Investigation of cluster growth in MR fluids using ultrasonic wave propagation

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Abstract. This research reports the experimental results of a study on cluster growth in Magneto-rheological (MR) fluid. The experiments were conducted by applying different magnetic field (M/F) sweep rates to MR fluid. A magnetic field was swept from 0 to 400 mT at different times. Since the MR fluid is opaque, an ultrasonic measurement method was applied. Ultrasonic propagation velocity (V) in MR fluid is dependent on magnetic field and is strongly related to cluster formation in this fluid. Therefore, ultrasonic propagation velocity was measured and the change of ultrasonic propagation velocity (ΔV/V₀) was calculated. Based on the experimental results, cluster growth in MR fluids can be analyzed experimentally. Effect of volume fraction in MR fluid on cluster growth is presented. Furthermore, the relation between the change of ultrasonic propagation velocity and M/F sweep rate is discussed.

1. Introduction
Magneto-rheological (MR) fluids are a type of magnetic functional fluid that changes from a free-flowing fluid to a semi-solid form on the application of a magnetic field. These fluids are formed from micron-sized magnetic particles and a carrier liquid. It is well-known that the magnetic particles in MR fluids will coagulate and form clustering structures parallel to magnetic force lines [1]. These clustering structures restrict the motion of the fluid, thereby increasing the viscous characteristics of the suspension [2]. The most important advantage of these fluids over conventional mechanical interfaces is their ability to achieve a wide range of viscosity (several orders of magnitude) in a fraction of millisecond [3].

The growth of clusters in a ferrofluid has been investigated by Józefczak et al. [4]. They reported that the ultrasonic propagation velocity changes as a function of the magnetic field sweep rate and the temperature of the ferrofluid. Cluster growth in MR fluids is rare. However, understanding the growth of clusters in MR fluids is important for developing applications of these fluids. Therefore, it is important to investigate cluster growth in MR fluids.

Several experimental methods have been used to investigate the inner structure of MR and magnetic fluids. López-López and Vicente [5] proposed a new method by measuring the change in the electromotive force induced in a sensing coil which was placed around the settling suspension. Their method can be used to analyze the effect of the magnetite volume fraction on the stability.

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Jolly et al. [6] conducted magneto-induction experiments to measure the microstructure response of quiescent MR fluid to an applied magnetic field. They measured the time scales associated with microstructure development by recording the evolution of fluid polarization in response to a step change in applied magnetic field. Sawada et al. [7] have applied another measurement method. They applied Rayleigh light scattering technique to visualize the inner structure of a diluted magnetic fluid with and without magnetic field.

In this study, experiments were performed by applying different magnetic field (M/F) sweep rates to MR fluids. Because MR fluids are opaque, an ultrasonic measurement method was utilized. The ultrasonic propagation velocities in MR fluids [8] were changed under the influence of an external magnetic field. Therefore, the ultrasonic propagation velocity was measured, and the change in the ultrasonic propagation velocity was calculated for various M/F sweep rates. Based on the experimental results, an analysis of cluster growth in the MR fluids is presented. In addition, the relationship between the change in the ultrasonic propagation velocity and the M/F sweep rate is discussed.

2. Experimental
A block diagram of the experimental apparatus is illustrated in figure 1. The MR fluid was placed in a rectangular container made from acrylic plates. Two ceramic oscillators were attached to the container. The ultrasonic frequency of these oscillators was 2 MHz. One oscillator acting as a transmitter was connected to the pulse generator, while the other, which acted as a receiver, was connected to the oscilloscope. A pulse generator was used to send an ultrasonic wave to the oscillator, while the digital oscilloscope was used to monitor the ultrasonic propagation between these oscillators. The oscilloscope was also used to measure the ultrasonic propagation properties such as the ultrasonic propagation velocity.

An electromagnet was used to generate the magnetic field in the test cell. The magnetic field was applied in a direction parallel to the ultrasonic propagation direction, as shown in figure 1. The magnetic flux density of the electromagnet was varied from 0 to 400 mT for different lengths of time, and the density of the magnetic flux was adjusted by changing the current in the power supply. A function generator was applied to adjust the power supply in order to produce

![Block diagram of experimental apparatus.](image-url)
Table 1. Properties of MR fluids at 40 °C.

| Property                | Value                      |
|-------------------------|----------------------------|
| Serial name             | MRF122-EG                  |
| Particle material       | Iron                       |
| Mean particle size      | 3 - 10 μm                  |
| Volume fraction         | 0.22                       |
| Carrier liquid          | Hydrocarbon oil            |
| Viscosity               | 42 ± 20 mPa·s              |
| Density                 | 2.28 - 2.48 × 10^3 kg/m³   |
|                         | MRF132-DG                  |
|                         | Iron                       |
|                         | 3 - 10 μm                  |
|                         | 0.32                       |
|                         | Hydrocarbon oil            |
|                         | 92 ± 15 mPa·s              |
|                         | 2.98 - 3.18 × 10^3 kg/m³   |

![Graph](image-url)  

Figure 2. Magnetic flux density (mT) vs. time (s) for various M/F sweep rate.

different M/F sweep rates.

In this experiment, two types of MR fluids, MRF122-EG and MRF132-DG from Lord Corporation, were used. The main difference between these MR fluids is the volume fraction of magnetic particles, which is 22 % for MRF122-EG and 32 % for MRF132-DG. The detailed properties of these fluids are given in Table 1.

For all the experiments, the temperature of the test cell was maintained at 25 °C, and M/F sweep rates of 500, 750, 1000, and 1250 mT/min were applied. For example, at an M/F sweep rate of 500 mT/min, 400 mT of magnetic flux density was swept in 48 sec. Figure 2 presents more detailed information on how the magnetic flux density was swept.

The ultrasonic propagation velocity was measured, and the change in the ultrasonic propagation velocity (ΔV/V₀) was calculated using the following equation:

\[
\frac{\Delta V}{V_0} = \frac{V - V_0}{V_0}
\]

where \(V\) and \(V_0\) are the ultrasonic propagation velocity with and without the applied magnetic field, respectively.
3. Result and discussion

Figure 3 shows the values of $\Delta V/V_0$ for (a) MRF122-EG and (b) MRF132-DG at various M/F sweep rates. At different M/F sweep rates, the value of $\Delta V/V_0$ increases with an increase in the magnetic field. It is well known that this change is due to the formation of clustering structures; when the magnetic field increases, more clusters are formed [1].

Figures 3 (a) and (b) show that the influence of the volume fractions of the MR fluid on $\Delta V/V_0$ is significant. At a lower volume fraction (MRF122-EG), the value of $\Delta V/V_0$ is lower than that for the higher volume fraction, and the cluster size is proportional to the volume fraction. As a result, the value of $\Delta V/V_0$ increases when the volume fraction of the MR fluid increases. In other words, the size of the cluster increases for higher volume fractions. This result suggests that the volume fraction and M/F sweep rate affect the formation of the clustering structures in MR fluids.

Figure 4 shows the maximum values of $\Delta V/V_0$ for the two types of MR fluids at various M/F sweep rates. From the figure, it can be seen that the maximum value of $\Delta V/V_0$ decreases at higher applied M/F sweep rates. It appears that the magnetic particles in the MR fluids do not have sufficient time to form clusters of greater size at high M/F sweep rates. Therefore, the

![Figure 3](image1.png)

**Figure 3.** Change of ultrasonic propagation velocity in (a) MRF122-EG and (b) MRF132-DG vs. time for various M/F sweep rates.

![Figure 4](image2.png)

**Figure 4.** Maximum value of change in ultrasonic propagation velocity vs. M/F sweep rates.
maximum size of the cluster decreases at higher M/F sweep rates. This result indicates that the M/F sweep rate affects the maximum size of the clusters in MR fluids.

4. Concluding remarks
Experiments were conducted to investigate cluster growth in MR fluid. Two different volume fractions of MR fluids were subjected to magnetic fields using different sweep rates. The size of the clusters increased for higher volume fractions. The maximum value of $\Delta V/V_0$ decreased at higher applied M/F sweep rates. The results indicate that the volume fraction and M/F sweep rate affect the formation of the clustering structures in MR fluids.

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