ACADEMIC
PRESS

Available online at www.sciencedirect.com

SCIENCE DIRECT®

Journal of Sound and Vibration 267 (2003) 57–65

JOURNAL OF
SOUND AND
VIBRATION

www.elsevier.com/locate/jsvi

Material characterization of ER fluids at high frequency

Jaehwan Kim*, Jung-Yup Kim, Seung-Bok Choi

Department of Mechanical Engineering, INHA University, 253 Younghyun-Dong, Nam-Ku, Inchon 402-751, South Korea

Received 20 March 2001; accepted 4 October 2002

Abstract

In this paper, the material characterization of ER fluids at high frequencies is studied. To characterize the properties at high frequencies, an experimental apparatus is provided, based upon the wave transmission through ER fluids in the presence of electric field. Details of the experiment and how to extract the complex shear modulus of ER fluids are addressed. A moderate increase in the storage modulus and loss modulus was observed when the weight ratio of ER particles and the electric field were increased. The proposed method is a comprehensive material characterization of ER fluids in high frequencies for ER smart structures.

1. Introduction

ER fluid is a colloidal suspension of very fine dielectric particles in an insulating medium, and it exhibits changing rheological properties in the presence of applied electric field. The variable property change of ER fluids is utilized in smart structures. Smart structure is a structure that can tune its properties due to the incorporation of a controllable component such as ER fluid. In studying ER-fluid-based smart structures, the investigation of the complex shear modulus of ER fluids is very important because the shear deformation of ER fluid layer mainly causes the controllable behavior of the structure [1].

Some efforts for measuring the shear material properties of ER fluid have been devoted during the last decade [2–5]. Gamota and Filisco have studied dynamic shear stress response of ER materials to sinusoidal strains at various frequency ranges (below 100 Hz) [2]. They considered ER fluids in three rheological regions as the basis for the quantitative study of ER material behavior; pre-yield, yield and post-yield regions. In the pre-yield region, ER fluid behaves like a linear viscoelastic material, while it does like a non-linear viscoelastic material in the yield region and a

---

*Corresponding author. Tel.: +82-32-860-7320; fax: +82-32-868-1716.
E-mail address: Jaehwan@inha.ac.kr (J. Kim).

0022-460X/03/$ - see front matter © 2002 Elsevier Science Ltd. All rights reserved.
doi:10.1016/S0022-460X(02)01411-6

plastic material in the post-yield region. Fig. 1 represents the three regions of ER fluids. The study of yield and post-yield regions is very important in designing ER devices, such as dampers, mounts, shock absorbers and clutches. These devices utilize the yield and post-yield regions of ER fluids. Most efforts on measuring ER properties have been focused on yield and post-yield regions since ER fluids have been mainly applied to dampers and mounts.

In contrast, the pre-yield region behavior is important in ER smart structures for noise controls and shock wave isolations. When acoustic waves travel along ER fluids, the wave motion produces a small strain, which belongs to the pre-yield region. Usually, ER smart structures for vibration control are limited to low frequencies since vibrations at fundamental modes are dominant. However, due to the existence of high-frequency components in shock waves, these structures for shock wave isolation have to deal with high-frequency region. In this paper, we aim at investigating the material properties of ER fluids at high frequencies in pre-yield region. Since viscoelastic properties of ER fluids are mainly dominated by the particle chain structure, the state at each time can be analyzed from the rheological parameters such as storage modulus and loss modulus. Researchers have investigated these dynamic properties of ER fluids with various types of rheometers, for example, rotational Couette, parallel plate and vertical oscillation type rheometers [3]. However, these types of rheometers are limited to low frequencies (below 1 kHz) and post-yield region of ER fluids. Especially, when ER inserts for shock wave reduction is considered, the ER fluid properties evaluated from these rheometers are no longer valid. The material properties of ER fluids should be investigated at high frequencies in such a way that the properties should be able to closely describe the behavior of ER smart structures.

Therefore, an experimental apparatus that is based on wave propagation is designed to investigate the complex shear modulus of ER fluids at high frequencies in pre-yield region. The change in ultrasonic shear wave properties of ER fluids under the influence of a strong electric field has been investigated by means of an ultrasonic shear wave reflectometry technique [4]. However, this measurement system is away from the configuration of ER sandwich beam structures since the electric field direction is parallel to the wave propagation direction. Shock

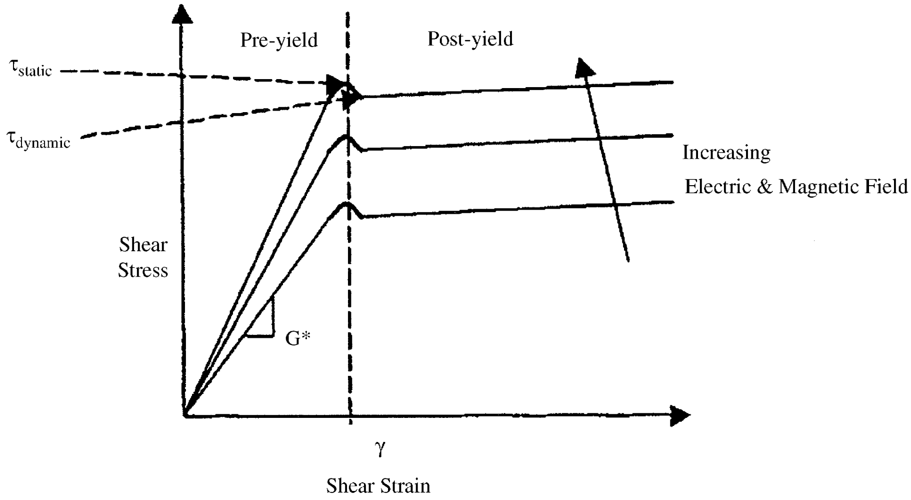


Fig. 1. Pre- and post-yield regions of ER fluid.

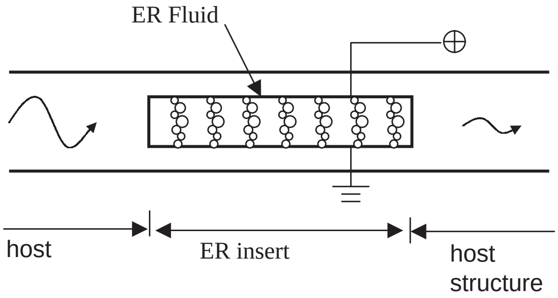


Fig. 2. Schematic diagram of ER smart structure for shock wave isolation.

waves normally travel along the structure as bending waves so that the electric field in ER inserts is perpendicular to the wave propagation direction (Fig. 2). Thus, a new experimental set-up for wave propagation test is provided, which has similar configuration of ER sandwich beam structures. Details of the experimental set-up and how to measure the complex modulus are described in this paper.

2. Experiment

The idea for measuring the storage modulus and loss modulus of ER fluid is based on a wave propagation technique. An experimental set-up for the wave propagation in ER fluids is provided. Fig. 3 shows the schematic diagram of the experimental set-up. 0.5 mm thick aluminum plates are erected on the base as front and rear panels, and a flexible film is used to cover the sides of the panels such that they comprise a reservoir. ER fluid is filled in the reservoir. Rectangular piezoceramic patch (PZT4-D, 25 mm × 60 mm, 1 mm thickness) is bonded on the front panel to generate acoustic waves propagating into the fluid. The piezoceramic patch is electrically insulated from the plate by using a fast curing epoxy. Multi-layered electrodes unit that has 2 mm gap in each electrode, is submerged into the ER fluid reservoir so as to apply the electric field to the ER fluid. Fig. 4 shows the photograph of the experimental set-up. A pulse signal of five burst is generated from personal computer and after converting to analog signal and amplifying to 20 V, it is sent to the piezoceramic transmitter. Once the front aluminum plate radiates pulse waves the waves travel along the fluid including the electrode plates perpendicular to the electric field direction, and at last, they arrive at the rear aluminum plate. B&K accelerometers (Type 4374) are mounted at front and rear panels to measure the accelerations of transmitted and received waves. The speed of sound in ER fluids and the wave attenuation can be calculated by measuring the time delay of received signal from point B, and the ratio between the input signal at point A and the output signal at point B. The speed of sound can be determined by

$$C_L = \frac{l}{\Delta t}, \tag{1}$$

where l is the distance between points A and B and Δt is the time delay. The distance between the front and rear aluminum panels is 70 mm. Generally, soft viscoelastic solids and liquids of high

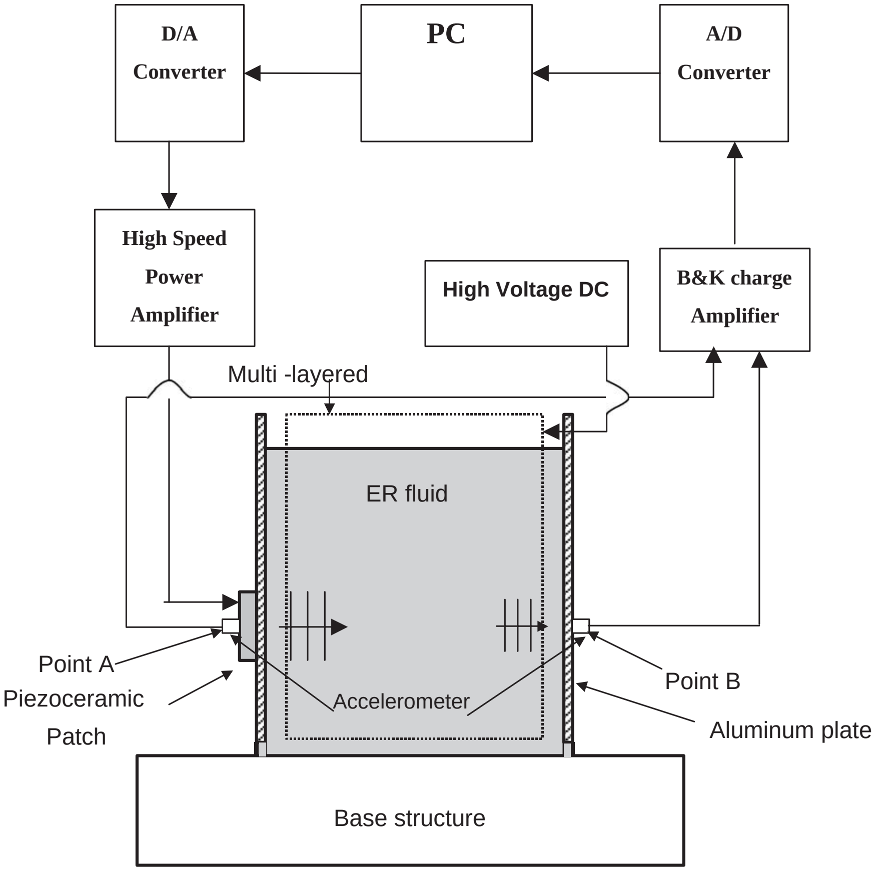


Fig. 3. Experimental set-up.

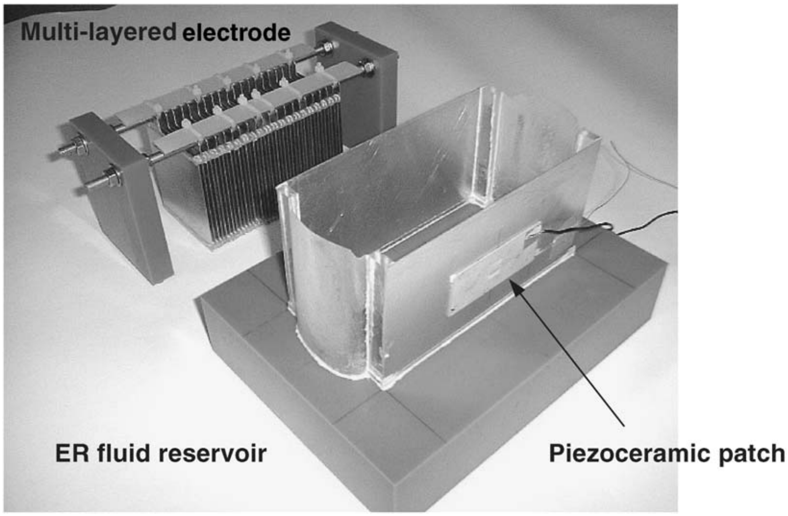


Fig. 4. Photograph of ER property test set-up.

viscosity have the following relations [5]:

$$G' = \frac{E'}{3}, \tag{2}$$

where G' is the storage modulus and E' is Young's modulus. From the relationship between Young's modulus and the bulk wave speed, the storage modulus can be determined by

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

where C_L is the measured longitudinal wave speed and ρ is the density of the ER fluid.

Before testing the wave propagation of ER fluids, the wave leak test of the reservoir was conducted in the absence of the fluid. When the piezoceramic patch transmitted a longitudinal pulse wave, no signal was detected at the rear panel. This confirms that there are no wave leaks at the base and side walls of the test set-up. In advance, the speed of sound of silicone oil (30 cs) was measured to confirm the accuracy of the test set-up. As the result, the bulk wave velocity of the silicon oil was found to be 972.2 m/s. This value is reasonable because that of 10 cs silicone oil is 968 and 980 m/s for 100 cs silicon oil [6].

To measure the loss modulus of ER fluids, the amplitude of the received signal with the electrode, A_l, and that without the electrode, A_0, are measured. By knowing the acoustic characteristic impedance of the silicon base oil, z_w, and that of ER fluids, z_l, the attenuation coefficient of ER fluid can be calculated by [1]

$$\alpha_l = \frac{\log(TA_l/A_0)}{l}, \tag{4}$$

where the transmission coefficient of ER fluids $T = (4z_w z_l)/(z_w + z_l)^2$. Thus, the loss modulus of ER fluids can be determined by

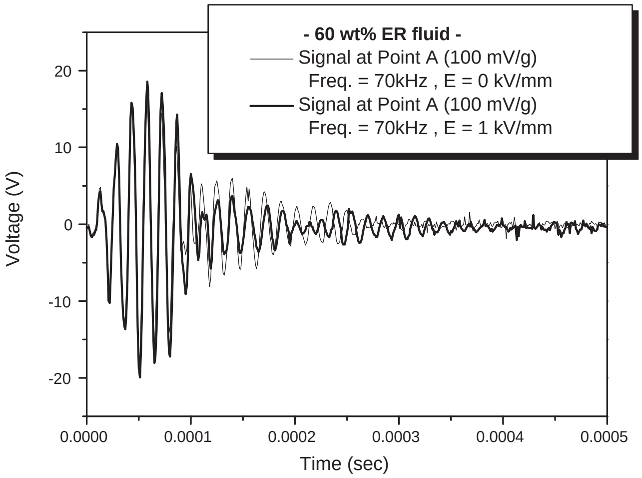
$$G'' = G' \tan\phi = G' \tan\left(\frac{\alpha_l}{k}\right), \tag{5}$$

where the wave number $k = \omega/c_l$.

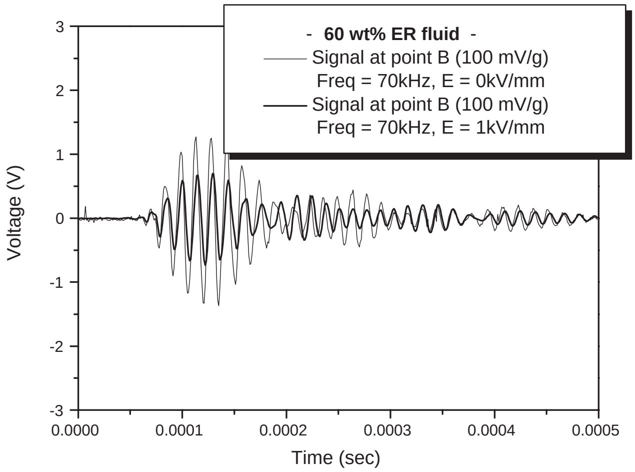
To investigate the electrode effect in the apparatus, the wave transmission in the silicon oil was measured with and without the electrode array. There was no significant change of the time delay but a slight change in the attenuation was observed. This proves that the inclusion of electrodes does not significantly influence the storage modulus measurement. However, the loss modulus may be slightly affected by the presence of the electrodes. In fact, the loss modulus is not bulk loss modulus. This value is obtained from the sandwich beam configuration. Therefore, this loss modulus is rather suitable for the configuration of ER smart structures, which are mainly targeted in this research.

3. Results and discussion

ER fluids of soluble starch (Junsei Chemical, 9L1182) mixed with silicone oil (Shin-Etsu,KF-96-30cs) were tested. Three weight ratios of ER particles in ER fluids, 30, 45 and 60 wt% were investigated at temperature and it remained the same. Fig. 5(a) shows the transmitted acceleration signals at point A when 0 and 1 kV/mm of electric field are applied on the 60 wt% ER fluid at



(a) at point A



(b) at point B

Fig. 5. Received signals of accelerometer at points A and B (60 wt% ER fluid at 70 kHz).

70 kHz. Vertical axis represents the acceleration corresponding to 1 g/100 mV. After a big echo signal is observed, small signals are followed due to the presence of wall reflections and the fluid attenuation. Fig. 5(b) represents the received acceleration signal at the rear panel (point B). By measuring the time delay between the transmitted and received signals, the speed of sound was determined by dividing the distance between the front and rear panels by the time delay. The speed of sound of ER fluids is plotted in Fig. 6. The value of speed of sound is increased with the excitation frequency when the ER fluid is 60 wt% except the ER fluids of 30 and 45 wt%. It is because the higher wt% of ER particles allows faster speed of sound. Fig. 7 shows the storage modulus of ER fluids. The trend of the storage modulus is exactly same that of the speed of sound. Table 1 represents the averaged storage modulus between 50 and 100 kHz. Note that these

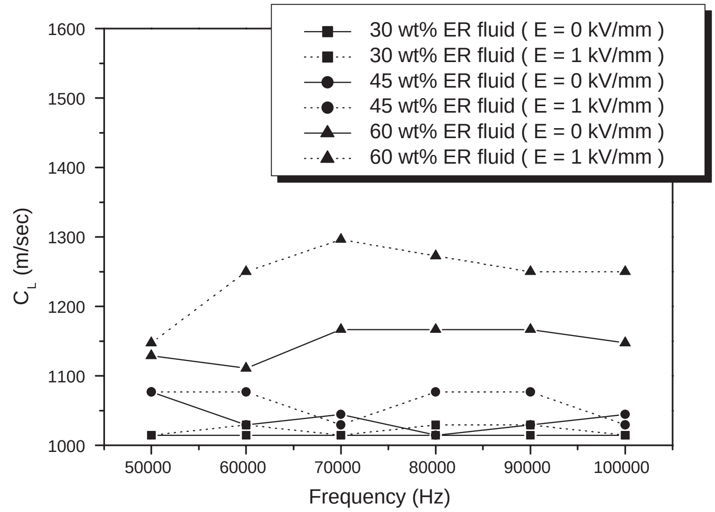


Fig. 6. Speed of sound of ER fluids.

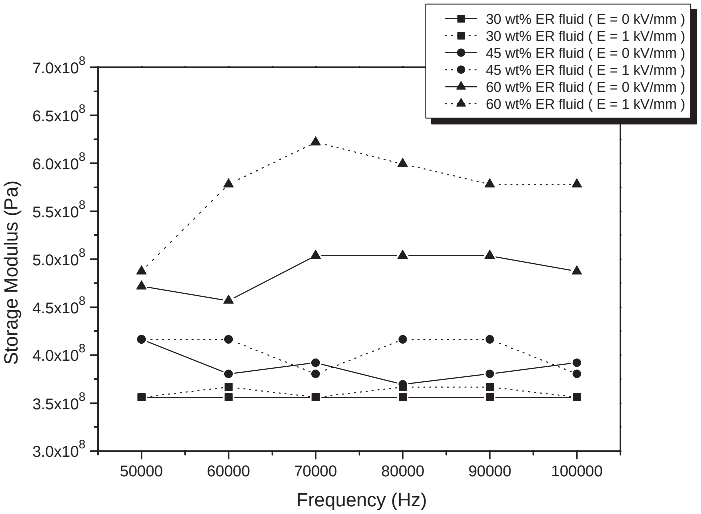


Fig. 7. Storage modulus of ER fluids.

Table 1
The storage modulus of ER fluid according to electric field and fluid types

ER fluid type (wt%)	G' (Pa) at $E = 0\,\text{kV/mm}$	G' (Pa) at $E = 1\,\text{kV/mm}$
30	3.56×10^8	3.61×10^8
45	3.88×10^8	3.94×10^8
60	4.87×10^8	5.71×10^8

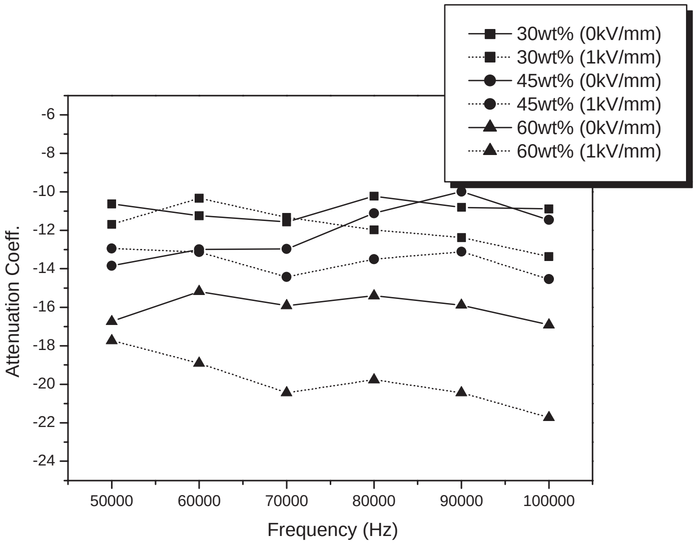


Fig. 8. Attenuation coefficient of ER fluids.

values are much higher in the order of three than the low-frequency data found in the literature [3], while the current results exhibit the same trend with those of the Ref. [4].

Fig. 8 represents the attenuation coefficient found from Eq. (4). The acoustic characteristic impedance of ER fluids was calculated from the measured speed of sound: $z_l = c_l \rho_l$, where ρ_l is the density of ER fluids. The acoustic characteristic impedance of base silicon oil is $z_w = c_w \rho_w = 968 \times 970 = 938\,960 (\mathrm{kg/s\,m^2})$. The transmission coefficient was calculated from the acoustic characteristic impedance for the ER fluid as well as the base silicon oil. Fig. 9 shows the loss modulus of ER fluids. The loss modulus is increased with respect to the frequency when the ER fluid is 60 wt%. However, it does not change significantly when the ER fluids are 45 and 30 wt%. These values are also much higher than the low-frequency data found in the Ref. [3], while the current results are comparable to those of the Ref. [4]. This claims that the loss modulus is proportional to the concentration ratio of ER particles, the strength of electric field and the excitation frequency.

4. Conclusions

The material properties of ER fluids at high frequencies were studied according to the excitation frequency, weight ratio of ER particles and applied electric field. To characterize the properties at high frequencies, an experimental apparatus that is based on the wave propagation through ER fluids in the presence of electric field was provided. The storage modulus was found from the wave velocity of ER fluid and the loss modulus was derived from the measured attenuation coefficient. The storage modulus was increased when the frequency as well as applied electric field were increased when the ER fluid is 60 wt% except the ER fluids of 30 and 45 wt%. The loss modulus was increased with respect to the frequency when the ER fluid is 60 wt%.

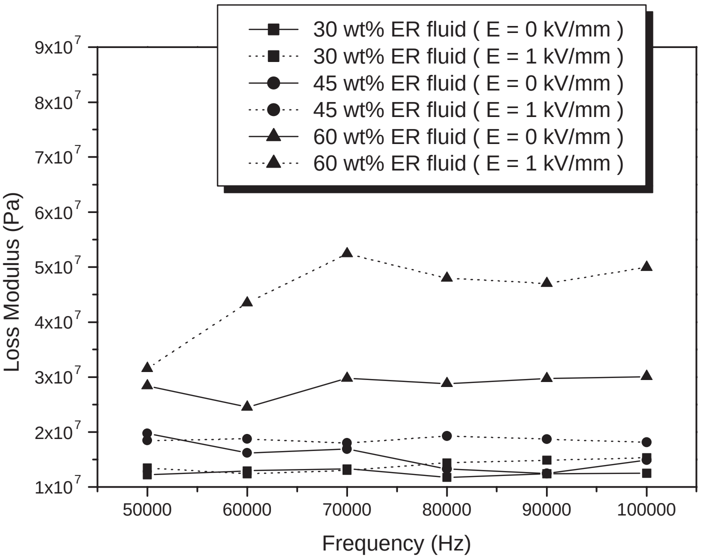


Fig. 9. Loss modulus of ER fluids.

Higher weight percent of ER particles has strong effects on the storage modulus and loss modulus, which is related to the formation of chains in ER fluid. The proposed method is a comprehensive material characterization of ER fluids in high frequencies instead of using the extrapolated low-frequency data found in the literature.

Acknowledgements

This work was supported by Grant No. 1999-2-304-005-3 from the interdisciplinary Research program of the KOSEF.

References

[1] J. Kim, J.-Y. Kim, S.-B. Choi, K.-S. Kim, Smart structures for shock wave attenuation using ER inserts, Proceedings of SPIE's Eighth Annual International Symposium on Smart Structures and Materials, 2001, pp. 4237–24.

[2] D.R. Gamota, F.E. Filisko, Dynamic mechanical studies of electro-rheological materials: moderate frequencies, Journal of Rheology 35 (1991) 399–425.

[3] M.S. Cho, Y.J. Choi, H.J. Choi, S.G. Kim, M.S. Jhon, Viscoelasticity of an electrorheological fluid using a vertical osillation rheometer, Journal of Molecular Liquids 75 (1998) 13–24.

[4] J.L. Bellin, R. Holsinger, A.W. Chow, The measurement of ultrasonic shear wave properties in electrorheological fluids, Journal of Acoustical Society of America 92 (2, Part 1) (1992) 1174–1186.

[5] R. Roy, J. Richardson, Ultrasonic propagation in electrorheological suspensions, Journal of Acoustical Society of America Supplement 1 87 (1990) S85.

[6] J.D. Ferry, Viscoelastic Properties of Polymers, Wiley, New York, 1980.