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Contactless magnetic manipulation of magnetic particles in a fluid

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ABSTRACT

The objective of this study was to demonstrate contactless magnetic manipulation of a magnetic particle along a designated orbit among other magnetic particles suspended in a fluid at rest or in motion, and also to understand the behaviors of those surrounding particles during the contactless magnetic manipulation. In addition, the possibility of breaking up chains of clustered magnetic particles under such conditions was also studied. We first describe contactless magnetic manipulation of magnetic particles by feedback control in which the feedback signal was the measured coordinates of the tracked particle. By the feedback control monitoring the location of the tracked particle using a high-speed image analyzer, the reach of the dipole magnetic field created by the magnetized magnetic particles could be kept relatively small. As a result, the tracked magnetic particle could be dragged along the designated orbit by magnetic force. Second, we describe the breaking up of chains of clustered magnetic particles using an alternating magnetic force. The results showed that chain-clustered magnetic particles that had been aggregated under the condition of contactless magnetic manipulation could be broken up reproducibly by an alternating magnetic field. These results constitute useful information for advancements in the handling of magnetic micro- or nanoparticles.

1. Introduction

Magnetic forces on micro- or nanoparticles such as ferrite particles in a fluid can be used for drug delivery, cell/DNA manipulation, and magnetic separation [1–11]. Pamme [12] summarized various studies on such procedures as ferro-fluidic pumping, mixing, and magnetic sensing as well as magnetic manipulation and separation. Tieno et al. [13] also reported a propulsion system using magnetic particles called “artificial swimmers” that were actuated by an external magnetic field generated by three coils. In these applications, magnetic particles are influenced by the magnetic force caused by the magnetic field gradient, as well as by the forces of gravity and buoyancy, when magnetic particles are suspended in a fluid. Magnetic torque [14] also causes them to align their magnetic moments in the direction of the applied magnetic field. Furthermore, for micro- or nanoparticles, the viscous force and the force between the magnetized magnetic particles themselves [14,15] cannot be neglected. Here, Rikken et al. [16] introduced in detail those forces and the manipulation of micro- and nanostructure motion with magnetic fields. As for particle interaction that is closely related to micro- and nanostructure motion, Bharti et al. reviewed [17] various examples of assembly of colloidal particles, and showed the importance of studies about controlled particle interactions using a magnetic field.

As mentioned above, it is important to gain an understanding of the forces affecting a magnetic particle and, in cases where designated magnetic particles are surrounded by other similar-size or dis-similar-size magnetic particles, to understand the influence and reach of inter-particle forces created by the dipole magnetic field. It is also important to drive the particles not with a very high magnetic field, but with an appropriate magnetic field, i.e., the minimum effective field.

In a past study, we examined a method for visualizing the motion of micro-magnetic particles under a dynamic magnetic field [18]. We have also studied the contactless grasp of a micro-magnetic particle suspended in a fluid at rest or in motion, and have developed a method for quantitatively estimating the influencing forces [19]. However, an experimental investigation on contactless magnetic manipulation and magnetic separation applying feedback control with a full understanding of the forces affecting the particle or of the influence and reach of inter-particle magnetic force has until now not been performed.

Magnetic particles are magnetized during contactless magnetic manipulation such as drug delivery and cell/DNA handling or magnetic separation. Therefore, magnetic particles within close range of each other become chain-clustered due to this inter-particle magnetic force during contactless magnetic manipulation [20]. Even

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if the magnetic field has been cut off, it can hardly be expected that the chain-clustered particles are dispersed naturally because the particles have already been magnetized. To avoid such problem, a method of dispersing magnetic particles with electrostatic repulsive force by coating the surface of the magnetic particles is often applied [21]. However, it has not yet been sufficiently studied whether the chain-clustered magnetic particles can be broken up by a magnetic force.

The objective of this study was to demonstrate contactless magnetic manipulation of a magnetic particle along a designated orbit among other magnetic particles suspended in a fluid at rest or in motion, applying the method of contactless grasp mentioned above [19], and also to understand the behaviors of those surrounding particles during the contactless magnetic manipulation. In addition, the possibility of breaking up chains of clustered magnetic particles produced by contactless magnetic manipulation was also studied.

In this paper, we first tried contactless magnetic manipulation of magnetic particles by feedback control in which the feedback signal provided the measured coordinates of the tracked particle. Here, the controlled object was a designated magnetic particle (orchain-clustered magnetic particles) suspended in a fluid in a quartz vessel, either at rest or in motion. By feedback control monitoring of the particle location using a high-speed image analyzer, the reach of the dipole magnetic field created by the magnetized magnetic particles was kept relatively small. Thus, our contactless magnetic manipulation was able to minimize the formation of particle chains. The results showed that the surrounding magnetic particles that had volumes on average 3.6% different from the tracked magnetic particle were manipulated along the same designated orbit as the tracked particle in the midst of magnetic particles having much greater difference in volumes. Surrounding magnetic particles having volumes 20.9% or more difference from the tracked magnetic particle did not join the designated orbit due to the different interplay of viscosity and gravitational forces although they were surely influenced by the magnetic force. These results show that it is possible to realize selective contactless magnetic manipulation and magnetic separation.

Second, we studied the breaking up of chains of clustered magnetic particles. A method of affecting the alternating magnetic force to break up the chain-clustered magnetic particles was applied considering such magnetic aggregation under contactless magnetic manipulation. The results showed that chain-clustered magnetic particles that were aggregated under the condition of the contactless magnetic manipulation could be broken up reproducibly by an alternative magnetic field. Furthermore, from the result of the relation between the frequency of the excited magnetic field and the length of the chain-clustered magnetic particles, it was found that long chains of clustered magnetic particles could be broken even at a relatively low frequencies while the short chains of clustered magnetic particles could be broken only at higher frequencies.

These results constitute useful information for advancements in the handling of magnetized micro- or nanoparticles.

2. Materials

Magnetic ferrite particles (diameter, 300 nm–300 μm) in pure water in a vessel were used. The magnetization ratio χ was 2.3 (magnetic field intensity $H = 4 \times 10^4$ A/m), and the saturated magnetization was 1.8×10^5 A/m. The linear approximation value of the gradient in the M–H curve ($-4 \times 10^4 < H < 4 \times 10^4$ A/m) was used as the magnetization ratio for calculating the magnetic force affecting the particles [19]. The relationship between magnetic field intensity H and magnetization M is given by

$$M = 2.18\ H. \tag{1}$$

3. Motion of particles

As shown in Fig. 1, when magnetic particles are suspended in a fluid under a magnetic field, they are influenced by the magnetic force caused by the magnetic field gradients, as well as the by forces of gravity and buoyancy. Furthermore, for micro- and nanoparticles, the viscous force and the forces between the magnetized particles must be considered.

The magnetic force $\mathbf{F}_\mathrm{p}$ is given by

$$\mathbf{F}_p = V_p \cdot (\chi \mathbf{H}_a) \cdot \nabla(\mu_0 \mathbf{H}_a), \tag{2}$$

where μ_0 is the permeability, V_p is the volume of the particle, $\mathbf{H}_\mathrm{a}$ is the applied magnetic field intensity, and χ is 2.18 as noted above.

The gravitational force and the buoyant force could be calculated from Eqs. (3) and (4), substituting the volume obtained from image processing.

The gravitational and the buoyant force are given by

$$\mathbf{F}_g = \rho_p \cdot V_p \cdot g \qquad \text{and} \tag{3}$$

$$\mathbf{F}_b = \rho_f \cdot V_f \cdot g, \tag{4}$$

where ρ_p and ρ_f are the densities of the particles and fluid, respectively.

The viscous force [22] is roughly estimated using Eq. (5) below. The viscous force of a Newtonian fluid is given by

$$\mathbf{F}_v = 6\pi\eta R_p \cdot (v_p - v_f), \tag{5}$$

where η and v_f are the viscosity and the velocity of the fluid, respectively, and R_p and v_p are the radius and velocity of the particle, respectively.

When there are two magnetized magnetic particles with magnetic moments $\mathbf{P}_{m1}$ and $\mathbf{P}_{m2}$, the magnetic dipole interaction energy Um is given by

$$U_m = -\left(\frac{\mu_0}{4\pi}\right) \cdot \left(\frac{3(\mathbf{P}_{m1} \cdot \mathbf{r}) \cdot (\mathbf{P}_{m2} \cdot \mathbf{r})}{r^5} - \frac{(\mathbf{P}_{m1} \cdot \mathbf{P}_{m2})}{r^3}\right), \tag{6}$$

where r is the distance between the magnetized magnetic particles. Assuming that those two magnetic moments are parallel on a line, the magnetic dipole interaction energy U_m is given simply by

$$U_m = -\left(\frac{\mu_0 \cdot P_{m1} \cdot P_{m2}}{2\pi \cdot r^3}\right). \tag{7}$$

In this case, the force between the magnetized magnetic particles, F_r, is given by

$$F_r = \frac{\partial U_m}{\partial r} = \left(\frac{3\mu_0 \cdot P_{m1} \cdot P_{m2}}{2\pi \cdot r^4}\right). \tag{8}$$

From the view point of thermal energy, micro- or nanoparticles are influenced by Brownian motion in some cases [23]. The force by Brownian motion [22] has been reported as

$$F_h < \frac{kT}{D_p}, \tag{9}$$

where F_h is the magnitude of the force affecting the particle by Brownian motion, k is Boltzmann's constant, and T is the absolute temperature.

In this study, the rotation behavior caused by an alternating magnetic field is used for breaking up chains of clustered magnetic