ASTEX MICROGRAVITY EXPERIMENT: SIMULATING ASTEROID REGOLITHS

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Abstract

AstEx is a microgravity experiment selected to fly on ESA's 51st Microgravity Research Campaign in November 2009. The experiment will investigate the dynamics of regolith on asteroid surfaces. Despite their very low surface gravities, asteroids exhibit a number of different geological processes involving granular matter. Understanding the mechanical response of this granular material subject to external forces in microgravity conditions is vital to the design of a successful asteroid sub-surface sampling mechanism, and in the interpretation of the fascinating geology on an asteroid. The AstEx experiment uses a microgravity modified Taylor-Couette shear cell to investigate granular flow caused by shear forces under the conditions of parabolic flight microgravity. It is intended to determine how a steady state granular flow is achieved in microgravity conditions, and what effect prior shear history has on the timescales involved in initiating a steady state flow in a granular material. Presented are the technical details of the AstEx experimental design with particular emphasis on how the team have designed the equipment specifically for the parabolic flight microgravity environment.

INTRODUCTION

Asteroid science is an exciting and rapidly developing field within planetary sciences. Leftover building blocks from the formation of the Solar System 4.5 billion years ago, asteroids offer a wealth of information regarding the early Solar System and the mechanisms responsible for its formation and evolution. Asteroids range in size from small (∼10 m) boulders to bodies 1000 km across with consequently larger range in mass, from a few thousand tonnes to 10^{21} kg. However, even the most massive of asteroids, Ceres, has a mass which is only a fraction of a percent of the mass of the Earth. As a result, asteroid surface gravities are many orders of magnitude smaller than that of the Earth. The geology and geophysics of asteroids is a fascinating and constantly surprising field. Regolith, granular material covering the uppermost layer of solid planetary bodies, plays an important role in the surface geology of asteroids. Regolith dynamics have been both observed by in-situ spacecraft and modelled.

To date there have been two space missions sent to characterise an asteroid in detail: the NEAR Shoemaker mission to (433) Eros, and the Hayabusa sample return mission to (25143) Itokawa. These in-situ observations have increased our knowledge of asteroid surface properties whilst highlighting the complexities and variations in the surface environments.

Space agencies are planning sample return missions, other than the current Hayabusa mission, to near Earth asteroids to bring back to Earth a pristine sample of an asteroid surface. These missions aim to investigate early Solar System processes by applying the vast array of laboratory analytical tools to these samples, to link meteorite classes to asteroid classes, and study components (such as interstellar grains, organics and volatiles) that do not survive the atmospheric entry or terrestrial contamination of meteorites. To ensure that the returned samples are unaltered there are requirements that the sample shall contain grains of sufficient size so that their interior will have been protected from cosmic radiation and weathering effects. An additional requirement is that sufficient sample mass must be returned to satisfy some of the ground based laboratory analyses of rare components. To meet these sample requirements a suitable sampling mechanism must be chosen and developed.

As described above, the surface properties of an asteroid can vary and are not easily determined from ground based astronomical observations. Hayabusa used a generic impact sampling device to ensure sample collection from any type of target [1]. However, this mechanism returns a limited mass consisting of only small grains from the surface. To ensure larger grains and greater mass are collected a sticky pad has also been developed and tested on parabolic flights [2]. However, the sticky pad does not allow retrieval from depth or uncontaminated retrieval. A multitude of different sampling mechanisms for retrieving samples at depth can be thought of including simple scoops and rotating corers. Designing a suitable anchorage mechanism necessary to attach a lander to the surface or a sub-surface sampling mechanism requires knowledge of how the regolith granular matter responds to various different external forces/pressures.

The state of a granular system is characterized by density, granular temperature and pressure. In some situations granular materials have also been known to exhibit memory-effects. An example of this which will be looked at in greater detail in this paper is the fact that the direction of prior shear influences how granular matter starts to flow [3]. Due to the increased importance of inter-particle dynamics in a microgravity environment typical at an asteroid surface, the regolith may respond differently to the same regolith on Earth. Therefore a sampling mechanism designed to work in a 1 g environment on Earth may not necessarily work in a lower gravity environment such as the microgravity environment encountered at an asteroid.

Considering all of the above, a better understanding of granular material dynamics under different conditions would not only bring certain benefits to our understanding of asteroid science but would also lead to a wide range of applications, such as efficient design of an anchoring mechanism, a sub-surface mechanism or any device aimed at interacting with the surface of regolith covered bodies.

GRANULAR MATERIALS

Granular materials consist of a very large number of discrete particles that interact with each other only through dissipative contact forces [4]. The particles are massive enough (with sizes from 100 to 3000 μm [5]) so that their potential energy is orders of magnitude larger than their thermal energy [6]. Without an external drive their kinetic energy is rapidly lost and the system is referred to as being non-thermal. Despite this deceptively simple description, granular matter exhibits many complex behaviours that are difficult to predict.

Although individual particles are solid, granular materials exhibit both solid-like and liquid-like behaviour. In a solid-like state, such as a heap or pile, the material is said to jam [7]. When the material jams, the individual particles are in a stable mechanical equilibrium with their local neighbours. The weight of the solid-like material is distributed through a complex force distribution network that depends on the positioning and packing of the individual particles. This grain network resists reorganisation when stressed and imposes a granular drag force when a solid object is pushed through the material; again this acts via the force distribution network [8].

In a liquid-like state the material is said to “flow”. Granular flows can be divided into two types: rapid dilute flows, and dense flows [9]. Rapid dilute flows can be described with some success by kinetic theories for hard spheres that interact through uncorrelated and instantaneous binary collisions [10]. Dense flows are dominated by many-body interactions and occur when particles have long-lived contacts with many neighbours. In turn, dense flows can be divided into two regimes: fast dense flows dominated by the inertia of particles, and slow dense flows where inertia is negligible. Inertia dominates when the kinetic energy of a particle is much greater than the energy needed to move a particle past its neighbour.

In the low gravity regime of an asteroid the potential energy of an individual grain is lower and thus the energy required to move past its neighbours is reduced. Assuming an individual grain has the same kinetic energy as on Earth, the flow which on Earth would have been in the slow dense regime, may move to the fast dense regime on the surface of the asteroid due to the inertia no longer being negligible.

Due to their dissipative nature, granular materials will only flow under the application of a continuous input of energy. This energy can be provided by applying shear stresses to the material. Granular materials and ordinary fluids react differently to shear stresses. Fluids deform uniformly whilst granular materials develop shear bands [11]. A shear band is a narrow zone of large relative particle motion bounded with essentially rigid regions. Shear bands mark areas of flow, material failure, and energy dissipation, and as such they are important in many geophysical processes.

Before a granular material can flow, its particles must transition from the jammed state when solid-like to the un-jammed state when liquid-like. The passage from a solid-like behaviour to a liquid-like flow can also be achieved by increasing the slope of a granular pile in a gravity field [12]. There exists a maximal angle of stability, or avalanche angle, at which the pile inevitably begins to flow. Likewise there is an angle of repose defined as the angle at which the system comes back to rest. It is a manifestation of a material property called the internal angle of friction which is analogous to the coefficient of solid friction. In the range between these two angles, the system exhibits bistable behaviour where it can be in both states. The jammed state is conditionally stable; however, an avalanche can be triggered by finite perturbations.

Taylor-Couette Shear Cell

In order to investigate the effect of shear on granular materials experimentally, a Taylor-Couette shear cell can be used [3]. The Taylor-Couette geometry is shown in Figure 1. There are two concentric cylinders. The outer cylinder is fixed and its inside surface is rough with a layer of glued on particles, the outer surface of the inner cylinder is also rough but it is free to rotate, and the floor between the two cylinders is smooth and fixed in place. The gap between the two cylinders is filled with granular material on which the rotating inner cylinder applies shear stresses. Large velocity gradients are then produced near the inner cylinder as the energy input in to the granular system by the rotating inner cylinder is dissipated by friction in a narrow band. This localised region of shearing is known as a shear band (as described in the introduction). The size of the gap between the two cylinders is made to be $\sim 50d$ where d is the average diameter of particles filling the gap.

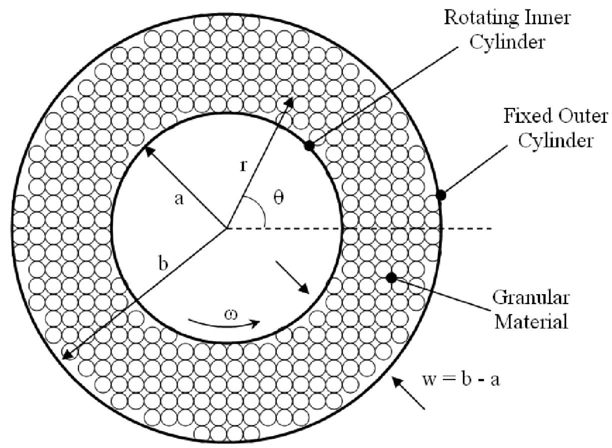

Figure 1: The Taylor-Couette Geometry [13]. (a = Inner Cylinder Radius, b = Outer Cylinder Radius, w = Width of Shear Region, r = Radial Distance, θ = Angular Distance, ω = Inner Cylinder Rotation Rate)

Previous Experimental Results

It has been shown that the flow of granular matter is strongly influenced by the network of direct contacts with neighbouring particles. This contact network, in turn, is shaped by how the material evolved with time. When uniform shear or compression is applied a stronger contact network in the direction of forcing develops. When the shear direction is reversed, or the direction of compression is changed, the material rearranges until it forms a new contact network that can best support the new direction of compression or shear [14]. The force chains aligned to cause jamming in one direction are not suited to jam under the reverse driving. Therefore, time is required to re-form a force chain network subsequent to reversal.

Investigations into particle velocity distributions in a Taylor-Couette shear cell [14] examine the angular velocity measured in concentric rings during the experiment described above. When sheared in the initial direction the system reaches steady state during which three of the six rings do not experience any appreciable flow. If the driving is discontinued and then reapplied the system reaches the same steady state immediately. However if the driving is stopped and then applied in the reverse direction, a transient sets in during which flow is evident both in the regions that were flowing and in the previously jammed regions. Average flowing velocities in all regions are faster initially and drop off with roughly the same time scale in all regions.

The implication is that regions that normally do not move under steady shear, move significantly during reversal of the shear direction. Studying the reversal of shear in a granular material in microgravity has the potential to shed light on different modes of deformation that are evident when granular material is sheared in different directions.

Additionally, the flow fields during shear reversal are accompanied by compaction due to gravity. It is not clear how the force chains would break and reform in the absence of a preferred guiding direction such as gravity.

Applying these experimental results to asteroids indicates that the dynamics of granular materials on their surfaces could also depend on the direction of shear that they have undergone. For instance impact phenomena [15] [16], tidal forces from planetary encounters [17], and YORP spin up [18] could apply shear forces to the surface. Therefore, their surface materials may not necessarily behave as a classical Mohr-Coulomb one as one might expect.

The characteristic timescales for a shear reversal experiment previously conducted on the ground is on the order of a few seconds [19]. After rotation of the inner cylinder is started at a rotation frequency of 0.02 Hz, a steady flowing state is reached within the first 0.4 s. When the motion of the cylinder is stopped and is restarted in the direction opposite to the prior shear direction, the steady flowing state is reached only after several seconds. A single complete shear reversal experiment would take $\sim$20 s, which is similar to the microgravity time available during a single parabola of a parabolic flight.

ASTEX EXPERIMENTAL OBJECTIVES

The AstEx experiment will investigate how a steady state (constant) flow is achieved in a granular material in microgravity conditions. A flow will be started by applying rotational shear forces to the granular material contained within a microgravity modified Taylor-Couette shear cell. Individual particles of the granular material will be tracked so that their velocities can be determined. By monitoring the particle velocities, the time needed for a steady state flow to start can be determined. Once a steady state flow is achieved particles can be tracked for the length of microgravity time available during a single parabola. This will tell us how a steady state flow in microgravity differs from a steady state flow on Earth. Another investigation will determine what effect reversing the direction of shear has on the steady state flow already started in microgravity. Again this will be compared with ground based results. These three investigations (time to start a steady state flow, monitoring the flow, and effect of shear reversal on the flow) will be repeated with granular materials of different particle sizes, and with different shear rates to determine the effect of these variables.

ASTEX EXPERIMENTAL DESIGN

The Experimental Rack

Figures 2 and 3 show how a Taylor-Couette shear cell will be mounted inside the A300 Zero-G aircraft for testing in microgravity conditions. The experiment rack consists of two parts: a test compartment, and a laptop work station. The test compartment is where the intended experiments will take place and it will contain one removable shear cell that is to be tested. Built into the test compartment is a motor powered by an inverter, an enclosed toothed belt pulley system, four illumination lights, and two high speed cameras, which are required to conduct the experimental tests. Situated next to the test compartment is the laptop work station where two laptops will be mounted to allow two people to control the various components of the experimental hardware and to perform the experimental tests. The entire experiment rack will be 1006 by 1250 by 750 mm in size, and have a total mass of ∼150 kg.

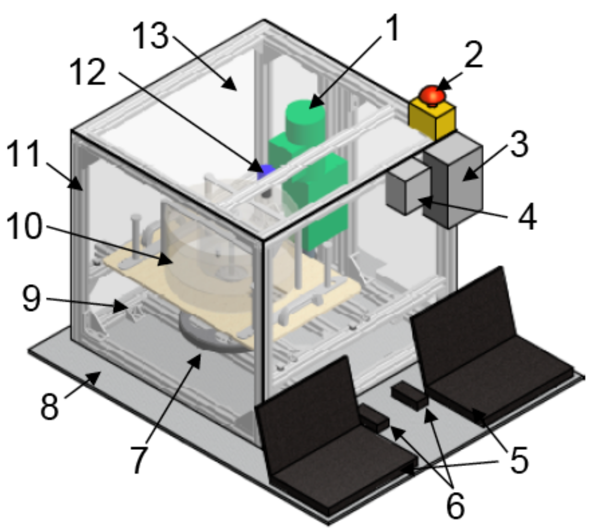

Figure 2: The AstEx Experimental Rack. (1) Motor (2) Emergency stop button (3) Electronics box (4) Motor inverter (5) Laptops (6) Laptop power adapters (7) Large toothed gear (8) Aluminium baseplate (9) Inside 45x45 attaching bracket (10) Shear cell (11) Support structure frame (12) High speed camera (13) Transparent double containment panel

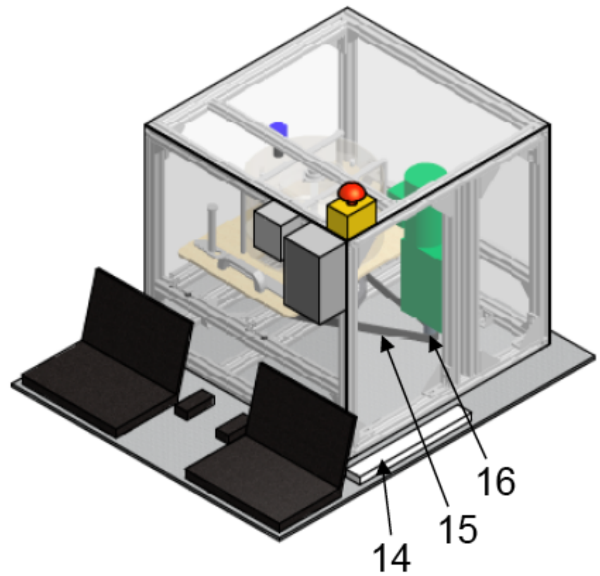

Figure 3: The AstEx Experimental Rack rotated 90 degrees. (14) Switched socket extension lead (15) Toothed pulley belt (16) Small toothed gear

The Microgravity-Modified Shear Cell

The shear reversal will be studied using Taylor Couette geometry as described above. Figure 4 shows a single shear cell. They will be mounted on a Perspex base 650 mm long and 450 mm wide, the outer cylinder will have an outer diameter of 400 mm and a height of 200 mm, and the whole unit will have a total mass of ∼27.5 kg when filled with beads. The Perspex base will feature two carrying/shaking handles used to carry and shake the shear cell. The outer cylinder is made from a cast Acrylic tube with a 400 mm outside diameter and a 5 mm wall thickness, and the inner cylinder is made from the same material but with a 200 mm outside diameter and a 3 mm wall thickness. This gives a gap size of 95 mm between the inner and outer cylinders, or ∼48 bead diameters if 2 mm size beads are used. The inner cylinder has a steel shaft running through the its centre and is attached to the outer cylinder by two bearings contained inside a housing unit. This steel shaft will attach to the driving shaft and transmit the torque produced by the motor to the inner cylinder.

Figure 5 shows the internal workings of a shear cell.

In a normal Taylor-Couette shear cell the granular material does not have a top constraint [3]. This

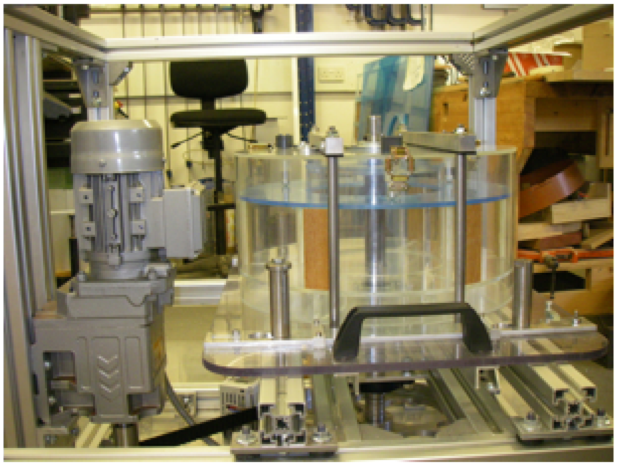

Figure 4: A photo of the microgravity modified Taylor-Couettte shear cell

allows the granular material to change its depth and density during shear. However, without a top constraint in microgravity the granular material will just float away.

Therefore, a movable and transparent pressure disk is used to keep the granular material contained. It is loaded by 3 weak springs to apply a very small force e.g. sprung loaded roller balls (see Figure 6). The transparent pressure disk can also be fixed in place so that experiments can be performed at constant volume. To maintain a granular seal the spaces between moving parts are made to be very small at 0.5 mm to prevent a single glass bead from escaping. The glass bead granular material fills the shear cells to a height of 100 mm.

Since the shear cells are self-contained units each shear cell contains glass beads of a certain size that cannot be easily exchanged. In total four shear cells will be built: one with 2 mm size glass beads ($\sim$1.26 million beads), one with 3 mm glass beads ($\sim$0.37 million beads), one with 4 mm glass beads ($\sim$0.16 million glass beads), and one constant volume shear cell containing 2 mm glass beads ($\sim$1.08 million beads). The shear cells can be easily exchanged between flights when the plane is on the ground to allow testing of different shear cells during one parabolic flight campaign.

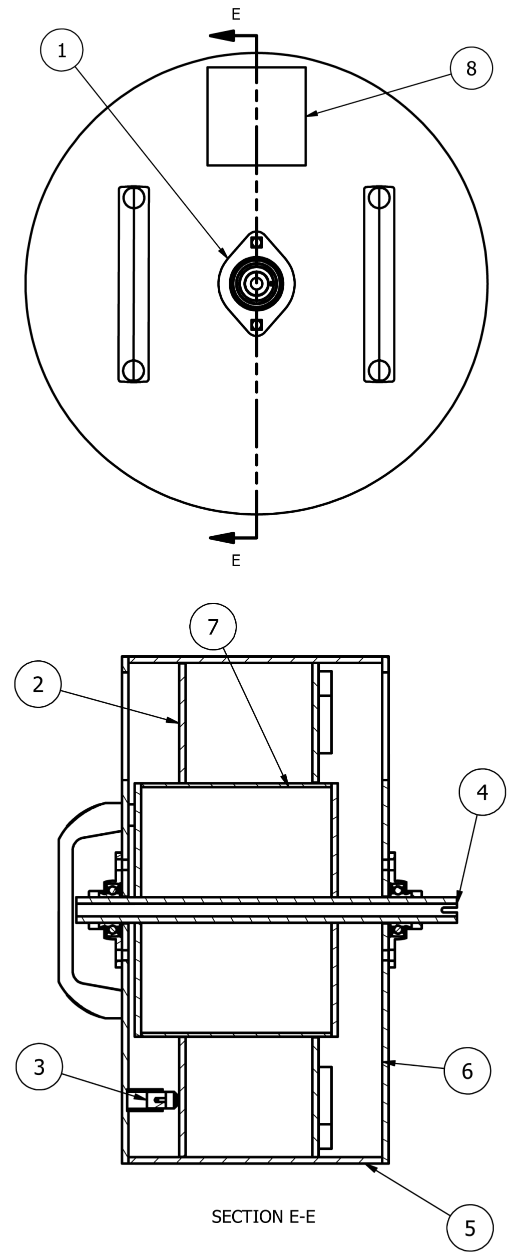

Figure 5: The internal workings of a microgravity shear cell. (1) Housing unit with bearing. (2) Movable pressure disk. (3) Pressure springs. (4) Steel shaft. (5) Fixed outer cylinder. (6) Fixed bottom plate. (7) Rotating inner cylinder (8) Camera viewport.

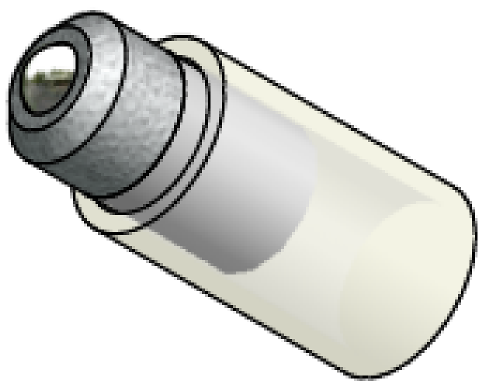

Figure 6: The ball transfer unit.

Shear Cell Mounting

Figure 7 indicates how a shear cell will be mounted inside the experiment rack. The shear cell itself is attached to the Perspex base via two aluminium securing bars. These can be easily undone to replace the current shear cell with a different one without the need for making a separate mounting for each shear cell. The Perspex base, with a test shear cell attached, is secured to the rack by four guide rods running through four holes in the Perspex base. Two sliding locking bars connect the two guide rods on each side of the shear cell. The positions in which these are set determine whether the Perspex base is free to move up and down the guide rods, or whether it is fixed in place. During a parabola the Perspex base will be locked in place to allow experiments to be performed. It will be unlocked during level flight to allow the experimenters to shake the shear cell between parabolas to reset the granular material contained inside the shear cell for the next experimental test. This is required to prevent the shear memory effect of granular materials affecting the outcome of consecutive independent experimental tests. During a shear experiment the grains will rearrange themselves to form a contact network that suits the last direction of shear imposed upon it. This contact network is not broken when the shear force is removed, and shaking is one of the easiest options available to break this contact network and create a random arrangement of grains in the granular material.

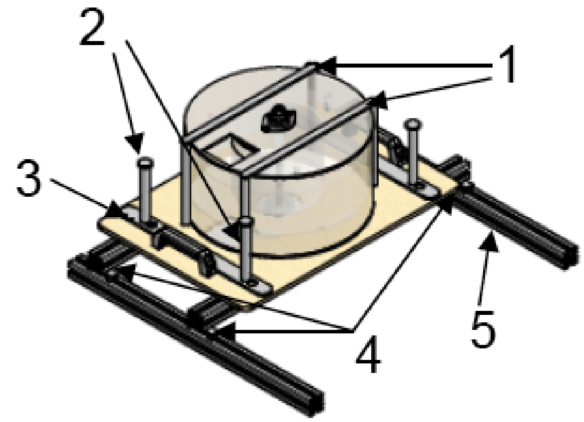

Figure 7: Shear cell mounting. (1) Shear cell securing bars (2) Guide rods (3) Sliding locking bars (4) Silent blocks (5) Support structure

Counteracting Imperfect Microgravity

The microgravity environment on a parabolic flight is not perfect; there are small fluctuations about zero g of magnitude ± 0.05 g. This means at times the experiment will experience small amounts of negative g. It is uncertain whether negative g will just reset the grain contact network. To ensure that all gravity fluctuations are positive, very low positive gravity must be simulated on the experiment during the constant pressure experiments. This is acheived by using the sprung loaded movable pressure disk to provide a small force in a preferred direction to simulate the effect of very low positive gravity (see Figure 5).

This small force must be equal to the maximum amplitude of the gravity fluctuations i.e. 0.05 g. When applied to the grains in the experiment they will experience an effective gravity fluctuating between 0 and 0.1 g.

Vibrations may also reset the contact networks set up in the granular material. To get statistically valid results the experiment ideally needs to be free of aircraft vibrations and free of gravity jitters during the microgravity phases. To minimise these effects the shear cell will be isolated from vibrations. This is done by mounting silent blocks between the two strut profiles on which the shear cell is resting, and the rest of the support structure frame (see Figure 7).

The Mechanical System

The experiment requires rotating the inner cylinder of the shear cell at a very slow speed i.e. <1 RPM. To provide the driving force a Watt Drive HU50C 64K4 inline helical geared motor is used. It is a three phase motor and is controlled by a Moeller DF51-322-025 three phase inverter. The motor operates at 120 W and runs at 1330 RPM. However, the motor has an in built gear system with a ratio of 123.14:1, giving an output speed of 10.8 RPM. To achieve the desired rotation speed for the experiment a toothed belt pulley system is used to achieve the final 10:1 reduction in rotation rate. The driving shaft of the pulley system connects to the shaft of the inner cylinder via a pin and groove slotting principle. The inner cylinder shaft then rotates the inner cylinder at the desired very slow speed of <1 RPM. A specific rotation speed can be set by the inverter, and a load trip will be programmed to protect the shear cell if the torque transmitted to the inner cylinder becomes too great.

Data Collection

The two high speed cameras (Matrix Vision Blue Fox 120aG) will image the top and bottom glass bead layers of the shear cells. The imaging speed will be ∼100 frames/sec so that the particles do not move more than 1/10 d between consecutive frames. The cameras will be mounted to the experiment rack in the test compartment and image the glass beads through camera viewports built into the shear cells. See Figures 4, 5 and 7 above. Four GU10 energy saving reflector lamps will be mounted next to the cameras (two for each camera) to illuminate the glass beads and have been chosen for their low power consumption and low temperature operation.

The cameras will also measure the height of the pressure disk as well as tracking the glass bead motions. On the pressure disk suitable markers will be drawn (e.g. cross hairs) so that they can be imaged by the cameras. The separation distance between these markers as they appear in the camera images will tell us the height of the pressure disk.

In order to monitor the torque exerted on the inner cylinder the current consumed by the motor will be measured by the inverter powering the motor.

The two laptops (one per camera) mounted to the experiment rack will be used to collect and store data from the experiment. It is expected that ∼150 GB of data per flight and ∼450 GB of data in total will be generated.

Health and Safety Requirements

Since the glass beads used in this experiment are small (2-4 mm) they are given the same precautions as a fluid onboard a parabolic flight and therefore require double containment. The shear cells themselves are self-contained units and act as a single layer of containment. The double containment will be provided by covering the experiment rack with 3 mm thick polycarbonate panels. Half of the top panel will be able to slide open to give access to the shear cell in order to exchange it. However, shear cells will only be exchanged between flights when the plane is on the ground.

The complete electrical system of the experiment is protected by a single, easily accessible emergency stop button. In the event of an emergency, actuating this button will cut off all 220 V AC power to the equipment. It is also protected by a differential circuit-breaker rated at 30 mA, and a fast fuse rated at 6 A. Individual components of the experimental hardware will also be protected by their own fuse but of lower values specific for their needs.

ASTEX EXPERIMENTAL METHODOLOGY

Upon entry into the A300 Zero-G aircraft the experiment rack will be assembled with the appropriate shear cell to be tested. During the experimental phases (described below) the high speed cameras will image the granular material by imaging reflections off coloured particles. This will allow for subsequent tracking of particle motions. The motor inverter will measure the amount of current being consumed by the motor in order to monitor the amount of torque exerted on the inner cylinder. Two experimenters are needed throughout the experiment: one to supervise the Taylor-Couette shear cell and one to manage the data.

Slightly different experiments will be performed in each of the three parabolic flights in order to investigate three different effects. Each experiment type will be performed with the same granular material for 5 experiments i.e. 5 parabolas. Described in Tables 1 to 3 below are the experiments planned for the three parabolic flights. There are two different modes of experiment:

- Mode 1: the motor rotates the inner cylinder in the same direction for the full 20 seconds of microgravity.
- Mode 2: the motor rotates the inner cylinder in one direction for the first 10 seconds of microgravity and then stops and reverses the direction for the remaining 10 seconds.

There are three phases during a single parabola of a parabolic flight: a ∼20 second 1.8 g injection phase, a ∼20 second microgravity phase, and a ∼20 second 1.8 g recovery phase. There is a 2 minute 1 g rest between parabolas and so parabolas are repeated every 3 minutes. After 5 parabolas it is standard for the A300 Zero-G to take a longer 1 g rest of 4-8 minutes. The experimental procedure is timed with these different phases. Approximately 10 seconds before the start of the parabola the experimenters start the recording of the high speed cameras. During the 1.8 g injection phase the experimenters do nothing except monitor the experimental equipment for any malfunctions. As soon as the microgravity phase starts the experimenters blink the lights to time stamp the high speed camera recording and start the motor. Halfway through the microgravity phase the direction of the motor rotation can be reversed if needed. During the second 1.8 g recovery phase the motor is left running in the direction it was at the end of the microgravity phase. And finally, when the 1 g rest phase starts the motor and high speed cameras are stopped. During the 2 minute rest period the experimenters must ensure all data from the high speed cameras are saved to the laptop hard drives, and prepare the shear cell for the next experiment. The shear cells will be prepared for the next experiment by inspecting them for any damage or leaks, and shaking them by hand to reset the glass beads back to a reasonably consistent initial arrangement. This procedure is repeated for each parabola; however, during the longer 4-8 minute rests the motor rotation speed can also be adjusted.

ASTEX: AFTER THE FLIGHT CAMPAIGN

Data Analysis

Particles on the top and bottom layers, imaged with both cameras, will appear as bright spots in the images. A Matlab particle tracking algorithm will then be used to identify these bright spots, and track them from frame to frame. By generating particle positions in each frame the average displacement and velocities of particles are then computed. An analysis will then be performed to determine how particle velocity varies with radial distance from the inner cylinder and how long it takes for the particle velocities to become constant i.e. for the system to reach a steady state. Further analysis will allow us to determine the width of the shear band and if this width increases upon shear reversal in a microgravity environment. All of this analysis will be performed for data taken during constant pressure and constant volume experiments.

The current consumed by the motor will be recorded throughout each experiment. This will provide a relative measurement of the torque exerted onto the granular material. From this information the shear stress will be calculated. Investigations will be performed into how shear stress varies as a function of shear displacement (i.e. inner cylinder displacement). A research question also of interest is to determine if there is a transient weakening of shear stress upon reversal as observed in 1 g [14].

The final measurement, the height of the pressure plate, will allow determination of the bulk density of the granular material. Having this information will allow determination of density as a function of shear displacement and how this is affected by shear reversal. A comparison will be made with the results of Toiya et al [3] who found that during shear in 1 g the height remains constant during steady state flow but drops during shear reversal.

It is known that in 1 g a lower density does not correspond to a weaker state [3]. By combining the shear stress results with the density measurements it should be possible to determine the material strength as a function of density and thus verify if the same principle holds in microgravity.

Throughout the data analysis phase there will be collaboration with the Losert Lab of the University of Maryland, U.S.A.. They have great experience in analysing such data and have done very similar experiments in their lab as AstEx plan to do in microgravity.

Expected Results

In previous experiments the history dependence of the shear flow was found in a situation where gravity is confining the system. So when the shear stress is reversed the initial contact network breaks but then gravity quickly compacts the system, and this is seen at the start of the shear flow. So in microgravity, if the shear rate is large compared to the gravitational timescales then we might expect the system to fall apart dramatically rather than compact. If pushed too hard along an axis that does not have force chains, the ensemble of grains might offer essentially no shear resistance. Since the resistance is already low during shear reversal even though the system compacts, it should be even lower in microgravity! So a very dramatic weakening of the material is expected in microgravity.

Future Work

The experimental results will be used to validate an N-body model based on the parallel code *pkdgrav* [20] which will be developed to simulate the behaviour and response of granular materials to various external pressures and forces. This *pkdgrav* code has previously been used to successfully compute the gravitational re-accumulation phase during catastrophic disruption of pre-shattered parent bodies [21], perform simulations of the collisional and gravitational dynamics of aggregates, with or without cohesion [22] in addition to many other complex N-body numerical simulations. Once this code has been validated for a number of different gravitational conditions it can be applied to any solid planetary body to determine the dynamical response of any granular material found on its surface.

A centrifuge could be used to create higher gravity conditions (>2 g) but will not be representative of asteroid surface gravities. However, a follow up study on a centrifuge could extend the range of gravities studied for further validation of the N-body model.

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Table 1: Microgravity Flight 1: "Constant" Pressure, 2 mm Beads

Parabola Numbers	1-4	5	6-9	10	Change Motor Speed	11-14	15	16 - 19	20	Change Motor Speed	21-24	25	26-29	30
Bead Diameter (mm)	2	2	2	2		2	2	2	2		2	2	2	2
Motor Frequency (mHz)	4	4	4	4		8	8	8	8		16	16	16	16
Experiment Mode	1	1	2	2		1	1	2	2		1	1	2	2
Shake in 1g? (Y/N)	Y	N	Y	N		Y	N	Y	N		Y	N	Y	N

Table 2: Microgravity Flight 2: “Constant”Pressure, 4 mm Beads

Parabola Numbers	1-4	5	6-9	10		11-14	15	16 - 19	20		21-24	25	26-29	30
Bead Diameter (mm)	4	4	4	4	Change	4	4	4	4	Change	4	4	4	4
Motor Frequency (mHz)	4	4	4	4	Motor	8	8	8	8	Motor	16	16	16	16
Experiment Mode	1	1	2	2	Speed	1	1	2	2	Speed	1	1	2	2
Shake in 1g? (YES/NO)	Y	N	Y	N		Y	N	Y	N		Y	N	Y	N

Table 3: Microgravity Flight 3: Constant Volume, 2 mm Beads

Parabola Numbers	1-4	5	6-9	10		11-14	15	16 - 19	20		21-24	25	26-29	30
Bead Diameter (mm)	2	2	2	2	Change	2	2	2	2	Change	2	2	2	2
Motor Frequency (mHz)	4	4	4	4	Motor	8	8	8	8	Motor	16	16	16	16
Experiment Mode	1	1	2	2	Speed	1	1	2	2	Speed	1	1	2	2
Shake in 1g? (Y/N)	Y	N	Y	N		Y	N	Y	N		Y	N	Y	N