The Vibration Damping Effect of an Electrorheological Fluid

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ABSTRACT

The attenuation of longitudinal vibrations in structures can be achieved through a change in the impedance of the structure. This impedance change can be produced by an electrorheological fluid. The transmission of a known vibration input along a test structure will be correlated to the impedance characteristics of the electrorheological fluid. This impedance characteristic of the fluid will be expressed in terms of the applied electric field.

The attenuation characteristics of the electrorheological fluid on longitudinal vibration have been presented through experimental and numerical results. The results of this study showed an attenuation of 4 dB in the transmissibility of acceleration from the forward to the aft ends of the test structure. This level can be increased by using a fluid possessing a lower zero state viscosity.

A secondary result of this investigation is understanding the physics of the damping mechanism in the test module when the electric field was increased from 1.2 kV/mm to the value of 1.6 kV/mm. During this increase in the electric field, the logarithmic decrement increased by more than a factor of three. The transmissibility data also shows that the resonant frequency decreased.

INTRODUCTION

The application of electrorheological (ER) fluids have been cited by many authors, such as the work of Stanway et al. (1987), Coulter et al. (1989), Duclos (1988), Stevens et al. (1984) and by Margolis and Vahdati (1989), as an effective means for vibration isolation and control. The many applications of these fluids include clutches, viscous dampers, and active engine mounts. In the vibration isolation applications, the predominant method of vibrational energy dissipation is the interaction between a plunger mechanism and the ER fluid. The fluid properties are actively altered by the magnitude of the electric field applied; thus, the response of the structure is altered and controlled.

In this paper, an application of an ER fluid to attenuate the longitudinal vibration in a flexible cylindrical structure is discussed. The attenuation of the longitudinal vibration (Figure 1) will be achieved by the relative shearing of the fluid at the inner surface of the flexible boundary and a region of fluid driven by an applied electric field.

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The shear interface is developed between the driven, center line, fluid posing a resistance to the zero state fluid entrained with the flexible cylinder motion. The vibrational energy in the wall of the flexible cylinder will be dissipated through the relative shearing of the driven and zero state ER fluid.

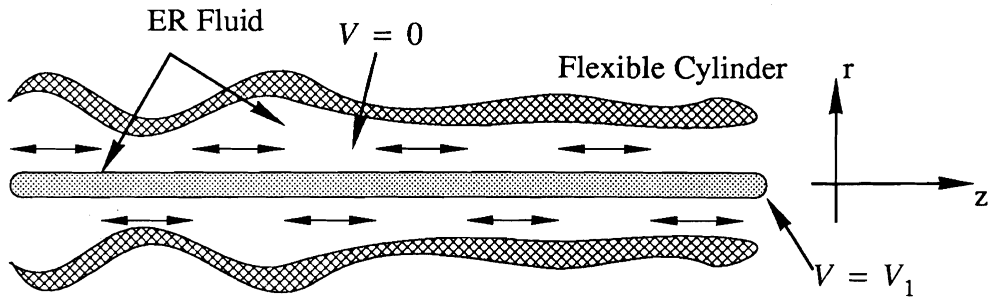

Figure 1. ER Shear Application

The results of this analysis show an increase in attenuation with an increase of the applied electric field. This analysis also shows an extreme increase (3 times) in the damping of the system as the electric field transitions in the range of $1.2 < E \leq 1.6$ kV/mm dc. This extreme increase in the system damping ratio can be explained by the results of Jaggi et al. (1989) and Tao et al. (1989) concerning a phase transition at a critical electric field.

EXPERIMENT

The objective of the experimental portion of this investigation was to determine the attenuation effect that an ER fluid has on the longitudinal vibration in a flexible structure. The geometry of the test structure is shown in Figure 2. The internal components of the ER test module consist of the ER fluid and the electric field device. The electric field device contains 190 electrodes made of copper disks. The electric field is contained within a 5mm gap between the electrodes. The test module consisted of a cylinder approximately 150 cm in length and a diameter of 7.5 cm. The electric field device was approximately 95 cm long. The diameter of the copper electrodes was 3.125 cm. This provided a gap between the inner wall of the flexible cylinder and the edge of the electrode of 2.1875 cm. It is this annulus of zero state ER fluid moving parallel and over the electrically driven ER fluid along the center line which dissipates the vibration in the flexible cylinder.

This investigation was conducted using a corn starch and mineral oil fluid mixture. The fluid was prepared in the following manner:

(1) The mineral oil was filtered to remove foreign particles (40 mesh filter).
(2) The corn starch had a water content of approximately two percent.
(3) The corn starch was added with a measuring (1 cup) cup.
(4) The starch was packed by lightly tapping the cup on the table.
(5) The starch was sifted into mineral oil (50% by volume).
(6) The starch was blended into mineral oil with electric mixer (132 ml quantities, total of 8 liters).
(7)The mixture was degassed in a vacuum chamber.

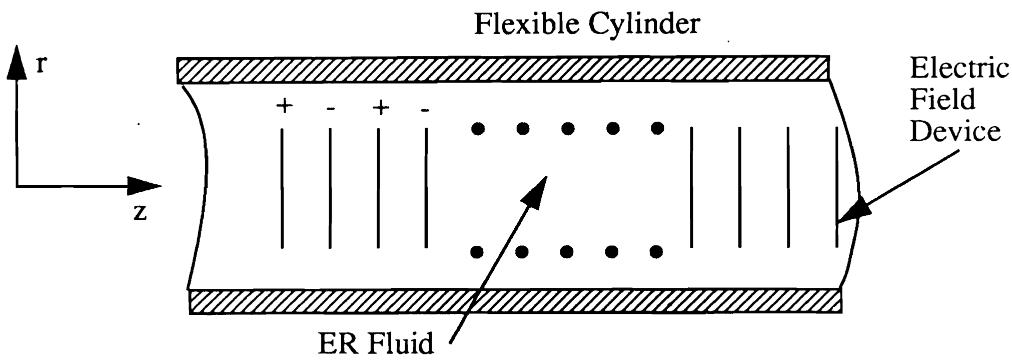

Figure 2. Electrorheological Test Module

The experimental apparatus consisted of the ER test module attached to an electrohydraulic shaker and tensioned to a force of approximately 445 N. The instrumentation included a force transducer and accelerometer at both ends of the ER test module as shown in Figure 3.

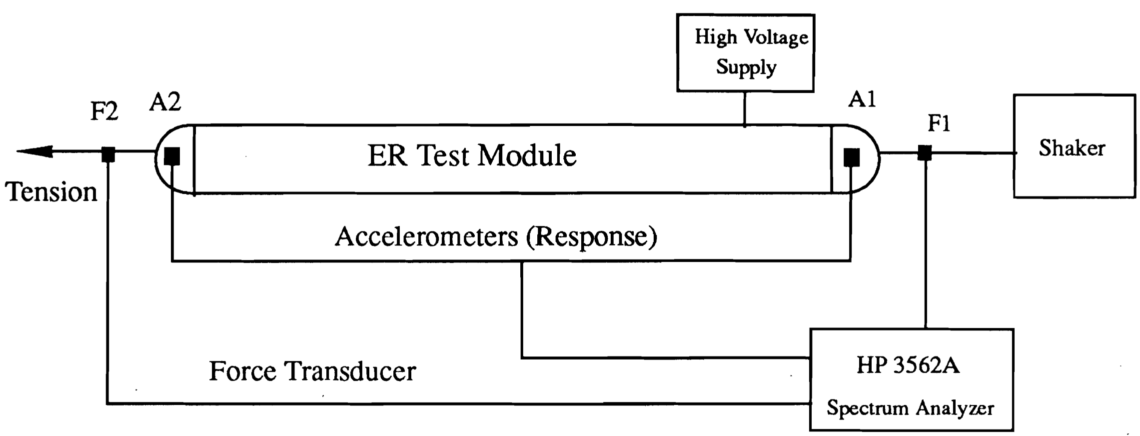

Figure 3. Configuratiuon of the Experiment

The experiments were conducted by exciting the ER test module in the axial direction with a swept sine (1 - 300 Hz) input. The data (average of three samples) was recorded in the form of frequency response functions. The use of a frequency response function is preferred since the results can be applied to predict the response of the structure to other excitation functions. The recorded frequency response functions included the ratios of the aft acceleration to the forward acceleration, the forward force to the forward acceleration and the forward force to the aft acceleration. The data used in this paper focuses on the frequency response function of the acceleration ratio. The experiments were conducted at electric field strengths of 0.0, 0.4, 0.8, 1.2, and 1.6 kV/mm dc. This set of data was generated when the fluid was one day old. These experiments were conducted at each value of the electric field twice. The repeatability at each value of the electric field was excellent, within ±0.2dB; however, the same experiment was executed twenty-four days later which generated values that differed by forty percent over the first set of experimental results. This extreme variance highlights the need for a fluid possessing a longer shelf life.

Figures 4-7 illustrate the data acquired during the first set of experiments. These figures represent the frequency response functions calculated from the ratio of the aft acceleration to the forward acceleration. The abscissa represents frequency in the units of cycles/sec (Hz). The ordinate represents the magnitude of the acceleration ratio (transmissibility) expressed in decibels (dB). Figures 4, 5, and 6 show the damping contribution of the ER fluid at 0.4, 0.8, and 1.2 kV/mm respectively. The resonant peak in these plots has been reduced without a noticeable shift in the resonant frequency. The resonant frequency may have been shifted to the right in Figures 4 - 6, but due to the resolution of the data over the given frequency range, the effect was not evident. A series of zoom measurements will be made to explore the possibility of a shift in resonant frequency at these electric field strengths. At an electric field of 1.6 kV/mm, Figure 7, the magnitude of the resonant peak as well as the resonant frequency decreased due to the ER fluid effect. From the comparison of this data there appears to be a change in the damping mechanism when the electric field is increased between 1.2kV/mm to 1.6kV/mm. This will be discussed in terms of the system damping properties in the next section.

QUANTITATIVE RESULTS

The magnitude of damping provided by the ER fluid has been quantified by the calculation of the system amplitude ratio (AR) and the logarithmic decrement (δ). These quantities depend on the calculation of the system damping ratio (ξ). The system damping ratio can be calculated from experimental data by three methods, as shown in Steidel (1979) and Nashif et al. (1985). These methods are by the half power points, the shift in frequency and from the phase angle.

The half power point method provides a good approximation to the system damping for damping values less than 0.1. Since the system damping in this case is greater than 0.1, the half power point method will generate erroneous results for the system damping coefficient at the higher electric field values. Another technique to calculate the system damping ratio from the experimental data is to use the shift in natural frequency of the damped system. The damped natural frequency will be lower than that of the undamped natural frequency. The relationship between the damped natural frequency and the undamped natural frequency is given by the following equation from Steidel (1979):

$$\xi = \sqrt{1 - \left(\frac{\omega_d}{\omega_n}\right)^2} \tag{1}$$

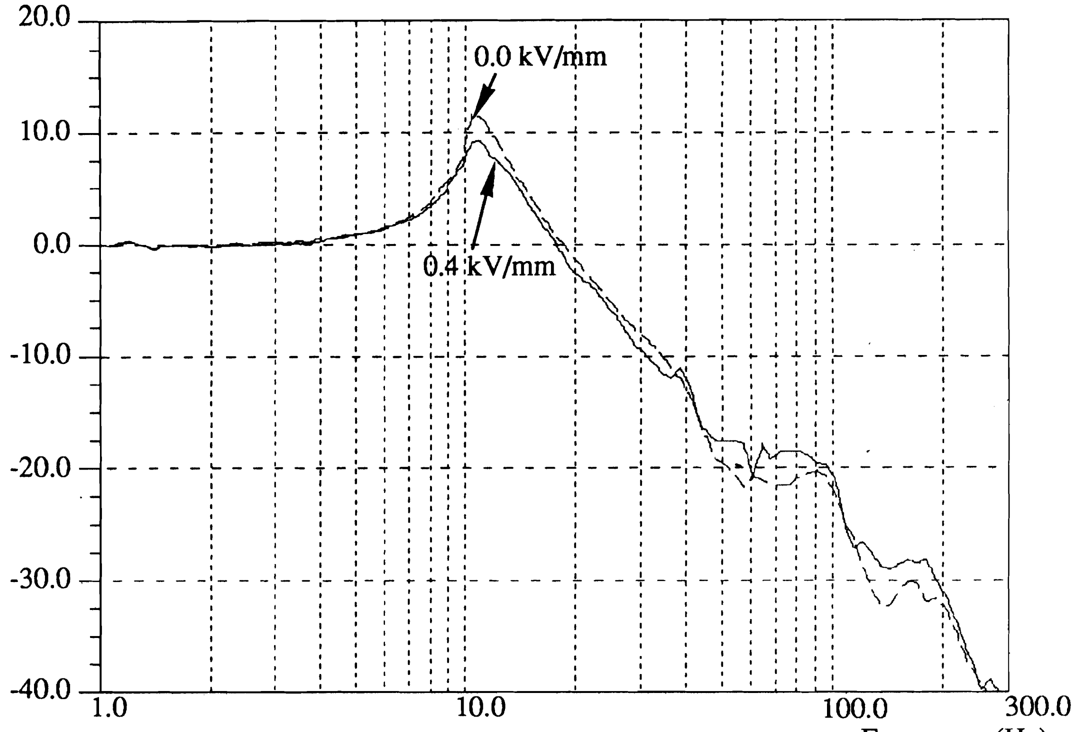

Figure 4. Magnitude of Acceleration Ratio in dB

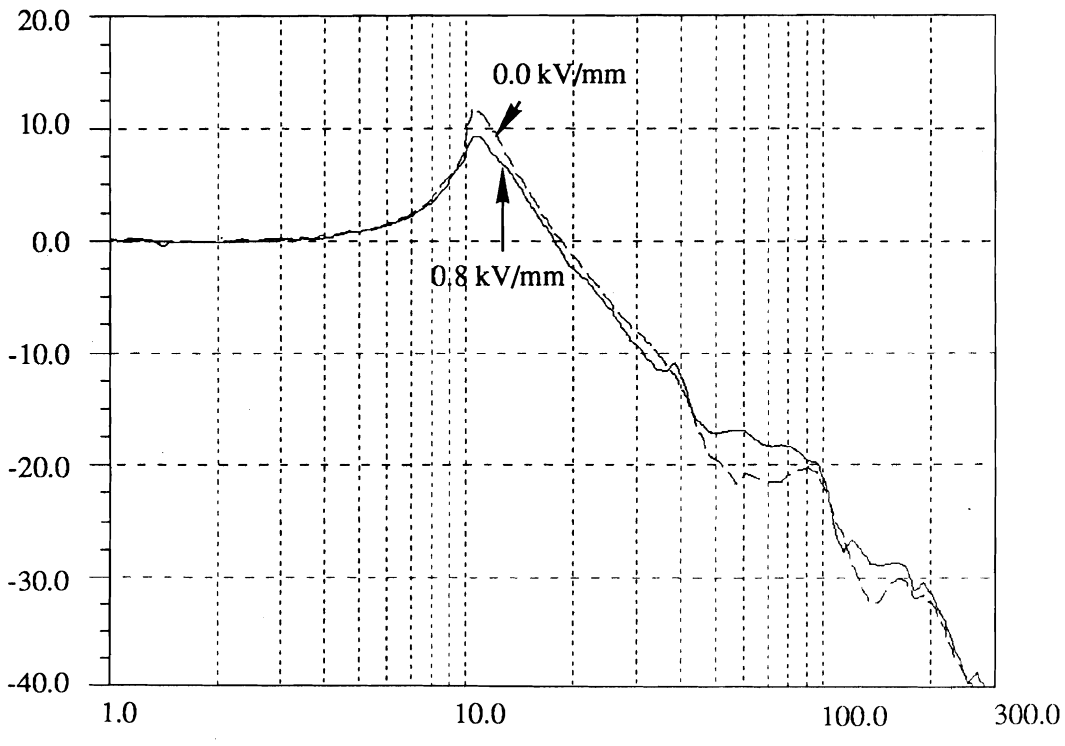

Figure 5. Magnitude of Acceleration Ratio in dB

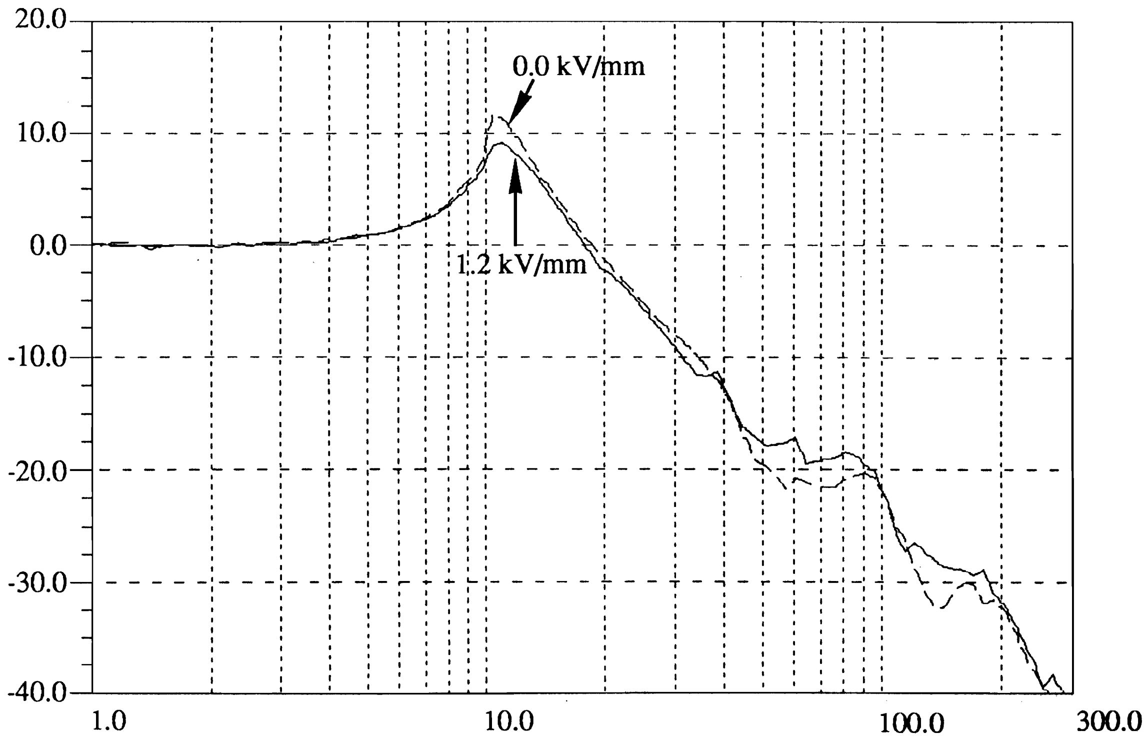

Figure 6. Magnitude of Acceleration Ratio in dB

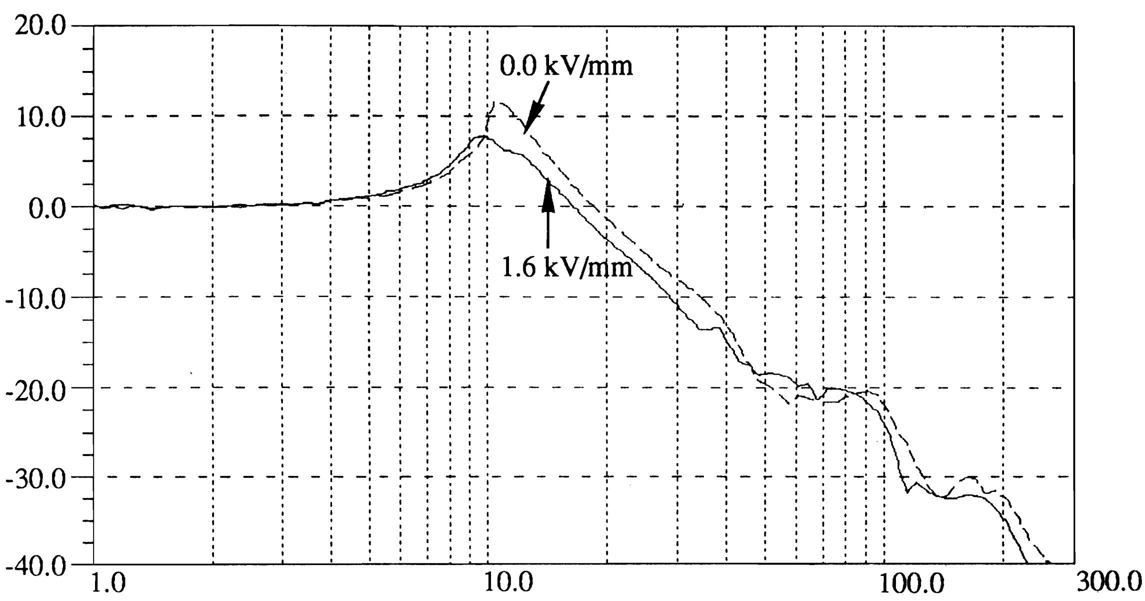

Figure 7. Magnitude of Acceleration Ratio in dB

This method was useful on the 1.6kV/mm data only since the data resolution of the other resonant frequencies did not show this shift in frequency.

The phase angle information generated can be used to estimate the damping characteristics of the system with respect to the applied electric field. If the structure contained no damping then the phase angle would be zero for all frequencies up to the resonant frequency. At the resonant frequency the phase angle would instantaneously increase to π radians and remain at this value for all frequencies (Figure 8).

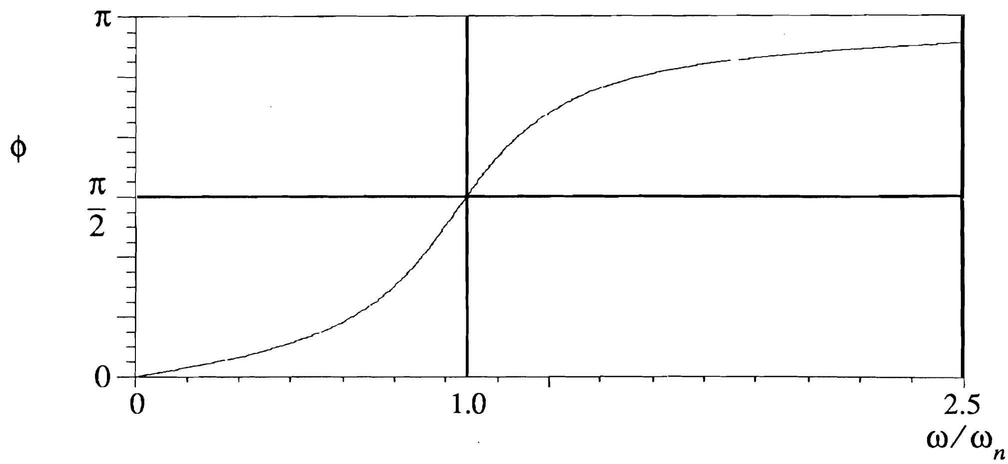

Figure 8. A Phase Angle vs Frequency Ratio Plot

The phase angle has a value between zero and π radians when damping is present in the structure. The phase angle is to equal π/2 radians at the resonant frequency. For a given value of the phase angle at a given frequency, the system damping ratio can be calculated from the following equation in Steidel (1979):

$$\xi = \frac{(\omega^2 - \omega_n^2)}{2\omega\omega_n} \tan\phi \qquad (2)$$

This expression provides a relationship between phase and frequency as a comparison of the system damping. This method is used in the calculation of the system damping ratio to represent the effect of the electric field on the ER fluid. The phase angle method is the most accurate for the given data set.

The result of the system damping ratio calculation by the phase angle method is shown in Figure 9. This figure shows the increase in the damping effect as a function of the electric field and frequency. The entries in Table I are the system damping ratios normalized by the zero state result. This normalization was performed to illustrate the effect that the electric field has on the system damping ratio. The system damping ratio values in Table I are reported at the natural frequency of 10.366 Hz

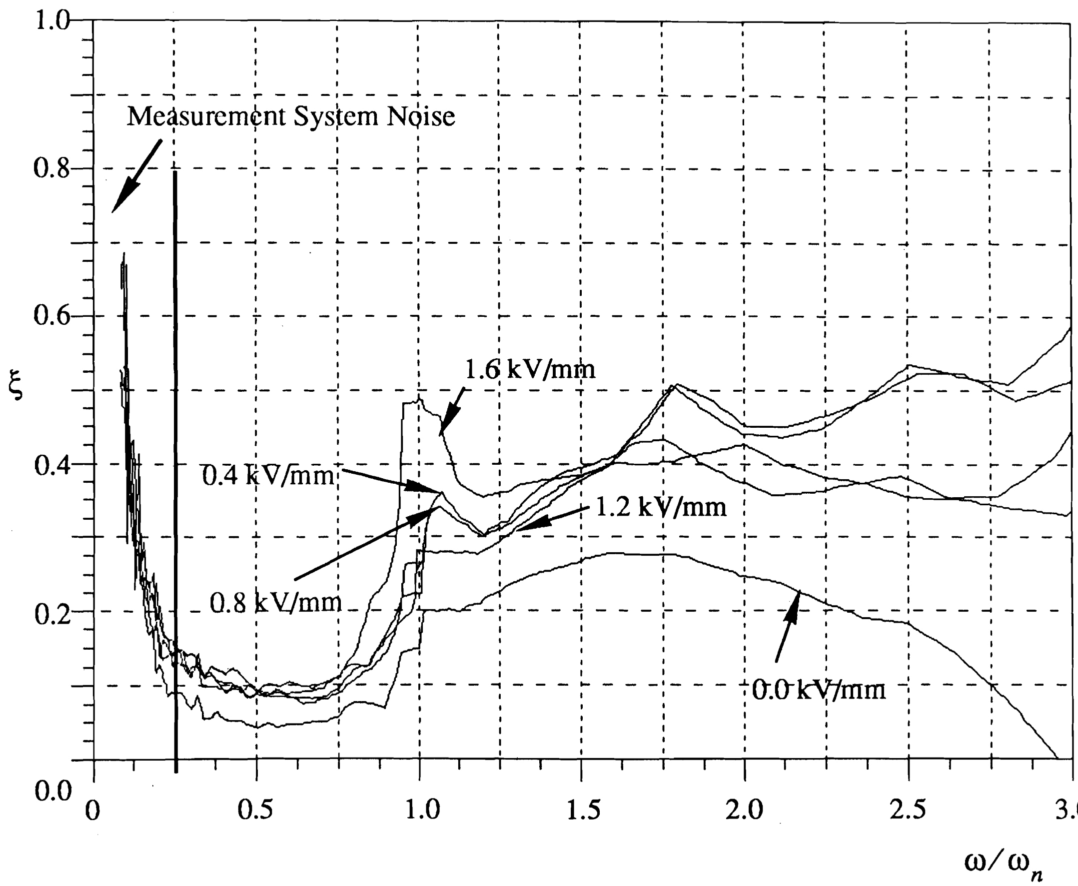

Figure 9. Damping Ratio vs. Frequency Ratio

Table I. System Damping Ratios (ξ)

Electric Field Strength	Phase Angle	Shift in Frequency
1.6 kV/mm	3.575	2.299
1.2 kV/mm	1.089	-
0.8 kv/mm	1.175	-
0.4 kV/mm	0.939	-
0.0 kV/mm	1.0	1.0

KEY RESULTS

The results of this analysis will be represented in terms of the amplitude ratio and the logarithmic decrement. The amplitude ratio provides a relative comparison of the damping effect on the system due to the applied electric field. The amplitude ratio derived for a viscous damped, single degree of freedom system excited by a harmonic forcing function can be found in Steidel (1979) as:

$$AR = \frac{1}{\sqrt{\left[1 - \left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left[2\xi\left(\frac{\omega}{\omega_n}\right)\right]^2}} \tag{3}$$

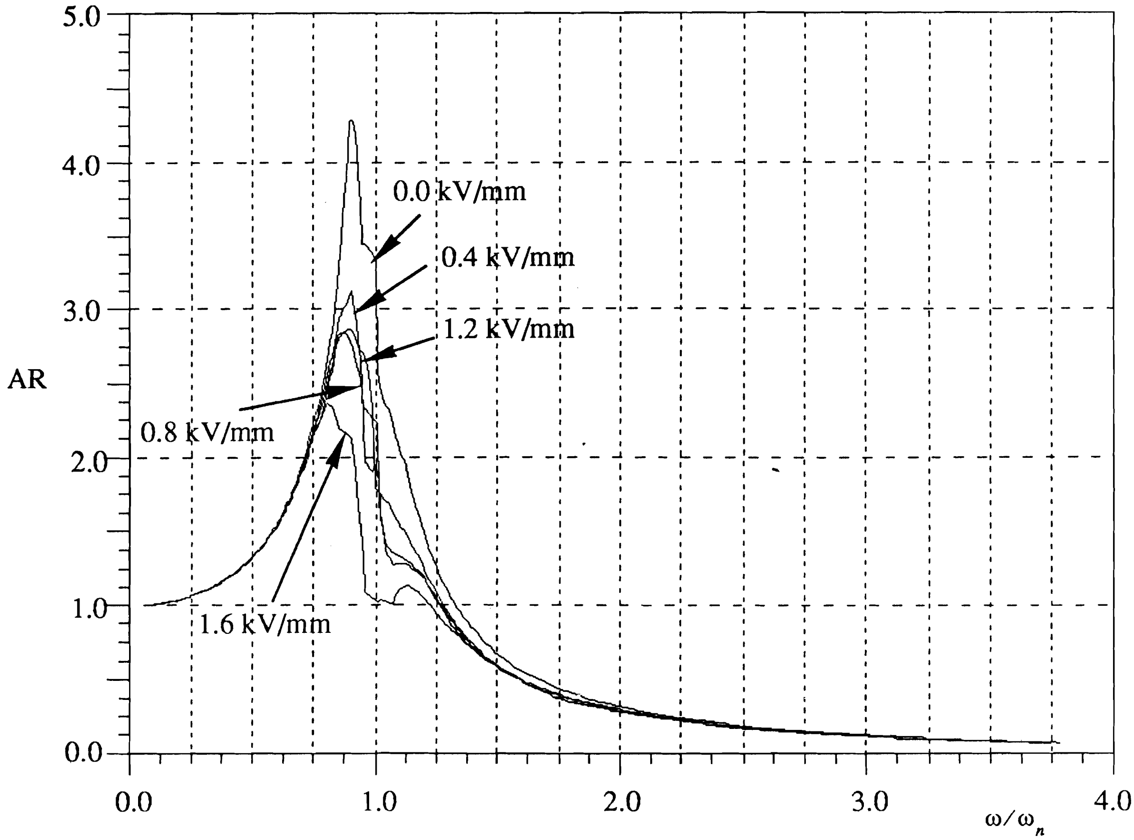

Figure 10. Amplitude Ratio vs. Frequency Ratio

By comparing the reduction of the amplitude ratio (Figure 10) at 1.6kV/mm to the zero state, an attenuation of approximately 4.0 dB is realized. The shift in the resonant frequency is also evident for the 1.6kV/mm case.

An additional measure of the system damping capacity of the ER fluid is the logarithmic decrement. The logarithmic decrement provides a measure of the amplitude reduction from cycle to cycle. This reduction in amplitude is of the form, $X_n = X_0 e^{-\delta n}$. The logarithmic decrement is defined in Steidel (1979) as:

$$\delta = \frac{2\pi(\xi)}{\sqrt{1-\xi^2}} \tag{4}$$

The values of the logarithmic decrement calculated from equation (4) are listed in Table II. These calculations were made at the damped natural frequency, which corresponded to the particular case using the phase angle calculation for the system damping ratio.

Table II. Logarithmic Decrement

Electric Field Strength	Logarithmic Decrement
1.6 kV/mm	3.454
1.2 kV/mm	0.989
0.8 kV/mm	1.070
0.4 kV/mm	0.850
0.0 kV/mm	0.906

For comparison, the logarithmic decrement of a new automobile shock absorber is approximately 4 (Steidel (1979)). From the results in Table II, in general, system damping improves as the electric field is increased from the zero state to the value of 1.2 kV/mm. The effect of the electric field is not strong in this electric field range. When the electric field was increased to 1.6 kV/mm the logarithmic decrement dramatically increased by a factor of three. This dramatic increase in the system damping ability indicates a physical change in the damping mechanism of the structure.

CONCLUSIONS

A result of this analysis is that the vibrational input was attenuated by 4.0 dB through the use of an ER fluid. This value of attenuation is low when compared to the results of other applications (Stanway et al. (1987), Stevens et al. (1984) and Margolis and Vahdati (1989)). The results of this application depend on the relative shearing between the ER fluid along the flexible boundary and the center where the ER fluid is driven by the electric field. The zero state viscosity of the corn starch/mineral oil mixture was high (209 centipoise). A less viscid zero state fluid would provide better results in this application by producing a larger gradient between the electric field driven fluid and the outer fluid. A silicone oil based fluid (50 centipoise) will be utilized for future experimentation to prove this statement.

A secondary result, but the most interesting, is what happened inside the ER test module when the electric field increased from 1.2kV/mm to 1.6kV/mm. The quantification of the transition was attempted by taking data at smaller increments of electric field (0.1 kv/mm); however, the fluid was found to be past its usable life. A possible explanation to describe the damping mechanism could be made based on the critical electric field theory of Jaggi et al . (1989) and Tao et al. (1989). The work of Jaggi (1989) and Tao (1989) predicts a critical electric field where the onset of a phase transition in the ER fluid occurs. With the existence of a phase transition electric field, the ER fluid in the test structure would not have become a 'solid' at the electric fields below 1.2kV/mm. Since the zero state viscosity of the ER fluid was high, the difference in phase state between the fluid regions may not have been sufficient to produce an interface where the shear dissipation was to occur. At the electric field of 1.6kV/mm (or between 1.2 and 1.6kV/mm), the ER fluid driven by the field became 'solid'; thus, developing the shear interface between the fluid regions.

This will be experimentally verified in the near future by reproducing Jaggi's experiment with the fluid used in this investigation.

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