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ABSTRACT
This study uses the effect of flexibility on the propulsive efficiency of swimmers that consist of superparamagnetic particles and which are subjected to an oscillating field to control the movement in a low Reynolds number environment. To achieve nonreciprocal motion for a flexible swimmer using a simple and stable structure, two types of artificial flexible swimmers are constructed using self-assembled beads without links and the flexibility and the bending rigidity are investigated under various frequencies. At a low frequency, both the head and the tail oscillate almost synchronously with the field, which leads to a nearly rigid and reciprocal oscillation. The phase angle trajectory for the head significantly leads the tail at a higher frequency of oscillation, which results in a prominent flexible structure and propulsion generation. Furthermore, the flexibility initially increases linearly with the frequency and then reaches the highest value at a specific frequency. The instantaneous velocity of the swimmer almost linearly increases with its flexibility. The most effective oscillating frequency to manipulate the locomotion for the magnetic microbeads swimmer would be at f=7-10 Hz, which resists the amplitude and enhances the flexibility of the microswimmer. Finally, a flexible swimmer associated with a moderate high oscillating amplitude is a favorable configuration for propulsion generation.

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I. INTRODUCTION
Magnetic microbeads with self-assembled ability have been studied because of their many potential applications, as drug deliverers, sensors, pumps and mixers and swimmers. A more detailed analysis of the applications of magnetic particles is available from other sources, which detail the behaviors of microdevices in an environment with a low Reynolds number. A challenge for artificial swimmers is that the propulsive mechanism must have a nonreciprocal motion due to the Scallop theorem of Purcell. The Scallop theorem pertains to a corkscrew or a flexible rowing motion. Artificial swimmers that have nearly rigid helical tails behave like a corkscrew in the presence of rotating fields. A sperm-like artificial swimmer that is fabricated using magnetic microbeads and DNA linkage has been used to demonstrate a highly planar beating flagellum. A more recent easy and reversible method to fabricate a magnetic artificial microswimmer is to aggregate self-assembled superparamagnetic microbeads that are not linked. Numerous studies show that flexibility has a significant effect on the performance and the structure of microdevices in an environment with a low Reynolds number.

Fewer studies concern the flexible mechanism of a microswimmer that is composed of self-assembled superparamagnetic particles of different sizes than those on a flagellum that consists of magnetic particles of a uniform size. This study uses different sizes of magnetic beads to design two types of swimmers with optimal propulsive efficiency. The undulating swimmers are modeled as continuous elastic flagella and their maximum dimensionless curvature and bending rigidity are derived as a function of the frequency of undulation. The synchronous phase angle trajectory between the head and tail of the
swimmer is used to elucidate the flexible behaviors and the non-reciprocal motion for a particle-based swimmer. Besides, the effect of the structural flexibility on the propulsive efficiency of the swimmer is experimentally and theoretically determined in this work.

II. MATERIALS AND EXPERIMENTAL SETUP

The magnetic microswimmer is formed using two types of self-assembled superparamagnetic particles that use iron oxide magnetite (Fe$_3$O$_4$) embedded in polystyrene microspheres suspended in distilled water, whose viscosity is 0.89 cp. The mean diameters of the microbeads are $d = 4.5$ and $2.8 \mu m$ and the magnetic susceptibilities are $\chi = 1.6$ and 1.0, respectively. The microbeads produced by Thermo Fisher Scientific Inc. (Dynabeads M-450 Epoxy and Dynabeads M-270 Epoxy) have a saturation magnetization of $M = 28000 - 32000$ A/m and do not exhibit a magnetic hysteresis or remanence, which indicates the magnetic beads for this study are linearly magnetized or demagnetized by the application or removal of an external field. It is known that Reynolds number is the ratio of the inertial forces to the viscous forces within a fluid. At really small scales,
typically for nano/micro-sized organisms or devises, the inertial force is negligible compared to the viscous force, which results in a low Reynolds number condition. Thus, the micro-sized magnetic swimmers used in our experiments were regarded as manipulating in a low Reynolds number environment. The motion of the beads and the swimmers were recorded using an optical microscope that is connected to a high-speed camera, whose maximum rate of capture is 200 frames/s.

The experimental setup for this study is similar to the apparatus for Ref. 24. A homogeneous unidirectional magnetic field, denoted as $H_d$, is applied to the initially dispersed magnetic microbeads. The static field induces magnetic dipole moments in superparamagnetic microbeads that are parallel to the orientation of the field, so the beads are attracted to each other to form swimmers. A dynamic sinusoidal field $H_f$ with a maximum amplitude $H_p$ and an adjustable frequency $f$, that is, $H_f = H_p \sin(2\pi ft)$, is imposed in a direction perpendicular to $H_d$. These two fields have competing amplitudes, so the overall field oscillates with a phase angle trajectory ($\theta$) of $\theta(t) = \tan^{-1}((H_p/H_d) \cdot \sin(2\pi ft))$.

III. THE EFFECT OF FREQUENCY AND THE CONFIGURATION OF THE MAGNETIC SWIMMER

Figure 1 shows the most significantly deformed images of two swimmers with different configurations that are subjected to an identical field strength of $H_p=2000$ A/m, $H_d=1930$ A/m, with varying frequency. Both swimmers were initially manipulated at a low frequency of $f=1$ Hz and then the frequency was gradually increased to 10 Hz to observe acceleration. The images in the upper row demonstrate the flexible pattern for a swimmer composed of two large and two small microbeads (denoted as L2S2). The snapshots in the lower row show the evolution of a flexible swimmer composed of one large and three small beads (denoted as L1S3) in identical field conditions. At a low frequency of 1Hz, the L2S2 swimmer is nearly rigid but the L1S3 swimmer has a slightly deformed shape. When the frequency is increased, there is significant deformation for both swimmers. However, the undulating patterns of the two swimmers differ because of variations in their configuration. It is seen that L1S3 flexes more prominent than the L2S2 swimmer. In addition, the oscillating amplitude of the head of the swimmer is also different from that of the tail because of the asymmetrical structure of each swimmer, which results in the non-reciprocal asymmetric motion that is required to generate propulsion.

IV. THE MECHANISM FOR THE ASYMMETRIC MOVEMENT OF THE SWIMMER

The flexible characteristics and the asynchronous oscillation of a swimmer are explained in terms of the phase angle trajectories of the head and tail, as shown in Figure 2. In Figure 2(a), all the heads and tails oscillate periodically along the direction of an external field. The maximum instantaneous speeds of microswimmers plotted against maximum dimensionless curvatures ($C_{max}=d/R$) of the swimmers shown in Figure 1.
field with a strength of $H_p=2000$ A/m, $H_d=1930$ A/m and frequency of 1Hz. The low frequency and shorter length of the swimmer lead to the nearly synchronous phase angles of the heads and tails. When the frequency is increased to 10 Hz, the phase angles for the heads and tails lag behind the field more significantly, as shown in Figure 2(b). When the maximum field of $\theta_{A_{\text{max}}} = 46.04^\circ$ at $t = 0.25s$ is achieved, the head of the L2S2 and L1S3 swimmers have just moved to a phase angle of $\theta_{A_{\text{max}}} = 36.6^\circ$ and $34.2^\circ$ respectively. The greater phase angle trajectory for the L2S2 swimmer is attributed to the presence of the two large magnetic beads in the head of the L2S2 swimmer, which has stronger induced magnetic dipole moment to trigger oscillation of the greater amplitude in a field of the identical strength. The same scenario happens to the tails of L2S2 and L1S3 swimmers.

![Sequential images of (a) the L2S2 and (b) L1S3 swimmers in an oscillating field with a strength of $H_p=2000$ A/m, $H_d=1930$ A/m, and frequency of 10Hz. T represents the time when the swimmer starts swimming at the greatest velocity and then cruises at constant speed. (c) Moving trajectories for the two swimmers swimming for a duration of 10 seconds. The L2S2 swimmer travels nearly 1.5 times as far as the L1S3 swimmer in the same duration.](image-url)
V. A COMPARISON OF THE FLEXIBILITY OF MICROSWIMMERS OF DIFFERENT CONFIGURATIONS

The flexibility of the swimmer can be determined by the value of the maximum dimensionless curvature (denoted as C_{max}), which is the ratio of the diameter of the magnetic particle to the swimmer’s radius of curvature. The bending rigidity $\kappa$ of the undulating swimmer is obtained as:\(^1,8,24\)

$$C_{\text{max}} = \frac{\pi B}{3d} \sqrt{\frac{(d/2)^4\chi^2}{\kappa\mu_0}} = \frac{d}{R} \tag{1}$$

where $R$ is the swimmer’s radius of curvature and $B$ and $\mu_0$ respectively represent the overall magnetic field intensity and the vacuum permeability. Figure 3(a) shows the relationship between the swimmer’s flexibility and the frequency of the oscillating field. For the two different configurations of the swimmer, the maximum dimensionless curvature (C_{max}) firstly increases linearly with the frequency and then has its highest value at a specific frequency for each specific swimmer. As shown in Figure 3(a), the equilibrium maximum values for C_{max} are almost 0.35 and 0.5 at $f=7$-$10$Hz for L2S2 and L1S3, respectively. The higher value of C_{max}=0.5 for the L1S3 swimmer indicates that the configuration of the L1S3 swimmer allows a sufficient flexible structure for an one-dimensional magnetic microbeads swimmer to achieve movement in a low-Reynolds number environment.

Figure 3(b) shows the bending rigidity ($\kappa$) obtained from (1) for the two swimmers shown in Figure 1. The bending rigidity is inversely proportional to the frequency. In addition, the magnetic swimmer is least rigid when the frequency is increased to 7-10 Hz. This trend indicates that the flexibility of the magnetic swimmer is limited at a specific high frequency for an oscillating field. The limitation to the bending rigidity shows that the greater field frequency doesn’t affect the flexibility of structure and the dynamic behavior of the magnetic swimmer. As a consequence, the most effective oscillating frequency for the locomotion of the magnetic microbeads swimmer would be at $f=7$-$10$ Hz, which results in sufficient flexibility for its structural stability and generates propulsion in low Reynolds number condition.

VI. A COMPARISON OF PROPULSIVE EFFICIENCY OF MICROSWIMMERS

Since a flexible structure allows a planar beating microswimmer to generate propulsion, the effect of flexibility on its propulsive efficiency is important. Figure 4 shows the comparison of the instantaneous swimming velocity for the L2S2 and L1S3 swimmers steered in different flexibility (C_{max}). It is seen that the velocities of L2S2 and L1S3 swimmers almost linearly increase with the flexibility and reach the highest values at their corresponding C_{max} of 0.35 and 0.5, respectively, which are consistent with the greatest values of C_{max} shown in Figure 3(a). As a result, the most effective frequency to manipulate the swimmers would be at $f=7$-$10$Hz. In addition, the distribution of the value of speed reveals that the swimmer swims in an environment with a low Reynolds number of $3 \times 10^{-6}$-$3 \times 10^{-5}$. The propulsive efficiency was measured by recording the moving trajectories of the swimmer when the swimmer starts being manipulated at a frequency $f=10$ Hz. Figure 5(a) and 5(b) shows the images of the L2S2 and L1S3 swimmers moving at maximum velocity for 10 seconds. The accurate comparison of the swimming effectiveness for the two swimmers is shown in Figure 5(c). It is seen that the L2S2 swimmer moves farther than the L1S3 swimmer in the same period. The maximum respective average velocities for L2S2 and L1S3 swimmers are 2.08 $\mu$m/s and 1.34$\mu$m/s. This result can be attributed to the greater amplitudes and longer length of the L2S2 swimmer, which generates a greater net projection of the normal and tangential force along the axis of thrust. This argument shows good agreement with the mechanism for the motion of spermatozoa proposed by Gray et al.\(^26\) Based on our experimental results, a flexible swimmer associated with a moderate high oscillating amplitude is a favorable configuration for propulsion generation in a low Reynolds number environment.

VII. CONCLUSIONS

This study demonstrates a simple technique for the fabrication and manipulation of a flexible magnetic microbead swimmer with no extra links. At a low frequency, the swimmer oscillates almost synchronously with the field and has a nearly rigid structure. When the frequency increased, the oscillations of the head and tail of the swimmer become significantly asynchronous, which result in the significant flexible structure of the swimmer. This study demonstrates two different flexing characteristics for magnetic microbeads swimmers in an oscillating field. The results show that the head and tail of the L2S2 swimmer have the greater oscillation amplitudes than the counterparts of L1S3 swimmer. Additionally, the value of C_{max} firstly increases linearly with the frequency, and then reaches its highest value at the specific frequency for a specific swimmer. The L2S2 and L1S3 swimmers have an equilibrium maximum value of C_{max} = 0.35 and 0.52 when the frequency is increased to $f=7$-$10$Hz. The instantaneous velocities of L2S2 and L1S3 swimmers almost linearly increase with the flexibility and reach the highest values at their corresponding C_{max} of 0.35 and 0.5, respectively. The maximum average velocity of the L2S2 swimmer is approximately 2.08 $\mu$m/s and that for L1S3 is 1.34$\mu$m/s, which indicates that a moderately higher oscillating amplitude of a flexible swimmer is also a dominated factor for the propulsion generation in an environment with a low Reynolds number of $3 \times 10^{-6}$-$3 \times 10^{-5}$. This study describes the behavior of a flexible microbeads swimmer and investigates the effective manipulating method to trigger the flexible motion of the swimmer, which can be applied to improve the propulsive efficiency for microdevices in a microfluidic system.

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