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Manipulations of vibrating micro magnetic particle chains

Yan-Hom Li, Shih-Tsung Sheu, Jay-Min Pai, and Ching-Yao Chen[a)]
Department of Mechanical Engineering, National Chiao Tung University, Taiwan

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We investigate the motion of a micro-chain consisting of several magnetic particles. The chain is firstly formed by a uniform directional field, and then manipulated by a vibrating field. We demonstrate where the chain appears to display distinct behaviors, from rigid body vibrations, bending distortions to breaking failures, by increasing either the chain's length or vibrating amplitude. In addition, the vibrating chain can be successfully driven forward, mimicking a micro-swimmer by connecting particles of different sizes. © *2012 American Institute of Physics*. [doi:10.1063/1.3675269]

I. INTRODUCTION

The dynamics of magnetorheological suspensions under a rotating magnetic field have been studied extensively due to their potential applications in micro-electro-mechanical-systems (MEMS), such as micro-mixers.[1–5] It has been revealed that breakups of rational chains are dominated by the dimensionless Mason number,[5] which represents the ratio of hydrodynamic drags to dipolar forces. Furthermore, it has been demonstrated that an asymmetric microchain creates thrust to move forward in a vibrating magnetic field.[6] To apply the microchains in MEMS effectively, detailed analysis regarding the behaviors of the chain's motion are essential. In this paper, we manipulate and analyze motion of the magnetic particle chains subjected to a vibrating field. Experiments of chains consisting of particles with different sizes, which mimic micro swimmers, are also presented.

The magnetic particles used in our experiments are aqueous superparamagnetic polystyrene microspheres coated with iron oxide grains produced by Invitrogen Life Tech., whose diameters are 4.5 μm and 2.8 μm, with no magnetic hysteresis or remanence. A static unidirectional magnetic field, denoted as H_d, is generated firstly by a pair of coils powered by DC power sources. Magnetic particles magnetized by the unidirectional field tend to aggregate and form chains because of dipolar forces. To create a vibrating field, another pair of coils are placed perpendicular to the former pair and connected to AC power supplies to generate a sinusoidal dynamical perpendicular field with a maximum field strength H_p and frequency f, i.e. $H_p \sin(2\pi f t)$. This additional dynamical perpendicular field and the original static directional field result in a vibrating field. The magnetic particle chain would vibrate under the presence of such a vibrating field. The motion of the particle chain is recorded by an optical microscope connected with a CCD. Representative snapshot images, which are modified from the actual recorded movies[7] by improving their contrasts and resolutions, are presented in the following section.

[a)]Author to whom correspondence should be addressed. Electronic mail: chingyao@mail.nctu.edu.tw.

II. RESULTS AND DISCUSSION

Figure 1 shows the sequential images taken from a chain consisted of 8 particles subjected to a vibrating field strength of $H_d = 48.02$ Oe, $H_p = 58.74$ Oe and $f = 1$ Hz (or period P = 1 s). The chain behaves like a rigid body and vibrates almost synchronously with the field. If the chain's length is increased to consist of 15 particles and subjected to a weaker field strength of $H_d = 17.11$ Oe, $H_p = 45.85$ Oe and $f = 1$ Hz, significant phase angle lag associated with apparent bending distortion are observed as shown in Fig. 2. Significant phase lag and deformation of the chain are attributed both to

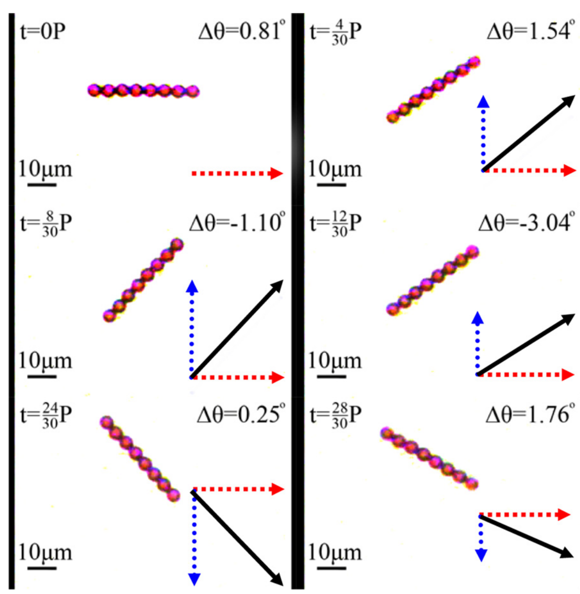

FIG. 1. (Color online) Images of a vibrating chain consisted of 8 particles (P8) in a vibrating field of $H_d = 48.02$ Oe, $H_p = 58.74$ Oe and frequency $f = 1$ Hz. The solid line indicates orientation and magnitude of the overall magnetic field, while the dash line and dot line represent static (directional) and dynamical (perpendicular) components of the field, respectively.

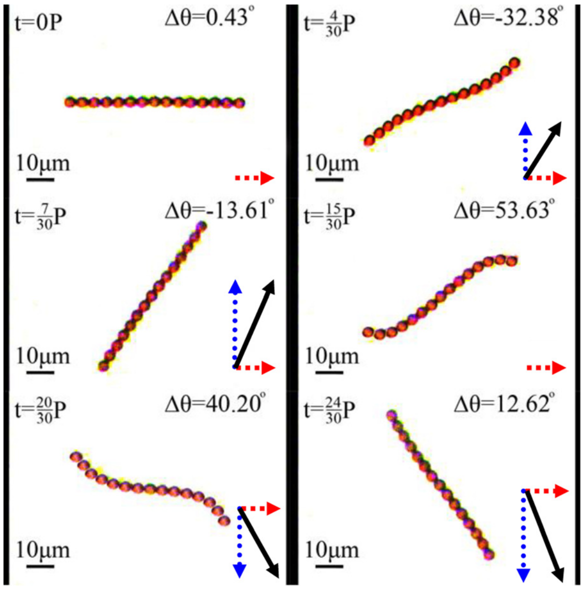

FIG. 2. (Color online) Images of a 15-particle chain (P15) in a field of $H_d = 17.11$ Oe, $H_p = 45.85$ Oe and $f = 1$ Hz. The chain undergoes apparent deformation with significant phase lags.

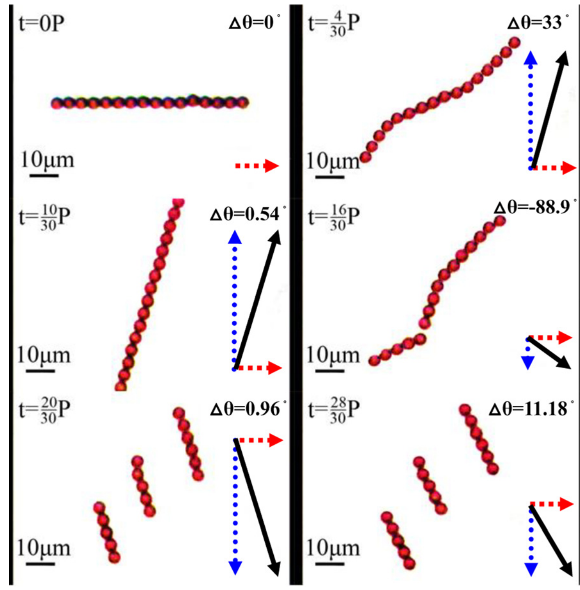

FIG. 4. (Color online) Images of a 16-particle chain under a field of $H_d = 17.11$ Oe, $H_p = 56.25$ Oe and $f = 1$ Hz. The chain evolves from bending distortion to breaking failures, and is ruptured to three segments, which rotate independently.

increases of the hydrodynamic drag as well as the moment arm. Nevertheless, the dipolar attractions are still sufficiently strong to sustain the chaining formation. Figure 3 demonstrates the phase trajectories of external fields and chains within a vibrating period for cases shown in Figs. 1 and 2. Consistent with the previous observations, the field and the microchain follow an almost identical trajectory for a shorter 8-particle chain, while a significant phase lag occurs for the case of a longer chain with 15 particles due to its stronger drag.

Effects of the field strength are investigated by raising the perpendicular field strength to $H_p = 56.25$ Oe to a chain with 16 particles as shown in Fig. 4, while the strength of the directional field and frequency are fixed at $H_d = 17.11$ Oe and $f = 1$ Hz. This stronger perpendicular field strength leads

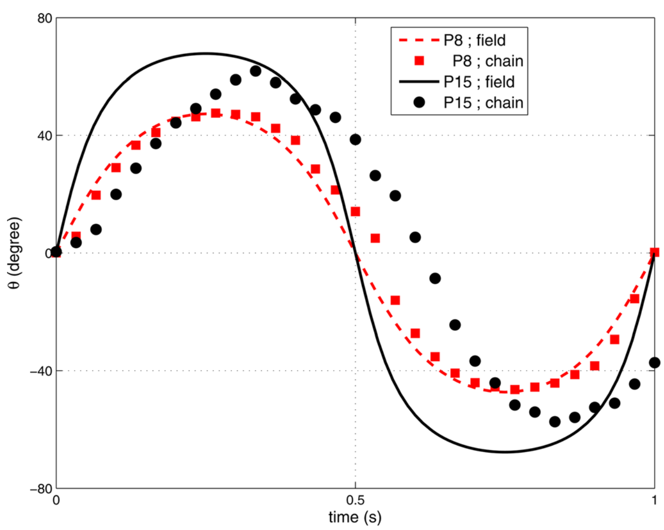

FIG. 3. (Color online) Trajectories of phase angles of external fields and chains within a vibrating period for cases shown in Fig. 1 (P8) and Fig. 2 (P15).

to a larger amplitude of vibration as well as a faster angular velocity compared to the similar case in Fig. 2. The chain evolves from bending distortion at an early time to breaking failures. At the time of t = 4/30 P, the chain bends to S-shape then reaches to the maximum vibrating angle at t = 10/30 P, when the chain experiences maximum total external field and returns to rigid form. The chain starts to rupture at t = 16/30 P just after the reverse motion, and then breaks into three segments at t = 20/30 P. Eventually, the three shorter chains vibrate with the field independently with insignificant phase lags. Rupture of the chain is a consequence of stronger drags induced by the current faster vibrating speed. It should be noticed that such chain's ruptures should be carefully taken care to applications in MEMS.

Another interesting application of microchains is to serve as a bionic microswimmer. To generate forward thrust,

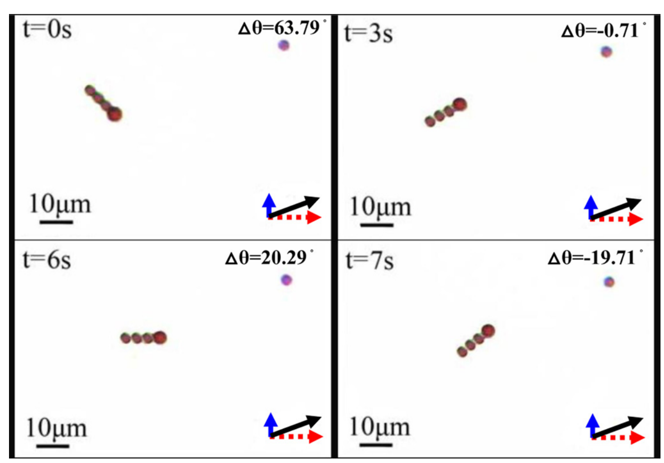

FIG. 5. (Color online) Images of a 4-particle (P4, S3 + L1) microswimmer under a vibrating field of amplitude A = 7.86 μm and frequency $f = 11$ Hz.

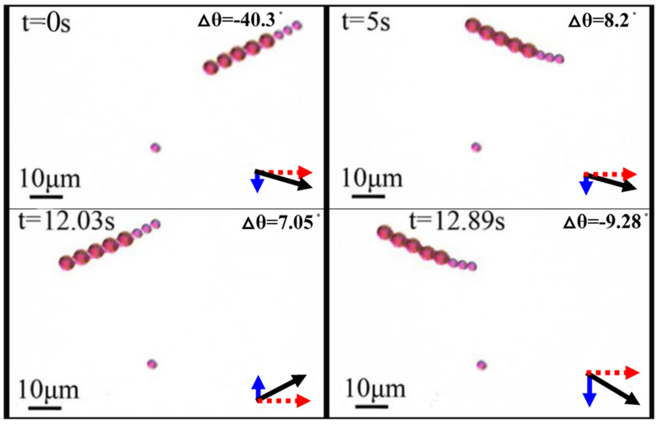

FIG. 6. (Color online) Images of an 8-particle (P8, L5 + S3) microswimmer in a field of A = 17.13 μm and f = 11 Hz.

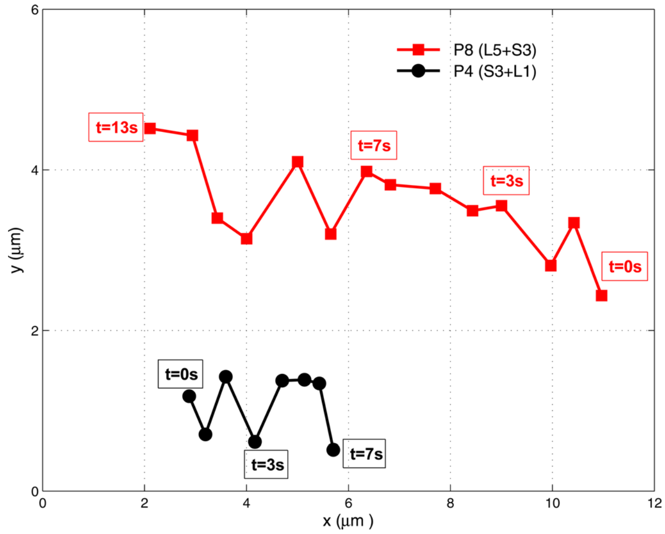

FIG. 7. (Color online) Moving trajectories of microswimmers for cases shown in Fig. 5 (P4, S3 + L1) and Fig. 6 (P8, L5 + S3). Chains always swim toward the direction of larger particles.

the symmetry of vibrating motion needs to be broken. Chains consisting of particles with different sizes are constructed and shown in Fig. 5 (3 small particles in the left associated with a larger one in the right, denoted as S3 + L1) and Fig. 6 (8 particles, L5 + S3), and subjected to a constant frequency of 11 Hz. The vibrating amplitudes of S3 + L1 and L5 + S3 are 7.8 μm and 17.13 μm, respectively. The microchains swim apparently toward the directions of their centers of mass (larger particles), such that they move to the right in Fig. 5 and the left in Fig. 6. Their correspondent moving trajectories are displayed in Fig. 7. A dimensionless parameter Strouhal number (or St) is often used to measure the propulsive efficiency of a swimmer. The Strouhal number is defined as St = f A/U, where U and A represent the forward velocity and the vibrating amplitude of swimmer. The correspondent values of averaging St of S3 + L1 and L5 + S3 are 32.63 and 67.12, respectively. It is well known that the Strouhal numbers of effective natural swimmers ranged between 0.25 to 0.4, which is two orders less than these particular microswimmers. It indicates more efforts would be desired to improve their efficiencies.

III. CONCLUSIONS

In this work, we successfully carry out experiments on manipulations of micro magnetic particle chains under vibrating magnetic fields. Distinct types of vibrating behaviors, such as rigid vibrations, deformation and breakups, are evolved depending on lengths of chains and strengths of applied fields, which are crucial to the induced hydrodynamic drags. In addition, microswimmers are created by constructing chains with partciles of different sizes. The mciroswimmers are demonstrated to be driven toward their centers of mass sucessfully. The Strouhal numbers of experimented are found to be two orders greater than biological swimmers, so that further improvements would be desired.

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[7]The original recorded movies can be viewed on the URL: http://www.youtube.com/user/athomeli#p/u.