Experimental analysis of clustering structures in magnetic and MR fluids using ultrasound

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Abstract. The formation of clustering structures in magnetic and MR fluids has an influence on ultrasonic propagation. We propose a qualitative analysis of these structures by measuring properties of ultrasonic propagation. Since magnetic and MR fluids are opaque, the non-contact inspection using this ultrasonic technique can be very useful for analyzing the inner structures of magnetic and MR fluids. We measured ultrasonic propagation velocity in a hydrocarbon-based magnetic fluid and MR fluid precisely. Based on these results, the clustering structures of these fluids were analyzed experimentally in terms of elapsed time dependence, effect of external magnetic field strength and angle, and hysteresis phenomena. A comparison of ultrasonic velocity propagation between magnetic and MR fluid was discussed.

1. Introduction
Magnetic fluid and magneto-rheological fluid are typical magnetic functional fluids that change their rheological properties when an external magnetic field is applied. The main difference between these two fluids is the inner particle size. The particles in a magnetic fluid are about 10 nm in diameter, while those in an MR fluid are in a range of 100 nm to 10 \textmu m. When an external magnetic field is applied to magnetic or MR fluids, some of the inner particles coagulate and form a clustering structure. Because these clusters have a strong influence on the properties of these two fluids, it is important to analyze these clustering structures with regard to applications of magnetic functional fluids. However, because both fluids are opaque, it is difficult to analyze them by normal optical methods.

Ultrasonic propagation velocity and attenuation in magnetic and MR fluids change with the application of an external magnetic field \cite{1}. It seems that the formation of clustering structures influences the ultrasonic propagation. Therefore, we propose a qualitative analysis of these structures by measuring properties of ultrasonic propagation. Because this ultrasonic technique can be applied to an opaque fluid, it can be useful for analyzing the inner structures of magnetic and MR fluids.

Several theoretical \cite{2} and experimental \cite{3} studies have been conducted to investigate the properties of ultrasonic propagation in relation to the inner structures in magnetic \cite{4} and MR fluids. However, the inner structures are complicated and are still not clear. In this study, we measured ultrasonic propagation velocity in each of a hydrocarbon-based magnetic fluid and MR fluid precisely.
Based on these results, the clustering structures of these fluids are analyzed and the application of non-contact inspection in these fluids by ultrasonic techniques is discussed.

2. Experimental apparatus

Figure 1 shows a block diagram of the experimental apparatus. The ultrasonic measurement scheme is based on the pulse method. Ultrasonic propagation velocity in the test fluid can be calculated using this apparatus.

Figure 2 shows the details of the test cell. Two 5 mm diameter ceramic oscillators function as ultrasonic transmitter and receiver respectively. The ultrasonic frequency is 2 MHz. The test cell is made of transparent acrylic. The temperature of the test fluid in the square test cell (32 × 32 mm) is controlled and kept constant by a temperature control unit. The temperature control unit uses water as a liquid temperature control. The magnetic field is applied by an electromagnet that can be varied from 0 to 550 mT. A DC power supply is used for the electromagnet. The angle $\phi$ between the direction of the magnetic field and the direction of ultrasonic wave propagation can be adjusted freely between 0° and 180°. A digital oscilloscope is used to stimulate and measure the receiving ultrasonic wave. The properties of the magnetic and MR fluids used are shown in Table 1. These properties were measured at 40°C.

![Figure 1. Experimental apparatus](image1)

![Figure 2. Detail of the test cell](image2)

**Table 1. Properties of magnetic and MR fluids at 40°C.**

| Property               | Magnetic Fluid | MR Fluid    |
|------------------------|---------------|-------------|
| Manufacturer           | Ferrotec      | LORD Co.    |
| Serial name            | EXP04019      | MRF132-DG   |
| Particle material       | Ferrite       | Ferrite     |
| Mean particle size     | 10 nm         | 10 μm       |
| Volume fraction        | 0.19          | 0.32        |
| Carrier liquid         | Hydrocarbon oil | Hydrocarbon oil |
| Viscosity              | 2.18±0.2 mPa.s | 92±15 mPa.s |
| Density                | 1.049×10³ kg/m³ | 2.98−3.18×10³ kg/m³ |
3. Result and discussion

Figure 3 shows the change in ultrasonic propagation velocity in the magnetic fluid (MF) and MR fluid (MRF) versus the elapsed time of applying the magnetic field. In this experiment, the magnetic field intensity is kept at 100 mT and 500 mT, the angle $\phi$ is 0° and the temperature of the test fluid is kept at 25°C. Measurements are performed over 30 minutes. The change in ultrasonic propagation velocity is expressed by $\Delta V/V_0$. Here, $\Delta V$ is defined by $\Delta V=V-V_0$ where $V$ and $V_0$ are ultrasonic propagation velocities with and without an external magnetic field, respectively. Average value of $V_0$ was founded 1092.34 m/s for MF and 803.79 m/s for MR fluid in this experiment.

The ultrasonic propagation velocity in the magnetic fluid increases with time while the magnetic field is applied. The change becomes almost constant after about 5 minutes. On the contrary, the ultrasonic propagation velocity in the MR fluid instantly increases. These changes seem to be caused by differences in cluster formation and indicate growth of clustering structures over the time the magnetic field is applied. The clusters seem to continue to grow until the ultrasonic propagation velocity becomes constant. On the other hand, robust clusters seem to form almost instantly in the MR
fluid and we cannot detect the growing process of the clusters based on these measurements. It seems that the clusters grow very fast, in advance of the first measurement at 30 seconds and become stable after 30 seconds.

Figure 4 shows that ultrasonic propagation velocity in both magnetic and MR fluids changes with the application of an external magnetic field for $\phi = 0^\circ$ ($\parallel$) and $\phi = 90^\circ$ ($\perp$). When the magnetic field intensity increases, the ultrasonic propagation velocity also increases. It seems that cluster formation is thicker when a higher magnetic field is applied. For the MR fluid, the positive gradient of the $0^\circ$ curve is higher than that of the $90^\circ$ curve. This clarifies that the direction of cluster formation is parallel with the direction of the magnetic field. An ultrasonic wave has more difficulty propagating across the $90^\circ$ cluster formation than the $0^\circ$ case.

On the other hand, the magnetic fluid has unique curves when the external magnetic field is applied at $0^\circ$ and $90^\circ$. Both curves are nearly the same for values below 200 mT but very different for values above 200 mT. It seems that cluster formation has not yet fully developed when under the smaller magnetic field and only primary clusters are formed. Then secondary clusters appear under the higher magnetic fields. Again, ultrasonic propagation velocity at $90^\circ$ is lower than at $0^\circ$.

An interesting hysteresis phenomenon appears when the magnetic field is increased to and decreased from a certain value, 530 mT in this experiment. The magnetic field is applied using the following process: the magnetic field intensity is increased by 12 mT every minute until 530 mT, and there after, the magnetic field intensity is decreased by 12 mT every minute.

In the magnetic fluid, during the increasing process, the change rate $\Delta V/V_0$ also increases as shown in figure 5. This phenomenon appears to be caused by the formation of chain-like clusters in proportion to the magnetic field intensity. However, $\Delta V/V_0$ remains at nearly same value during the decreasing process. It seems that the chain-like clusters do not break instantly, similar to the situation in our previous reports on water-based magnetic fluids [5]. The cluster formation remains in the magnetic fluid even though the external magnetic field becomes zero.

Hysteresis for the magnetic fluid also changes when the angle $\phi$ is changed. For the angle $\phi = 90^\circ$, hysteresis only appears at small magnetic filed intensity, below 150 mT. For the angle $\phi = 0^\circ$, hysteresis appears aver almost the whole range of magnetic field intensity. This indicates that the hysteresis phenomena can be better studied at the angle $\phi = 0^\circ$. Hysteresis for the MR fluid is shown in Figure 6. The hysteresis curves are quite different in comparison with the magnetic fluid. Even though there is hysteresis with the MR fluid, the curve returns to the initial value. It seems that cluster formation in the MR fluid breaks more quickly and eventually becomes the same as the initial conditions after the external magnetic field intensity is zero. The effect of angle $\phi$ is similar to that for the magnetic fluid.

4. Concluding remarks

A precise experimental investigation of the ultrasonic velocity propagation in magnetic and MR fluids under a uniform external magnetic field was conducted. The ultrasonic propagation velocities in magnetic and MR fluids change according to the magnetic field intensity, interval time and angle of magnetic field $\phi$. These results seem to be related to Brownian motion and clustering of the particles in the magnetic and MR fluids under an external magnetic field. In order to understand these clustering phenomena better, it is necessary to investigate the Brownian motion of magnetic particles, the time and the size of cluster formation. It is also necessary to consider the influence of sedimentation of the magnetic particles.

References

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