Steering of Magnetic Micro-Swimmers

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We experimentally investigate the motion of micro-swimmers consisting of several magnetic particles with different sizes. Swimmers are firstly formed by a static unidirectional field, and then manipulated by an additional dynamical perpendicular field. It is known that such magnetic-particle swimmers (or chains) driven by an external field would oscillate with the orientation of the field but lagging behind by a certain phase angle. In this work, we demonstrate if a swimmer subjected to a strong oscillating field which results in an instantaneous phase lag greater than $\pi/2$, the swimmer can be steered perpendicularly to its original direction. Detailed swimming mechanism and trajectory are presented. By this innovative steering technology, orientation of a micro-swimmer can be effectively manipulated without a physical reconfiguration of the external field arrangement.

***Index Terms*—Magnetic particles, micro-swimmer, oscillating field, steering mechanism.**

I. Introduction

MAGNETORHEOLOGICAL(MR) suspension is an artificial fluid composed of paramagnetic solid particles suspended in a nonmagnetic solvent. Research on the dynamics and aggregation processes of magnetorheological fluids subjected to dynamical magnetic fields have been studied intensively, such as in a rotational field [1]–[5] and oscillating field [6]–[9]. These early literatures reveal that the micro-chains under a dynamical magnetic field may behave from rigid body motion, bending distortions and rupture failures. Moreover, an oscillating microchain composed of superparamagnetic particles of different sizes has been successfully applied to mimic a micro-swimmer [6], [7]. Such a micro-swimmer possesses great potential applications in Bio-MEMS, e.g. transportation of biological cells [6]. Li *et al.* [7] created re-dispersible artificial micro-swimmers by simply chaining beads, instead of enhancing bonding forces by DNA. Sufficient propulsion can be generated to drive the simplified swimmers forward. Nevertheless, these micro-swimmers can only generate thrust to move toward the direction along the oscillating axis of the field. It is naturally desired if the swimming orientation can be effectively manipulated for more robust applications. An apparent way to steer the swimmer is the reconfiguration of external fields and alter the field oscillating axis to desired orientation. Nevertheless, such a field reconfiguration involves an instantaneous switch of input currents to the correspondent coil pairs. In this work, we propose an innovative and much simpler methodology to effectively manipulate the orientation of the micro-swimmers. The methodology applies a newly identified phenomenon, referred to as "trajectory shift" [9], in which the chain aligns perpendicularly to the external field when the phase angle lag (defined as the value of phase angle of the dynamical field ahead of the oscillating chain) exceeds $\pi/2$. Detailed swimming mechanism and trajectories of steered swimmers are presented to demonstrate the applicability of such technology.

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II. Experimental Procedure

The experimental procedure in this work is mostly the same with what has been addressed in Li *et al.* [7]–[9]. Micro-sized magnetic particles are initially dispersed in distilled water. The particles used in our experiments are superparamagnetic polystyrene microspheres coated with iron oxide grains produced by Invitrogen Life Tech. The mean radius of the microspheres (denoted as a) are 2.25 μm and 1.4 μm, with susceptibility of $\chi = 1.6$ and 1.0, respectively. A static unidirectional magnetic field, denoted as H_d, is generated first by a pair of coils powered by DC power sources. This static field is applied to form the swimmer. Another pair of coils are placed perpendicularly to the former pair and connected to AC power supplies to generate a sinusoidal dynamical perpendicular field (H_v) with a maximum field strength H_p and frequency f, so that $H_v = H_p sin(2\pi ft)$. This additional perpendicular field and the original static directional field result in an overall oscillating field (H) of $H = H_d i + H_v j$, in which i and j are unit vectors in the directional and perpendicular axis, respectively. Under such a field configuration, the phase angle (θ) trajectory of the external field is prescribed as $\theta(t) = tan^{-1}[(H_p/H_d)sin(2\pi ft)]$. Representative snapshot images of the swimmer's motion, modified from the recorded movies (http://www.youtube.com/user/athomeli#p/u) by improving their contrasts and resolutions, are presented.

III. Results and Discussion

A. Steers of Micro-Swimmers

An effective steering manipulation is demonstrated first. Fig. 1 shows the sequential images of a swimmer consisting of two small and two large particles (denoted as an S2L2 swimmer) in a constant directional field strength of $H_d = 24.15$ Oe. The oscillating frequency is increased by 3 stages, such as $f = 1$ Hz, 5 Hz and 10 Hz at $\mathrm{t} < 1$ s, $1\ \mathrm{s} < \mathrm{t} < 5$ s and $\mathrm{t} > 5$ s, respectively. A perpendicular field strength of $H_p = 25.08$ Oe is initially applied within $0\ \mathrm{s} < \mathrm{t} < 10$ s to drive the swimmer moving toward right direction, and then increased to $H_p = 169.9$ Oe at $10\ \mathrm{s} < \mathrm{t} < 15$ s to turn the swimmer 90 degrees counterclockwise and point upwardly. Within $15\ \mathrm{s} < \mathrm{t} < 40$ s, the swimmer turns counterclockwise again and moves toward the left when the perpendicular field strength is resumed to $H_p = 25.08$ Oe. Similar schemes are applied to

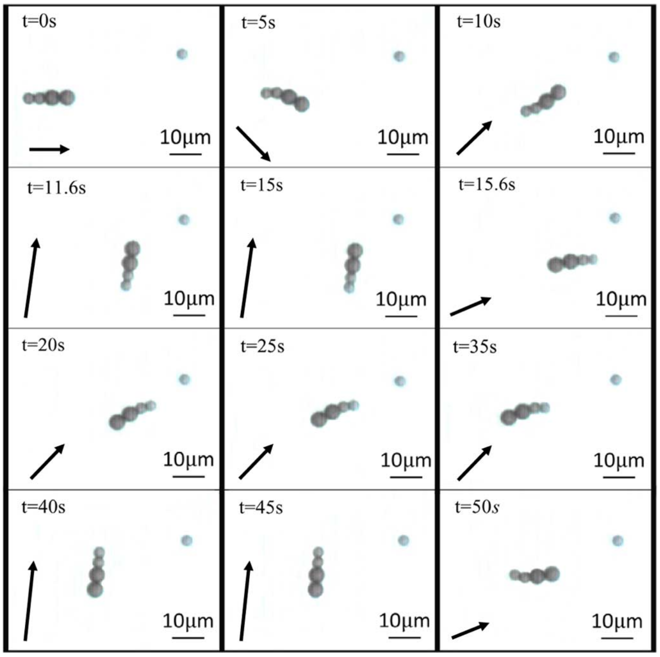

Fig. 1. Sequential images of steering manipulation to an S2L2 swimmer. The arrow represents the instantaneous orientation and strength of the overall dynamical field. It is successfully demonstrated the swimming direction can be steered toward distinct orientation with the external field. The stationary isolated particle shown in the upper-right corner can be served as a reference position.

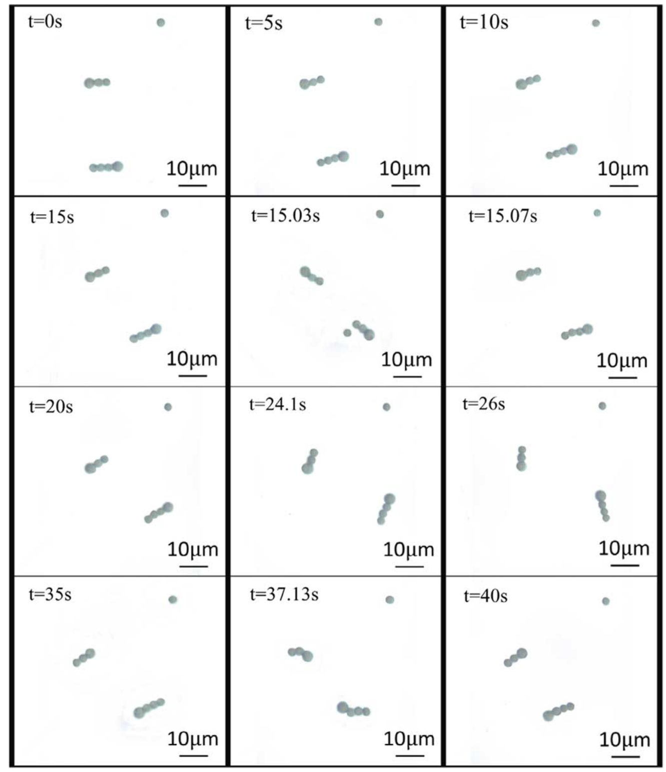

Fig. 2. Successfully synchronous steering of dual L1S2 and S3L1 swimmers. Partially structural instabilities, such as instant rupture and re-chaining, in the tail of the S3L1 swimmer is observed at $\mathrm{t} = 15.03$ s.

turn the swimmer points downwardly and back toward right again at $35\ \mathrm{s} < \mathrm{t} < 45\ \mathrm{s}$ and $\mathrm{t} > 45\ \mathrm{s}$, respectively.

The mechanism of steering can be explained by the orientation of magnetic torque. It is well known that the motion of a magnetic chain is dominated by the competition between induced hydrodynamic drags and the magnetic force. The two values are applied to define the dimensionless Mason number (Mn). When a chain composed of N particles is in a rotational field, the chain experiences a magnetic torque (M^m) and an opposing viscous drag (M^v) with a correspondent Manson number given as [2], [3]

$$M^m = \frac{\mu_0\mu_s}{4\pi}\frac{3|\vec{m}|^2N^2}{2(2a)^3}\sin(2\Delta\theta_L) \tag{1}$$

$$M^v = \frac{4}{3}N\pi a^3\frac{2N^2}{\ln\left(\frac{N}{2}\right)}\eta\omega \tag{2}$$

$$Mn = \frac{32\eta\omega}{\mu_0\chi^2|\vec{H}|^2} \tag{3}$$

Here μ_0 and μ_s stand for the vacuum permeability and the relative permeability of the solvent, respectively. m is the dipole moment of a magnetic particle, and η is the viscosity of the solvent fluid. The angular speed of the chain is expressed as ω. According to (1), the magnetic torque changes sign when $|\triangle\theta_L| > 90^\circ$, so that the chain would start to oscillate oppositely to the original external field. Nevertheless, when the lagging phase angle reduces to $|\triangle\theta_L| < 90^\circ$, the magnetic torque change sign again, and the chain resumes to its original oscillating trajectory. For detailed descriptions regarding such as "trajectory shift", please refer to Li *et al.* [9]. Even though the sizes of particles consisted in the present swimmer are not uniform, the fundamental physics acting on the swimmer (or a chain consisted with particles of various sizes) is identical. The behaviors of the present swimmer can also be described qualitatively by the above equations.

Another interesting case in steering a pair of dual micro-swimmers synchronously is also demonstrated in Fig. 2. The dual L1S2 and S3L1 swimmers move horizontally during $0\ \mathrm{s} < \mathrm{t} < 20\ \mathrm{s}$, and then turn counter-clockwise consecutively at $\mathrm{t} < 24.1\ \mathrm{s}$ and $\mathrm{t} > 35\ \mathrm{s}$, when the field strength is altered. The L1S2 swimmer moves very inefficiently due to its shorter tail. Much more effective movement is observed for the S3L1 swimmer. Nevertheless, swimming performance might be affected because of its structural defects, such as tail bending or instant rupture and re-chaining as shown at $\mathrm{t} = 15.03$ s.

B. Trajectories Analysis

The swimming trajectory of the center of mass of the S2L2 swimmer presented in Fig. 1 is depicted in Fig. 3. In general, more efficient movements are found when the swimmer moves horizontally, i.e. within $0 < \mathrm{t} < 15$ s toward right and $20\ \mathrm{s} < \mathrm{t} < 35$ s toward left, compared with their counterparts moving perpendicularly. Trajectories for the L1S2 and S3L1 swimmers are also demonstrated in Fig. 3 and appear the similar trend, in which the efficiencies of swimmers oriented perpendicularly are much less than the periods of horizontal movements. By a more detailed inspection on the images of the swimmers, e.g. Fig. 1, the swimmer appears an S-shaped tail oscillation at $\mathrm{t} < 10$ s, which is expected to generate greater propulsion to move forward. However, during the time interval of $10\ \mathrm{s} < \mathrm{t} < 15$ s, the

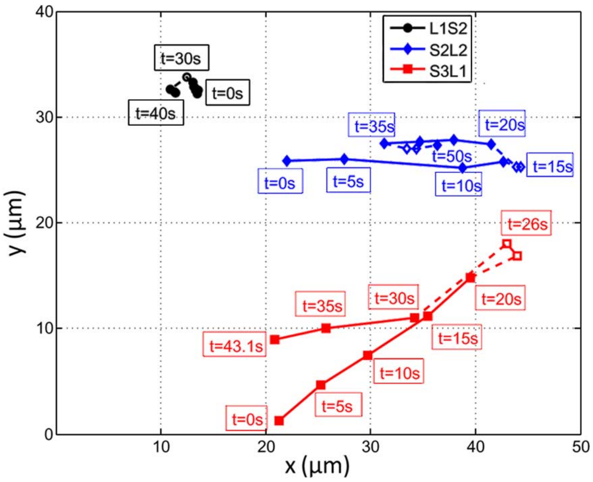

Fig. 3. Swimming trajectories of the artificial swimmers shown in Figs. 1 and 2. The solid and dash lines represent the trajectories when the swimmers orient horizontally and perpendicularly, respectively. In general, better swimming efficiency are found when the swimmer moves horizontally.

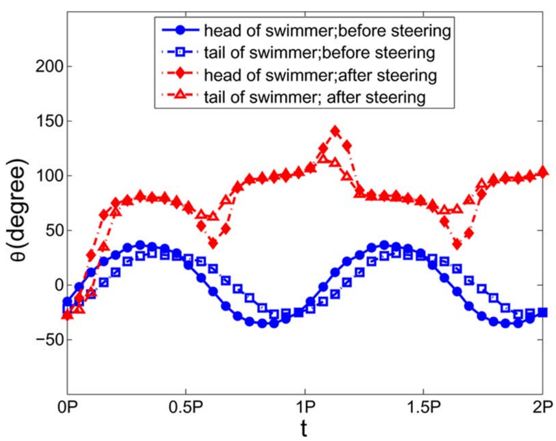

Fig. 4. Phase angle trajectories of the S2L2 swimmer shown in Fig. 1 before (oriented horizontally) and after (oriented perpendicularly) steering within 2 arbitrarily oscillating periods. After steering, both the trajectory patterns of the swimmer's head and tail apparently deviate from the original sinusoidal oscillation before the steering. In addition, the trajectories between the head and tail after steering behave more synchronously. As a result, the swimmer moves more ineffectively when orients perpendicularly after steering.

vibrating motion of the swimmer's tail is nearly rigid. This more rigid vibration explains a less efficient swim when orienting perpendicularly.

Further understandings of the distinct performances can be obtained by comparing the trajectories of the S2L2 swimmer's head and tail. Shown in Fig. 4 are the correspondent trajectories before (swimmer moving rightward) and after (swimmer moving upward) the steering are turned on. After steering, the trajectory pattern apparently deviates from the original sinusoidal oscillation before the steering. In addition, the trajectories of the head and tail after steering appear more synchronous. As a result, the swimmer moves more ineffectively when orients vertically after the steering. The fact suggests the presented technique is most suitable to a reverse movement by consecutively steering the swimmer twice.

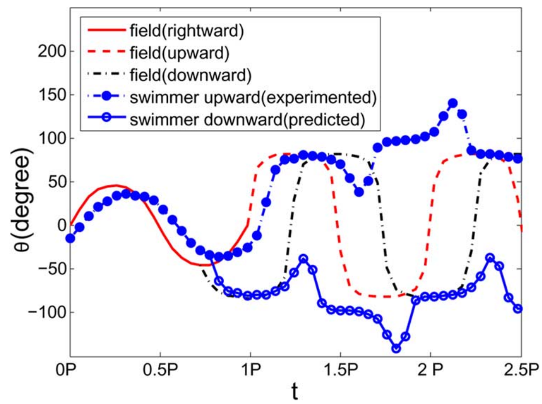

Fig. 5. Scenarios for precisely steering orientation control. Whether the swimmer will re-orient counter-clockwise or clockwise is determined by a positive or negative value of instantaneous phase lag at the timings to enhance the external field strength. The measured trajectories of the counter-clockwise steering S2L2 swimmer presented in Fig. 1 and its correspondent external field are represented by solid circular marks and dash line, respectively. Predicted trajectories of a clockwise steering swimmer and the external field, based on physical understandings, are also depicted by empty circular marks and dot-dash line.

C. Steering Mechanisms

Another nontrivial issue is the determination of steering orientation. In the cases presented above, the swimmers are steered counter-clockwise consecutively. They are achieved by enhancing the field strengths at the timings associated with a positive instantaneous phase angle lag, as detailed trajectories of the filed and swimmer demonstrated in Fig. 5. By the same token, if a clockwise reorientation is desired, the steering should be activated at the timings associated with a negative value of instantaneous phase lag. Based on this argument, the trajectory of a clockwise steering, which behaves similar to the counter-clockwise steering, can be predicted and also displayed in Fig. 5. We like to point out such clockwise steering has also been observed in our experiments, even the precise manipulations would need more sophisticated real time measurements of the instantaneous phase lags.

IV. Concluding Remarks

In the present work, the novel steering technology of magnetic micro-swimmers under an oscillating field is successfully experimented. The swimmer originally moving horizontally can be steered to re-orient perpendicularly by varying the instantaneous field strength to result in an excessive phase angle lag of $|\triangle\theta_L| > 90^\circ$. By the present methodology, the driving directions of micro-swimmers can be controlled even without physically re-configuring the arrangements of directional and dynamical fields. Nevertheless, it should also be to point out, that the swimmers perform less efficiently if steered to a new perpendicular orientation due to a distinct oscillation pattern, which is unfavorable to generate thrust. As a result, the technique is most suitable to a reverse movement by consecutively steering the swimmer twice. In addition, a precise control of the steering orientation, i.e., clockwise or counter-clockwise, should be possible if real time measurements of the instantaneous phase lags are available. We have also proposed the applicable schemes of such manipulations based on physical understandings.

Acknowledgment

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References

[1] S. Melle, G. G. Fuller, and M. A. Rubio, "Structure and dynamics of magnetorheological fluids in rotating magnetic fields," *Phys. Rev. E*, vol. 61, p. 4111, 2000.

[2] S. Melle and J. E. Martin, "Chain model of a magnetorheological suspension in a rotating field," *J. Chem. Phys.*, vol. 118, no. 21, Jun. 2003.

[3] T. G. Kang, M. Hulsen, P. Anderson, J. D. Toonder, and H. Meijer, "Chaotic mixing induced by a magnetic chain in a rotating magnetic field," *Phys. Rev. E*, vol. 76, p. 066303, 2007.

[4] I. Petousis, E. Homburg, R. Derks, and A. Dietzel, "Transient behaviour of magnetic micro-bead chains rotating in a fluid by external fields," *Lab Chip*, vol. 7, p. 1746, 2007.

[5] S. Biswal and A. Gast, "Rotational dynamics of semiflexible paramagnetic particle chains," *Phys. Rev. E*, vol. 69, p. 041406, 2004.

[6] R. Dreyfus, J. Baudry, M. Roper, M. Fermigier, H. Stone, and J. Bibette, "Microscopic artificial swimmers," *Nat.*, vol. 437, p. 862, 2005.

[7] Y. H. Li, S. T. Sheu, J. M. Pai, and C. Y. Chen, "Manipulations of oscillating micro magnetic particle chains," *J. Appl. Phys.*, vol. 111, p. 07A924, 2012.

[8] Y. H. Li, C. Y. Chen, S. T. Sheu, and J. M. Pai, "Dynamics of a microchain of superparamagnetic beads in an oscillating field," *Microfluid Nanofluid*, vol. 13, p. 579, 2012.

[9] Y. H. Li, H. C. Lin, and C. Y. Chen, "Trajectory shift of magnetic microchains in an oscillating field," *Microfluid Nanofluid* [Online]. Available: DOI: 10.1007/s10404-012-1094-4