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THE COLLECTIVE DYNAMICS OF SELF-PROPELLED PARTICLES

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Summary We propose a method that can be used for the dynamic simulation of a collection of self-propelled particles. In our description, each particle is treated as a rigid sphere with a force dipole of constant magnitude. In isolation, it would move at constant velocity set by the magnitude and direction of the force dipole. When it coexists with many such particles, its hydrodynamic interactions with other particles rotates it and therefore changes its direction of motion, and also induces an additional stresslet on it. We have adapted the Stokesian Dynamics technique to simulate up to 80 active particles in unbounded domain. Our simulations show the streaming motion of active particles, similar to that observed in a previous study. The velocity distribution is highly non-guassian, in contrast to that of sheared passive particles.

INTRODUCTION

Self-propelled (or “active”) particles, such as bacteria, spermatozoa and other microorganisms, exhibit several intriguing features in the collective dynamics, such as the spontaneous formation of spatio-temporal patterns, convection cells etc. The driving force for the patterms can be a spatial variation in the concentration of chemical species, called chemotaxis, or an external body force such as gravity, called gravitaxis. Bioconvection, is an example of the latter, where the motion of the microorganisms against gravity induces a Raylegh-Benard type instability. Understanding these phenomena is important from a purely scientific viewpoint, but this knowledge is also of potential utility in cell biological applications.

Previous attempts [1] at modelling the collective dynamics of self-propelled particles have either been phenomenological or at a coarse-grained level where the particles are treated as constituting a phase, and hence the concentration field describes the nature of the system. These treatments cannot correctly describe the microstructures that form at the length scale of a few-to-several particle diameters, and may therefore to miss the fluid mechanical phenomena that result from them.

THE MOTION OF AN INDIVIDUAL SELF-PROPELLED PARTICLE

Many studies have investigated the motion of a single active particle, from the point of view of its fluid mechanics [2] as well as its biophysics and biomechanics [3]. Typically, a single microorganism in a fluid medium swims a distance of roughly 3 to 50 times its own size every second, and randomly changes its direction of motion after swimming a distance of roughly 10-100 times its size. The motion of the particle can be driven by the beating of its flagella or cilia, spiral motion of a single flagella, or sometimes even a reversible polymerization/de-polymerization reaction at one end of the organism. However, the mechanism of propulsion is not very important in analysing the fluid mechanics around these particles. As the particles are self-propelled, and not by an external force, far away they appear as point dipoles [4].

COLLECTIVE DYNAMICS

We model a collection of active particles as a collection of hydrodynamically interacting force dipoles. Each particle is treated as a rigid sphere with a force dipole of constant magnitude. In isolation, it moves at constant velocity set by the magnitude and direction of the force dipole. When it coexists with many such particles, its hydrodynamic interactions with them rotates it and therefore changes its direction of motion, and also induces on it an additional stresslet. As a result, interactions between particles tend to randomize the orientation, and hence the velocity, of the particles. We have adapted the Stokesian Dynamics [5] technique to simulate up to 80 active particles in unbounded domain. Our simulations are for a monolayer of active particles, i.e. the particles are constrained to lie in a plane at all time. The sequence of snapshots in the simulations clearly show the streaming motion of active particles, similar to that observed for bacteria in freely suspended film [6].

The velocity distribution of the particles, shown in figure 1, has peaks at $\pm v_0$, the speed of a isolated self propelled particle, a ‘crater’ at speeds less than v_0, and decays rapidly at velocities larger than v_0. Note that though the distribution is roughly symmetric about $v = 0$, it is is quite different from a Gaussian distribution. This is very different from the distribution of particle velocities in sheared suspensions of “passive” particles, which is approximately Gaussian. The mean square displacement of the particles varies approximately lineary with time for large time (not shown), implying that the collective motion of the particles is diffusive.

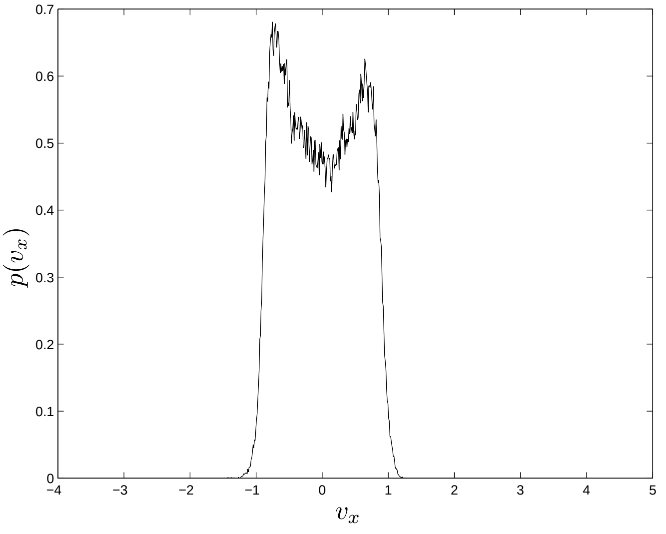

Figure 1. The probability density of the velocity in the x direction for a suspension of active particles of 10% area fraction.

CONCLUSION

Our preliminary results indicate that hydrodynamic interactions alone yield a rich structure in the collective dynamics of self propelled particles. We intend to also incorporate forces on the particles that mimic chemitaxis and gravitaxis, and thereby study physically realistic systems.

References

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