Dynamics of passive tracers in a bath of self-propelling granular particles

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Abstract. We report on our experimental investigation of the dynamics of a passive tracer in a bath of active self-propelling granular particles. We found a caging like dynamics of the passive tracer such that for low active particle concentrations the passive tracer exhibits longer periods of inactivity. For increasing active particle concentration the occurrence of short period inactivity increases.

1. Introduction

Active matter consists of systems wherein constituent particles undergo self-propulsion due to energy supplied to each of the particle. Due to the constant supply of an energy source and that this energy is also dissipated, active matter is a good example of a system far from equilibrium. For instance it was found out that the mobility of bacteria is affected by the amount of food present in the surrounding medium [1]. Self-propelling colloidal particles also constitutes active matter [2]. Pattern formation is an interesting consequence of a bath containing active particles. Biological examples range from flocking type motion of birds and fishes to spiral wave dynamics of the motion of a microorganism, Dictyostelium discoideum [3-4]. Although a general framework wherein one can understand different active matter systems is still lacking, there has been consistent effort to find a general theory of active matter. Recently physicists have found interest on active matter system due to the interesting prospect of applying results in statistical mechanics to some properties of active matter [5-6].

A particular problem of interest is how to characterize active bath. Two approaches have been gaining steam on this. First is to do single particle tracking of one of the active particles. For the trajectories one can obtain correlations that can be used to describe the system [7]. The second approach is putting a passive tracer in the active medium. The mean square displacement of the passive tracer is then used to describe the dynamics of the active medium [8].

A granular bath containing self-propelling granular particles constitutes an active bath [7]. Already in our previous experiment we found that the active granular bath can be used to extract energy to perform work [9]. In this paper we are interested on a general way to characterize active granular bath. Our preferred approach is to use a passive tracer. There are many types of active
granular particles and characterization of these active baths by the same passive tracers could reveal a general picture of the dynamics of active matter.

2. Experiment methodology
The experimental set-up consists of a bath of active particles on an acrylic platform driven out of equilibrium by a shaker (see figure 1). The active particle has a head and a tail part. The head of the active particle is a rectangular prism shaped acrylic (6.7 x 6.7 x 10mm) and this is coupled to 7 loosely connected metal beads (5mm dia.) forming the tail. We varied the number of active particles used in this experiment from 3, 10, 20, 40, 50, and 68 particles. This corresponds to area fractions $\Phi = 0.0063, 0.0211, 0.0421, 0.0842, 0.105$ and 0.1433 where the area fraction is defined as the ratio of the total body area of the active particles to the area accessible to the active particles $A = 212.42 \text{ cm}^2$. To characterize the random motion of the bath we use a Styrofoam disk (7mm thickness and 26mm dia.) with a reference dot (5mm dia.) for tracking.

Figure 1.(a) Active particles and passive particle in the vibrated acrylic substrate. (b) Schematic diagram of experimental set-up.

Active particles require a constant supply of energy to move around the acrylic platform. This is achieved by vibrating the shaker with a constant frequency set at 28 Hz. At this frequency the active particles move head first then turn randomly which allows it to explore the bounds of the platform. The amplitude of oscillation is kept constant throughout the whole experiment.

The boundary of the acrylic platform (170 x 170 x 5mm) used in this experiment has curved shapes to prevent jamming of active particles that would happen on the corners of a square platform. The curved shapes ensure the smooth movement of the active particles throughout the acrylic platform.

A camera placed on top of the vibrating acrylic platform monitors the each experimental run at 30 frames per second. The video recording of each experiment is deconstructed into a series of images using Virtualdub and then the images are processed by our own particle tracking software written in IDL. Our software detects the intensity difference in the grey scaled images; using this information it can calculate for the position of the reference dot on a passive tracer via centroid algorithm. The result from this procedure gives information of the passive particle’s position in pixels. Using a scaling factor we can convert the number of pixels into units of distance. We obtain tracking resolution better than 0.1 mm. We gathered 2000 images per experimental condition.

3. Results and discussion
When we turn ON the shaker we observe the active particles exploring the bounds of the acrylic platform sometimes colliding with each other, the walls of the boundary or colliding with the
Styrofoam disk that we are using as a passive tracer for the experiment. When the active particle(s) collide with the tracer, momentum is imparted onto the tracer causing it to move. The tracer’s displacement varies depending on the net impulse delivered to it.

\[ \Delta i = \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2} \]

where \((x_i, y_i)\) is the particle position computed at a frame \(i\). We found that the displacements fitted a normal curve with a mean around zero. However we found deviation to the Gaussian distribution for higher concentration of active particles where we were able to see non-Gaussian tails, figure 2c, such as the case when \(\Phi = 0.105\). Currently the precision of our data is not sufficient to see a clear trend on this property of the probability distribution. We note that the presence of Gaussian and non-Gaussian tail in a probability distribution is a signature of a system far from equilibrium.

3.1. Dwell time statistics during caging

From the trajectory we found that the passive tracers undergo a caging-like dynamics, i.e. they are immobile at some time until hit by an active particle whence they move. In the following section we examine the cage like dynamics manifested by the passive tracer at different active particle concentration. Figure 3a is the trajectory of the passive tracer for \(\Phi = 0.0063\). We can see there are
periods of movement (run) and stagnation (caging). The curve describing the path of the passive tracer becomes very dense if little or no motion occurs. Examples of the inactivity are highlighted in the passive tracer trajectories in Figure 3a. To characterize this type of dynamics we measure the dwell time, i.e. the total time the particle is inside the cage. We set a threshold of displacement of < 0.1 mm between succeeding particle positions to determine if the particle is in a cage. The dwell time is then the total time spent by the tracer when its displacement is below the threshold. Figure 3b is the histogram for the distribution of time intervals of the inactivity of the tracer. We see that there are instances of relatively long inactivity for the tracer in a bath of 3 active particles.
The long intervals of inactivity are attributed to the low probability of impact between the passive tracer and the active particles.

For larger concentrations of active particles such as in figure 3c and figure 3e the periods of inactivity are smaller as evidenced by the more convoluted trajectory of the tracer. This is supported by the histograms of the dwell times in figure 3d and figure 3f. Both histograms in figure 3d and figure 3f show a decrease in large time scale inactivity owing to the increase in probability of collisions. Another noticeable attribute of the histograms is the increase in short time scale inactivity as the number of active particles increase. To highlight this observation we plot the mean dwell time as a function of the number of particles in figure 4. We found that the mean time exponentially decays with $\Phi$.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure4.png}
\caption{Exponential decay fit of mean inactivity time of the passive tracer for $\Phi$. The solid line is an exponential fit $y = A_1 \times \exp(-x/t_1)$ with $A_1 = 1.046$ and $t_1 = 34.42$}
\end{figure}

4. Conclusion
We found that the length of inactivity of the passive tracer decreases with increasing $\Phi$ which implies higher probability of collisions of the tracer with the self-propelling particles at higher concentration of the latter. Moreover we found that for higher values of the area fraction the probability distribution of $\Delta$ yields a Gaussian part with a non-Gaussian tail. Non-Gaussian tails are not seen in the probability distribution of the displacement for $\Phi < 0.02$. This work can be extended to other types of active granular particles. If the dynamics is consistent with this work we might be able to find a general picture of active granular particles.

5. References
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