ARCHIVES OF ACOUSTICS
27, 3, 229–240 (2002)

EXPERIMENTAL STUDY OF SOUND TRANSMISSION LOSS IN ELECTRORHEOLOGICAL FLUIDS UNDER DC VOLTAGE

M.L. SZARY

College of Engineering
Department of Technology, Acoustics Laboratory
Mailcode 6603
Carbondlae, IL 62901-6603
E-mail: szary@engr.siu.edu

The electrorheological (ER) liquids possess the ability to change their physical properties like the apparent viscosity and modulus of elasticity which is related to stiffness under influence of external electric field. They serve successfully in the field of semi-active/active vibration control — as well as in many other areas. The STL was investigated for various kinds of ER suspensions in the frequency range from 100 Hz to 2 kHz. An influence of the electric field density on the STL was different for normal and tangential sound wave propagation. In both cases the STL decreases with the increasing electric field density. Those properties can be potentially useful in sound propagation control applications.

1. Introduction

Among many varieties of "smart" materials there are certain suspensions known as controllable fluids. Their mechanical properties such as viscosity and modulus of elasticity can be changed through the application of an externally applied field. Many types of fields may be used including electric, magnetic, pressure or other field types. Of particular interest in this work are liquids which properties are controlled by electric fields — electrorheological (ER) liquids. They are able to change their physical properties as elasticity (Young's modulus), apparent viscosity, normal and shear stress upon application of electric field on them. ER suspensions consist of solid particles (solid phase) dispersed in insulating liquid (liquid phase). Under the influence of electric field, particles of the solid phase form chains and later columns along the direction of an electric field. This results in enhanced yield shear stress, such liquid exhibits also resistance to flow (apparent viscosity increases) as well as an increased stiffness (modulus of elasticity). For those reasons the transition had been described as liquid-solid. In the presence of a strong electric field the ER liquid takes on the appearance of a rigid gel-less or more solid. For description of ER suspensions behavior Bingham model of plastics flow is used most frequently [7, 8, 27]. This means that flow is observed only after exceeding a minimum yield shear stress. That yield shear stress increases dramatically when an electric field is applied to ER suspension. Under normal (compressive) stress and applied electric field the increase in the hardness of the ER liquid is observed. In some cases the hardened ER can withstand forces in excess of 1 GN/m^2 [7, 8, 25]. That effect can be described in terms of changes of the modulus of elasticity [11, 25]. Solid materials are capable of supporting shear and compressional stress. That means in solids, shear (transverse) and torsional, along with compressional (longitudinal) waves may propagate. In thin barriers, sound propagation in the audio frequency range is primarily through excitation of bending waves, which are a combination of shear and compressional waves [23]. The response of the barrier excited by an incident sound wave, when forcing occurs simultaneously across its surface is the development of a spatial pattern over the entire surface of the barrier. Response of the thin barrier to such an excitation is referred to as a forced wave. In contrast to free bending waves, the speed of the forced bending wave does not depend on frequency, barrier thickness or its surface mass; the amplitude of the response, however, does depend on those variables. When the coincidence between the incident sound wave and the free bending waves in the barrier occurs, the results are complete sound transmission, if the barrier had no internal damping. To account for internal damping a complex modulus of elasticity is often considered. In finite-size barriers, the sound-forced bending waves run into the edges of the barriers and develop free bending waves that lead to resonances. Calculations in those cases are often involved and solutions are usually complex in order to take into account resonances, anti-resonances, etc., that occur in a coupled resonating system.

Since its discovery, ER effect has been recognized to have great potential in a number of hydraulic, robotic and other applications [1-6]. ER liquids have found many applications: they are being employed in brakes, clutches, shock absorbers, etc. There are also vibration damping systems based on those suspensions [9, 10, 12, 14]. Application of ER fluids in a controllable barrier for sound is the subject of this investigation.

2. Sound transmission loss measurement system

Setup for all investigations is based on the modified SAE J1400 standard for the sound transmission loss (STL) measurements [21]. It is not always convenient to measure STL using the standard method. That system of measurement needs samples to be of a relatively large area (opening for a specimen increases with decreasing frequency). For expensive materials this in not economical. There are also materials (as, for example, investigated ER liquids) that are difficult to handle and operate when the size of the specimen is relatively large. For those, a modified testing method has been employed [22]. Instead of using a large reverberation room that these anechoic chamber or two reverberant rooms, it is possible to work with two chambers. As a sound source system in the primary chamber, a sine generator along with an amplifier and a speaker are use. The secondary or receiving chamber is placed behind the sample. The system is presented in Fig. 1. The sample that is placed between two standing wave tubes, is a system of two electrodes with an ER fluid between the electrodes surfaces, powered by the high-voltage DC power supply. Two electrode systems are designed: in the first one the direction of the electric field and the sound wave propagation are perpendicular. In the second the direction of the electric field and the sound wave propagation are parallel.

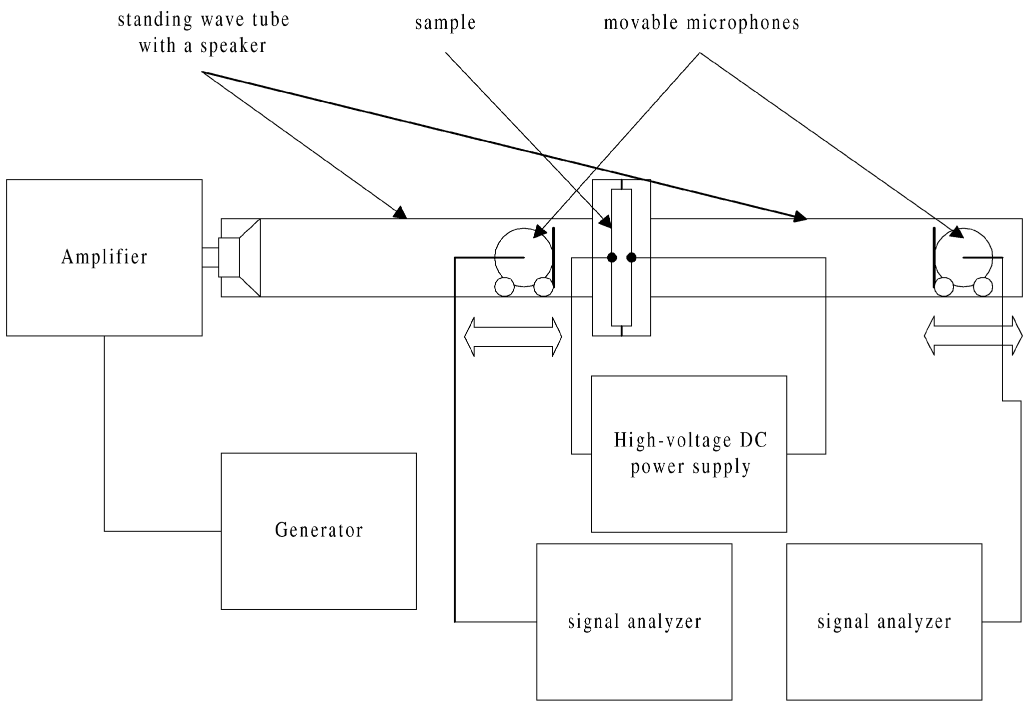


Fig. 1. Proposed measurement system.

Signal analyzers allow for examination of two signals: one of them is the source sound, the second is the sound after it passes through the system of electrodes. Both signals are analyzed for approximately every 1/3 of the octave of frequency (100, 125, 160, 200, 250, 315, 400, 500, 630, 800, 1k, 1.25k, 1.6k, 2k, 3.1k [Hz]). The equipment units employed in the measurements were:

- standing wave apparatus (2 units) B&K type 4002,
- sine/random generator B&K 1027,
- power amplifier McIntosh MC2125,
- 2 real time 1/3 octave signal analyzers B&K 3347,
- high-voltage DC power supply Spellman RHSR5PN50.

The first step of the STL investigations was the verification of the measurement setup. In order to do that the barrier materials of known characteristics of STL determined theoretically and by SAE J1400 standard were measured in the proposed measurement setup. Comparison of theoretical predictions (STL mass law) and measurements according to SAE J1400 standards with results obtained using the proposed measurement setup indicates that the designed apparatus is relatively accurate. From statistical analysis of those results it has been found that the relative error is less than 5%. The mass law equation used in calculations is given by [23]:

$$\mathrm{STL} = 10\log\left[1 + \left(\frac{\rho_s\omega}{2\rho_0 c_0}\right)^2\right],$$

where ρ_s — mass per unit area of the sample, $\rho_0 c_0$ — characteristic impedance of the air, $\omega = 2\pi f$ — angular frequency.

3. ER liquids

The liquids that have been employed in the measurements were suspensions of zeolite particles (20% and 30% of weight, respectively) in a transformer oil. Additional investigations were conducted on the modified commercial fluid VersiFlo$^{\mathrm{TM}}$ ER-201 from the Lord Corporation [24]. The modification was done by adding some transformer oil to ER-201 so the final product was 80% suspension (weight) of ER-201 in the transformer oil. The reason was that initially the ER-201 was too dense and was difficult to mix after the solid particles in suspension sedimented in the electrode system. In that case the results of STL measurements were very inconsistent.

4. Measurements methodology

To perform measurements, the electrode system shown in Fig. 2, after filling it with the ER suspension, was placed in the opening between two standing wave tubes and sealed with the oil-based putty. The frequency of the sound sine wave was then adjusted along with the maximum value of the incident wave pressure level. The average sound pressure level (SPL) was measured on both sides of the electrode systems.

Those measurement steps were repeated for every frequency in the range between 100 [Hz] and 2 [kHz] and the electric field densities of 0, 0.2, 0.4, 0.6, 0.8, and 1 [kV/mm], respectively.

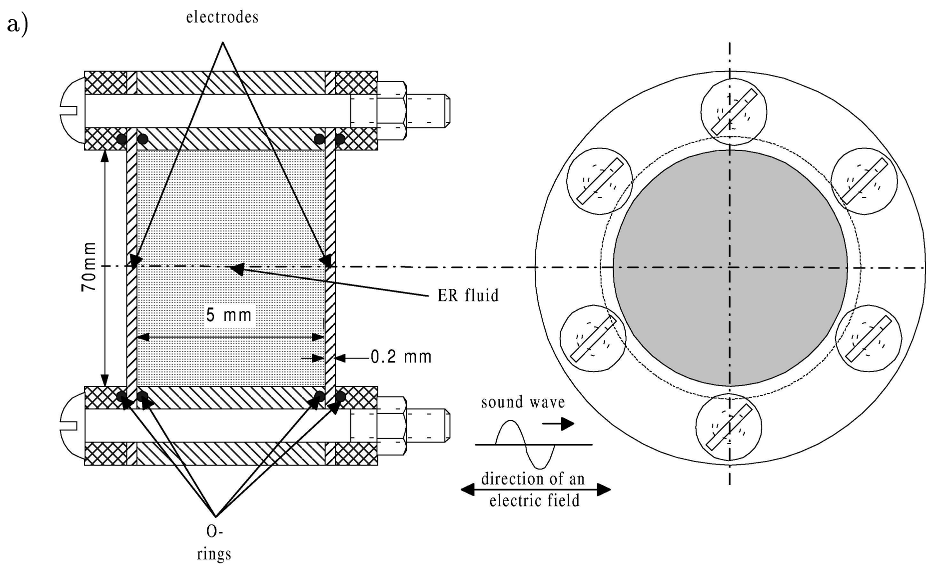
Before every measurement all ER fluids were well mixed in order to assure that the sedimentation processes did not affect the results of experiments.

All experiments were conducted at 20°C (293°K) and the humidity was kept within the range of 50-60%.

5. Results

5.1. Results of the STL *measurements for the* DC *electric field parallel to the direction of propagation of the sound wave*

This portion of experiments was conduced using the parallel plate configuration of electrodes (Figs. 2a and 3). One set of measurements was done for the positive voltage, another one for the negative voltage applied. Figure 4 presents the sound transmission



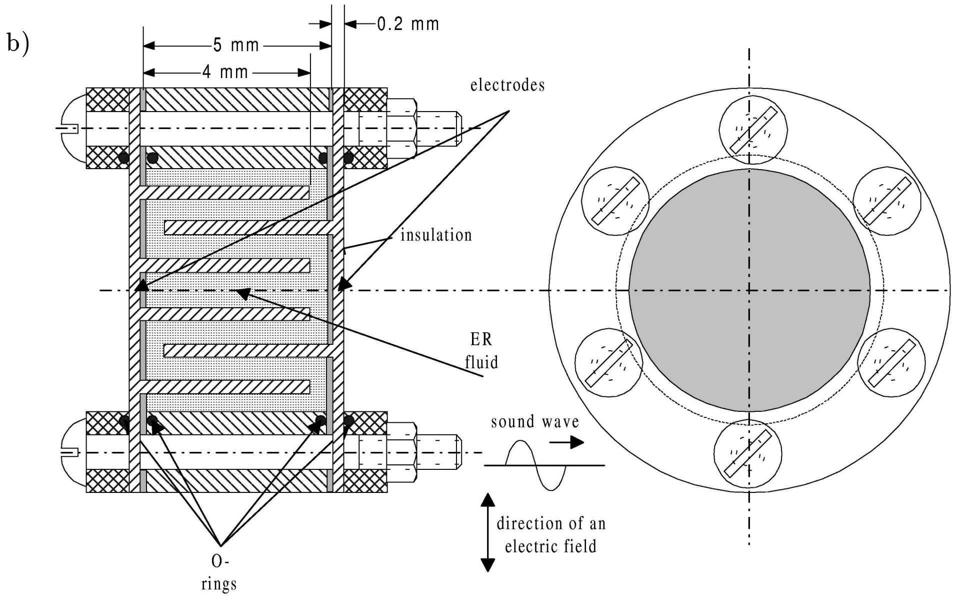


Fig. 2. Electrode configurations: a) system of electrodes where sound wave propagation is parallel to the direction of the electric field, b) system of electrodes where sound wave propagation is perpendicular to the direction of the electric field.

loss of all three ER fluids used in experiments; the STL curves are shown for the whole spectrum of frequencies (100 [Hz] – 2 [kHz]) and for the various levels of the electric field density. It can be noticed that the increased in the electric field density results

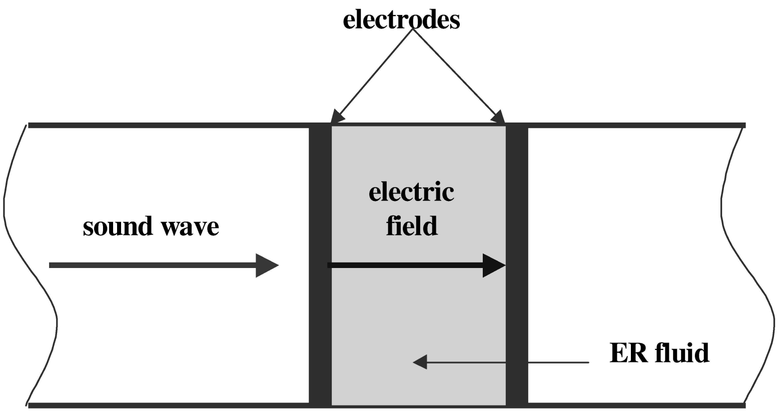
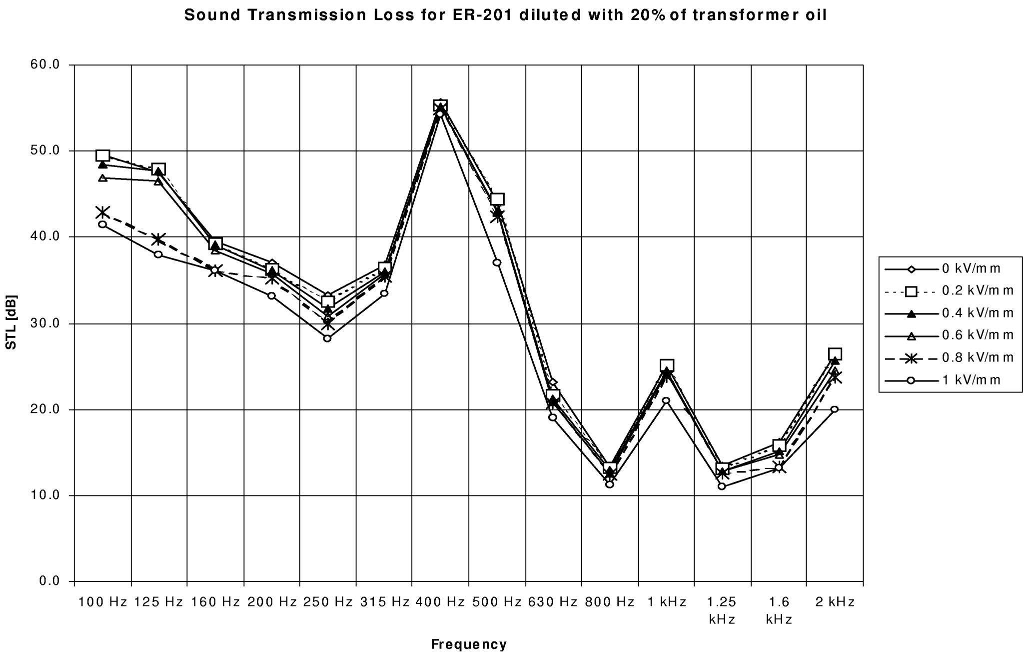


Fig. 3. Measurements of the STL with the electric field parallel to the direction of sound wave propagation.

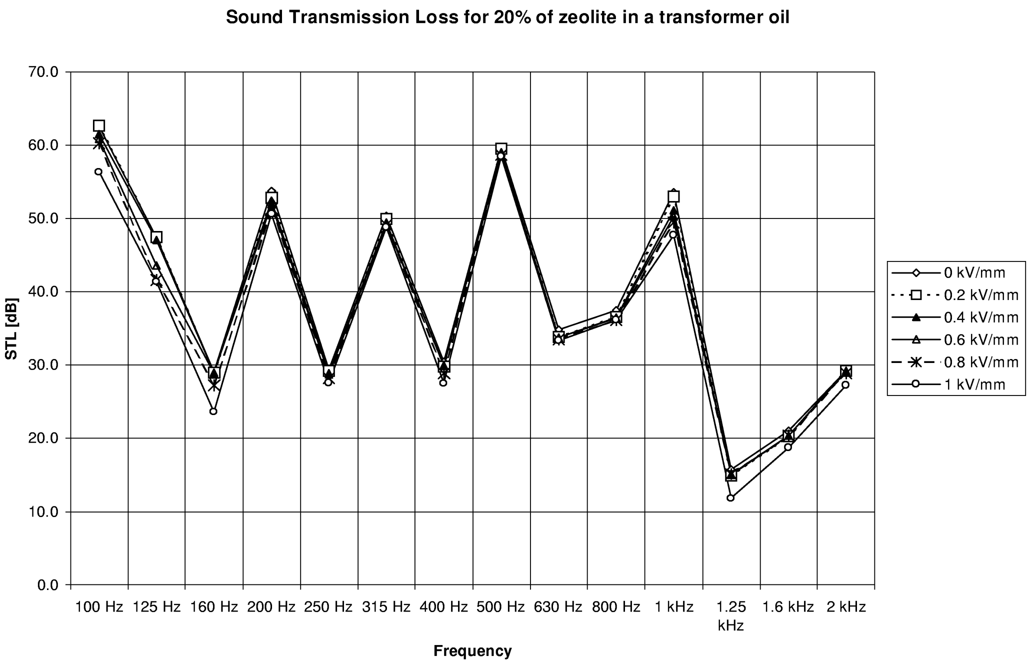
in the lowing of the sound transmission loss values for the whole range of frequencies and for all three investigated liquids. It means that an application of the electric field allows for more of the sound to go through the whole structure and seems to be of a greater value for the low frequencies 100-250 Hz. As a comparison level the STL values

a)



[Fig. 4a]

b)



c)

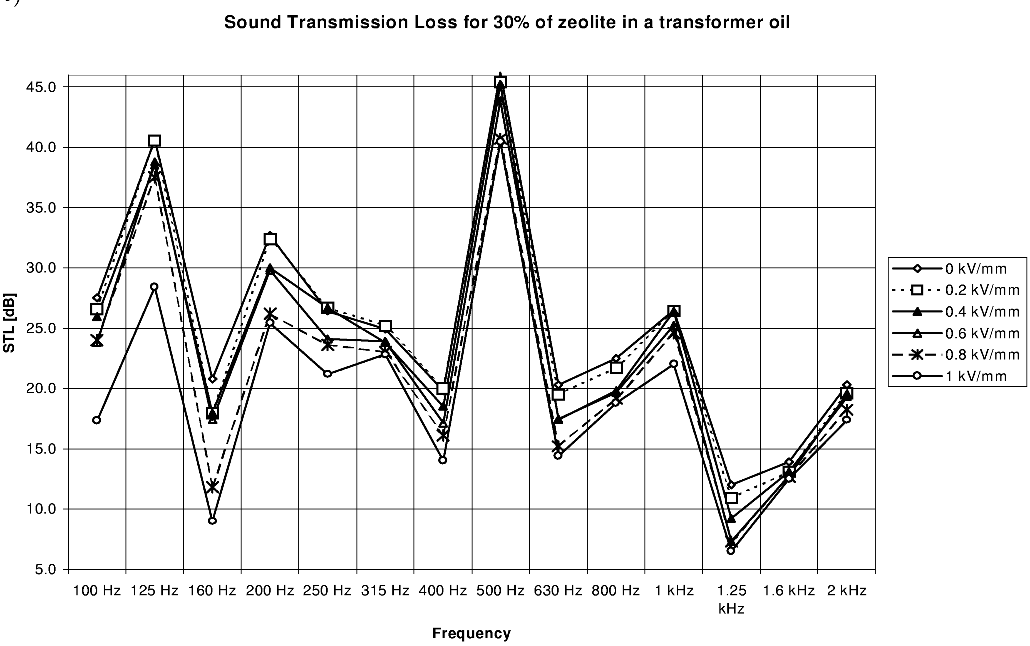


Fig. 4. Sound transmission loss of a) ER201 suspension, b) 20% of zeolite in the transformer oil, c) 30% of zeolite in the transformer oil (negative voltage) -◇- 0 [kV/mm], –□– 0.2 [kV/mm], -▲- 0.4 [kV/mm], -△- 0.6 [kV/mm], -∗- 0.8 [kV/mm], -○- 1[kV/mm].

for the electrode system without the voltage applied were used. After application of the highest electric field density level of 1 [kV/mm], the biggest STL drop for the ER 201 suspension was 9.6 [dB] at 125 [Hz], the smallest one was 1.4 [dB] at 400 [Hz]. The corresponding values in the case of 30% suspension of zeolite were: 11.8 [dB] at 160 [Hz] and 1.4 [dB] at 1.6 [kHz]. In a similar way, the values for 20% suspension of zeolite are presented: 6.2 [dB] at 100 [Hz] and 1.1 [dB] at 500 [Hz]. The power of the transmitted sound increased more than three times where the STL drop was the biggest (11.8 [dB] drop for 30% zeolite suspension).

5.2. Results of the STL measurements for the DC electric field perpendicular to the direction of propagation of the sound wave

For this part of the experiments the electrode system shown in Figs. 2b and 5 was used. The STL was measured again for the 100 [Hz] – 2 [kHz] frequency band and electric field densities 0, 0.2, 0.4, 0.6, 0.8 and 1 [kV/mm], respectively. The results are presented in Fig. 6. The STL drop for this configuration of electrodes was not very significant, though one should notice that the active surface of electrodes was very small. On the other hand, shear stress is at least ten times less than normal stress in the same electric field density [25]. After application of the highest electric field density level of 1 [kV/mm] the biggest STL drop for the ER 201 suspension was 1 [dB] at 200 and 250 [Hz], the smallest drop was 0.1 [dB] at 630, 800 and 1600 [Hz]. The values of the biggest and smallest STL drop for the 30% suspension of zeolite were: 3.3 [dB] at 100 [Hz] and 0.2 [dB] at 315 and 800 [kHz], respectively. Likewise the values for 20% suspension of zeolite are presented: 3.9 [dB] at 630 [Hz] and 0 [dB] at 2 [kHz].

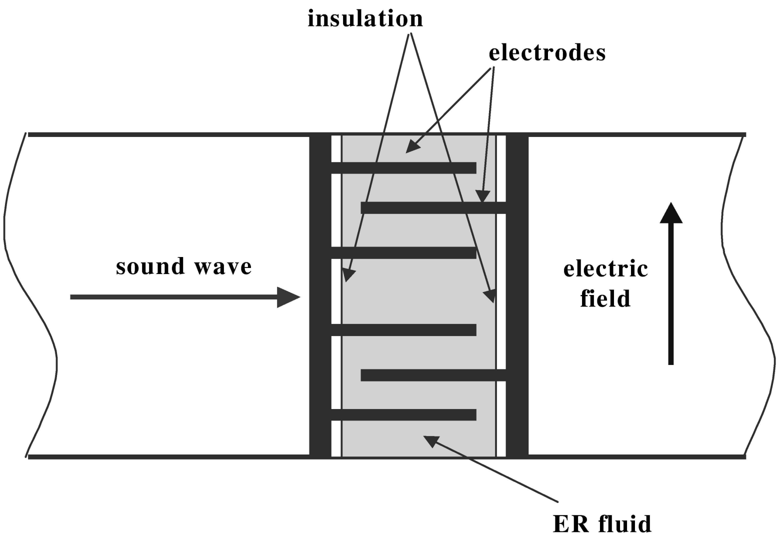
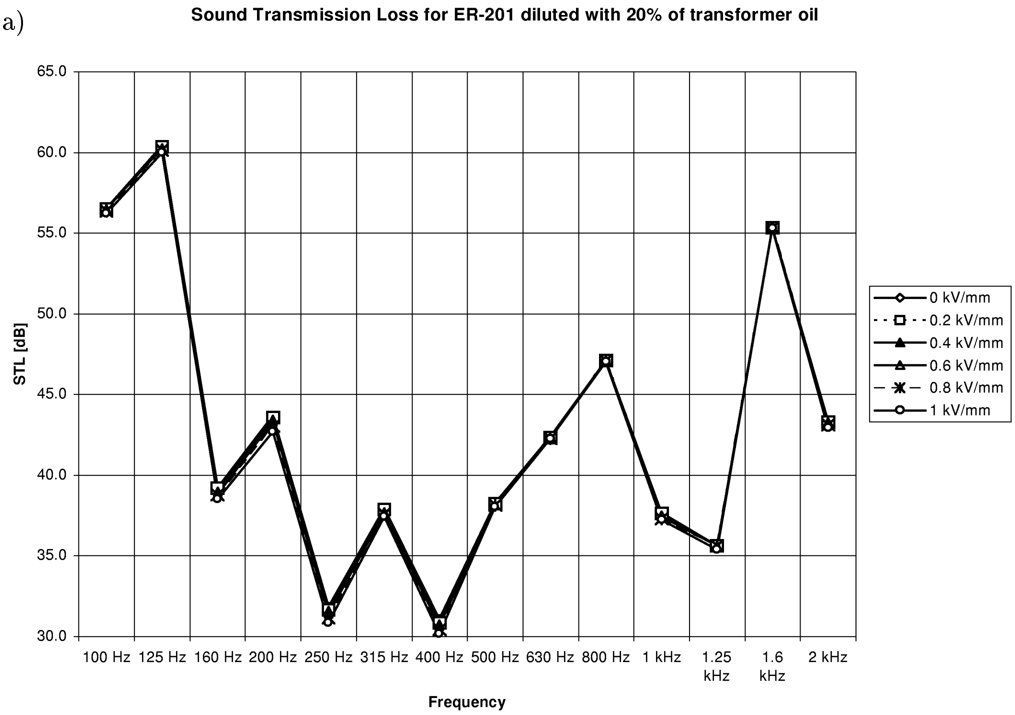
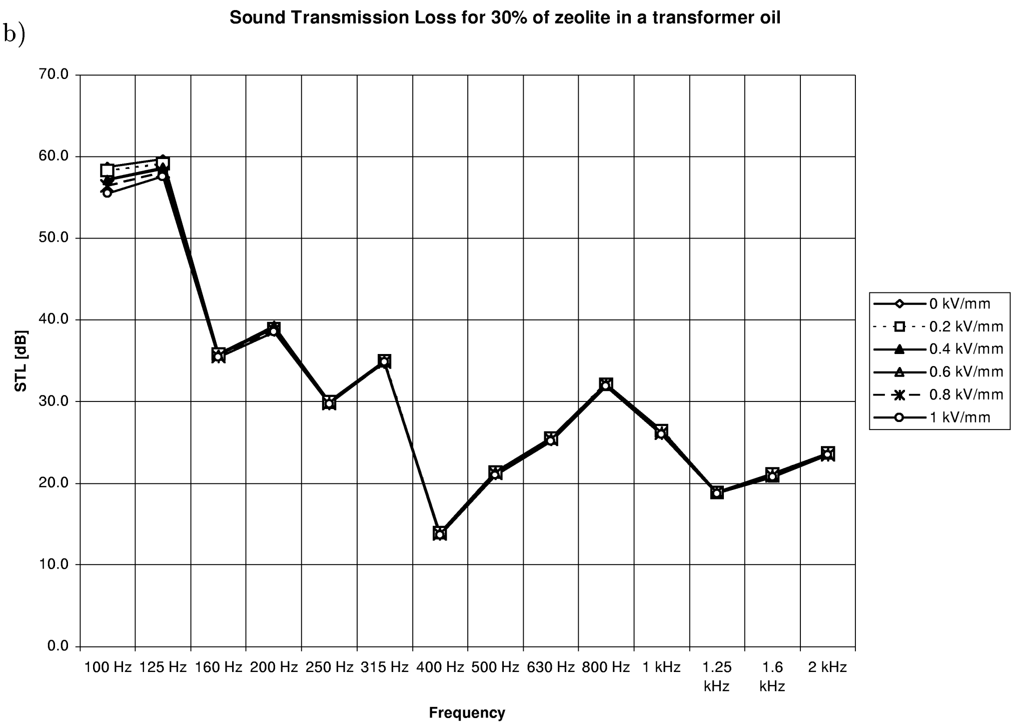


Fig. 5. Measurements of the STL with the electric field perpendicular to the direction of the sound wave propagation.

a)


Sound Transmission Loss for ER-201 diluted with 20% of transformer oil
STL [dB]
Frequency
100 Hz 125 Hz 160 Hz 200 Hz 250 Hz 315 Hz 400 Hz 500 Hz 630 Hz 800 Hz 1 kHz 1.25 kHz 1.6 kHz 2 kHz
0 kV/mm
0.2 kV/mm
0.4 kV/mm
0.6 kV/mm
0.8 kV/mm
1 kV/mm

b)


Sound Transmission Loss for 30% of zeolite in a transformer oil
STL [dB]
Frequency
100 Hz 125 Hz 160 Hz 200 Hz 250 Hz 315 Hz 400 Hz 500 Hz 630 Hz 800 Hz 1 kHz 1.25 kHz 1.6 kHz 2 kHz
0 kV/mm
0.2 kV/mm
0.4 kV/mm
0.6 kV/mm
0.8 kV/mm
1 kV/mm

[Fig. 6a, b]

c)

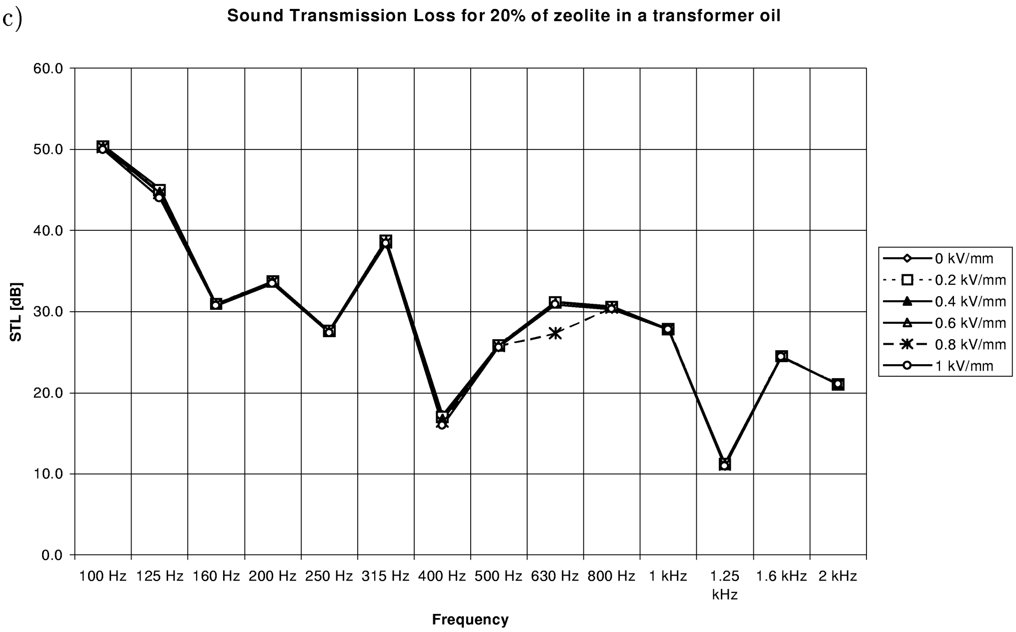


Fig. 6. Sound transmission loss of a) ER201 suspension, b) 30% of zeolite in the transformer oil, c) 20% of zeolite in the transformer oil, -◇- 0 [kV/mm], –□– 0.2 [kV/mm], -▲- 0.4 [kV/mm], -△- 0.6 [kV/mm], -∗- 0.8 [kV/mm], -○- 1[kV/mm].

6. Summary

Characteristics given in Figs. 4 and 6 indicate that the density of the electric field does affect the STL of ER suspensions. It was observed that with the increase of the voltage between electrodes the transmission loss was decreasing for all the ER fluids at all the measurement frequencies. The most significant STL drop was observed for the frequency range between 100 and 250 [Hz]. The fluid that seemed to show the biggest STL drops was the 30% suspension of zeolite in the transformer oil. There are many possible explanations for that effect; one might make use of the mechanical coupling between electrodes via the ER fluid structure formed under influence of the electric field, another one can consider the electrical forces interactions in the ER suspension. Also presented results were obtained in frequency range where stiffness of the sample dominates STL.

For the electric field perpendicular to the direction of the sound wave the graphs of STL vs. frequency (Fig. 5) do not show a significant STL change with an electric field increase. The active electrode area was very small in this particular case and that could be a possible explanation for the small STL drop. Another reason is that the shear stresses that ER fluids are able to withstand are 10 – 100 times smaller than corresponding compressive stresses [6, 7, 25–27]. Although not very discernible, this STL drop effect was present and occurred for the entire measurement frequency range and for all three investigated suspensions. Again, as in the case of flat, plain electrodes configuration, the biggest drop in the STL values was registered for the 30% zeolite suspension.

The conclusions are:

- The sound transmission loss of ER suspensions can be controlled by the external DC electric field. The STL of those ER fluids decreased with the increase of the electric field density applied. For a flat-parallel system, where the electric field was parallel to the direction of the incident sound wave, the sound transmission loss drop was up to 12 [dB] for the highest (1 [kV/mm]) electric field density applied. That means that the amount of sound power transmitted through the partition consisting of electrodes and ER fluid increased more than 3 times.
- The observed STL drop values were higher for the lower frequency range of the measurement band (100-300 [Hz]) for all the suspensions.
- The STL drop was also observed in the electrode system where the electric field was perpendicular to the direction of the sound wave – the values of that drop were not high (maximum of 3.3 [dB] was observed at the frequency of 100 [Hz] for the 30% suspension of zeolite in the transformer oil).
- Potential applications are STL controllers, esp. in the low frequency range, active noise control devices, etc.

References

[1] E.V. Korobko, Z.P. Shulman and G.V. Voronovich, *Electrorheological damping in precision systems*, Proceedings Of SPIE, **3041**, 868–873, 1997, Smart Structures And Materials, 3-6 March 1997, San Diego, CA., Bellingham, Wash., SPIE 1997.

[2] D.J. Peel, R. Stanway and W.A. Bullough, *The ER Long-Stroke Damper: Experimental verification of mathematical models*, Rheology and Fluid Mechanics of Nonlinear Materials, FED - **243**/MD - **78**, 249–259 1997, ASME 1997.

[3] S. Choi, Y. Park and C. Cheung, *Active vibration control of intelligent composite laminate structures incorporating an electro-rheological fluid*, J. Intelli. Mater. Sys. Struct., **7**, 411–419, 1996.

[4] H.P. Gavin and R.D. Hanson, *Electrorheological devices with annular electrodes*, Proceedings Of 10^{th} Conference ASCE, Boulder, CO., May 21-24, 1995, **2**, 1231-1234, ASCE, New York, 1995.

[5] S.J. Dyke, B.J. Spencer, JR., M.K. Sain and J.D. Carlson, *Seismic response reduction using magnetorheological dampers*, Proceedings The IFAC World Congress, San Francisco, Ca., June 30-July 5, 1996.

[6] H. Block and J.P. Kelly, *Electro-rheology*, J. Physics D: Appl. Physics, **21**, 12, 1661–1667, 1988.

[7] T.C. Jordan and M.T. Shaw, *Electrorheology*, IEEE Trans. Electrical Insulation, **24**, 5, 849–878, 1989.

[8] D.L. Klass and T.W. Martinek, *Electroviscous fluids II. Electrical Properties*, J. Appl. Physics, **38**, 1, 75–80, 1967.

[9] A.H. Shiang and J.P. Coulter, *A comparative study of AC and DC electrorheological material based adaptive structures in small amplitude vibration*, J. Intell. Mater. Systems Struct., **7**, 455–469, 1996.

[10] S. Kudallur, G.H.Conners and K.W. Buffington, *Electrorheological damper for precision applications*, Developments in Electrorheological Flows, ASME, FED- **235**/MD- **71**, 21–27, 1995

[11] H. Conrad and Y. Chen, *Electrical properties and the strength of electrorheological (ER) fluids* [ed] by K.O. Havelka and F.E. Filisko, [in:] Progress in Electrorheology, 55–85, Plenum Press, New York, 1995

[12] C.J. Radcliffe, J.R. Lloyd, R.M. Andersland and J.B. Hargrove, *State Feedback Control Of Electrorheological Fluids*, presented at 1996 ASME International. Congress & Exhibition, Nov. 17-22, Atlanta, GA.

[13] G. Leitmann, *Semi-active control for vibration suppression in a system subjected to unknown disturbances*, J. Of Circuits, Systems And Computers, **4**, 4, 379–393, 1994

[14] Y. Ribakov and J. Gluck, *Active control of MDOF structures with supplemental electrorheological fluid dampers*, Earthquake Engineering & Structural Dynamics, **28**, 143–156, 1999

[15] K. Maemori and T. Sajto, *A new type of hydraulic shock absorber using electrorheological fluid*, JSME Int. J., Series C, **41**, 1, 156–163. 1998

[16] G. Leitmann, *Semiactive control for vibration attenuation*, J. Intelli. Mater. Systems Struct., **5**, 841–846, 1994

[17] M. Yalcintas and J.P. Coulter, *Electrorheological material based non-homogeneous adaptive beams*, Smart Materials & Structures, 7, 128–143, 1998

[18] D.J. Klingenberg, D. Dierking and C.F. Zukoski, *Stress of transfer mechanisms in electrorheological suspensions*, Journal Of Chem. Soc. Faraday Trans., **87**, 3, 425–430, 1991

[19] J.G. Kohl and J.A. Tichy, *Expressions for coefficients of electrorheological fluid dampers*, Lubrication Science, **10**, 2, 135–143, 1998

[20] M. Parthasahathy and D.J. Klingenberg, *Large amplitude oscillatory shear of ER suspensions*, J. Non-Newtonian Fluid Mech., **81**, 83-104, 1999

[21] *Laboratory measurement of the airborne sound barrier performance of automotive materials and assemblies* - SAE J1400, May 1990

[22] M. Noras, *Sound transmission loss control using electrorheological fluids*, December 1999, Ph.D. thesis, Southern Illinois University

[23] L.L. Beranek and I.L. Ver, *Noise and vibration control engineering: Principles and applications*, Wiley, New York 1992

[24] VersaFlo^{TM} Fluids Product Information: Lord® Corporation, Form#P101-ER201A

[25] G.J. Monkman, *The Electrorheological effect under compressive stress*, J. Physics D: Appl. Physics, **28**, 588–593, 1995

[26] L.C. Davis and J.M. Ginder, *Electrostatic forces in electrorheological fluids* [in:] Progress in Electrorheology, [Ed.] K.O. Havelka and F.E. Filisko, Plenum Press, New York 1995, 107–114.

[27] H. Conrad and A.F. Sprecher, *Characteristics and mechanisms of electrorheological fluids*, J. Of Statistical Physics, **64**, 1073–1091, 1991