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Journal of Sound and Vibration 283 (2005) 121–133
JOURNAL OF SOUND AND VIBRATION
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Material characterization of MR fluid at high frequencies

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Received 26 February 2003; received in revised form 7 January 2004; accepted 1 April 2004
Available online 17 September 2004

Abstract

Magnetorheological (MR) fluid is made of fine iron powders dispersed in silicon oil, which is utilized in many smart structures and devices because of its significant rheological property changes by the applied magnetic field. The evaluation of high frequency characteristics of MR fluids is necessary in many smart structure applications, for example, noise reduction and shock wave attenuation. The characterization of MR fluid is experimentally performed in the frequency range of 50–100 kHz. An experimental setup based on wave transmission test is made and the storage and loss moduli of MR fluid are found from the measured speed of sound and attenuation data. To investigate the magnetic field effect, the magnetic fields are applied in parallel and orthogonal directions to the wave propagation direction. The storage modulus of MR fluid trends to be linearly increased with the frequency. The direction effect of magnetic field and the loss factor for MR fluid are discussed.

1. Introduction

Magnetorheological (MR) fluid is composed of fine iron powders dispersed in base oil, which is frequently utilized to smart structures and devices because of its significant rheological property changes by the applied magnetic field [1]. One of the examples is MR fluid-inserted smart structure for shock wave attenuation. When MR fluid layer is inserted into a plate or beam structure, the shear deformation of the MR fluid layer causes attenuation of the bending waves in the structure. The attenuation can be controlled by the magnetic field on the MR fluid layer. In designing such

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0022-460X/$ - see front matter
doi:10.1016/j.jsv.2004.04.004

structures, the information of MR fluids in terms of complex shear modulus is necessary. However, it is not easy to find the complex shear modulus of MR fluids, especially at high frequency.

Li et al. [2] studied in an experimental investigation, the dynamic properties of MR fluids in terms of storage modulus, loss modulus, and loss factor at various frequency ranges (below 100 Hz). The storage modulus as well as loss modulus increases with the frequency. However, the loss factor does not change in the same way as the storage modulus and loss modulus. Most efforts have been focused on the material characterization of MR fluids at low frequencies below 100 Hz and treated material properties such as stress, strain, viscosity, and shear strain of MR fluids. Generally, viscoelastic materials have three rheological regimes as the basis for the quantitative study of the behavior: pre-yield, yield, and post-yield regimes. In the pre-yield regime, MR fluids behave like a linear viscoelastic material while they exhibit nonlinear viscous properties in the post-yield regime. Most application devices for MR fluids, for example, dampers, mounts, clutch, and brakes, have used MR fluid characteristics in post-yield regime. Also, these application devices are used in the low-frequency region. In contrast, the pre-yield regime behavior is important for wave related applications, for example, MR smart structures for noise control and shock wave isolation since the wave amplitude in MR fluids is so small compared to the wavelength that the magnetic particle chains have mostly maintained. For these application devices, the frequency range is high compared to the damper applications. Thus, the evaluation of MR fluid properties in the pre-yield regime at high frequency is important for wave-related applications. Wu [3] studied phase velocity and attenuation of viscoelastic materials used in ultrasonic applications for shear waves (2.2–7.6 MHz). This frequency range is too high for smart structure applications.

In this paper, the MR fluid properties are characterized in terms of storage and loss shear moduli at high frequency range (50–100 kHz) with the assumption that the deformation is in the pre-yield regime. In the pre-yield regime, MR fluids typically exhibit elastic properties. The properties exhibited by MR fluids in this regime are described by the classical relationships that exist between the storage modulus and loss modulus [4]. A wave transmission test setup is made for the characterization. Details of the experimental setup and how to measure the complex modulus of MR fluid are described in this paper.

2. Experiment

The idea for measuring the storage and loss moduli of MR fluid is based on a wave transmission technique. When acoustic waves travel along the MR fluid, the speed of sound and the wave attenuation can be measured, and they can determine the storage modulus and loss modulus, respectively. Fig. 1 shows the schematic diagram of the acoustic wave transmission on MR fluid layer. Acoustic pulse waves travel along the base fluid and they enter the MR fluid layer perpendicularly. By comparing time-of-flight differences Δt between the signals received at the point B of the case with the inserted MR fluid layer and that without the MR fluid layer, the speed of sound of MR fluid C_L^{II} can be determined by [3]

$$C_L^{II} = \frac{C_L}{1 - \Delta t C_L / d}, \tag{1}$$

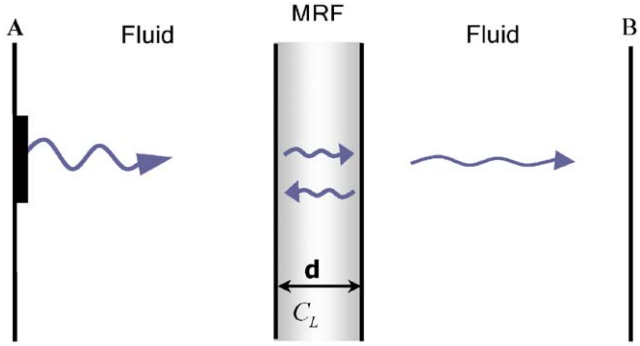


Fig. 1. Wave transmission of MR fluid layer.

where d is the thickness of MR fluid layer and C_L is the speed of sound of the base fluid. If MR fluid is soft viscoelastic material at high frequency, the storage modulus G' can be determined by [5,6],

$$G' = \frac{(C_L^{II})^2 \rho}{3}, \tag{2}$$

where ρ is the density of the MR fluid.

To measure the attenuation coefficient, amplitude of the received signal with the MR fluid layer, A_1, and that without the MR fluid layer, A_0, are measured. The attenuation coefficient of the MR fluid can be calculated by [3],

$$\alpha_l = \frac{\log(TA_1/A_0)}{d}. \tag{3}$$

The transmission coefficient, T, of MR fluid can be determined by

$$T = (4z_w z_l)/(z_w + z_l)^2, \tag{4}$$

where z_w is the acoustic characteristic impedance of the base fluid and z is that of MR fluid. From the measured attenuation coefficient, the loss modulus of MR fluid can be determined by [7]

$$G'' = G' \tan\phi = G' \tan\left(\frac{\alpha_l}{k}\right), \tag{5}$$

where the wavenumber $k = \omega/C_L^{II}$.

The wave transmission setup for MR fluid measurement was made. Fig. 2 shows the schematic diagram of the experimental setup. 0.5 mm thick aluminum plates are erected on the base as front and real panels, and a flexible film is used to connect the sides of the panels so as to make a reservoir. Silicon oil is filled in the reservoir as the base fluid. The distance between two aluminum plates is 103 mm. Circular piezoceramic patch (PZT4-D, 25 mm in diameter and 1 mm thickness) is bonded on the front plate to generate acoustic waves propagating into the base fluid. A MR fluid layer is made with MRF-132LD (Lord Co., USA) by containing it in a transparent film chamber (50 mm × 40 mm × 10 mm). An electromagnet is made with 0.8 mm copper wire wound 110 times around a frame, and the electromagnet is installed outside of the test setup to apply the

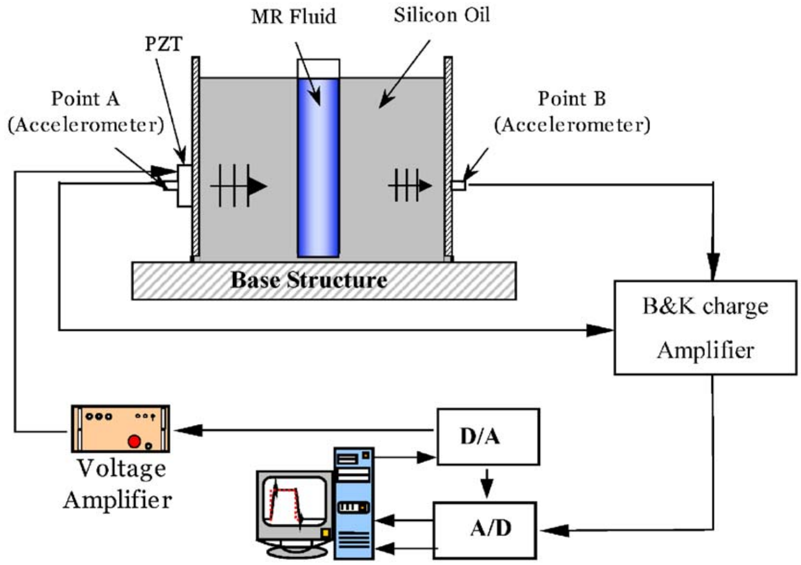


Fig. 2. Schematic diagram for experimental setup.

magnetic field in the MR fluid layer. A pulse signal is generated at personal computer and it is applied to the piezoceramic patch after converting to analog signal and amplifying to 20 V. An acoustic pulse wave is generated from the piezoceramic patch according to the applied electric signal, and once the acoustic wave propagates into the base fluid of which material properties are known, at last the wave arrives at the rear aluminum plate. Two accelerometers (B&K 4374) are mounted at front and rear panels to measure the accelerations of transmitted and received waves. The received signal from the accelerometer is converted into a digital signal via A/D converter and processed on the computer.

Before investigating the MR fluid, a preliminary test was performed for the transparent film chamber. To investigate the effect of the film thickness on the transparent film chamber, the chamber is filled with the identical base fluid–silicon oil, and the received signal is compared with the case without the transparent film chamber. Fig. 3 represents the sensitivity along with the excitation frequency for the two cases. The case of 'only oil' indicates that the reservoir is filled with the base oil, and the case of 'oil layer' means that the transparent film chamber for the MR fluid layer is completely filled with the same base fluid and the layer is inserted into the base fluid reservoir. The sensitivity is defined by the amplitude ratio of the received signal to the incidence signal measured by the accelerometers. Although the sensitivity of the oil layer case is a little bit lower than that of the only oil case due to the presence of the film thickness of the transparent film chamber, the trend of two cases is similar. Thus, the film thickness effect of MR fluid layer is negligible. Another important information in the experimental result is that the sensitivity is not the same. It is high at 60 kHz and is increased up to 100 kHz. This is due to the resonance of the piezoceramic patch. The first resonance of the piezoceramic patch is near 60 kHz.

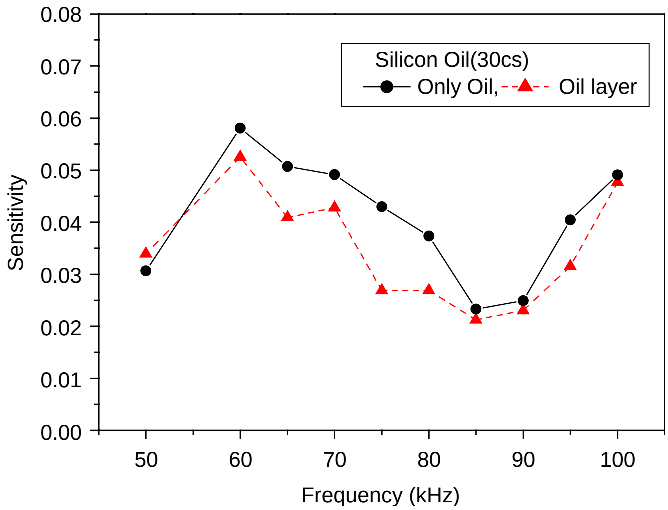


Fig. 3. Sensitivity with and without fluid layer.

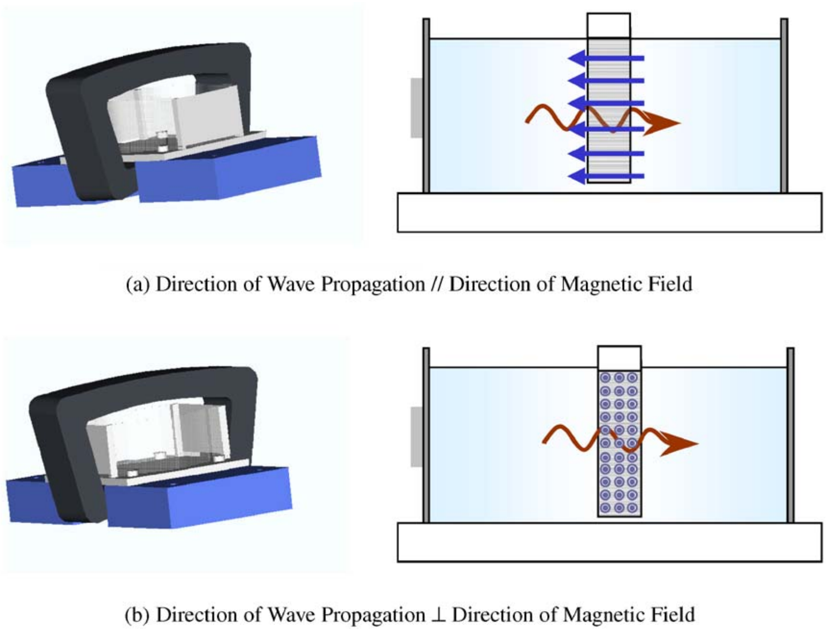


Fig. 4. (a, b) Schematic diagram of MR chamber and electromagnet for magnetic field directions.

3. Results and discussion

The MR fluid of MRF-132LD (Lord Co., USA) was tested in room temperature. The density of the MR fluid is 3055 kg/m^3. The magnetic field was applied to two directions—parallel and

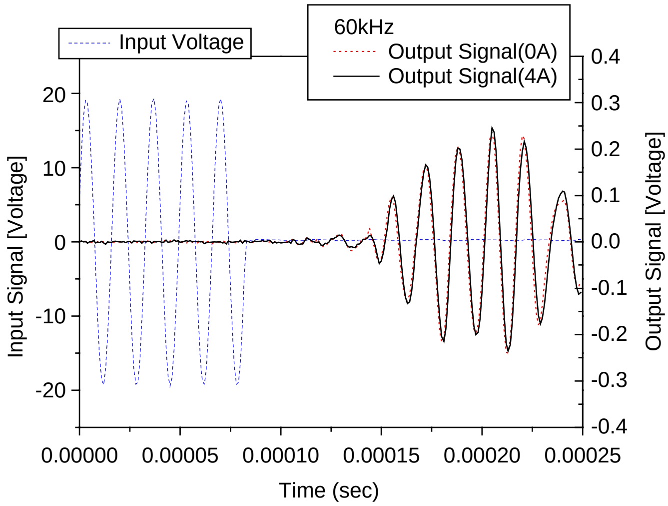


Fig. 5. Transmitted and received signals for MR fluid layer (parallel magnetic field).

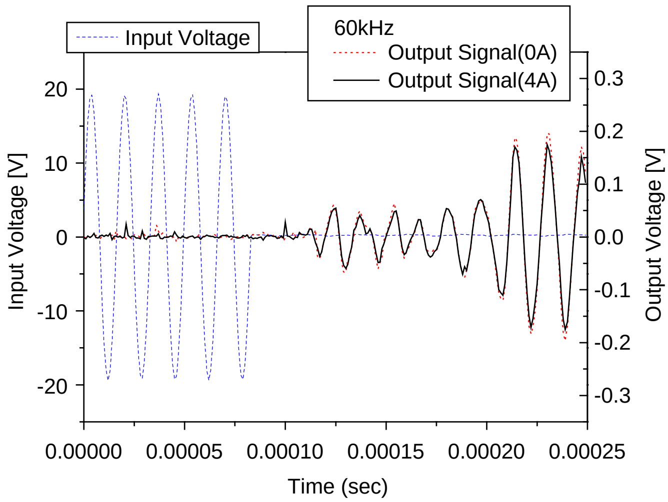
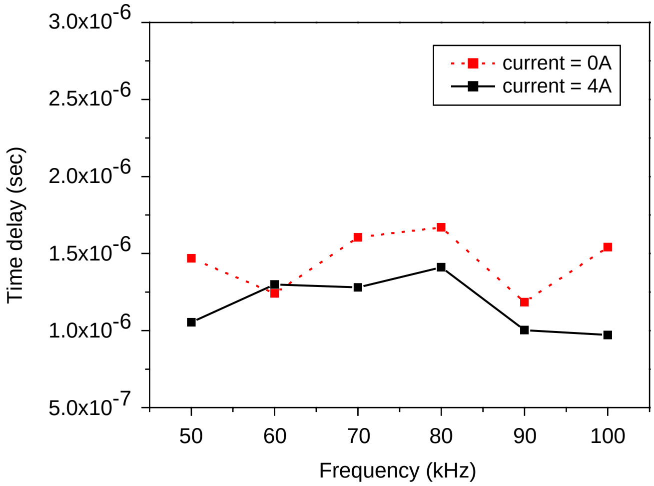
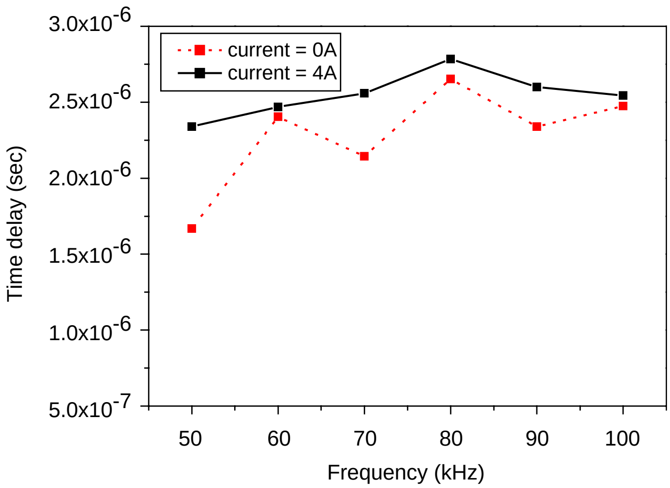


Fig. 6. Transmitted and received signals for MR fluid layer (orthogonal magnetic field).

perpendicular to the wave propagation direction by installing the electromagnet in two directions. Fig. 4 shows the magnetic field directions along with the wave propagation direction. The wave frequency is tested in the range at 50–100kHz. Fig. 5 shows the received accelerometer signals when the magnetic field is parallel to the wave propagation direction. The excitation frequency of transmitted signal is 60 kHz and the applied current on the electromagnet is 4 A. The case of 0 A is when the magnetic field is not applied. Time delay Δt in Eq. (1) is found from the wave-propagation time difference between points A and B (Fig. 2) with and without MR layer. The presence of MR layer will delay the wave propagation time between points A and B. When the magnetic field is parallel, the time delay is found to be 1 μs. Also the wave reduction of 5% was



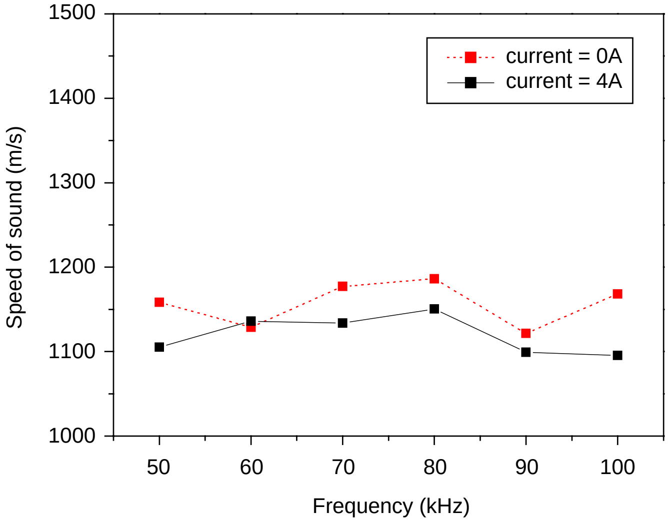
(a) Parallel type



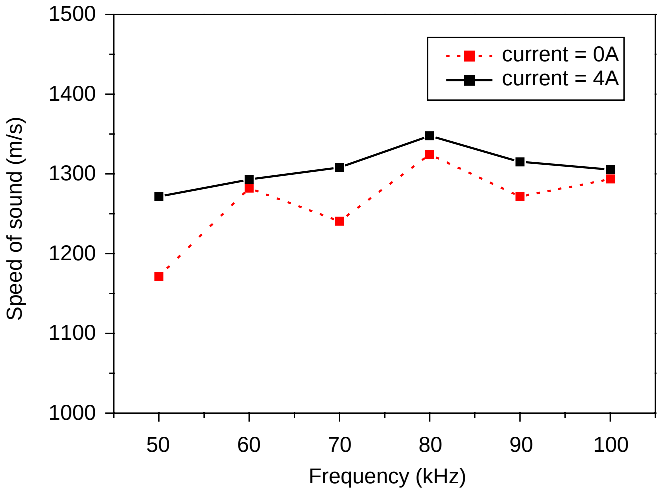
(b) Orthogonal type

Fig. 7. (a, b) Time delay.

found from the difference of maximum received signals in Fig. 5. Fig. 6 shows the received accelerometer signals when the magnetic field is orthogonal to the wave propagation direction. At the same way, the time delay was found to be 1.5 μs and the wave reduction is 10%. More time delay and wave reduction were obtained when the magnetic field is perpendicular with respect to the wave direction. Fig. 7 represents time delays for the parallel and perpendicular cases. Fig. 8 shows the speed of sounds found from Eq. (1) for the parallel and perpendicular cases. It is clear that the speed of sound of the orthogonal case is higher than that of the parallel case. In the parallel case, the current application rather decreased the speed of sound in contrast to the orthogonal case. This may be due to the presence of MR chains that are parallel to the wave propagation direction such that waves are easily propagated. In overall, the speed of sound of MR



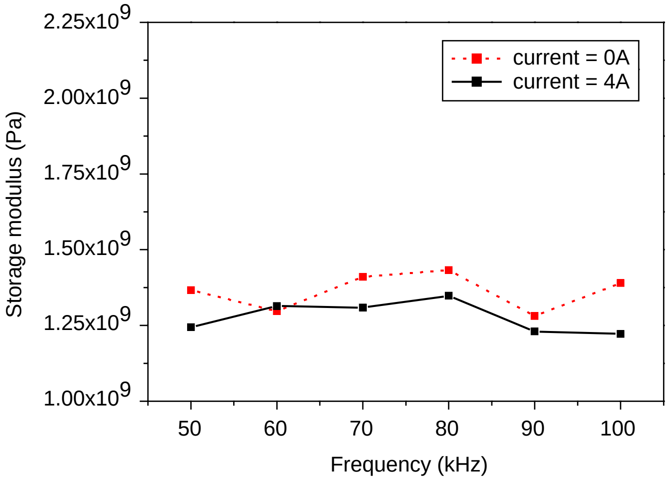
(a) Parallel type



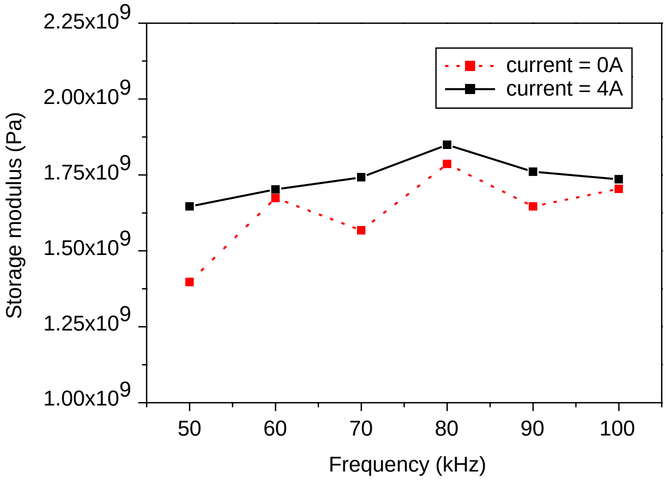
(b) Orthogonal type

Fig. 8. (a, b) Speed of sound.

fluids has an increasing tendency with the excitation frequency, although some decreases are shown at some points. This may be due to some reasons such as inaccuracy of delay time measurement and the limited frequency band of the accelerometers. The resonance frequency of the accelerometer is 100 kHz. Thus, the useful frequency band will be below 90 kHz. Fig. 9 represents the storage modulus G' found from Eq. (2). The trend of the storage modulus is exactly same as that of the speed of sound. The storage modulus increases in the range of 1.65–1.8 GPa when the magnetic field is orthogonal, whereas it is ranging from 1.2 to 1.3 GPa when the magnetic field is parallel. The orthogonal magnetic field gives more MR effect than the parallel



(a) Parallel type

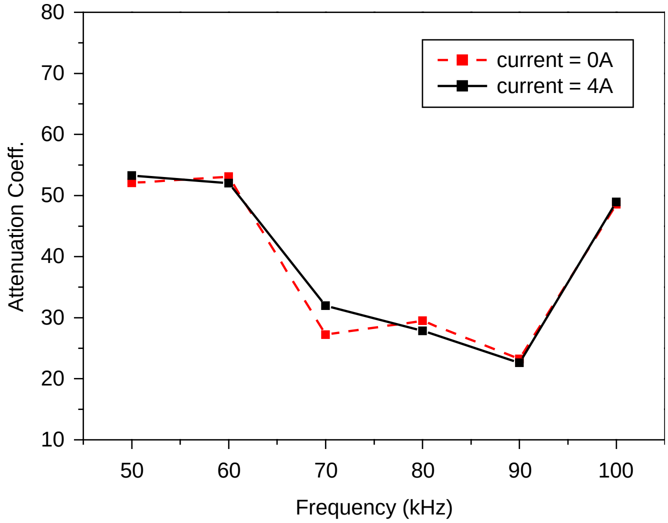


(b) Orthogonal type

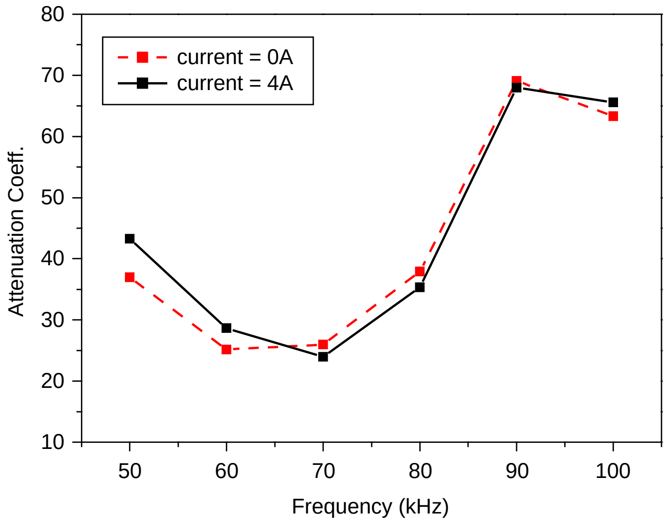
Fig. 9. (a, b) Storage modulus.

case since the acoustic waves are resisted more by the magnetic particle chains in the fluid when the magnetic field is orthogonal. The increase of storage modulus of the MR fluid with respect to the excitation frequency coincides with Ref. [3].

Fig. 10 represents the attenuation coefficient found from the sensitivity and the transmission coefficient given by Eqs. (3) and (4). The attenuation coefficients exhibit different patterns according to the magnetic field directions. The attenuation coefficient for the parallel case tends to be decreased along with the frequency except 100 kHz. One remarkable thing is that the magnetic field does not produce significant attenuation change. This might be due to the wide MR layer thickness so that the magnetic field strength is not so strong. Fig. 11 shows the loss modulus found from the storage modulus and the attenuation coefficient. The trend of the loss modulus is similar



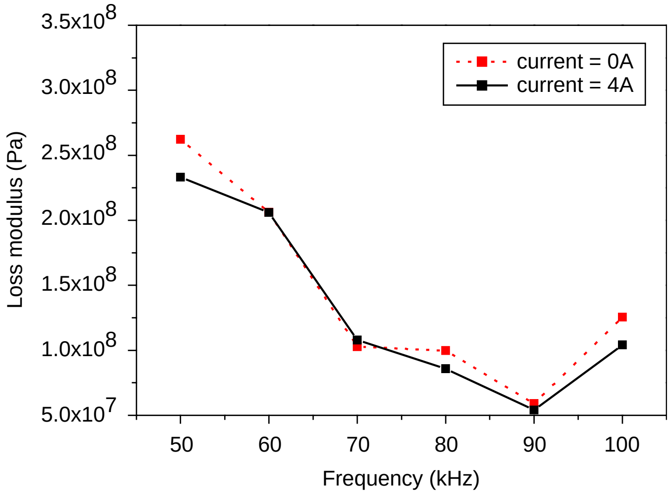
(a) Parallel type



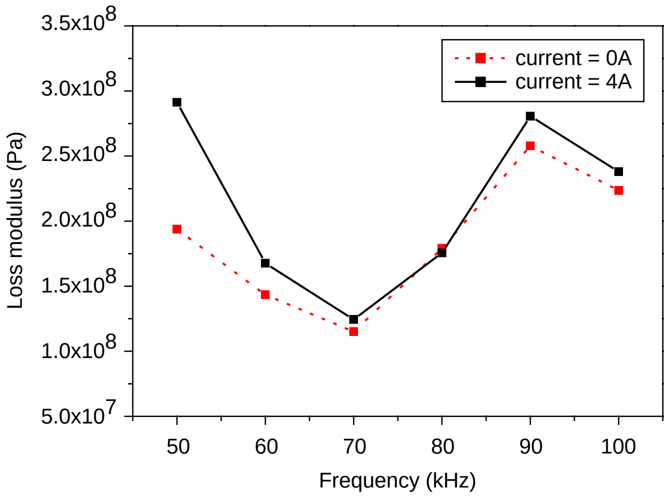
(b) Orthogonal type

Fig. 10. (a, b) Attenuation coefficient.

to that of the attenuation coefficient. The loss modulus is decreased with the frequency from 200 to 60 MPa when the magnetic field is parallel. When the magnetic field is orthogonal, however, the loss modulus is changing up and down between 300 and 130 MPa without any tendency. This trend is different from the MR fluid properties in low frequency region [2], which dictates a slight increase of loss modulus along with the frequency. Perhaps, the difficulty in measuring the sensitivity might result in an error in the loss modulus calculation. Nevertheless, when the loss factor ($\eta = G''/G'$) is calculated, the range of loss factor for the tested MR fluid is 0.03–0.2



(a) Parallel type

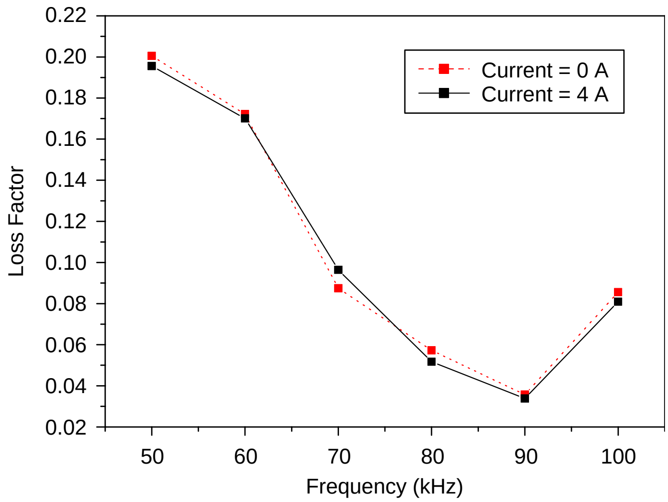


(b) Orthogonal type

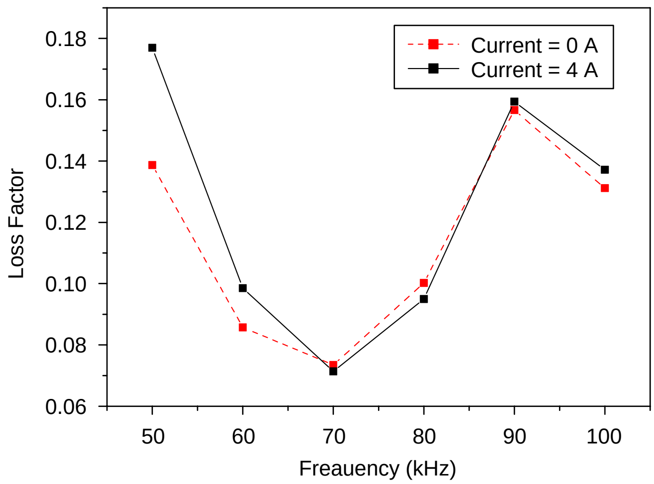
Fig. 11. (a, b) Loss modulus.

(Fig. 12). This range is comparable with the low frequency data in Ref. [2], in which the loss factor is saturated below 0.2 as the frequency is increased.

Since the thickness of the MR fluid layer (10 mm) was insufficient compared to the wavelength (22 mm at 50 kHz) of acoustic waves, the time delay as well as the attenuation coefficient seem not to be fully exhibited in the experiment. Another problem in the experiment was nonuniformity of the magnetic field produced by the electromagnet. Nonetheless, the experimental data of complex modulus for MR fluid still give important information for MR fluid application in smart structures.



(a) Parallel type



(b) Orthogonal type

Fig. 12. (a, b) Loss factor.

4. Conclusions

In this paper, the material characterization of magnetorheological (MR) fluid at high frequencies was studied. The characterization was based on the wave transmission, and the storage and loss moduli are found from the measured wave speed and attenuation coefficient. The tested frequency range was 50–100 kHz. The storage modulus is in the range of 1.65–1.8 GPa when the magnetic field is orthogonal, and in the range of 1.2–1.3 GPa for the parallel magnetic field. The storage modulus is increased with the excitation frequency. The loss modulus was in the range of 200–60 MPa when the magnetic field is parallel, and in the range of 300–130 MPa when the magnetic field is orthogonal. The range of loss factor for the tested MR fluid is 0.1–0.2, which is comparable with other reference. The orthogonal direction of the magnetic field resulted in the increase of storage modulus and loss modulus. More investigation is necessary to confirm the frequency dependency of the loss modulus.

Acknowledgements

This work was supported by the grant #R01-1999–00257 of the Interdisciplinary Research Program of KOSEF, and Brain Korea 21.

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