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Characteristics of electrorheological fluids under single and mixed modes

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Abstract. This paper is concerned with an experimental assessment of the rheological performance of Electrorheological (ER) fluids when utilized under single and mixed modes of operation. The experimental facility, which incorporated a dedicated ER cell, was developed to enable the instantaneous measurement of the mechanical and electrical responses of the ER fluid. The ER cell comprises a cylinder, which provides the reservoir for the ER fluid, and a piston. The cylinder is subjected to an oscillatory sinusoidal motion while the piston is fixed. The current ER cell was designed to permit the ER fluid, which is sandwiched between its cylindrical and circular gaps, to be energized either separately or simultaneously to simulate the fluid operation under either a single shear or a single squeeze or a mixed shear and squeeze modes, respectively. The transient rheological characteristics of the fluid were determined for various mechanical and electrical input conditions, which were done using a combination of displacement, force, velocity and acceleration transducers. The results have shown that the force transmitted across the fluid in squeeze is greater than that transmitted when the fluid is in shear. However, the transmitted force level was further enhanced when the fluid was utilised under mixed shear and squeeze mode of operation. In addition, the implications of the results to vibration control, where the ER fluid is employed in an engine mount, are discussed.

Introduction

Electrorheological (ER) fluids involve suspensions of semiconducting solid particulates, typically micrometres in size, in dielectric liquids. Their response to an applied electric field is the familiar chaining of the particles in the direction of the field and the resulting 'solidification' or increase in their apparent viscosity. The fast and reversible field-induced rheological changes of ER fluids have presented them as a solution to advance the performance of many electromechanical devices that are potentially useful in the automotive, aerospace, structural, medical, and other industries. Since their discovery by Winslow [1] in the forties of last century, numerous investigations have been carried out in order to improve the mechanical, chemical and electrical characteristics of ER fluids and increase their potential for industrial applications [2-6]. Vibration control has been recognised as one of the most promising areas of industrial applications of ER fluids, which is due mainly to the fact that damping levels required by many vibration suppression applications fall within the capability of commercially available ER fluids [7]. There are, however, many other areas where the static yield stresses exhibited by these fluids have failed to meet industrial requirements [8].

The majority of ER fluids have been applied in either a simple shear or flow mode of operation [9-12]. Alternatively, a squeeze mode of operation, in which the fluid is subjected to oscillatory compression and subsequent tensile stresses (resulting in a variable fluid gap) was identified [13] and found to deliver a yield strength with an order of magnitude higher than that in shear mode [14]. As a result, systematic experimental, theoretical and numerical studies have been carried out by the author and others to evaluate the mechanical and electrical properties of ER fluids in squeeze, which have helped to provide design information on the application of ER fluids in the area of short-stroke damping (see for example [15-19]).

This paper is concerned with an experimental assessment of the comparative performance of an ER fluid in dynamic shear, squeeze and, mixed shear and squeeze modes, in which the fluid was energised by a constant electric field module. Also, the relevance of this work in the application to vibration control using a short-stroke damper is discussed.

Experimental Arrangement

The experimental rig (Figure 1) consists of a Ling Dynamic Systems electromagnetic shaker (Model No. V450) which is capable of providing vertical oscillatory motion with a maximum amplitude of 19 mm peak-peak (P-P) over a frequency in the range D.C to 7.5 kHz.

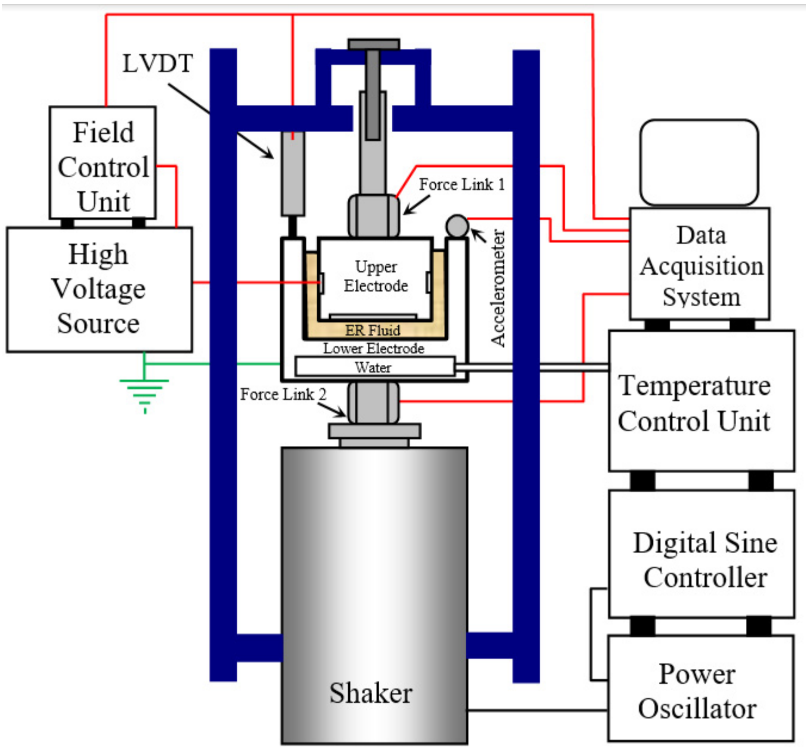

Figure 1. Experimental arrangement.

The shaker head is attached rigidly to a Kistler (Model No. 9311A) piezoelectric force link and an earthed brass electrode having a recessed cylindrical cavity of diameter 74 mm, which provides the reservoir for the ER fluid. The high voltage upper electrode consists of a circular brass disc and a circular brass cylinder of diameters 56 and 70 mm, respectively. The height of the latter electrode was chosen to be about 11 mm so that its exposed area is equivalent to that of the former electrode. The circumferential edge and rear face of both electrodes are surrounded and supported by a PTFE collar, Figure 2, which is rigidly attached to a second identical force link and positioning assembly to the supporting frame.

The instantaneous displacement and velocity of the lower electrode are measured using an RDP (Type GTX 2500) LVDT and an RDP (Type 240A0500) self-induced velocity sensor, respectively whilst its acceleration is measured using an Endevco (Type 7254-100) accelerometer. These three sensors are attached to the upper surface of the lower electrode. Electrical excitation of the ER fluid is achieved by means of a Trek (Model 664) high voltage amplifier, driven by a Thander (Model TG102) function generator.

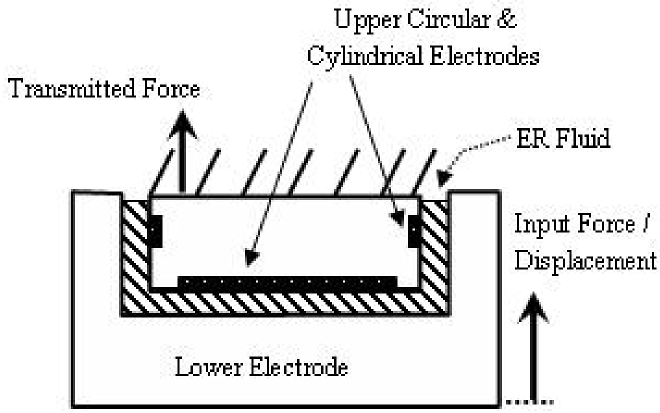

Figure 2. ER fluid cell.

In addition, a National Instruments analogue-to-digital converter, model NI9205 in conjunction with a cDAQ-9172 CompactDAQ USB chassis capable of simultaneous sampling, which was controlled by a National Instruments data acquisition software, type LabVIEW running on an IBM compatible personal computer, was used to collect and record the data from the sensors. Feedback control was not imposed in these tests although it could be achieved, if required, using a Ling Dynamic Systems (Model DSC4) digital sine controller employing as input the signal from the accelerometer. However, an electric field strength controller is used to control the electric field across the gap between the circular electrodes, which varies under the oscillatory motion input. This field controller uses the LVDT signal to determine the instantaneous gap and then control the Trek high-voltage output to maintain the required electric field strength across the fluid gap [20]. In order that meaningful comparisons could be made between the results of the various tests, the ER fluid temperature was controlled by re-circulating water through a closed cavity in the lower electrode using a Grant Instruments (Model LTD6) temperature controller.

Both force links were calibrated statically by sequential loading using small weights, while the LVDT was calibrated using a micrometre calibration unit that was specifically designed for the accurate calibration of LVDTs. The accelerometer, pre-calibrated by the manufacturer, was found to function as specified to within ± 0.6% when its maximum transverse sensitivity was checked using the digital sine controller. As an additional check, the displacement signal from the LVDT was differentiated twice using central differences and the resulting signal was found to compare well with that from the accelerometer. The data acquisition system was checked against a direct current signal supplied by a millivolt calibration unit (Time Electronics Ltd, Model 404S) and was found to be accurate to within ± 0.5%.

The ER fluid used in this investigation is a suspension of agglomerated calcium alumina silicate in silicone oil. The solid phase was supplied with an average diameter of 90 μm and was subsequently ground and sieved, using an Endecots Ltd laboratory test sieve system in conjunction with a Fritsch analysette (Type 03502) mechanical vibrator, to produce particulates in the range 10 to 28 μm. The electrical conductivity of the solid phase was measured in a dedicated cell and found to be 4.0×10^{-10} S/m. The kinematic viscosity of the oil at 20 ºC was 50 cSt and the weight fraction of the solid phase was chosen to be 57%. A 5% by weight stabiliser was added to the fluid to reduce the solid phase sedimentation.

Results and Discussion

The performance of ER fluids in dynamic shear, squeeze and mixed shear and squeeze modes was systematically assessed for a range of electrical and mechanical input conditions using a dedicated cell that simulates a short-stroke damper.

In this experimental investigation, simultaneous measurements of the input force delivered by the shaker, the transmitted force across the fluid, the applied voltage, and the current passing through the fluid, in addition to the displacement, velocity and acceleration of the cylinder were carried out. Using the employed data acquisition system, these measurements were collected at a sampling frequency of 5 kHz when the shaker was set to deliver sinusoidal input vibrations with mechanical frequencies in the range 2 to 18 Hz. The input displacement amplitude of the cylinder, for the electrically unstressed fluid, was chosen as 0.6 mm (P-P) at the resonant frequency of the system, which was found to be 7 Hz. The mean gap between the plane circular electrodes was set at 2.0 mm, which was also maintained in the gap between the cylindrical electrodes of the ER cell. In the adopted experimental set up of this investigation, the fluid was energised by a constant electric field in the range zero to 2.0 kV/mm whilst the fluid temperature was maintained at 30 °C throughout the tests.

For a mechanical frequency of 7 Hz, which is the resonant frequency of the system, the variation of the input displacement of the lower assembly of the ER cell is shown in Figure 3 for the three cases when the ER fluid was utilised under a single shear, single squeeze, and mixed shear and squeeze operation modes.

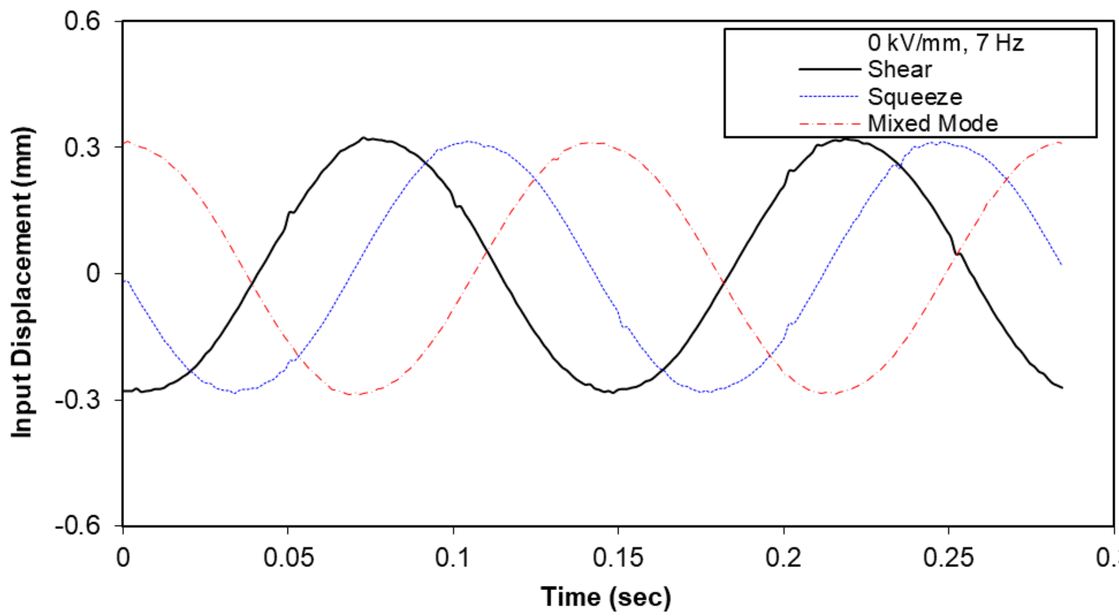

Figure 3. Variation of input displacement with time (mech Freq = 7 Hz; applied field = 0 kV/mm)

When a constant electric field of about 0.75 kV/mm was applied across the fluid (Figure 4), the zero-field displacement of the lower assembly of the ER cell was reduced by 25%, 42% and 79% when the fluid was utilized under shear, squeeze and mixed modes of operation, respectively.

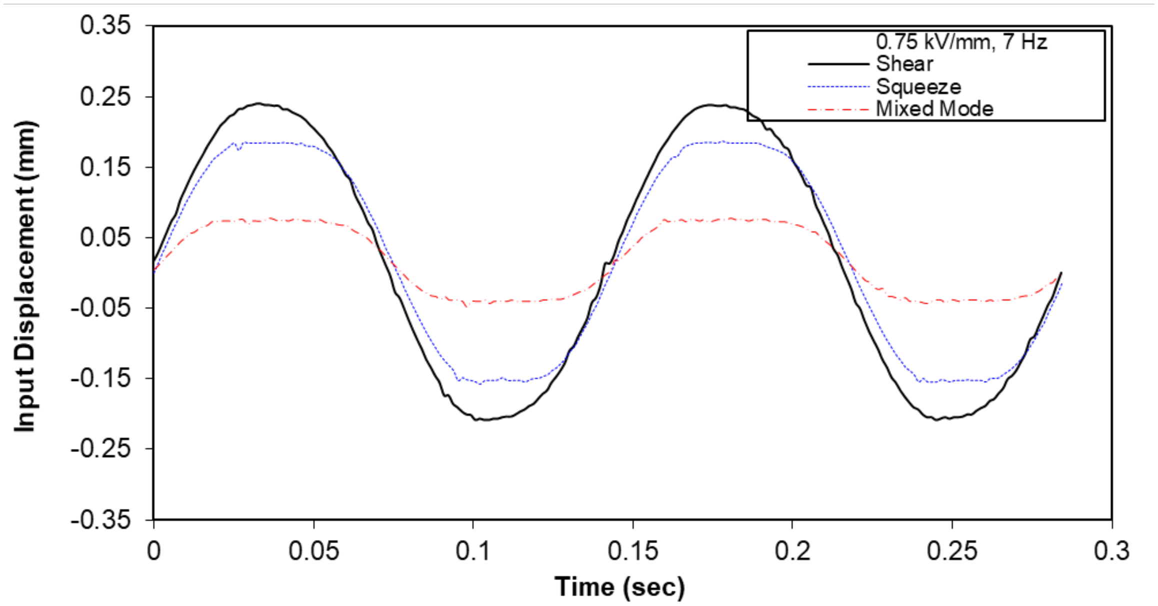

Figure 4. Variation of input displacement with time (mech freq = 7 Hz; applied field = 0.75 kV/mm)

Figure 5 shows the reduction in the input velocity of the lower assembly of the ER cell when a constant field of about 0.75 kV/mm was applied across the ER fluid. It can be seen that the largest reduction in the input velocity was achieved when the fluid was utilised in a mixed shear and squeeze mode, indicating that the ER effect is larger with this mode of operation in comparison with the cases when the fluid was employed under single modes.

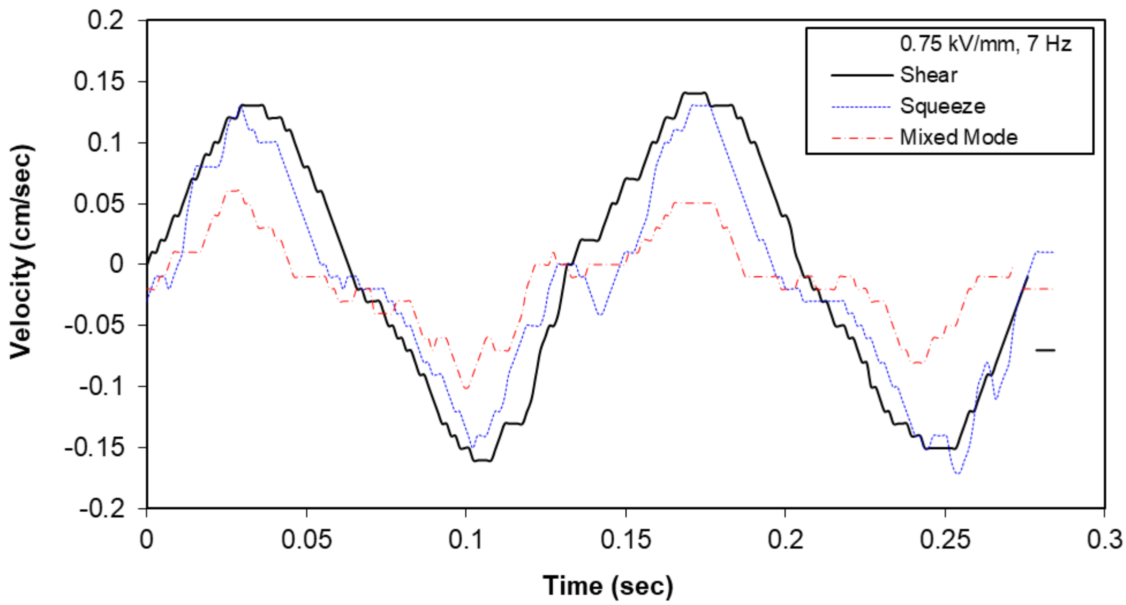

Figure 5. Variation of input velocity with time (mech freq = 7 Hz; applied field = 0.75 kV/mm)

The variations of the transmitted force across the ER fluid under a mechanical frequency of 7 Hz and electrical excitation of 0.75 kV/mm is shown in Figure 6. It can be seen that the fluid utilised under the mixed mode produced a P-P transmitted force in excess of 15 N, which was about 47% and 64% greater than the forces that were caused under the squeeze and shear modes, respectively.

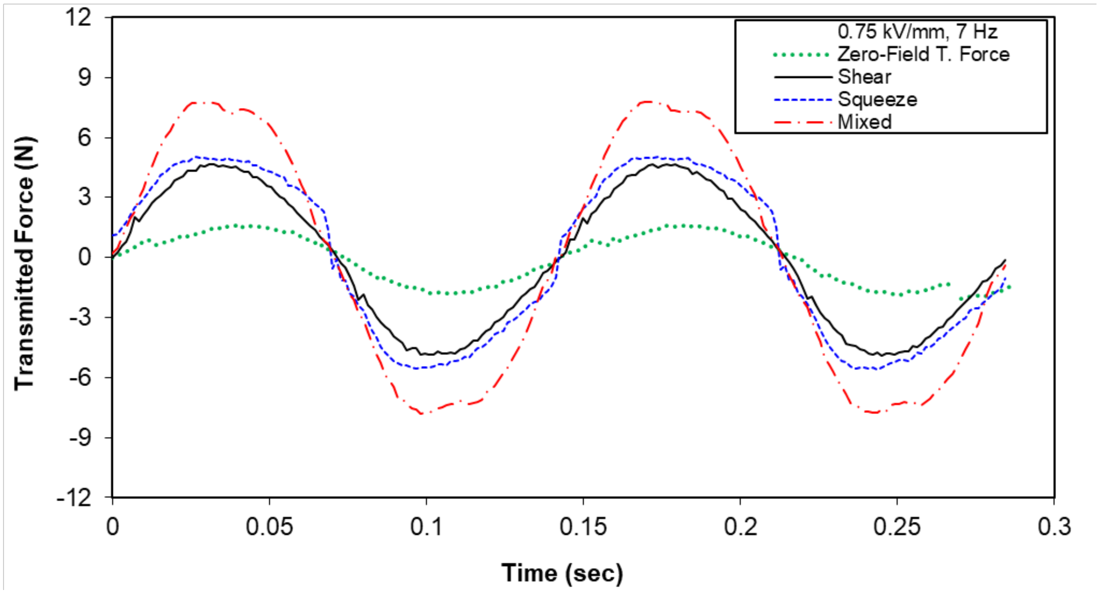

Figure 6. Variation of transmitted force with time (mech freq = 7 Hz; applied field = 0.75 kV/mm)

The zero-field transmitted force is also shown in this figure, which is caused mainly by the viscous effect of the fluid.

A comparative assessment of the performance of the ER fluid under the shear mode of operation is shown in Figure 7 where the variation of the transmitted force with input displacement is presented for a range of electrical field strengths, namely between 0 and 1.5 kV/mm.

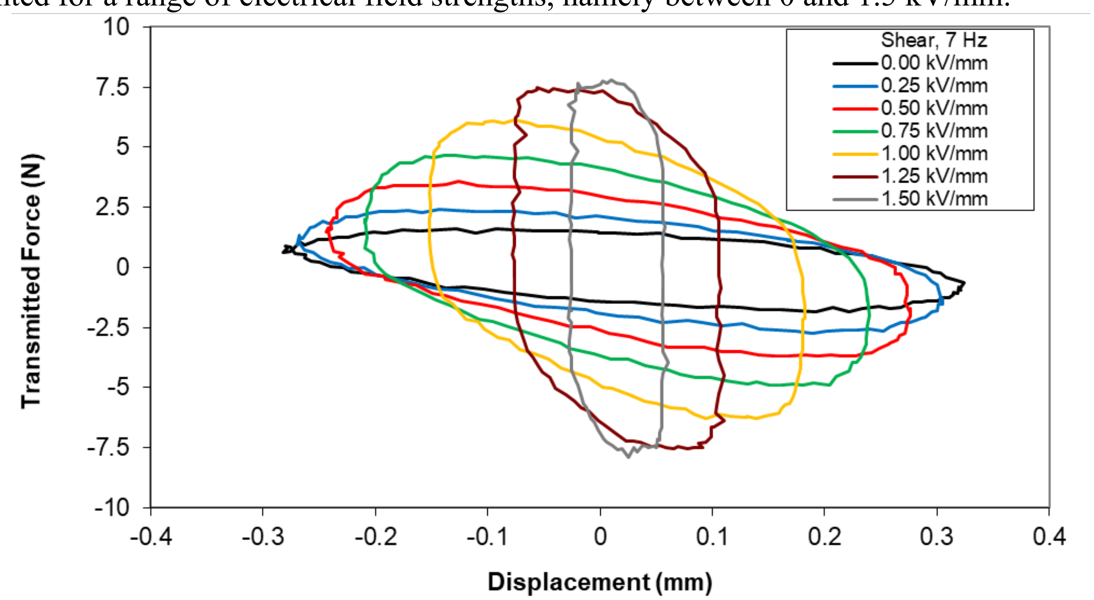

Figure 7. Transmitted force versus displacement for the ER fluid under shear mode

In this figure, the shape of the individual curves, which represent one cycle of the vibration delivered by the shaker, are likely to be influenced by the inherent nonlinearity of ER fluids, which were also shown by other smart fluids when utilised under similar conditions as part of their short-stroke damping applications [21].

For the fluid utilised in the shear mode and under the same above applied conditions, the variation of the transmitted force with the input velocity is shown in Figure 8. It should be noted that for clarity, data for some of the applied electric fields were removed from this figure, but the retained curves should clearly show the effect of increasing the electric field strength on the behaviour of the ER cell. In particular, the results confirm that as the electric field is increased, the fluid transmits higher forces, which is attributed to the fact that the fluid develops higher yield stresses with increasing field strength.

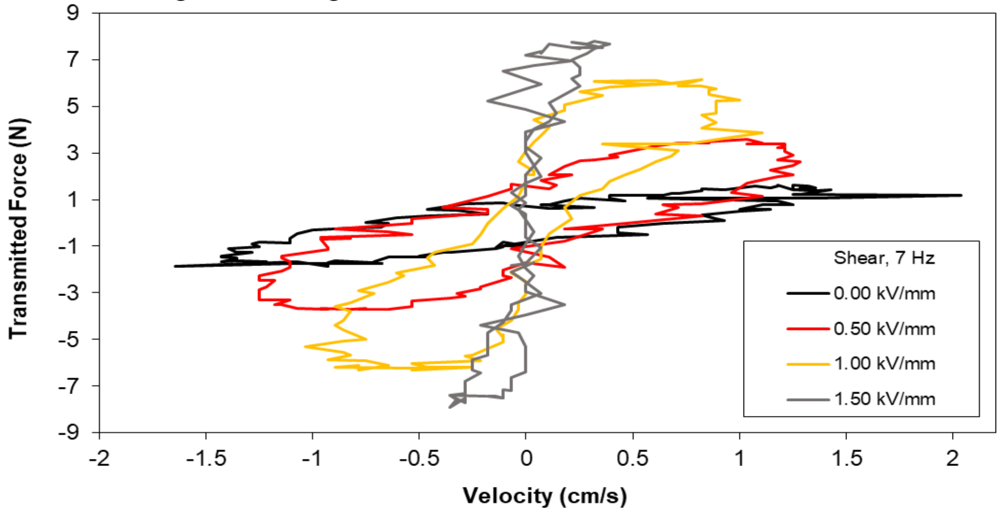

Figure 8. Transmitted force versus velocity for the ER fluid under shear mode

It is worth mentioning that the same trend in the results was found when the ER fluid was employed under the squeeze mode. However, the results have shown that the best fluid performance was again obtained under the mixed shear and squeeze mode operation, which can be seen in Figures 9 and 10 where the variations of the transmitted force was plotted against the input displacement and velocity, respectively for a range of applied electric field strengths between zero and 0.75 kV/mm.

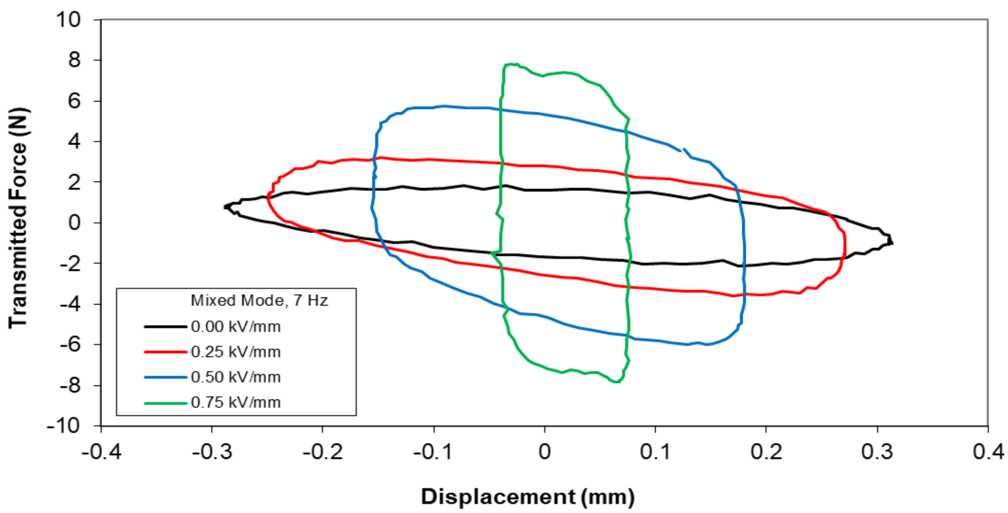

Figure 9. Transmitted force versus displacement for the ER fluid under mixed mode

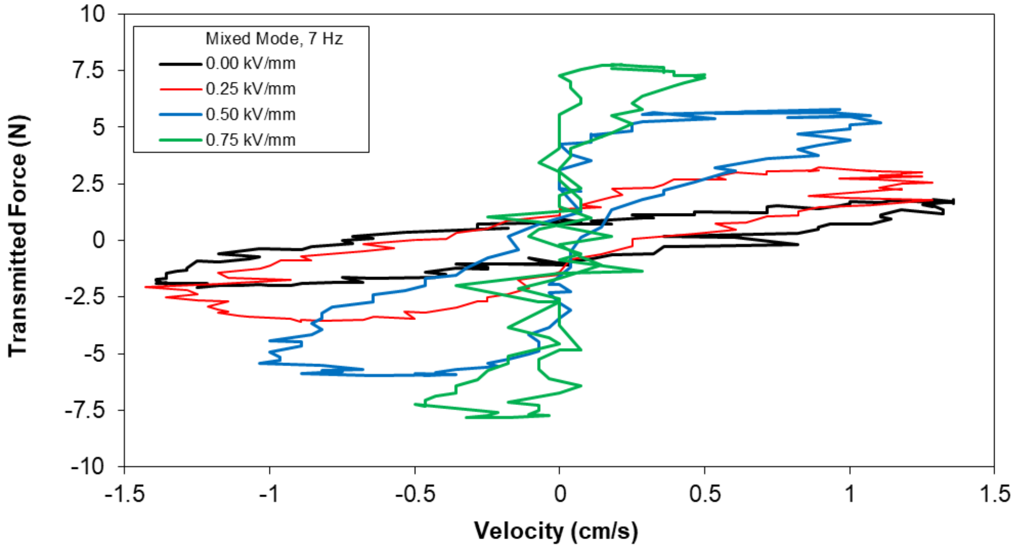

Figure 10. Transmitted force versus velocity for the ER fluid under mixed mode

It is clear that under the mixed mode of operation, the fluid exhibits solid-body characteristics when the fluid is subjected to high electric field excitations, which caused the shaker motion to be almost arrested. The electric field magnitude that produced such performance was found to be lower than those caused similar rheological properties under the single squeeze or single shear modes.

Conclusions

This paper is concerned with an investigation of the comparative performance of electrorheological (ER) fluids, applied in a specially designed short-stroke vibration isolation cell, under dynamic shear, squeeze and mixed shear and squeeze modes. The results have confirmed that the best fluid performance was achieved under the mixed shear and squeeze mode, since the transmitted force was higher than that developed by the fluids in a single shear or squeeze modes. This was also evident, when the fluid employed under the mixed mode operation caused the largest reduction in the zero-field displacement of the lower assembly of the ER cell, which was about 79% in comparison with 25% and 42% that were achieved with the shear and squeeze fluid operation, respectively.

The mixed mode of operation of ER fluids with its enhanced damping characteristics is to be investigated further with the aim to develop a smart device that is capable of the reduction of transient disturbances in short-stroke vibration isolation over a range of operating conditions within which an automotive engine mount is likely to operate.

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