Experimental measurements of ultrasonic propagation velocity and attenuation in a magnetic fluid

2008 J. Phys.: Condens. Matter 20 204117

(http://iopscience.iop.org/0953-8984/20/20/204117)

IOP PUBLISHING JOURNAL OF PHYSICS: CONDENSED MATTER

J. Phys.: Condens. Matter **20** (2008) 204117 (5pp) doi:10.1088/0953-8984/20/20/204117

Experimental measurements of ultrasonic propagation velocity and attenuation in a magnetic fluid

M Motozawa[1], **Y Iizuka**[2] **and T Sawada**[2,3]

[1] Department of Mechanical Engineering, Tokyo University of Science, 2641 Yamazaki, Noda 278-8510, Japan
[2] Department of Mechanical Engineering, Keio University, Yokohama, Japan

E-mail: sawada@mech.keio.ac.jp

Received 1 April 2008
Published 1 May 2008
Online at stacks.iop.org/JPhysCM/20/204117

Abstract
The ultrasonic propagation velocity and attenuation in a magnetic fluid subjected to magnetic field are measured precisely. Various characteristic properties of ultrasonic propagation in magnetic fluid such as hysteresis and anisotropy are observed. These results show that the ultrasonic propagation velocity and attenuation are dependent upon the intensity and the length of time for which the magnetic field is applied. When the magnetic field is applied, some of the magnetic particles in the magnetic fluid form clustering structures that influence ultrasonic propagation in a magnetic fluid. Our results indicate that the inner structure of a magnetic fluid can be analysed experimentally and we discuss the application of this non-contact inspection of the clustering structures in a magnetic fluid by ultrasonic techniques.

1. Introduction

A magnetic fluid is a stable colloidal dispersion of small surfactant-coated magnetic particles in a liquid carrier, such as water or kerosene. The preparation of a stable magnetic fluid involves a delicate balance between the attractive and repulsive forces on each particle. The particles are in Brownian motion and remain suspended under room temperature conditions. When an external magnetic field is applied to the magnetic fluid, the colloidal particles coagulate and form clustering and chaining structures. This clustering has a significant influence on ultrasonic propagation in the magnetic fluid.

Several studies have been performed to investigate the properties of ultrasonic propagation in a magnetic fluid. Parsons [1] proposed a linear hydrodynamical theory of a magnetic fluid under an external magnetic field. He derived an expression of the sound attenuation coefficient assuming the magnetic fluid acts as a liquid crystal. Chung and Isler [2] measured attenuation coefficients and ultrasonic propagation velocity in a magnetic fluid. Their experiments revealed the anisotropy of ultrasonic propagation. However, there are some differences between Parson's theoretical results and the Chung–Isler data. Taketomi [3] calculated an attenuation expression considering chain-like cluster formation. Both the rotational and translational motions of the magnetic particles were considered. Recently, Skumiel *et al* [4] measured the ultrasonic propagation velocity under a magnetic field. In their paper, the anisotropy of ultrasonic propagation was observed experimentally and was compared with Taketomi's theory. Jozefczak *et al* [5] measured ultrasonic attenuation in a magnetic fluid subjected to a uniform external magnetic field at different sweep rates. In our previous study [6], we performed precise measurements of ultrasonic propagation velocity in water-based and kerosene-based magnetic fluids. Hysteresis and anisotropy of ultrasonic propagation were observed. Moreover, we also measured ultrasonic propagation velocity while changing the weight concentration of the magnetic fluid [7]. From these results, we discussed the process of chain-like cluster formation.

As mentioned above, several theoretical and experimental studies have been carried out to clarify ultrasonic propagation properties in magnetic fluids. But the actual mechanisms are very complicated and remain unclear. In this present paper, we discuss an experiment involving precise measurements of ultrasonic propagation velocity and attenuation in a kerosene-

[3] Present address: Department of Mechanical Engineering, Keio University, 3-14-1 Hiyoshi, Kohoku-ku, Yokohama 223-8522, Japan.

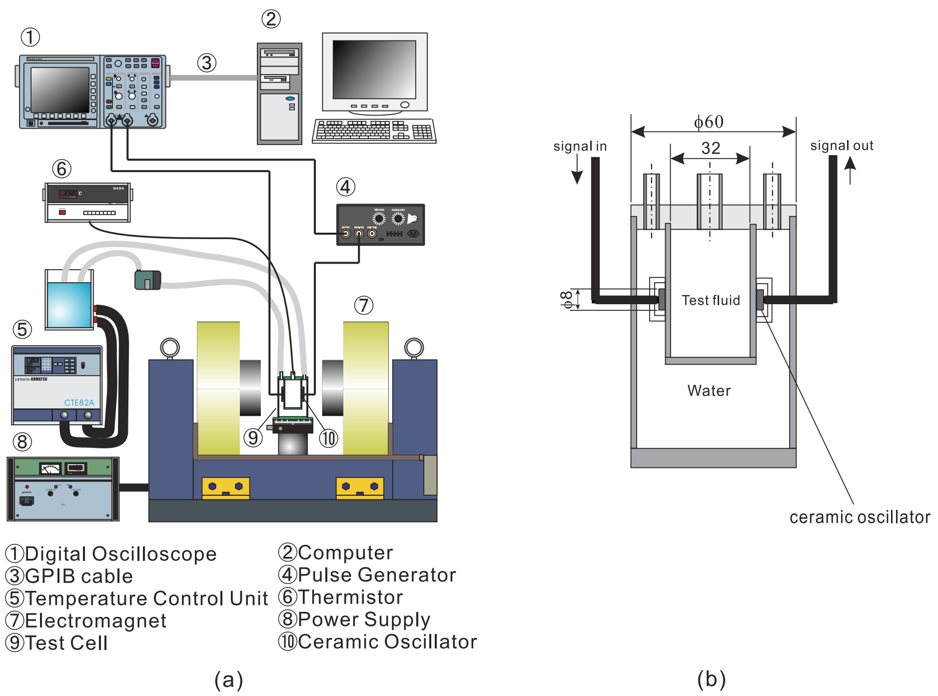

Figure 1. Experimental apparatus: (a) block diagram of the apparatus; (b) detail of the test cell in the apparatus. (This figure is in colour only in the electronic version)

based magnetic fluid. The measurements are made while changing external magnetic field intensity, the direction of the magnetic field and the duration of application of the magnetic field. Based on these results, the influence of the motion of the colloidal particles and the process of chain-like cluster formation on ultrasonic propagation is discussed. In addition, we suggest techniques for the non-contact inspection of the inner structures of a magnetic fluid based on measurements of changes in the properties of ultrasonic propagation.

Table 1. Properties of the magnetic fluid.

Fluid	EXP04019 (magnetic fluid)	Water	Kerosene
Particle material	Fe_3O_4	—	—
Particle diameter	About 10 nm	—	—
Carrier liquid	Kerosene oil	—	—
Density, kg m^{-3} (at 25 °C)	1060	997	782
Viscosity, mPa s (at 25 °C)	1.37	0.89	1.06

2. Experiment

2.1. Experimental apparatus

Figure 1 shows the experimental apparatus. The left figure (a) is a block diagram of the experimental apparatus and the right figure (b) shows the detailed structure of the test cell in the apparatus. The test cell has a concentric structure. The magnetic fluid is in an inner rectangular vessel. An outer cylindrical container is filled with circulating water, which is monitored by a temperature control unit to keep the magnetic fluid at 25 °C for all experiments. Two ceramic oscillators are set on opposite sides of the inner vessel as an emitter and a receiver, respectively.

The ultrasonic measurement scheme is based on the pulse method. A burst wave and trigger signal are synchronously generated by the pulse generator. The trigger signal is sent to the digital oscilloscope and the burst wave is transmitted to the ceramic oscillator in the test cell. Simultaneously, the ultrasonic pulse is generated at the oscillator, and propagates through the magnetic fluid in the cell. This ultrasonic pulse is received at the other ceramic oscillator on the opposite side of the cell. The received signal is also sent to the digital oscilloscope. After this signal is synchronized with the trigger signal, the travelling time of the ultrasonic wave can be measured on the digital oscilloscope. Ultrasonic propagation velocity in the magnetic fluid is calculated based on this time.

The ultrasonic frequency used is 2 MHz. The magnetic field can be varied from 0 to 550 mT by an electromagnet. The angle ϕ between the direction of the magnetic field and the direction of ultrasonic wave propagation can be adjusted freely between 0° and 90°.

The test fluid is a kerosene-based magnetic fluid named EXP04019 produced by Ferrotec Co. The properties of this magnetic fluid are shown in table 1. The volume concentrations of Fe_3O_4 and surfactant in this fluid measured by Ferrotec Co. are 8.6–11.6 vol% and 8.0–10.9 vol%, respectively.

2.2. Measurement of ultrasonic propagation velocity in pure water

Figure 2 shows a comparison of the ultrasonic propagation velocities in pure water, kerosene and magnetic fluid. The plotted points were obtained from our experimental apparatus,

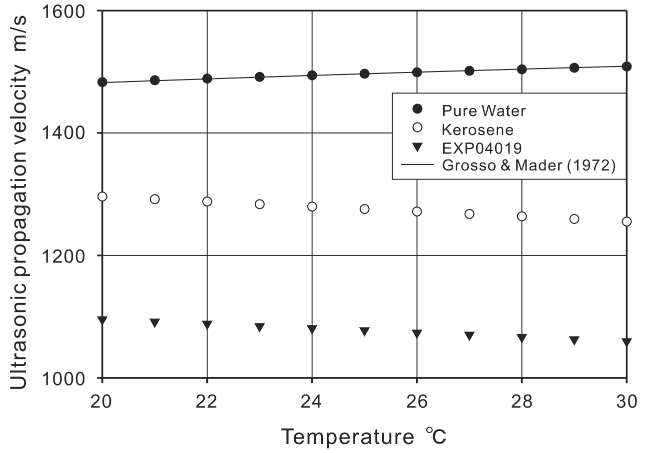

Figure 2. Ultrasonic propagation velocity in pure water, kerosene and magnetic fluid.

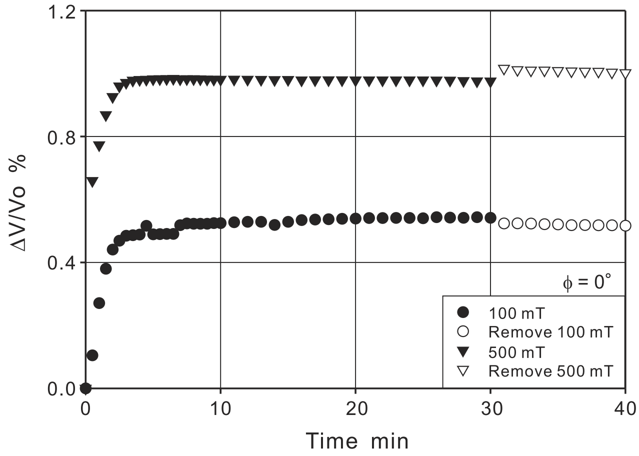

Figure 3. Elapsed time dependence of ultrasonic propagation properties—velocity.

while the solid line is a measurement of sound velocity in pure water obtained by Grosso and Mader [8]. It can be seen that the ultrasonic propagation velocity in pure water obtained in our experiment agrees very well with the result of Grosso and Mader.

2.3. Evaluation of ultrasonic propagation velocity and attenuation

Ultrasonic propagation velocity and attenuation both change with applied magnetic field. The change of ultrasonic propagation velocity can be expressed by $\Delta V/V_0$. Here, ΔV 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.

On the other hand, the change of attenuation of ultrasonic propagation can be expressed by $\Delta\alpha$. $\Delta\alpha$ is calculated based on the received waveform as follows:

$$\Delta\alpha = -\frac{20}{L}\log_{10}\left(\frac{P_1}{P}\right) - \left\{-\frac{20}{L}\log_{10}\left(\frac{P_0}{P}\right)\right\} = \frac{20}{L}\log_{10}\left(\frac{P_0}{P_1}\right). \quad (1)$$

Here, L is the travelling length of the ultrasonic wave. P is the sound pressure on the emitter. P_0 and P_1 are the sound pressure on the receiver with and without an external magnetic field, respectively. Although we cannot measure P, P_0 and P_1 can be measured. Therefore, $\Delta\alpha$ can be obtained by P_0 and P_1 without P using this expression.

3. Results and discussion

3.1. Ultrasonic propagation velocity in a magnetic fluid

The ultrasonic propagation velocities in EXP04019 and kerosene are also shown in figure 2. This figure indicates that the ultrasonic propagation velocity in EXP04019 is smaller than that in the carrier liquid because the magnetic particles have an influence on the ultrasonic propagation velocity. The Brownian motion of the inner particles becomes more active with temperature increase. The Brownian motion, however, appears to have a minimal influence on the ultrasonic propagation velocity in a magnetic fluid because the configurations of the velocity profiles of the kerosene and the magnetic fluid are similar.

3.2. Elapsed time dependence of ultrasonic propagation

Figure 3 shows the change of ultrasonic propagation velocity versus the elapsed time of applying the magnetic field. In this experiment, the magnetic field intensity is kept at either 100 or 500 mT, and the angles ϕ is 0°. The magnetic field is applied to a magnetic fluid for 30 min and is then removed while continuing to measure the ultrasonic propagation velocity.

The ultrasonic propagation velocity in the magnetic fluid increases quickly when the magnetic field is applied. This change becomes almost constant after about 5 min. This change seems to be caused by chain-like cluster formations. Because the inner magnetic particles form chain-like clusters along the direction of the magnetic field, the particle concentration in the area of cluster formation is thicker than that in the other areas. Therefore, the ultrasonic propagation velocity increases. In addition, it seems that the chain-like clusters continue to grow until the ultrasonic propagation velocity becomes constant. In this case, the clusters grow for about 5 min. Comparing with our previous measurements [6], it appears that time for growth of the clusters varies in different kinds of magnetic fluids. For example, in the case of water-based magnetic fluids, the clusters grew for 1.5 h. When the magnetic field is removed, the ultrasonic propagation velocity hardly changes. This indicates that the chain-like clusters do not break of their own accord. Because the ultrasonic propagation velocity in 500 mT is larger than that in 100 mT, it appears that the chain-like clusters grow larger under a stronger magnetic field.

On the other hand, figure 4 shows the change of attenuation in the same experiment. The attenuation of ultrasonic propagation changes widely during the initial 5 min. Comparing these results with the results for velocity, this indicates that the magnetic particles move more actively

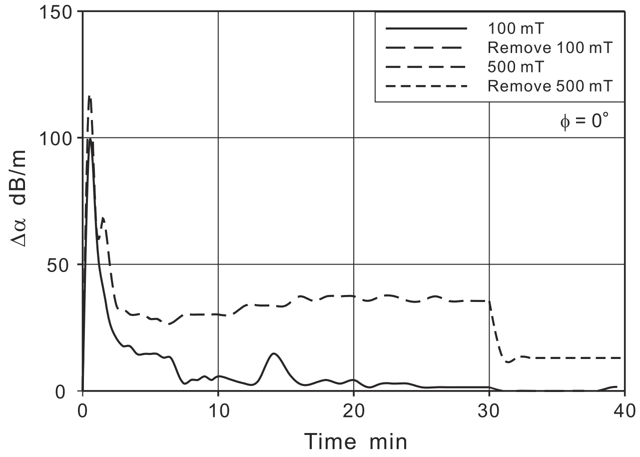

Figure 4. Elapsed time dependence of ultrasonic propagation properties—attenuation.

in forming the clustering structures when subjected to the magnetic field. Similar to the results for velocity, the chain-like clusters continue to grow and then the attenuation becomes constant. The clusters also appear to be larger under a stronger magnetic field.

3.3. Magnetic field dependence of ultrasonic propagation

Figure 5 shows the magnetic field dependence of ultrasonic propagation velocity in the magnetic fluid for $\phi = 0°$ and 90°. In these experiments, the magnetic field is applied using the following process: the magnetic field intensity is increased by 12 mT every 2 min until 550 mT is reached, and thereafter the magnetic field intensity is decreased by 24 mT every 2 min.

When $\phi = 0°$, there is clear hysteresis in relation to the applied magnetic field. When the magnetic field intensity increases, the ultrasonic propagation velocity also increases. It seems that the chain-like clusters grow in proportion to the increase of the magnetic field intensity. When the magnetic field intensity decreases, however, the ultrasonic propagation velocity remains constant. This indicates that the chain-like clusters do not break easily when the magnetic field intensity decreases.

In contrast, at $\phi = 90°$, there is no significant hysteresis. Because the directions of ultrasonic propagation and chain-like cluster formation are perpendicular, the chain-like clusters strongly interfere with ultrasonic propagation in the magnetic fluid. As such, the change of ultrasonic propagation velocity is smaller than that at $\phi = 0°$. However, this tendency is very complicated and difficult to explain. Because the chain-like cluster grows larger with the magnetic field intensity and the influence on ultrasonic propagation is stronger, the ultrasonic propagation velocity begins to decrease at about 200 mT.

The change of attenuation observed in the same experiment is shown in figure 6. When $\phi = 0°$, there is no significant hysteresis and the change of attenuation is rather small. Because the ultrasound propagates in the direction of formation of the chain-like clusters, these clusters have little influence on the ultrasonic propagation in the magnetic fluid.

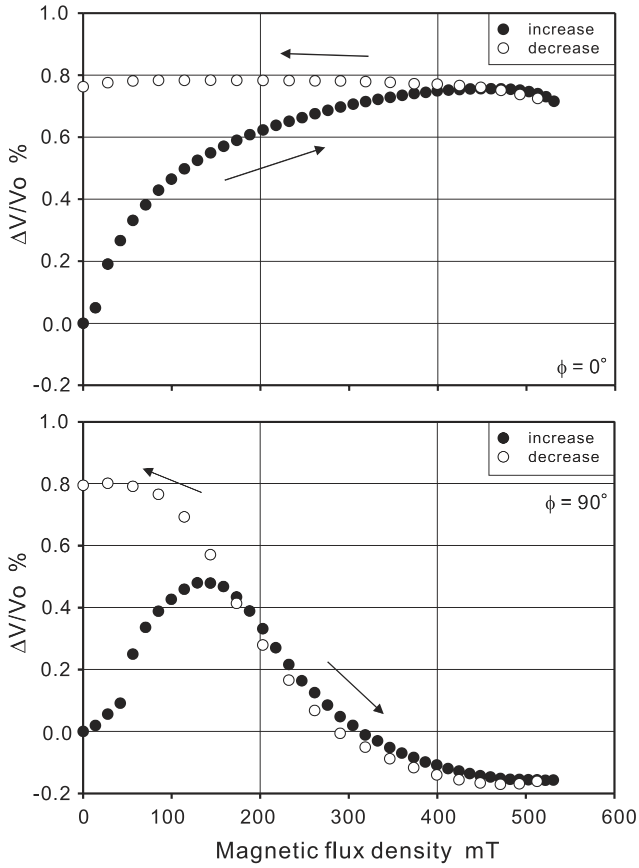

Figure 5. Magnetic field dependence of ultrasonic propagation properties—velocity.

On the other hand, when $\phi = 90°$, the profile of the change in attenuation is very complicated and similar to that of ultrasonic propagation velocity. Because the attenuation of ultrasonic propagation widely changes with magnetic field, the clusters have a strong influence on the ultrasonic propagation, similar to the results for velocity.

In comparison with the results obtained by Jozefczak *et al* [5], we found that the change in attenuation of ultrasonic propagation is very complicated, and our results are similar to their findings. A theoretical study of attenuation [3] has been proposed to clarify these complicated attenuation mechanisms, but this theory does not explain the experimental results.

3.4. Anisotropy of ultrasonic propagation

Anisotropies of ultrasonic propagation velocity and attenuation are shown in figures 7 and 8, respectively. Before each measurement, the magnetic field is applied for some minutes in order to provide time for formation of sufficient chain-like clusters.

It can be seen that the minimum ultrasonic propagation velocity is obtained at $\phi = 90°$, and the maximum velocity is obtained at $\phi = 0°$. Meanwhile, when the angle ϕ increases, the attenuation also generally increases. A remarkable level of anisotropy is observed and this anisotropy proves that the chain-like clusters form along the direction of the magnetic

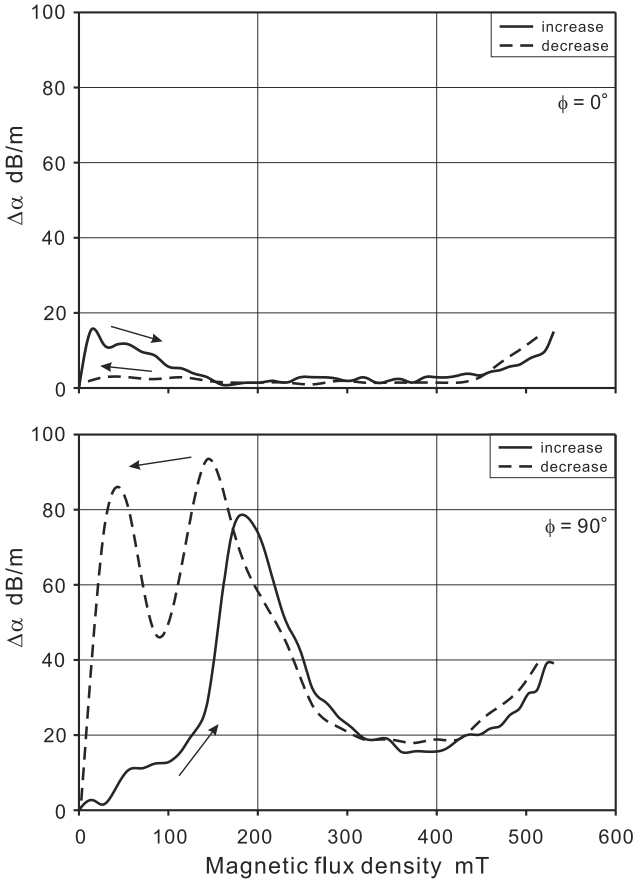

Figure 6. Magnetic field dependence of ultrasonic propagation properties—attenuation.

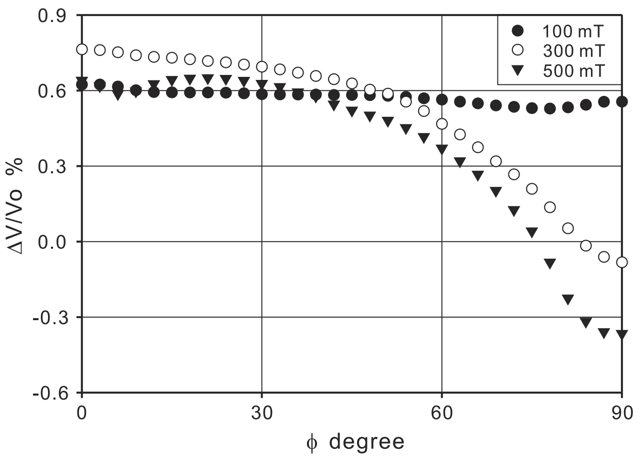

Figure 7. Anisotropy of ultrasonic propagation velocity.

field and grow end by end. However, as the detailed changes in the attenuation profile are very complicated, further detailed experiments need to be performed to clarify the anisotropy of the attenuation.

4. Concluding remarks

The ultrasonic propagation properties of a kerosene-based magnetic fluid subjected to uniform magnetic fields have been investigated experimentally. In particular, we performed

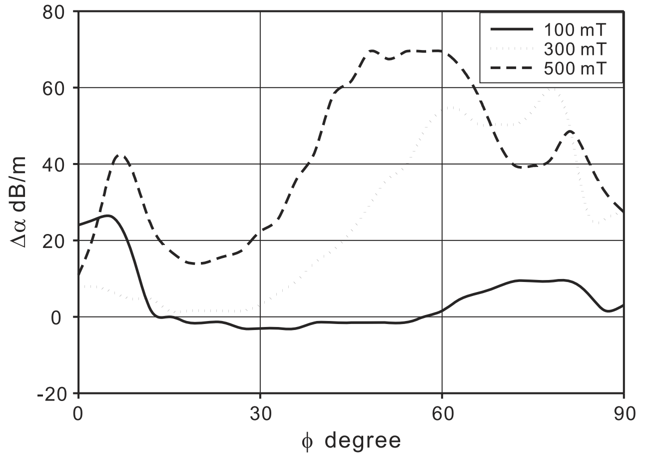

Figure 8. Anisotropy of attenuation.

detailed measurements of ultrasonic propagation velocity and attenuation.

The ultrasonic propagation velocity and attenuation both change with the applied magnetic field. These changes are caused by clustering structures in the magnetic fluid. By comparing the ultrasonic propagation velocity with attenuation, we can analyse the movement of the inner particles and the process of chain-like cluster formation. Moreover, hysteresis and anisotropy of ultrasonic propagation are observed, indicating that the clustering structures continue to grow as the magnetic field intensity increases and that these clustering structures do not break up easily when the magnetic field is removed.

We obtained several complicated experimental results concerning ultrasonic propagation in a magnetic fluid. These properties of ultrasonic propagation are useful for analysing the inner structure of a magnetic fluid. However, more detailed experiments need to be performed to clarify these complicated mechanisms of ultrasonic propagation properties in magnetic fluids.

Acknowledgments

We would like to thank Mr K Kobayashi of Honda Electronics Co., Ltd, and Mr H Takuma of Keio University for their collaboration on the experiments. This work was partially supported by a Grant-in-Aid for Scientific Research (for research fellow) from the Japanese Society for the Promotion of Science.

References

[1] Parsons J D 1975 *J. Phys. D: Appl. Phys.* **8** 1219
[2] Chung D Y and Isler W E 1978 *J. Appl. Phys.* **49** 1809
[3] Taketomi S 1986 *J. Phys. Soc. Japan* **55** 838
[4] Skumiel A, Labowski M and Hornowski T 1995 *Acoust. Lett.* **19** 87
[5] Jozefczak A, Labowski M and Skumiel A 2002 *J. Magn. Magn. Mater.* **252** 356
[6] Motozawa M, Matsumoto Y and Sawada T 2005 *JSME Int. J.* B **48** 471
[7] Motozawa M, Matsumoto Y and Sawada T 2007 *Int. J. Appl. Electromagn. Mech.* **25** 133
[8] Del Grosso V A and Mader C W 1972 *J. Acoust. Soc. Am.* **52** 1442