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Spontaneous population oscillation of confined active granular particles†

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Spontaneous collective oscillation may emerge from seemingly irregular active matter systems. Here, we experimentally demonstrate a spontaneous population oscillation of active granular particles confined in two chambers connected by a narrow channel, and verify the intriguing behavior predicted in simulation [M. Paoluzzi, R. Di Leonardo and L. Angelani, Self-sustained density oscillations of swimming bacteria confined in microchambers, *Phys. Rev. Lett.*, 2015, **115**(18), 188303]. During the oscillation, the two chambers are alternately (nearly) filled up and emptied by the self-propelled particles in a periodic manner. We show that the stable unidirectional flow induced due to the confined channel and its periodic reversal triggered by the particle concentration difference between two chambers jointly give rise to the oscillatory collective behavior. Furthermore, we propose a minimal theoretical model that properly reproduces the experimental results without free parameters. This self-sustained collective oscillation could serve as a robust active granular clock, capable of providing rhythmic signals.

Introduction

In active matter systems, constituent particles individually convert their own or ambient energy into self-propulsion or mechanical force.[1–3] Because of inherently violating time-reversal symmetry at single-particle level, active fluids often experience spontaneous collective flows that are unattainable in passive systems. The spontaneous collective motions generally exhibit either chaotic flow patterns like swarming[4–7] and active turbulence,[8–11] or directed flows due to symmetry breaking.[12–17] In contrast, the emergence of spontaneous collective oscillation from seemingly irregular motion of active particles is rare and unusual, which is of fundamental interest and practical importance. The exploration of spontaneous collective oscillation of active fluids is currently attracting more and more attention.

Spontaneous oscillation, also known as self-sustained oscillation, can generate and maintain regular periodic motion without a similar external periodic source,[18–20] which has been extensively investigated in nonlinear and out-of-equilibrium systems ranging from optical, biological, mechanical engineering systems, to electric circuits. In the context of active matter, self-sustained oscillation has sometimes been reported. For instance, single self-propelled camphor boat[21,22] and oil droplet[23] spontaneously generate oscillatory motion owing to nonuniform surface tension, and a photosensitive polymer gel exhibits reciprocating locomotion in a gradient illumination.[24] More interestingly, spectacular collective oscillation behaviors have recently been repeatedly discovered in various active fluids, including active nematics in solvent,[25,26] dense suspensions of *E. coli*[27,28] or self-oriented active disks[29] confined within a disc-shaped region, and colloidal Quincke rollers in a ring channel with an obstacle.[30] These spontaneous collective oscillations all require the presence of a fluid environment, such that hydrodynamic interactions play a critical role. Nevertheless, a recent numerical work shows that "dry" run-and-tumble particles confined in two circular chambers connected by a narrow channel can bring a novel collective oscillation, in which active particles alternately (nearly) fill two chambers,[31] further supported by the follow-up simulations with similar dry active particles.[32,33] This finding extends our knowledge of spontaneous collective oscillation in active matter, implying the hydrodynamic interactions are not a necessary condition for self-sustained collective oscillation of active matter. However, so far, the predicted population oscillation still lacks an experimental verification, presumably since it is nontrivial to choose an appropriate active system to perform the

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corresponding experiment. Particularly, for widely-studied active colloids such as bacteria and self-phoretic Janus particles, the strong hydrodynamic resistance from the nonslip boundaries of the very narrow channel or the boundary-induced phoretic osmosis could disable the formation of a stable unidirectional flow and hence the establishment of the collective oscillation.

In this paper, we construct a macroscale active system, namely self-propelled granular particles confined in two connected chambers, to experimentally realize the spontaneous population oscillation and corroborate the previous numerical prediction. Our experiment unambiguously demonstrates that the two chambers are periodically filled up and emptied by the active granular particles, in which the dependences of the oscillatory frequency and amplitude on the channel geometry and particle concentration are quantified. Furthermore, we propose a minimal theoretical model that can properly reproduce the characteristics of the spontaneous collective oscillation achieved in experiments and thus reveal its essential mechanism.

Experimental system

Two circular, acrylic chambers (radius of 32.5 mm), connected by a straight narrow channel, are mounted on an electromagnetic shaker, and they are partly filled with self-propelled granular particles, as sketched in Fig. 1(a) and (b). The vibration strength of the electrodynamic shaker is characterized by a dimensionless acceleration $\Gamma = 4\pi^2 f^2 A/g$, with f the vibrating frequency, A the vibrating amplitude, and g the gravitational acceleration. In experiments, the vibrating frequency $f = 80$ Hz and the dimensionless acceleration $\Gamma = 4.5$ are taken. The active granular particle has a dumbbell structure, consisting of a large ($d_l = 4$ mm diameter) and a small ($d_s = 2.5$ mm diameter) steel ball linked by a rigid rod (6 mm length), which translates into a dumbbell length $L_0 = 12.5$ mm. Due to symmetry breaking, the granular dumbbell converts the energy from the vertical vibration of the shaker into a horizontal self-propulsion along its long axis, whose self-driving mechanism is similar to those of previously designed active granular particles.[34,35] Fig. 1(c) plots representative trajectories of the active dumbbell, showing the directed motion accompanied by stochastic turns due to rotational noise (mean square displacement of the active granular dumbbell is provided in the ESI†).

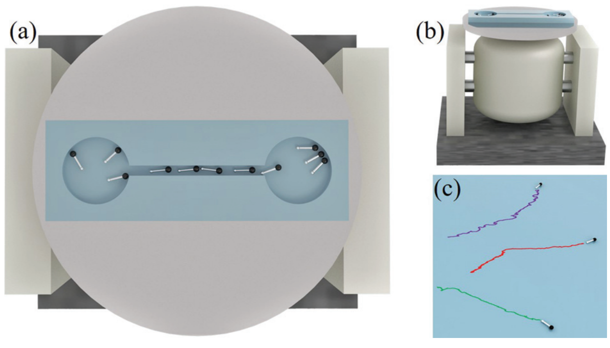

Fig. 1 Schematic diagram of the active granular system, (a) top view and (b) side view. (c) Typical trajectories of self-propelled granular particles on the vibrating plate.

The experimental system is quasi-two-dimensional, such that the self-propelled particles cannot stack each other in the chambers and channel. Through the narrow channel, the self-propelled particles can shuttle between two chambers. The migration process of the active granular particles is recorded by a digital camera and is analyzed using image recognition technique, yielding the time dependence of the particle number in each chamber.

Experimental results

Experimental snapshots in Fig. 2(a) show a time evolution process of the density of the active particles in the chambers, clearly manifesting a spontaneous population oscillation. Fig. 2(a-I,II) show that the active particles progressively migrate from the right chamber ("source") to the left chamber ("sink") through the narrow channel until the majority of particles complete the transfer. During this process, the active dumbbells in the narrow channel maintain a unidirectional motion and U-turn motion is prohibited. As the number of particles in the channel decreases and hence the unidirectional flow weakens, it is possible that the particles in the crowded sink chamber have more chances to move into the channel. If the numbers of the particles moving in two opposite directions are equal in the channel, a temporary stalemate forms [see Fig. 2(a-III)]. The stalemate will soon be broken, and then more active particles from the crowded sink chamber enter the channel than the dilute source chamber. Thus, a reverse unidirectional flow is spontaneously triggered, which remains until most

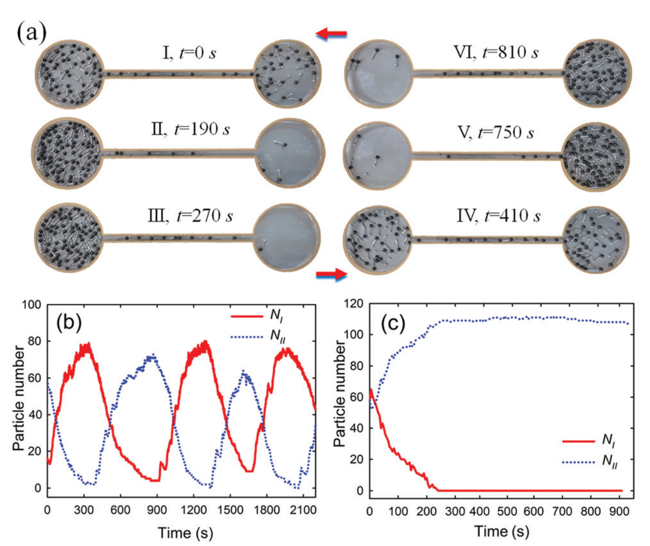

Fig. 2 (a) A complete spontaneous oscillation process is displayed. (b) The time evolution of the particle number in each chamber in the oscillatory state. (c) Jammed state caused due to too many particles filled in chambers.

particles in the left chamber move into the right chamber [Fig. 2(a-IV, V, VI)]. So, the self-propelled particles periodically and alternately (nearly) fill the two chambers, leading to a spontaneous collective oscillation, as shown in the video in the ESI.†

The periodically oscillatory behavior can be quantitatively characterized with the time evolution of the particle number in each chamber, as plotted in Fig. 2(b). Here, the channel width is $\sigma = 1.25$, reduced by d_l; the channel length is $L = 12$, reduced by L_0; the total particle number is $N = 80$. It should be noted that the periodic oscillating state happens only under appropriate conditions. If the particle number, channel width and length, and particle's activity are not chosen properly, a jammed state or non-periodic oscillation may occur. Fig. 2(c) shows that the oscillation is arrested due to excessive particles filled in two chambers. In this case, the sink chamber is fully filled, while in the channel there remains a long file of particles migrating from the source chamber. The particles in the overcrowding sink chamber fail to reorient and to compete against the unidirectional self-propelling force from the active particles in the channel, so that it is impossible to trigger the flow reversal and a long-lived jammed state survives.

From the experimental observation, the unidirectional particle flow in the channel, induced by the joint effects of the self-propulsion of the particles and the channel geometry, is one of the essentials responsible for the oscillation. To see this, the self-propelled particles are replaced by their passive counterparts (copper spheres) and other conditions maintain unchanged. It is found that both unidirectional flow and oscillatory behavior vanish, and the passive particles distribute uniformly in each chamber, as shown in the video (ESI†). On the other hand, the spontaneous periodic reversal of the unidirectional flow is another key factor for the oscillation. The two essential ingredients are influenced by many system parameters, such as the channel length and width, and the number of the active particles. In the following, we investigate the dependence of the collective oscillation behavior on the system parameters.

Total particle number effect on the oscillation

The total number of particles N significantly influences the periodic oscillation. With an appropriate range of N, the time evolution curves similar to Fig. 2(b) can be found, while the oscillation vanishes for too many or few particles. Due to the noise randomizing the oscillation, Fourier transform is employed to extract the oscillating frequency from the seemingly distorted evolution curves. The abscissa of the peak in the power spectrum $S(f)$ [see Fig. 3(a)] corresponds to the oscillating frequency. To characterize the oscillation intensity, an oscillating amplitude $\langle A \rangle$ is defined as the half ratio of the mean number of particles shuttling between two chambers during an oscillation period to the total particle number. As the total particle number increases, the oscillating frequency

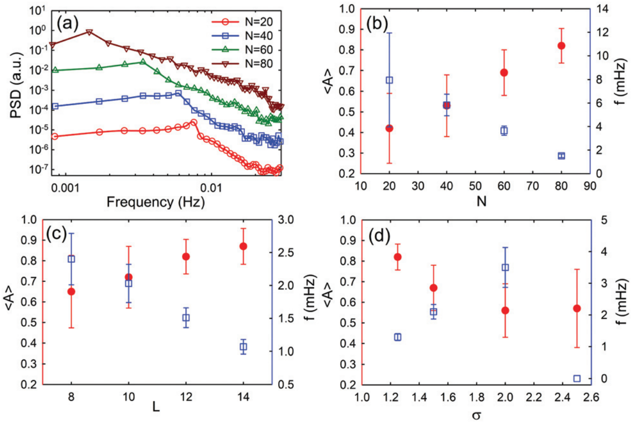

Fig. 3 (a) Power spectrum density (PSD) of the particle number evolution for different total number of the particles. The individual curves have been vertically shifted by dividing by 10^n with $n = 1, 2, 3, 4$, for clarity. The corresponding particle numbers are (from top to bottom) 80 (brown, triangle down), 60 (green, triangle up), 40 (blue, square), 20 (red, circle). The oscillating amplitude (red solid circle, left longitudinal axis) and frequency (blue open square, right longitudinal axis) as a function of (b) the total particle number N ($L = 12$, $\sigma = 1.25$), (c) the channel length L ($N = 80$, $\sigma = 1.25$), and (d) the channel width σ ($N = 80$, $L = 12$).

reduces [Fig. 3(b)], since the total migration time increases with N. In contrast, the oscillating amplitude increases with N, as more particles are involved in the migration from one chamber to another. The dependences of the oscillating frequency and amplitude on the N are consistent with those obtained in the previous numerical work.[31] To further compare with the numerical work, we experimentally measure the distributions of the particle number difference between the two chambers at different N, which exhibit a bimodal feature and are very similar to those in ref. 31 (see the ESI†).

Channel length effect on the oscillation

One of the crucial factors influencing the unidirectional flow of the particles in the channel is the channel geometry. We first focus on the role of the channel length L on the collective oscillation. The oscillation amplitude increases monotonically with the channel length. This is because the unidirectional flow becomes more stable in a long channel, driving more particles to migrate between two chambers. For example, the unidirectional flow in a long channel with $L = 14$ is stable and difficult to reverse; while the unidirectional flow in a relatively short channel with $L = 8$ changes its direction more easily, thus weakening the directed migration of active particles. Too short channels will eventually destroy the unidirectional flow, hence break the periodic oscillation. Moreover, as the channel length increases, particles cost more time to travel through the channel, leading to a declining trend of the frequency [Fig. 3(c)]. As a result, the increase of the channel length improves the quality of the periodic oscillation, suppressing the stochasticity in the reversal of the unidirectional flow.

Channel width effect on the oscillation

The channel width σ, like the channel length, also affects the unidirectional flow and the spontaneous oscillation. Fig. 3(d) shows the dependences of the oscillating amplitude and frequency on the channel width. The reducing tendency in the amplitude implies that the flow reversal becomes easy with increasing σ, namely the stability of the unidirectional flow weakens. On the other hand, the frequency rises with σ, since a wide channel allows for the entry of the particles from the chamber easily and thus effectively enhances the flow. However, as the channel width exceeds a threshold (*i.e.*, σ = 2.5 in our system), the channel flow is no longer unidirectional, such that particle clogging and stochastic flow reversal in the channel often happen. The absence of the stable unidirectional flow causes a sharp deterioration of the oscillating periodicity, so a nonzero oscillation frequency cannot be extracted from the experimental data [see Fig. 3(d)]. In order to provide more quantitative conditions under which the oscillations appear or disappear, we plot the phase diagram of the collective behavior of the active granular system in the parameter space of the channel length *versus* channel width in the ESI.†

Theoretical model

To clarify the physical mechanism of the spontaneous collective oscillation, a minimal theoretical model is constructed based on the fact that the reversal of the unidirectional flow will not be triggered until the total self-propelling force contributed by the active particles in the channel vanishes, meaning that the numbers of the active particles with two opposite polarities in the channel are roughly equal [see Fig. 2(a-III)]. The force balance condition triggering the flow reversal is established as follows.

The experimental observation shows that, during the stationary unidirectional flow, the channel basically contains the active particles only from the "source" chamber, such that the number density of particles in the channel, n_c, is the same as that of the source chamber, n_l, namely $n_c = n_l$. Thus, just before the flow reversal, the number of particles in the channel is $N_c = n_lL\sigma$, and hence the mean interparticle separation is $\Delta L = 1/n_l\sigma$. At this moment, when the forefront particle in the unidirectional flow enters the sink chamber with a high number density n_h, a space ΔL will be left at the end of the channel close to the sink chamber. Then, the active particles (moving against the original unidirectional flow) from the crowded chamber soon enter the channel and meet the unidirectional flow at a position $(\Delta L - L_0)/2$, away from the end of the channel near the crowded chamber (with L_0 the particle length). Consequently, in this situation, there are $n_h\sigma(\Delta L - L_0)/2$ particles in the channel, which come from the crowded chamber. We can thus write down the reversal condition of the unidirectional flow,

$$\frac{n_h\sigma}{2}\left(\frac{1}{n_l\sigma} - L_0\right) = n_lL\sigma - 1 \qquad (1)$$

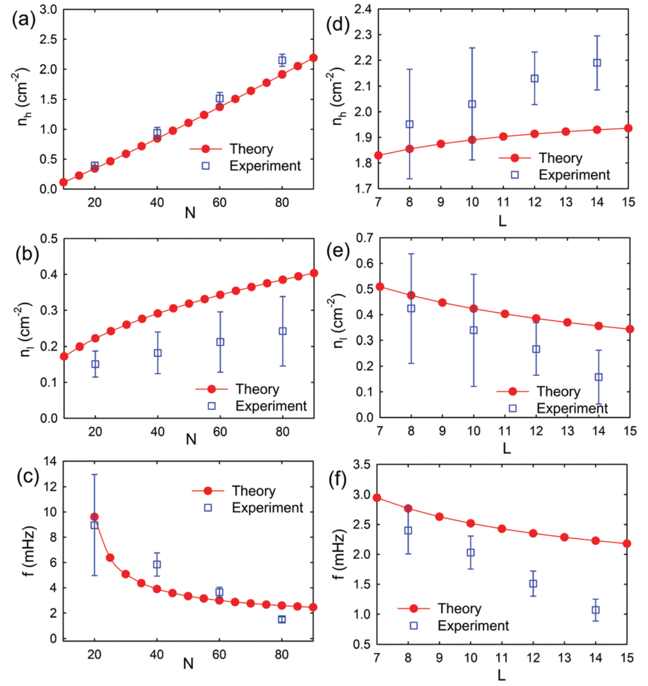

Fig. 4 Comparison of experimental and theoretical results. (a) high number density of particles n_h and (b) low number density of particles n_l at the flow reversal moment as a function of the total particle number. (d) n_h and (e) n_l *versus* the channel length. The oscillation frequency as a function of (c) N with L = 12 fixed, and (f) L with N = 80 fixed.

eqn (1) can be solved by combining the conservation equation of total particle number,

$$(n_h + n_l)S + n_lL\sigma = N \qquad (2)$$

with S the surface area of a chamber. Here, the second term on the left side of eqn (2) corresponds to the number of particles in the channel.

From eqn (1) and (2), we can determine the number density n_h and n_l in two chambers at the spontaneous reversal moment of the unidirectional flow. Fig. 4(a) and (b) show that both n_h and n_l increase with N, when the channel length is given. On the other hand, for a fixed N, n_h grows while n_l drops with the increase of the channel length, as plotted in Fig. 4(d) and (e). The theoretical results semiquantitatively and even quantitatively agree with the experimental measurements, without any fitting parameter. Since the number of particles shuttling between two chambers in an oscillating period is $2(n_h - n_l)S$, the oscillation amplitude directly reads $\langle A\rangle = (n_h - n_l)S/N$, which is also in agreement with the experimental results (not shown).

Further, we theoretically calculate the oscillating frequency based on the minimal model. The oscillating period can be expressed as

$$T = 2\int_{N_l}^{N_h}\frac{dN'}{J}. \qquad (3)$$

Here, $J = V_0\sigma N'/S$ is the flow rate of particles in the channel, with N' the particle number in the source chamber and V_0 the self-propelled velocity of an isolated active particle, and $N_l = n_l S$ ($N_h = n_h S$) refers to the minimum (maximum) number of the active particles in the chamber. From eqn (3) together with the above obtained n_h and n_l, the oscillating frequency can be easily calculated, as plotted in Fig. 4(c) and (f), which is consistent with the experimental measurement.

The minimal theoretical model, without free parameter, properly reproduces the particle number densities at the flow reversal and the oscillation amplitude and frequency of the experimental systems, indicating that it correctly captures the physical essence of the spontaneous population oscillation of the active granular particles. Nevertheless, the theoretical model is deterministic and does not account for the stochasticity of the collective oscillation. Here, three main factors that are responsible for the stochasticity of the oscillation have been ignored, including the randomness of the self-propulsion of active particles, the nonuniform separation between the particles in the channel, and the rare event of the active particles in the sink chamber entering the channel before the flow reversal. In addition, the minimal model does not consider the effect of the particle number density in the chamber on the entry of the particle into the channel. Another important assumption of the minimal model is the equality between the number density of particles in the channel and in the source chamber, $n_c = n_l$. Through direct experimental measurement, we find that $n_c = 1.43n_l$ is a more precise relationship in the range of parameters studied. Using the improved relation yields a better quantitative agreement with the experimental data (see the ESI,† for more details).

According to the proposed theoretical model, the physical picture for the emergence of the spontaneous population oscillation of the confined active system can be summarized as follows: first, the narrow channel, as a collimator, leads to a unidirectional flow of the active particles. Second, the long channel, as an innate amplifier due to accommodating more active particles, can stabilize the unidirectional flow and suppress the random entry of particles into the channel from the sink chamber, thus establishing a population difference between two chambers. Last, the competition between the forces from the unidirectional flow and the particles from the crowded sink chamber periodically triggers the flow reversal.

Conclusion

In the work, we have experimentally demonstrated the spontaneous population oscillation of self-propelled granular particles in confinement, and verified the intriguing phenomenon predicted by the previous simulation. We show that the frequency and amplitude of the collective oscillation significantly depend on the system parameters, including the number of particles and the channel length and width. Furthermore, we put forward a minimal theoretical model, which captures the essential mechanism underlying the spontaneous collective oscillation and properly reproduces the experimental data without fitting parameter. The present experiment of the dry active matter could stimulate further investigation using other types of active systems, where hydrodynamic interactions are also unimportant. Nevertheless, it remains an interesting question how hydrodynamics influences the spontaneous population oscillation.

Conflicts of interest

There are no conflicts to declare.

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