Left) Granular gas obtained for a packing fraction of $\phi = 1\%$. (Right) Clustered system obtained for a packing fraction of $\phi = 10\%$. The bulk is colored using a local density criterion.

For most simulated systems, clustering could be observed and a *phase diagram*, describing the encountered regimes, could be established. As shown in Figure 2, the occurrence of clustering can be linked to two dimensionless parameters. One is the packing fraction $\phi = Nv_g/V$, with v_g the volume of a grain and V the maximum volume of the container. The other is the reduced system size δ/R , where δ is the average distance between two points chosen randomly on each piston. Transitions points are obtained by testing the uniformity of the density distribution along the driving axis. Symbols correspond to different sets of parameters all described in the table. Systems situated above (below) the curve present a cluster (gaseous) regime. The solid curve is obtained by balancing energy propagation and dissipation due to successive collisions. A detailed description can be found in [13].



	A (mm)	L (mm)	h (mm)	R (mm)
●	4.0	30.0 - 47.5	30	0.5
○	5.0	30.0 - 47.5	30	0.5
■	6.0	35.0 - 47.5	30	0.5
□	5.0	32.5 - 47.5	30	0.6
▲	5.0	35.0 - 47.5	30	0.7
△	5.0	47.5	30	1.0
▼	5.0	30.0 - 47.5	15	0.5

Figure 2. Phase diagram describing the regimes for dilute driven granular media. Transitions points are obtained by testing the uniformity of the density distribution along the driving axis. Symbols correspond to different sets of parameters described in the bottom table.

These first simulations allowed us to describe the frontier between the gaseous and the cluster regime. It is now possible to predict, for both cell geometries, the apparition of a cluster. This new ability is important for the VIP-Gran instrument since the large field of parameters that had to be explored can be reduced dramatically regarding this results.

3.2 Clustering in a thermal gradient

The previous simulations were realized using a symmetric driving (same amplitudes and frequencies were used for both pistons). By using an asymmetric driving, it is possible to model a *thermal gradient* in the cell. In order to avoid a continuous phase shift, we decided to keep identical frequencies of oscillation on both pistons and to modify only their respective driving amplitudes noted A_c and A_h . We realized simulations for different container geometries and various amplitudes. As one can see in Figure 3, the cluster always forms near the cold piston. Moreover, its average position is determined by the amplitude ratio. Indeed, let us imagine the cluster as one solid particle, floating in the the cell about its equilibrium position \mathcal{P} . In order to stay there, the energetic impulses that impact the bulk from both sides must not only be of equal intensity but must also arrive at the same moment. With regards to the axis on Figure 3, the average position of the cluster is then given by

$$\mathcal{P} = \frac{L - \sigma}{2} \frac{1 - a}{1 + a}, \quad (1)$$

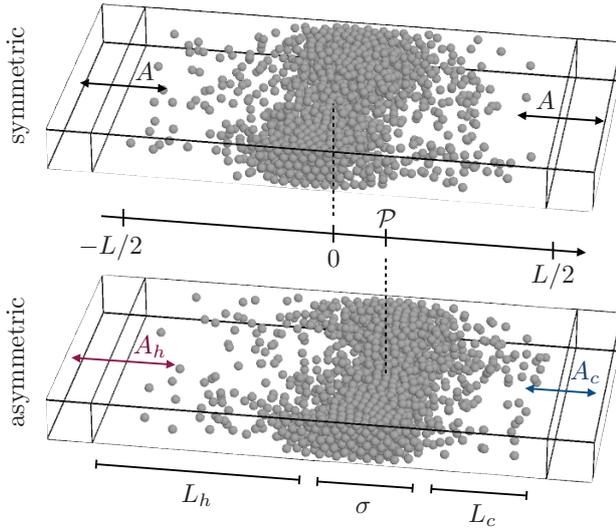


Figure 3. Simulation of a cluster under asymmetric driving in the quasi-2D container. The bulk forms always near the cold piston. Its average position \mathcal{P} can be tuned using the amplitude ratio $a = A_c/A_h$.

where σ is the width of the cluster and $a = A_c/A_h$ is the amplitude ratio. Since σ remains constant for a given cluster, a can be tuned in order to move the bulk precisely along the driving axis.

Controlling the amplitude ratio of the piston's movements in the VIP-Gran instrument allows us to modify the clustering position and thus to achieve *granular transport* in this kind of geometry. Moreover, the cluster is found to oscillate about its position of equilibrium with a characteristic frequency that can be linked to the mass of the bulk. For more information see previous works [14].

3.3 Segregation in bidisperse granular systems

Using different grains sizes impacts strongly on the dynamics of the system. For instance, the energy transmission from the pistons towards the center of the cell will be altered by the different encountered pairs of collisions. In order to study the possibility of segregation in microgravity, we realized simulations of bi-disperse granular media composed of N_s small beads of radius $R_s = 0.5$ mm and N_l large beads of radius $R_l = 1.0$ mm. Both species have the same density so that mass and size vary together. Depending on the filling conditions of the system, different structures appear as shown in Figure 4. For very low packing fractions, a granular gas is observed. Particles of any kind are distributed uniformly over the entire container. For higher packing fractions, *segregation* occurs. Large grains are forced into the center of the cluster while most of small grains are found in the surrounding gas phase. Finally, changing the mixing proportion of small and large particles can modify the morphology of the cluster so that stripy structures with alternatively high concentrations of each granular species arise.

We showed that shaking bi-disperse granular media in microgravity can lead to segregation even though mecha-

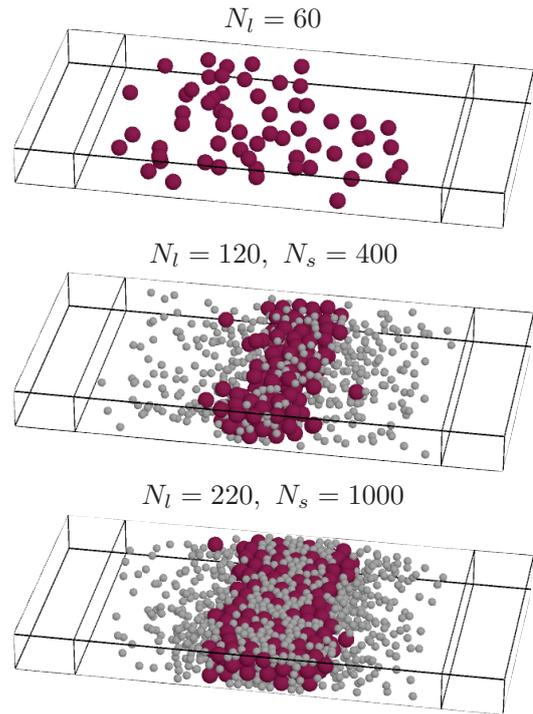


Figure 4. Simulation of driven bi-disperse granular media in the quasi-2D container. From top to bottom: Granular gas, Cluster made of large particles surrounded by a gas of small ones and Stripy structure.

nisms such as convection and percolation rely all on the presence of gravity. Moreover, size and mass effects are found to be in competition in our system which leads to the formation of complex patterns in the bulk. A detailed description of all our simulations as well as a complete phase diagram describing all regimes can be found in [15].

4 Parabolic flight experiments

Thanks to the previous simulations, the TT was able to prepare a series of promising experiments for PFC 63 and PFC 64 of the ESA. These campaigns are essential for a future implementation of VIP-Gran in the International Space Station (ISS). Indeed, in addition to the validation of our numerical models, parabolic flights help us to prepare for parasitic effects such as g-jitter. For instance, finding an efficient initialization protocol in order to homogenize the granular media before each shaking is still to be found.

Let us now have a look at the first experimental results concerning clustering. Given the shape of transition curve in our phase diagram, we investigated the occurrence of clustering by tuning either ϕ or δ all else equal. For both scenarios, clustering is reported as one can see in Figure 5. Snapshots correspond to 3D systems with respective packing fractions $\phi_a = 1.5\%$, $\phi_b = 8.5\%$, $\phi_c = 7.5\%$, $\phi_d = 7.5\%$ and respective system sizes $\delta_a = 35$ mm, $\delta_b = 35$ mm, $\delta_c = 22$ mm, $\delta_d = 31$ mm. The studied granular media is composed by bronze spheres of radius $R = 0.5$ mm that are excited with an amplitude $A = 2$ mm

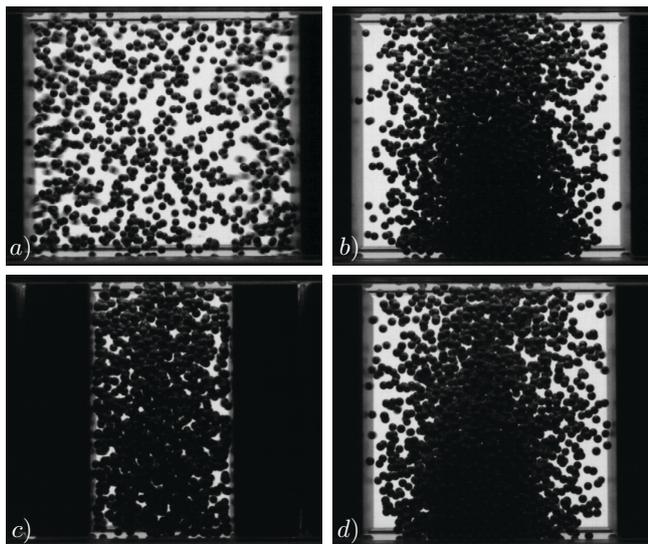


Figure 5. From snapshot *a*) to *b*) clustering is induced by an increase of the packing fraction ϕ for a fixed cell geometry. From snapshots *c*) to *d*) clustering is triggered by an increase of the system size δ while keeping a constant packing fraction.

and a frequency $f = 20$ Hz. In the top row, clustering is triggered by adding more particles into a container of fixed geometry. In the bottom row, clustering is induced by an increase of the system size while the packing fraction is kept constant constant by injecting additional grains. The transition has been tested for several packing fraction and system sizes. So far, the majority of the experimental results corroborate our model.

During PFC 64, the TT also explored experimentally the possibility of segregation in microgravity. As in our simulations, we used different concentrations of small and large bronze beads. In order to assure a good visibility of the phenomenon, experiments were realized within the quasi-2D container. The three expected regimes could be observed and are presented in Figure 6. Snapshots *e*),

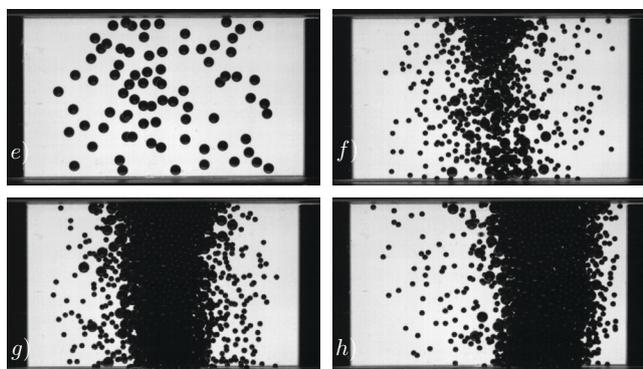


Figure 6. Segregation in bi-disperse granular media. *e*) Granular gas of large particles. *f*) Cluster of large particles surrounded by a gas of small particles. *g*) Stripy structure. *h*) Bi-disperse cluster exposed to asymmetric driving.

f), and *g*) correspond to a system with constant values of $\delta = 41$ mm, $A = 3$ mm and $f = 20$ Hz. The experiment starts with an initial loading $N_s = 0$ and $N_l = 80$, leading

to a granular gas. After the injection of 500 small grains, a cluster of large beads surrounded by a gas of small ones appears. Finally, 500 additional small beads and 150 large ones are injected and a stripy structure arises. Snapshot *h*, corresponds to a system with asymmetric driving conditions. A shift of the cluster's position towards the cold piston is noted, however, a precise measurement of \mathcal{P} was not yet realized.

5 Conclusion

Thanks to numerical simulations, the Topical Team prepared successfully the first microgravity experiments of the VIP-Gran instrument. The collected data has been used to tackle fundamental questions concerning clustering, segregation and the handling of granular matter in low gravity. The developed theoretical models, coupled to the experimental data from parabolic flight campaigns will be crucial for the implementation of VIP-Gran within the ISS.

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