Streaming flows produced by oscillating interface of magnetic fluid adsorbed on a permanent magnet in alternating magnetic field

S Sudo¹, M Ito², Y Ishimoto³, S Nix⁴

¹ Department of Machine Intelligence and Systems Engineering, Akita Prefectural University, Yurihonjo, Akita, Japan
² Graduate School of Systems Science and Technology, Akita Prefectural University, Yurihonjo, Akita, Japan
³ Department of Machine Intelligence and Systems Engineering, Akita Prefectural University, Yurihonjo, Akita, Japan
⁴ Department of Machine Intelligence and Systems Engineering, Akita Prefectural University, Yurihonjo, Akita, Japan

E-mail: sudo@akita-pu.ac.jp

Abstract. This paper describes microstreaming flows generated by oscillating interface of magnetic fluid adsorbed on a circular cylindrical permanent magnet in alternating magnetic field. The interface of magnetic fluid adsorbed on the NdFeB magnet responds to the external alternating magnetic field as harmonic oscillation. The directions of alternating magnetic field are parallel and antiparallel to the magnetic field of permanent magnet. The oscillation of magnetic fluid interface generates streaming flow around the magnet-magnetic fluid element in water. Microstreaming flows are observed with a high-speed video camera analysis system. The flow pattern generated by magnetic fluid motion depends on the Keulegan–Carpenter number and the Reynolds number.

1. Introduction
The importance of the study on microstreaming flows induced by oscillation of an object is well recognized. Such oscillatory flows have many potential microfluidic applications. Therefore, extensive investigations on the streaming flows have been studied by a number of researchers. For example, Sarpkaya observed the flow around a transversely oscillating cylinder in a fluid otherwise at rest [1]. Dütsch et al performed Time-averaged Laser Doppler Anemometry measurements and time-resolved numerical flow predictions to investigate the laminar flow induced by the harmonic in-line oscillation of a circular cylinder in water at rest [2]. Costalonga et al. reported on an experimental study of streaming flow induced by a vibrating beam in a Hele-Shaw cell of 2 mm span using long exposure flow visualization and particle-image velocimetry measurements [3]. Rigid mechanical direct vibration was used to generate the streaming flows in these studies. On the other hand, Streaming patterns around a oscillating bubble excited at acoustic frequencies were investigated with flow visualization measurements by Tho et al [4]. In this experiment, a thin 12mm diameter lead zirconate titanate (PZT) piezoelectric disk was used to excite the bubbles. The study on microfluidic mixing through electrowetting-induced droplet oscillation was also reported by Mugele et al. They used the...
wire and the underlying substrate electrode to trigger self-excited oscillations of millimeter-sized sessile droplet [5]. However, the non-contact energy supply method is important in the microfluidic applications.

In this paper, the non-contact energy supply system in order to generate microstreaming flows was proposed. Microstreaming flows were driven by the interface oscillation of magnetic fluid adsorbed on a small circular cylindrical permanent magnet. The magnetic fluid motion was actuated by the external alternating magnetic field. Flow characteristics of water around the magnet-magnetic fluid element were also revealed with a high-speed video camera system.

2. Experimental apparatus and procedures

A block diagram of the experimental apparatus is shown in figure 1. The experimental apparatus is composed of magnet-magnetic fluid element, external magnetic field generation system, and high-speed video camera analysis system. The test magnet-magnetic fluid element is composed of the circular cylindrical permanent magnet and magnetic fluid. The magnetic fluid was adsorbed to the permanent magnet. Letters N and S in figure 1 show the poles of the magnet. This test element was sandwiched between two acrylic plastic parallel plates. Figure 2 shows the test element system. The diameter of the cylindrical magnet is \( d_p = 5 \text{mm} \) and the length is \( \varepsilon = 5 \text{mm} \). The magnetic flux density of the magnet is \( B = 450 \text{mT} \). The sample magnetic fluid was kerosene-based Ferricolloid HC-50. This magnetic fluid is immiscible with water. The volume of magnetic fluid adsorbed to the magnet is \( V_m = 2 \times 10^{-7} \text{m}^3 \) (200 \( \mu l \)). This system was submerged in water as shown in figure 3. The alternating magnetic field was generated by applying alternating current voltage to the Helmholtz coil (Lake Shore MH6) as shown in figure 1. The alternating current signal was supplied from the frequency synthesizer (NF Corporation Multifunction Generator WF1943). The magnet-magnetic fluid element was located on a center part of the Helmholtz coil. The direction of the external magnetic field was parallel and anti-parallel to the direction of permanent magnet. The dynamic behavior of magnetic fluid was analyzed with the high-speed video camera system (Photron FASTCAM-ultima SE). The video camera system is composed a high-speed video camera, a cassette recorder, a video monitor, and a personal computer. The streaming flows generated by the interface oscillation of magnetic fluid were also observed by the high-speed video camera system.

![Figure 1. Block diagram of experimental apparatus.](image-url)
In this experiment, the applied voltage is given in the sinusoidal form as follows:

\[ E_c = \frac{E_0}{2} \sin(2\pi f_0 t) \]  

where \( E_0 \) is the amplitude of alternating voltage, \( f_0 \) is the frequency, and \( t \) is the time. In the experiment, \( E_0 \) and \( f_0 \) were varied. Most experiments were conducted at the condition of the total voltage amplitude \( E_0 = 90V \).

In the visualization experiment, milk was spread on the lower flat plate in the test system by a pipette. The experiments were performed under the condition of room temperature.

3. Experimental results and discussion

In this experiment, surface responses of magnetic fluid adsorbed on the permanent magnet were investigated with the high-speed video camera system. Then water flows produced by the magnetic fluid motions were visualized by using the thin milk film spread on the flat plate. Figure 4 shows an example of the visualization photograph of flow produced around the magnet-magnetic fluid element system. This flow was generated by the interface vibration of magnetic fluid subjected to external alternating magnetic field. A coordinate system was set to examine the interface vibration of magnetic fluid and water flows as shown in figure 5.

3.1. Interface oscillation of magnetic fluid

The responses of the magnet-magnetic fluid system in the water subjected to external alternating magnetic field were studied in the first stage. When alternating magnetic field was applied to the magnetic fluid adsorbed on the permanent magnet, the oscillation with small amplitude was generated on the magnetic fluid interface. Figure 6 shows a series of photographs of the interface oscillation of magnetic fluid adsorbed on the magnet. In general, the surface of magnetic fluid adsorbed on the permanent magnet responds to the alternating magnetic field in the elongation and contraction of its length \([6]\). It can be seen from figure 6 that the horizontal direction length of the magnetic fluid changes with time. Figure 7 shows an example of time variation of the interface displacement at the
Figure 4. Water flow generated by oscillation.

Figure 5. Coordinate system in test system.

Figure 6. Photographs showing magnetic fluid oscillation produced by alternating magnetic field.

Figure 7. Interface oscillation of magnetic fluid at the horizontal peak position.
horizontal peak. In figure 7, \( \eta_m \) is the displacement of magnetic fluid interface in the coordinate system defined as \( \eta_m = 0 \) at the interface in the condition \( E_0 = 0 \). It can be seen from figure 7 that the frequency of interface oscillation was precisely same that of the external alternating magnetic field. The amplitude of the interface oscillation depended on the frequency of the external alternating magnetic field at the constant applied voltage. Figure 8 shows the relation between total amplitude \( |\eta_m| \) and the excitation frequency \( f_0 \). The total amplitude \( |\eta_m| \) is defined by the difference between crests and troughs in \( \eta_m \). Frequency characteristics of total amplitude of magnetic fluid oscillation show peak region. The peak frequency is related to the natural frequency of magnetic fluid oscillation. In figure 8, the peak frequency is \( f_0 = 75 \text{Hz} \). In this experimental system, the dominant response of magnetic fluid was elongation and contraction in horizontal length as shown in figure 6. This is the first mode of magnet-magnetic fluid element response.

![Figure 8. Frequency characteristics of interface oscillation of magnetic fluid adsorbed on permanent magnet subjected to alternating magnetic field.](image)

3.2 Water flows produced around the magnet-magnetic fluid element

When the magnetic fluid adsorbed to the permanent magnet was subjected to alternating magnetic field, water flows were produced around the magnet-magnetic fluid element as shown in figure 4. Water flows around the magnet-magnetic fluid element subjected to external alternating magnetic field were studied in this paragraph. Figure 9 shows a series of photographs of process of water flow generation. Four small flows are visualized in figure 9. Those streaming flow outside as shown in figure 5. Figure 10 shows a position change of the flow tip with time. The flow tip gradually goes away from the magnet-magnetic fluid element with time. The velocity change of the flow tip was calculated by the figure 9. The velocity variation of the flow tip is shown in figure 11. In the beginning of interface oscillation, the speed shows a relatively higher value. After speed reached the peak value, the speed shows gradually decrease. Finally, the speed shows a constant value. The constant speed of the flow is approximately \( v_p = 1 \text{m/s} \) in figure 11.
Figure 9. A series of photographs indicating the progress of four flows produced around magnet-magnetic fluid element.

Figure 10. Position change of flow tip after the excitation by alternating magnetic field.
3.3. Effect of frequency in alternating magnetic field
In this paragraph, the influence of frequency in alternating magnetic field on the water flow was examined. Figure 12 shows the visualization photographs of water flow produced by the interface oscillation of magnetic fluid at different frequencies. In figure 12, \( t \) is the elapsed time during interface oscillation of magnetic fluid. These photographs show the flow state produced at the interface position \( P_4 \) and the elapsed time \( t=12\) s. It can be seen from figure 12 that the position of flow tip depends on the frequency \( f_0 \). Figure 13 shows the relation between the frequency of alternating magnetic field and the position of flow tip at the constant \( E_0 \). In figure 13, the position of flow tip shows a peak at \( f_0=75\) Hz.

In figure 12, \( KC \) is the Keulegan–Carpenter number, \( \beta \) is the Stokes number, and \( Re \) is the Reynolds number. These are key dimensionless parameters. The Keulegan–Carpenter number is defined by

\[
\frac{t}{s} = 12, E_0 = 90 \text{ V, } V_m = 200 \times 10^{-9} \text{ m}^3
\]
Figure 13. Relation between the tip position of flow produced by the interface oscillation and the frequency of alternating magnetic field.

\[
KC = 2\pi A/d_p
\]

(2)

where \( A \) is the amplitude of interface oscillation. The Stokes number \( \beta \) is defined by

\[
\beta = f_0 d_p / \nu
\]

(3)

where \( \nu \) is the kinematic fluid viscosity. The Reynolds number \( Re \) is defined by

\[
Re = KC\beta
\]

(4)

In figure 13, the position of water flow tip shows the peak in the domain that all these parameters have higher value. The flow field produced by the interface oscillation of magnetic fluid depends on three dimensionless parameters.

4. Conclusions

The non-contact energy supply system in order to generate microstreaming flows was proposed. Characteristics of microstreaming flows produced by oscillation of magnetic fluid adsorbed on a permanent magnet subject to the alternating magnetic field were studied with the high-speed video camera system. The results obtained are summarized as follows.

1. Micro water flows toward the four directions from the element are produced by the interface oscillation of magnetic fluid adsorbed on a permanent magnet subjected to alternating magnetic field.

2. The amplitude in interface oscillation of magnetic fluid depends on the frequency of alternating magnetic field. Frequency characteristics of the magnet-magnetic fluid element indicates the presence of a natural frequency in the magnetic fluid oscillation.

3. The flow field produced by the magnetic fluid interface oscillation depends on the Keulegan–Carpenter number, the Stokes number, and the Reynolds number.
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References
[1] Sarpkaya T 2002 J. Fluid Mech. 457 157
[2] Dütsch H, Durst F, Becker S and Lienhart H 1998 J. Fluid Mech. 360 249
[3] Costalonga M, Brunet P and Peerhossain H 2015 Phys. Fluid 27 013101
[4] Tho P, Manasseh R and Ooi A 2007 J. Fluid Mech. 576 191
[5] Mugele F, Baret J –C, Steinhauser D 2006 Appl. Phys. Lett. 88 204106
[6] Sudo S, Asano D, Takana H and Nishiyama H 2011 J. Magn. Magn. Mater. 323 1314