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Contactless grasp of a magnetic particle in a fluid and its application to quantifications of forces affecting its behavior

S. Tokura [a,b,*], M. Hara [a], N. Kawaguchi [a], N. Amemiya [b]

[a] Corporate Research and Development, IHI Corporation, 1 Shin-Nakahara, Isogo, Yokohama, Kanagawa 235-8501, Japan
[b] Department of Electrical Engineering, Kyoto University, Kyoto-Daigaku-Katsura, Nishikyo, Kyoto 615-8510, Japan

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ABSTRACT

In this study, the contactless grasp of a magnetic particle suspended in a fluid at rest or in motion by coil current control, and a method for estimating these forces quantitatively were developed. Four electromagnets were used to apply magnetic fields to magnetic ferrite particles (diameter, 300 nm–300 μm) in a fluid in a vessel. Particle-tracking velocimetry with high-speed image processing was used to visualize the behavior of the magnetic particles in the fluid. In addition, contactless grasp of a magnetic particle using the feedback control was accomplished. Furthermore, by making the magnetic force and the resultant force of the other forces affecting a magnetic particle be in balance, the vertical and horizontal forces affecting the minute magnetic particle, such as the viscous force or the magnetic force between magnetized particles, could be estimated quantitatively from the current in the coil of each electromagnet, without any physical contact with the particle itself. These results constitute useful information for studies on the issues in the handling of micro- or nano-particles.

1. Introduction

Magnetic forces on micro- or nano-particles in fluid can be used for drug delivery, cell/DNA manipulation, and other various applications [1–5]. In past study, a biomimetic, microscale system using the mechanics of swimming bacteria applying uniform or cyclic, rotational magnetic field to the microswimmer has been reported [4]. Cell alignment on a glass plate by using an external static magnetic field has also been reported [6]. However, the precise control of the behavior of micro- or nano-particles using magnetic forces has not sufficiently been demonstrated yet.

The behavior of a magnetic particle in fluid is affected by various forces such as the gravitational force, the buoyant force, and the viscous force as well as the magnetic force. It should be noted that the dipole magnetic field [7,8] generated by other magnetized particles also affect its behavior. The quantifications of such forces should be important for controlling behaviors of micro- or nano-particles in future various applications. Many authors have reported theoretical analyses of various forces that affect magnetic particles [1,3,9–13]. Here, the behaviors of ferromagnetic nano-particles in and around blood vessels have been studied using simulation for drug delivery [1]. As for theoretical analyses, an analytical model for predicting the transport and capture of magnetic nano-particles in the microvasculature has presented [3]. Furthermore, on the condition of being given a definite particle size and property, the behavior of the magnetic particle in a dilute solution can be predicted using a dissipative particle dynamics simulation [14]. On the other hand, experimental studies such as the estimation of the accumulation ratio of magnetic particles under a static or a cyclic magnetic field, or the consideration of motions of magnetic particles under magnetophoresis or a cyclic magnetic field have been reported [6,15,16,17–20]. However, the direct measurement of minute forces which are influenced by magnetic particles with various particle sizes or affect them has not been reported to understand the forces more precisely. Therefore, it is necessary to have a visualization method for nano- or micro-magnetic particles which are suspended or flowing in a fluid, and to have a contactless method for measuring the minute forces which act on them or are acted upon by them.

The objective of this study is, at first, to demonstrate the contactless grasp of micro-particles using magnetic force as the initial step of the precise control of their behaviors. Another objective is to quantify various forces which affect the behaviors of magnetic particles in fluid through grasping them by the magnetic force applied by using a combination of electromagnets.

In this paper, first, the contactless grasp of a magnetic particle suspended in a fluid at rest or in motion by controlling the coil currents under visualization of the particles, were developed. Here, S. Tokura et al. [21] have already studied the visualization of magnetic micro-particles in liquid and the control of their

* Corresponding author at: Corporate Research and Development, IHI Corporation, 1 Shin-Nakahara, Isogo, Yokohama, Kanagawa 235-8501, Japan.
Tel.: +81 45 759 2817.
E-mail addresses: susumu_tokura@ihi.co.jp, susumu_tokura@nifty.com (S. Tokura).

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motion using a dynamic magnetic field, and the motions of magnetic particles under a dynamic magnetic field were visualized successfully using the developed system. Four electromagnets were used to apply magnetic fields to magnetic particles in a fluid in a vessel. Particle-tracking velocimetry (PTV) has been used previously to visualize the motion of magnetic particles [21].

Second, a method for the quantitative estimation of forces influenced by and affecting the magnetic particles in a fluid has been developed, preliminary to controlling magnetic particles accurately by an external magnetic field considering the influences of these various forces. A method using a magnetic suspension and balance system [22,23] has been reported for the contactless measurement of a viscous force which affects a model in a flow of air. However, the size of that model containing a permanent magnet was over several centimeters, so that it was easy to visualize and could be placed in some kind of holder before starting suspension control. In this paper, based on the approach of the magnetic suspension and balance system [22], the vertical and horizontal forces affecting a magnetic particle were quantitatively estimated from the current in the coil of each electromagnet without any physical contact with the particle itself.

2. Materials

Magnetic ferrite particles (diameter, 300 nm–300 μm) in pure water in a vessel were used. Fig. 1 shows a typical microscopy image of a particle. The magnetization of the particles was measured using VSM (vibrating sample magnetometer). The magnetization ratio χ was 2.3 (magnetic field intensity $H=4\times10^4$ A/m), and the saturated magnetization was 1.8×10^5 A/m. The linear approximation value of the gradient in M–H curve ($-4\times10^4<H<4\times10^4$ A/m) was used as magnetization ratio for calculating the magnetic force affecting the particles. The relationship between magnetic field intensity H and magnetization M are given by

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

3. Motion of particles

When magnetic particles are suspended in a fluid under magnetic field, they are influenced by the magnetic force caused by the magnetic field gradients, as well as the forces of gravity and buoyancy. Furthermore, for micro- or nano-particles, the viscous force and the force between the magnetized particles themselves should be considered.

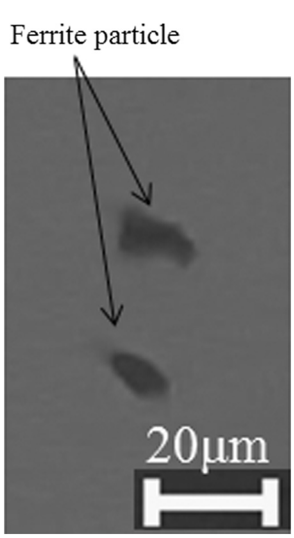

Fig. 1. Typical microscopy image of ferrite particles.

The magnetic force $\mathbf{F}_p$ is given by

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

where μ_0 is the permeability, V_p is the volume of the particle, $\boldsymbol{H}_a$ is the applied magnetic field intensity, and χ is 2.18 as noted above. The magnetic force affecting the particle by external electromagnets is calculated from Eq. (2), substituting values of magnetic field intensity and its gradient obtained from currents of each electromagnet coil, and a volume obtained from image processing as described in more detail later. Here, the relationships between the current of the electromagnet coil and the magnetic flux density (or the field gradient) are previously measured at the center of the electromagnet gap by a gauss meter. The examples of the measurement are shown in Fig. 2(a) and (b) respectively. From the measurement results, the relationships between the current and the magnetic flux density (or gradient) are given by

$$B_y=4.51\,I_v \tag{3}$$

$$\partial B_y/\partial_y=1.77\,I_v \tag{4}$$

$$B_x=4.17\,I_h \tag{5}$$

$$\partial B_x/\partial_x=1.61\,I_h \tag{6}$$

where B_x and B_y (mT) are the horizontal and vertical magnetic flux density, I_h and I_v (A) are the horizontal and vertical coil currents. As the current is applied below 20 A in this paper, the relationships between the magnetic flux density and the current are linear.

The gravitational force and the buoyant force could be calculated from Eqs. (7) and (8), substituting the volume obtained from image processing.

The gravitational and the buoyant force are given by

$$\mathbf{F}_g=\rho_p V_p\mathbf{g} \tag{7}$$

$$\mathbf{F}_b=\rho_f V_f(-\mathbf{g}) \tag{8}$$

where ρ_p and ρ_f are the density of the particles and the fluid, and $\boldsymbol{g}$ is the gravitational acceleration.

The viscous force [12] is roughly estimated using expression (9) below.

The viscous force of Newtonian fluid is given by

$$\mathbf{F}_v=6\pi\eta R_p(\mathbf{v}_p-\mathbf{v}_f) \tag{9}$$

where η and $\mathbf{v}_f$ are the viscosity and the velocity of the fluid, respectively. R_p and $\mathbf{v}_p$ are the radius and the velocity of the particle, respectively. When there are two magnetized magnetic particles which have the magnetic moment $\mathbf{P}_{m1}$ and $\mathbf{P}_{m2}$, the magnetic dipole interaction energy U is given by

$$U=-\left(\frac{\mu_0}{4\pi}\right)\left(\frac{3(\mathbf{P}_{m1}\mathbf{r})(\mathbf{P}_{m2}\mathbf{r})}{r^5}-\frac{(\mathbf{P}_{m1}\mathbf{P}_{m2})}{r^3}\right) \tag{10}$$

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 is simply given by

$$U=-\left(\frac{\mu_0 P_{m1}P_{m2}}{2\pi r^3}\right) \tag{11}$$