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Pattern formation and collective effects in populations of magnetic microswimmers

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Abstract

Self-propelled particles are one prototype of synthetic active matter used to understand complex biological processes, such as the coordination of movement in bacterial colonies or schools of fishes. Collective patterns such as clusters were observed for such systems, reproducing features of biological organization. However, one limitation of this model is that the synthetic assemblies are made of identical individuals. Here we introduce an active system based on magnetic particles at colloidal scales. We use identical but also randomly-shaped magnetic micropropellers and show that they exhibit dynamic and reversible pattern formation.

Keywords: active matter, magnetic micropropeller, microswimmer

Supplementary material for this article is available online

Coordinated movement is a widespread phenomenon [1] observed, for example, in colonies of bacteria [2, 3], flocks of birds [4], or human crowds [5]. Controlled experimental studies of such phenomena have been particularly fruitful at the microscale, for example, using biological molecular motors and filaments, or colloidal particles can be produced in very large numbers with relative ease and can be observed in controlled environments. While investigations of the interplay between biological molecular motors and filaments have led to various discoveries, and continue to be an important area of research [6–9], the main drawbacks of these biological systems include the difficulty and cost of purifying filaments and molecular motors and their limited long term stability. In addition, in such cases, the motor trajectory is predetermined by the filament track. Developing a synthetic equivalent at small length-scale will be of potential interest for reaching effective doses in drug delivery [10] or for environmental applications [11]. Therefore, the coordinated movement of synthetic systems has started to be investigated as well. These include photoactivated colloidal particles [12], self-propelled colloids [13] and colloidal rollers driven by Quincke rotation [14]. However, in these cases, the population is composed of identical particles, so developing an alternative system would constitute a step forward in reflecting the natural variability observed for bacteria or birds.

Magnetic fields can be used to control the assembly and function of synthetic structures [15–18]. Using magnetic fields, dynamic self-assembly experiments with colloidal particles have been performed [19, 20]. At the same time, the rotation of individual complex-shaped structures in water has recently been studied in the field of magnetic micro- and
nanopropellers [21–27]. Here we show that such differing propellers, when actuated by rotating magnetic fields, form field-dependent patterns.

We used identically shaped helical micropropellers made by glancing angle deposition (GLAD) [22], and also performed experiments with randomly shaped propellers [28]. The latter are based on magnetite nanoparticles glued together by hydrothermal carbonization (see the supplementary material ‘materials and methods’ (stacks.iop.org/JPhysD/50/11LT03/mmedia)). Electron microscopy images of the two propeller types are presented in figures 1(a) and (b).

In a typical experiment, a highly concentrated suspension of propellers is inserted in a capillary and imaged in a custom-designed microscope equipped with three orthogonal Helmholtz-coil pairs [28]. The propellers are then subjected to a rotating magnetic field, which in turn leads to rotation and thus translatory movement of the propellers (schemes in figures 1(c) and (d)). When fields of suitable field strength and frequency are applied (2 mT and 30 Hz in figure 1(f)), the propellers will eventually reach the top capillary surface and form clusters at the water–glass interface. The propellers have no directed motion in this configuration but keep rotating individually with the field frequency around their individual axes of rotation when assembled into a cluster (see video ‘cluster example 1’).

However, the observed patterns are by far richer than this simple clustering. We indeed obtained long chains forming at low frequencies, clusters at intermediate frequencies and small aggregates at high frequencies (figures S1(d)–(f)). As such, our results show that cluster formation is a generic phenomenon...
different sizes and volume magnetization (simulation part in the identical properties, as well as groups of propellers with different sizes and volume magnetization). The transition for forming a boundary layer is quite sharp, lying between 155 and 160%.

We performed simulations for groups of propellers with saturation magnetization of maghemite. The percentage values indicate the magnitude of the discrepancy between the simulations and measurements is due to the crude approximation of the propellers as spheres with complex shapes. The relatively large discrepancy between the simulations and measurements is due to the crude approximation of the propellers as spheres with complex shapes. The general trend and the order of magnitude are nevertheless the same in both simulations and experiments. (b) The average angular velocity is plotted against the distance from the cluster center as above, now focusing on simulations using 196 identical propellers. We indeed report on the effect of magnetization on the formation of the boundary region. The percentage values indicate the magnitude of the magnetic moment of the propellers with respect to the standard value of maghemite (100% corresponds to $1.2 \times 10^{-14}$ Am², or 1.5% of the saturation magnetization of maghemite).

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While the angular velocity in the boundary region does not depend strongly on the propeller properties, the angular velocity of the propellers near the cluster center drops quickly for clusters consisting of identical propellers. The inset highlights this difference: the angular velocity at a distance of 5 μm from the cluster center is plotted against the number of propellers in the cluster. The blue crosses are simulations with different propeller properties, the red circles correspond to simulations with identical propellers and the black squares are experimental data for identical propellers. For the experimental data, the number of propellers was estimated based on the cluster size, and the angular frequency was measured via a Fourier transform of the central region at different time points. The angular velocity of the randomly shaped micropropellers is not depicted as it cannot be determined experimentally by this technique. The relatively large discrepancy between the simulations and measurements is due to the crude approximation of the propellers as spheres with complex shapes.

Results are plotted for 36, 100, 196, 324, 484, 676, and 900 propellers in a cluster. Clusters larger than 36 propellers show a boundary region in which the angular velocity of the propellers is increased. With growing cluster size, the rotation frequency of the cluster drops. The angular velocity of the randomly shaped micropropellers is not depicted as it cannot be determined experimentally by this technique. The relatively large discrepancy between the simulations and measurements is due to the crude approximation of the propellers as spheres with complex shapes. The general trend and the order of magnitude are nevertheless the same in both simulations and experiments. (b) The average angular velocity is plotted against the distance from the cluster center as above, now focusing on simulations using 196 identical propellers. We indeed report on the effect of magnetization on the formation of the boundary region. The percentage values indicate the magnitude of the magnetic moment of the propellers with respect to the standard value of maghemite (100% corresponds to $1.2 \times 10^{-14}$ Am², or 1.5% of the saturation magnetization of maghemite).

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hydrodynamics of the propellers of random shapes moving upwards and towards a glass interface are from the rotating spheres that have sedimented. The use of magnetic micropropellers instead of spheres, however, opens up vast possibilities for more complex actuation patterns, since the magnetic propellers can move through water.

As a summary, the systems based on random-shaped magnetic microswimmers and the associated observed cluster formation may be thought of as a synthetic analog of living systems. Our system indeed goes beyond the typical colloidal active matter as it not only reproduces the variability in the population of biological organisms, but also their capabilities of reversible assembly.

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References