Oscillating granular layers produce stripes, squares, hexagons . . .

Take a bunch of granular particles, put them in a container on a rigid platform and shake the system vertically. You might find heaping, convective rolls, size segregation or traveling waves. Recent experiments with several layers of particles have produced, at a critical acceleration, a sharp transition from a flat surface to standing-wave patterns oscillating at either one-half or one-quarter the excitation frequency.

Experiments with vertically oscillating thin layers of granular particles show robust pattern formation. Studying the pattern dynamics may yield insight into basic mechanisms of granular flow and connect these patterns to those found in other dissipative systems.

When a group of researchers at the University of Texas at Austin oscillated a shallow granular layer, they produced squares and stripes; they found a continuous transition between these states as they varied the vibration frequency at constant acceleration. More recently the Texas team—Francisco Melo (now at the University of Santiago of Chile), Paul Umbanhowar and Harry Swinney—have been finding hexagons and period-doubling behavior.

Granular materials are ubiquitous, ranging from sand to sugar, from gravel to geological formations. Despite the importance of such materials to industry, only in the last several years have physicists and engineers begun to learn much about their peculiar nonequilibrium behavior as a function of time.

Umbanhowar points out that "there's no Navier–Stokes equation for the flow of granular materials. Granular materials act as fluids, solids and gases, depending on how they are excited." At present, there is no comprehensive understanding of the fluidlike state of granular materials, let alone the crossovers between fluid-, solid- and gas-like behavior. Heinrich Jaeger of the University of Chicago explains: "The fluidlike state in particular arises from a highly nonlinear response to external vibrations. Concepts from ordinary hydrodynamics or statistical mechanics fail for granular media because the thermal energy is irrelevant and all collisions are inelastic. This situation provides a tremendous challenge for physicists: the identification of an appropriate theoretical framework. Likewise for experimenters, research on granular materials provides an exciting opportunity to explore widely uncharted territory and to isolate key aspects of nonlinear dynamical behavior in a problem of immense technological importance. The recent experiments have done just that: They have provided benchmarks against which to test any forthcoming theoretical understanding."

Previous work

In 1831 Michael Faraday used thin layers of fine powder on vibrating plates to investigate the position of nodal and antinodal lines in an essentially two-dimensional system. He found that the powder formed heaps by means of a convective mechanism.

In 1989 Claude Laroche, Stephane Douady and Stéphan Fauve at the Ecole Normale Supérieure de Lyon studied a two-dimensional granular system, with one horizontal direction plus the vertical shaking direction (essentially a narrow shoebox); the system was only a few layers high. They found a parametric instability; that is, when they drove the granular system with a frequency f, it responded with $f/2$. So it takes two shaking cycles to come back to the original state. Since the experiments by Laroche, Douady and Fauve, a number of groups have done granular flow experiments on systems only a few layers high, either in the shoebox geometry or, by wrapping it around, in an annulus. The groups include Robert Behringer, Hyuk Pak and Eric Van Doorn at Duke University; Melany Hunt, Christopher Brennen and their collaborators at Caltech; A. Goldshtein and his collaborators in Israel; and Jean Rajchenbach and Eric Clément at Pierre and Marie Curie University in Paris.

Recently the University of Texas group and Jaeger and his collaborators at the University of Chicago have done such experiments in shallow layers that yield planar patterns. Both groups reported their results at a workshop on granular dynamics held at the University of Chicago in mid-May.

Another category of experiments involves granular convection in taller systems, many grains high. Pierre Evesque and Rajchenbach studied these systems in 1989, using a container that was a long, thin but tall box. When the acceleration of this system exceeded g, the acceleration due to gravity, large-scale convection rolls filled the container. This state resembles Rayleigh–Bénard convection in a small-aspect-ratio container and has a large heap of material at the point of maximum upflow. In this case, traveling waves occur, as seen by the Duke group, rather than the standing waves observed for shallow layers. At Caltech, Carl Wassgren, Brennen and Hunt have observed heaping, surface waves and arching.

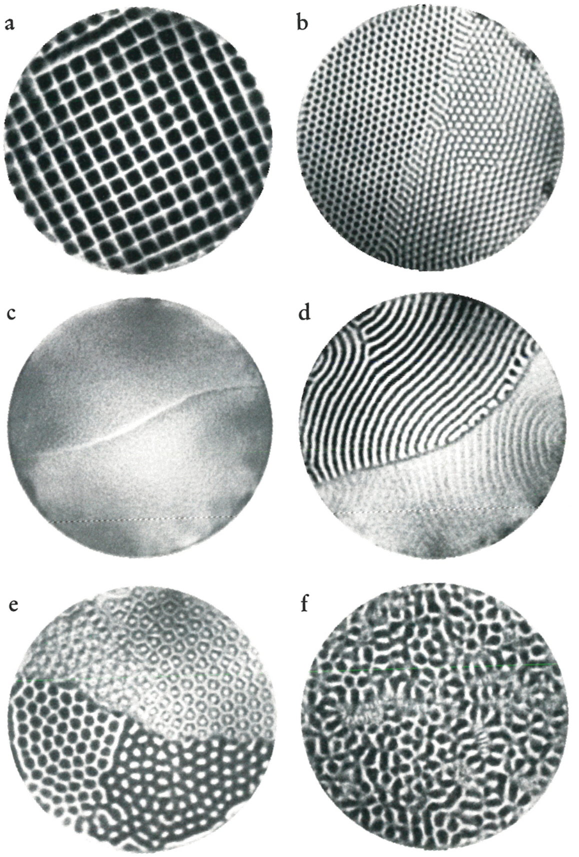
This year, two experiments have provided new insights into two of the most important of these mechanisms. One of these mechanisms, studied by E. E. Ehrichs, Jaeger, Greg Karczmar, James Knight, Vadim Kuperman and Sidney Nagel at the University of Chicago, is a ratchet effect involving friction between the sidewalls of the container and the grains. Using magnetic resonance imaging, the experimenters found that the fastest flow occurs in the thin boundary layer near the walls.[1]

The other key mechanism involves a kind of buoyancy provided by surrounding gas, an effect studied at Duke. After contradictory results on the effects of pressure on flow obtained by Laroche and his collaborators and Evesque and his collaborators, the Duke experimenters carefully controlled pressures between vacuum and atmospheric. They found[2] that the heaping and convection in tall layers was virtually independent of pressure above 10 torr, and ceased below 10 torr. Behringer explains that the key idea is that gas, which is trapped under the layer during each shaking cycle, is compressed as the material hits the container bottom. If the layer is shallow or the particles are large, gas seeps out quickly and plays no role in the shaking dynamics.

Texas experiments

In experiments reported early last year, Melo, Umbanhowar and Swinney vertically vibrated a thin layer of spherical particles in a container whose horizontal extent was much larger than the layer depth.[3] For increasing amplitude of the sinusoidally varying acceleration, the initially flat layer became unstable and standing-wave patterns emerged, oscillating at $f/2$. At lower frequencies these wave patterns (see the figure) appeared as squares, at higher frequencies, as stripes; the stripes and squares competed at intermediate frequencies.

"We expected to see convection and heaping like Rajchenbach and Fauve found," says Umbanhowar; so the Texas team was somewhat surprised to find patterns instead. What's the explanation? the group wondered. Similar patterns of squares and stripes are observed in convection in fluids and liquid crystals and in vibrated fluid layers. Says Swinney, "The analogy between a granular system and a fluid is deeper than the observation of similar spatial patterns: in both cases the transition from the initial uniform (flat) state to a pattern yields squares at low dissipation and stripes at high dissipation. The viscosity determines the dissipation of a fluid, while for a granular material, the dissipation arises from particle–particle collisions and is small at low frequencies where the layer is more dilated."



GRANULAR PATTERNS formed by a thin layer, seven particles deep, of 0.17-mm bronze spheres. The different patterns arise from a competition between a granular-wave instability and period doubling in the vertical motion of the layer. **a:** Squares occur at driving frequency $f=24$ Hz and dimensionless acceleration amplitude, $\Gamma=2.7$; **b:** Hexagons at $f=43$ Hz, $\Gamma=4.2$; **c:** Flat layer with kink at $f=67$ Hz, $\Gamma=5.8$; **d:** $f/4$ stripes at $f=70$ Hz, $\Gamma=6.8$; **e:** $f/4$ hexagons at $f=70$ Hz, $\Gamma=7.6$; **f:** Disorder at $f=67$ Hz, $\Gamma=8.5$. (Courtesy of Paul Umbanhowar, University of Texas.)

After learning about the Duke convection experiment showing the effect of air pressure, the Texas group had decided to repeat the earlier experiments using an evacuated container. With the air removed, a new set of patterns emerged in addition to squares and stripes oscillating at $f/2$. As Melo, Umbanhowar and Swinney increased the dimensionless acceleration amplitude $\Gamma = 4\pi^2 f^2 A/g$ (where A is the drive amplitude), hexagons and kinks appeared with frequency $f/2$; squares, stripes and hexagons with domains of different phase oscillating at $f/4$; and a disordered state.

The researchers explain the different patterns using a simple one-dimensional model that focuses on the vertical motion of the layer with respect to the container. Since the layer behaves much like a completely inelastic object, it does not bounce; so it leaves the bottom of the container only when the container accelerates downward faster than g. The appearance of waves appears to be determined mainly by the relative collision velocity of layer and container, while the particular wave pattern that is selected depends on the timing of successive collisions, as the group explains in a recent paper.[4]

When the acceleration amplitude first exceeds g, the layer loses contact with the container and later collides with the container. Because the gas pressure is low, the layer remains flat and heating is not observed. When the acceleration amplitude is raised to about 2.5 g, the collision velocity is large enough that the layer becomes unstable and wave patterns arise, the group says. With a further increase in acceleration amplitude, hexagonal patterns appear (part b of the figure) from either square or striped patterns due to a doubling of the period of the layer's vertical motion. This doubling occurs because the layer leaves the container with sufficient velocity that it doesn't land again until after the downward instantaneous acceleration of the container is already less than g. As a consequence, there are long flights followed by short flights. The relative collision velocity at the end of the long flight is smaller than the relative collision velocity at the end of the short flight; this introduces an additional forcing at $f/2$, since it now takes two container oscillation periods for the sequence to repeat. Two years ago experiments by Hanns Müller at the Ecole Normale Supérieure de Lyon on vertically oscillated fluid layers showed that forcing simultaneously at f and $f/2$ can lead to hexagons. Swinney says that in the granular system both phases of the period-doubled motion can be observed simultaneously because the long-flight–short-flight sequence can start on one cycle of the container motion or the next.

"As we turn up the acceleration, the hexagons vanish," says Umbanhowar, and the layer then consists of flat domains connected by a kink (part c of the figure). This occurs because of a resonance—the relative collision velocity of the layer and container goes to zero. Umbanhowar compares this behavior to an egg tossing contest at a county fair: "You toss raw eggs back and forth with a partner and move back one step after each successful throw. As the distances and velocities increase you must move your hands in the same direction and with nearly the same velocity as the egg so that you can reduce the egg's velocity as slowly as possible." Similarly, at the resonance, the layer and plate velocities are almost equal at the time of contact, and no waves are excited. "Even though the patterns go away, we still have one side of the layer staying in flight for more than one and a half cycles and then repeating, while the other side does the same thing 180 degrees out of phase, which is why we see the kink in the layer."

If the experimenters increase the acceleration amplitude further (to about 6 g), the layer hits harder and waves are again excited. Square and striped patterns reappear, but now, because the time between collisions is two periods, the waves oscillate at $f/4$. Part d of the figure shows that because of the degeneracy associated with period doubling, the group says, there are two domains differing in phase by π, so that one domain is taking off while the other is in mid-flight.

When the acceleration is increased so that the flight time is greater than two periods, intrinsic two-frequency forcing is restored (at $f/2$ and $f/4$) and hexagonal patterns reappear, now with four different phases (part e of the figure).

For still larger accelerations, the layer becomes disordered in both space and time. Part f of the figure shows multiple small domains of wave-like structures. "You see a random bunch of stripes," explains the Texas team. "We think the phase of the layer with respect to the cell isn't very stable. Some portions of the pattern miss the collision with the container, which changes the phase of that portion with respect to the rest of the pattern."

"The pattern formation phenomena we observe are robust," the group says. The patterns don't change qualitatively with particle restitution coefficient (0.5–0.9), density (2–11 grams per cubic centimeter) and size (0.05–3 mm); layer thickness (2–40 particles deep) and aspect ratio (2–100 pattern wavelengths); and the pressure (10^{-1}–10^{-6} torr).

"The simple one-dimensional model of a layer with inelastic collisions provides insight into the sequence of transitions in the patterns," says Swinney, "but a deeper understanding of why the different patterns are selected must await the development of an equation of motion for the granular layers."

Chicago experiments

Jaeger and his collaborators at the University of Chicago have also been doing experiments in a geometry similar to that used by the University of Texas group. Jaeger notes that the 1994 experiments by the Texas group were done at atmospheric pressure. So he feels their dispersion relation must be reevaluated at low pressure.

Two years ago Jaeger and his graduate student James Knight reported (at a meeting of Packard Fellows in Monterey, California) that they had observed surface waves oscillating at half the drive frequency. Their container was shaped like a fishbowl. Over the last year Thomas Metcalf, an undergraduate, has joined the project, and he has emphasized cylindrical containers with flat bottoms and straight sidewalls. Says Jaeger, "We find patterns just like the Texas group do in their (similarly cylindrical) system." Jaeger and his collaborators showed their patterns and the corresponding dispersion relations at the Chicago workshop in mid-May.

Jaeger and his collaborators believe that even in shallow layers, residual gas pressure above 100 millitorr modifies the collision behavior between rapidly colliding grains. The Chicago team finds that the preparation condition of the grains, in particular any residual moisture on them, affects the onset of patterns. "Under ambient conditions, these factors are not easily controlled and may change over time," says Jaeger. "That's why we systematically explored the effect of evacuation."

He continues: "We are still far from the point where we understand in detail how and why these wonderful patterns exist. I believe that ordinary hydrodynamic theory clearly fails in the limit of shallow vibrated granular layers, and that comparison to liquid results (such as dispersion relations) cannot give the needed insights. In a sense, that is good news, meaning that much still needs to be explored."

The study of pattern dynamics promises to lead to valuable insights concerning the basic mechanisms governing granular flow and to help in connecting these patterns to similar patterns found in many quite different dissipative systems driven far from equilibrium.

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Space-based Telescopes See Primordial Helium in Spectra of Distant Quasars

Looking way back in time, astronomers have found evidence of the primordial gases—first, hydrogen, and now, with the help of space-based telescopes, the more elusive helium.

According to the standard model, shortly after the Big Bang, primordial hydrogen and helium were spread nearly uniformly throughout space. After matter began to coalesce into galaxies and other structures, nuclear cooking within massive stars produced heavier elements. But researchers still expect to see traces of the primordial elements if they look far out in intergalactic space, at distances corresponding to the earliest times. In 1971 they saw signs of hydrogen clumped in clouds located billions of light-years away. Now, thanks to the availability of satellite-borne telescopes sensitive to ultraviolet radiation, they have found hydrogen's primordial companion.

The clouds in which the hydrogen was seen are presumably at or before the early stages of galaxy formation. No one has seen signs of relatively uniformly distributed hydrogen, corresponding to an even earlier era before any condensation. The absence of a hydrogen signal does not mean the gas is not there. Rather, in the harsh intergalactic region between the clouds, hydrogen appears to be almost totally ionized to single protons that do not absorb light and hence cannot be seen. Researchers had hoped that helium might fare better in the intense radiation; enough nuclei might retain single electrons to permit detection of these hydrogen-like ions.

The hopes of seeing helium have been realized in the recent measurements that found the singly ionized species. It is not clear, however, how smoothly the gas is distributed—that