Synchronized locomotion of freely suspended disjoint microbeads pairs

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The possibility of locomotion of a pair of disjoint spherical microbeads suspended in fluid is investigated experimentally. The beads interact magnetically and their nonreciprocal relative movements are coordinated using external uniform magnetic field. Locomotion is studied and demonstrated for cyclic swirling movements of the beads which mimics behavior often observed in bacterial swarms. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3132582]

The ability of tiny living creatures to propel themselves through fluid[1–4] has inspired a search for miniature mechanical devices that can mimic such locomotion. In the past few years, several types of mechanical devices simulating individual swimmers have been described.[5–8] Swimming of a linked chain of microspheres actuated magnetically has been demonstrated experimentally.[8] Living micro-organisms can also take advantage of hydrodynamic interaction to create collective locomotion, sometimes referred to as swarming.[9–11] Collective locomotion may provide certain advantages. One is that individual devices employed to achieve collective locomotion may be simpler to construct because they would not necessarily require the means for self-propulsion.

Collective locomotion of two disjoint spherical beads, each obviously unable to swim on its own, is demonstrated in this work. The main idea behind this demonstration is that simple disjoint objects such as beads can push and pull each other causing locomotion of the collection (pair in this case) using electric or magnetic fields, which can be due, for example, to their internal polarization. It is shown here that nonreciprocal relative motion of the beads can be created using magnetic field, although electric field could be employed in principle to achieve a similar result. Nonreciprocal relative motion is an essential requirement for locomotion[12] and two degrees of freedom existing in a system consisting of only two beads are sufficient to create this motion. Previous theoretical and experimental demonstrations of swimming employed devices with more than two degrees of freedom or used proximity of a substrate. In fact, the possibility that only two beads are sufficient to achieve swimming was questioned previously,[13] although later theoretical work corrected the initial errors.[14]

It is important to stress that the external magnetic field which is employed here to induce magnetic interactions between the beads is largely uniform and, therefore, does not apply any net force on the bead pair. The distinction between using magnetic field gradients and uniform magnetic fields is an important one. Gradients have been widely applied for separation and manipulation of materials, including both the manipulation of magnetic materials in nonmagnetic fluid,[15–17] and the manipulation of nonmagnetic materials in magnetic fluid.[18,19] However, in many applications, it is difficult to create sufficient field gradients from remote magnets. For this reason the results reported here could be of practical significance.

One of the difficulties in carrying out demonstrations of bead locomotion is the ability to keep them at a fixed level for imaging with a microscope. It is known[19,20] that nonmagnetic beads placed into magnetizable fluid kept between nonmagnetic substrates will experience forces helping them maintain a fixed level between the substrates when the magnetic field is applied to the system. This could be viewed as a form of diamagnetic levitation. Moreover, the beads will interact with each other magnetically, despite being nonmagnetic themselves, due to the difference in their magnetic susceptibility with the fluid.[19]

As illustrated in Fig. 1, the experimental demonstration is carried out using pairs of glass beads (BioSpec Products Inc.) suspended in oil-based ferrofluid (Ferrotec Corporation, type EFH1), which is contained between two glass slides separated by a 1.4 mm hydrogel spacer. The ferrofluid has a dynamic viscosity of 0.06 P, a density of 1.21 g/ml, and an initial magnetic susceptibility of 1.7. In order to make the ferrofluid more transparent to light, thereby enhancing the optical observation of the glass beads, we diluted it using light-mineral oil, with a dilution ratio of 1:5. The ferrofluid/glass bead assemblies are sealed using optical glue on all sides to avoid possible drying and evaporation. Several ferrofluid/glass bead assemblies were prepared, with some assemblies containing beads of different diameters (1.0 and 0.7 mm), while others contained beads of the same diameter (1.0 and 1.0 mm).

Uniform fields are applied both in the plane of the glass slides, as well as perpendicularly to them (Fig. 1). To test the field uniformity, we make sure that the bead pairs experience no net movement when the field is held constant. The perpendicular field component is created using an axially magnetized NdFe permanent ring magnet (1 in. outer diameter, 1/2 in. inner diameter, and 1/4 in. thickness) whose pole was placed at an adjustable distance below the ferrofluid/glass bead assembly. A light source is placed in the center of the permanent magnet ring in order to permit dark field imaging of the beads (the beads transmit light better than the ferrofluid). The perpendicular field component is responsible for repulsive forces that keep the beads separated from each other and positioned away from the top and bottom glass slides. This field component is held constant throughout each experiment. The repulsion from the top and bottom glass slides occurs due to the negative susceptibility difference at the ferrofluid/glass interface, which, in the presence of the

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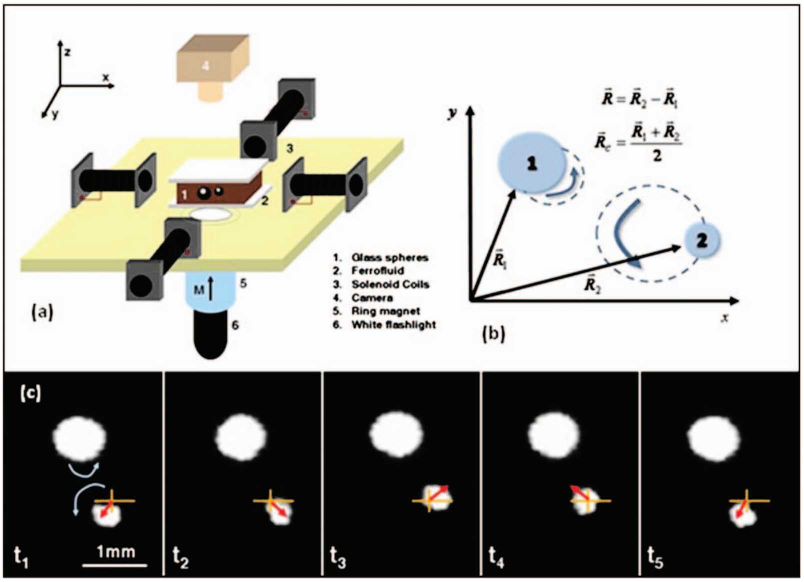

FIG. 1. (Color) (a) Illustration of the experimental setup used for the demonstration of swimming. (b) Illustration of bead trajectories. Relative distance between the beads is defined as R and the center of reaction is defined as R_c. (c) Five experimental snapshot images of the two beads suspended in ferrofluid as a uniform rotational field is applied. The beads rotate counter-clockwise as depicted by the blue arrows seen in the first frame. The times t_1, t_2, t_3, t_4, and t_5 correspond to 1, 2, 3, 4, and 6 s, respectively.

perpendicular field, results in effective image dipoles oppositely magnetized to the real beads.[19,20] In fact, the ability of the beads to remain stably suspended in the focal plane of the microscope is the primary reason for using this experimental set up. Magnetic beads with positive magnetic susceptibility cannot be suspended in a nonmagnetic fluid in the same fashion, as is well-known from the classical Earnshaw theorem.[21]

The magnetic interaction force between the beads is modulated by varying the direction and magnitude of the in-plane component of the external uniform field. The in-plane field produces two force components on each bead: one perpendicular to the line between the bead's centers and one parallel to the center line. These two force components cause the beads to move in a synchronized fashion along the in-plane trajectories which results in the locomotion of the bead pair. Dynamic uniform magnetic fields, controlled using National Instrument's LABVIEW, were created with two Kepco bipolar operational power supplies/amplifiers, attached to solenoids coils (2.8 cm inner diameter, 550 turns). A camera (Basler A601F Firewire IEEE-4394), capturing 30 frames per second, was used to record the motion dynamics of the glass beads. Real-time image acquisition and processing was performed using the NI Vision Development module. Position tracking software is tested by confirming that the time evolution of the mean square change in position is linear in time over the time scale of hours following the expected Brownian motion relation[22] in the absence of any field. It was also confirmed by fixing the bead's position that error due to imaging and tracking software and hardware was about 4 μm for a 1 mm bead.

We employed a superposition of rotating and constant magnetic field in the plane of the glass slides. When rotating uniform fields in the range of 300–320 G at 0.2 Hz, with a uniform constant perpendicular field of magnitude 70–90 G, were applied, the glass beads were experimentally observed to roughly follow a circular trajectory, as shown in the series of snapshots in Fig. 1(c). Given the bead velocity of about 1 mm/s, its size, fluid viscosity, and its density, the Reynolds number for the beads is between 10^{-3} and 10^{-4}, indicating that viscous effects dominate the inertial effects. The overall motion of the bead pair was clearly observable over a number of cycles. However, drift flow of the ferrofluid itself cannot be ruled out in the observations. Indeed, such ferrofluid drift flow is well-documented,[23] occurring due to the torque on individual magnetic nanoparticles and their resulting rotation which is transferred to the fluid.

In order to verify the presence of such fluid drift and to measure its velocity, one of the beads from the pair is positioned at the edge of the ferrofluid assembly (ensuring no bead interaction), while the other bead is brought to the same initial position as that of the original bead pair. Individual beads can be manipulated in the assembly by using a small (1 mm pole diameter) permanent magnet. The motion of the isolated bead, under the same field variation as applied to the bead pair, is recorded. Although this motion is sensitive to the initial position of the bead, when measured in a sequence of similar experiments, this is proved to be highly repeatable and is taken to be equal to the fluid drift. The magnitude of this motion appeared to be proportional roughly to the distance of the bead from the center of the ferrofluid drop. Subtracting the recorded trajectories of the isolated drifting bead from the recorded trajectories of the bead pair, we obtained the trajectory which revealed locomotion of the bead pair with respect to the fluid. The resulting movement of the pair over a number of field cycles is shown in Fig. 2 for bead pairs of the same (1.0 and 1.0 mm) and of different (1.0 and 0.7 mm) diameters.

It is clear from Fig. 2 that for identical beads, the pair center displacement is small (of the order 10^{-5}) and does not substantially change as the number of field cycles increases. However, for the beads of different sizes, the center displacement is substantially larger (of the order 10^{-4}) and increases with the number of field cycles. Although it does not vary periodically, the relative distance between the beads remains bounded, as shown in the inset [Fig. 2(b)].

The fact that beads of the same size do not exhibit locomotion is consistent with previously published models.[12,14] It is also consistent with considerations of symmetry. For beads of different sizes the locomotion direction is not uniquely dependent on the direction of the constant and rotating field components. Roughly speaking, these fields determine the line along which the pair swims. The swimming direction is coincident with the average magnetic interaction force on the smaller bead and, therefore, depends on the initial relative

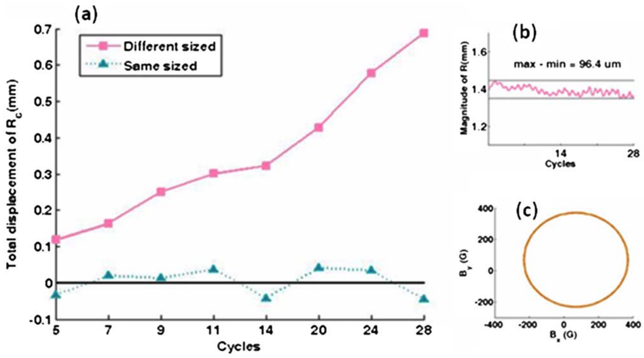

FIG. 2. (Color online) (a) Total displacement of the center of reaction R_c after drift removal for both experiments when different sized and same sized beads are used. Data points are shown for increasing time durations, from 5 field cycles to 28 field cycles. (b) The inset depicts the bounds of the relative distance of the two beads. (c) The inset depicts magnetic field profiles in x and y direction. The rotating uniform fields were approximately 300 G at 0.2 Hz and the constant uniform field was 70 G. The perpendicular field component was approximately 100 G.

position of the beads. In a way, the smaller bead acts as the main part of the system's motor, providing the push to move the bead pair. The larger bead plays the role of the attractor, which does not let the smaller bead get too far away.

To demonstrate that the behavior of the bead pair is in agreement theoretical predictions,[14] reciprocal relative movement of the beads was created by periodically turning on and off a constant magnitude uniform magnetic field. When the field was turned on, the beads moved slowly toward each other. When it was turned off, the beads moved apart due to repulsion induced by the presence of the fixed permanent magnet's perpendicular field. As expected, no drift flow of the ferrofluid was observed for such field variation and no net movement of the bead pair was observed after many cycles.

In summary, we have demonstrated that the locomotion of a pair of disjoint beads freely suspended in fluid is possible if their relative motion is coordinated. We show that this motion can be coordinated using a uniform magnetic field, however, other coordination mechanisms can be envisioned. This system can be regarded as a forerunner of a mechanical swarming system. In some sense, its behavior mimics that of some bacterial swarms. We believe that larger mechanical swarms consisting of many beads can also be constructed. This, however, requires proof through additional work. The present work also suggests possible strategies for locomotion of other simple nonsymmetrical objects. One intriguing possibility is locomotion of polar nonsymmetrical molecules in response to appropriate electric field coordination.

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