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Internal Organizational Measurement for Control of Magnetorheological Fluid Properties

Magnetorheological (MR) fluids change their physical properties when subjected to a magnetic field. As this change occurs, the specific values of the physical properties are a function of the fluid's time-varying organization state. This results in a nonlinear, hysteretic, time-varying fluid property response to direct magnetic field excitation. Permeability, resistivity and permittivity changes of MR fluid were investigated and their suitability to indicate the organizational state of the fluid, and thus other transport properties, was determined. High sensitivity of permittivity and resistivity to particle organization and applied field was studied experimentally. The measurable effect of these material properties can be used to implement an MR fluid state sensor. [DOI: 10.1115/1.2436588]

Introduction

Magnetorheological (MR) fluids, are part of a class of controllable fluids. MR fluids are suspensions of micron-sized magnetic particles dispersed in a fluid carrier such as a mineral or silicon oil. In these fluids physical properties of the fluid such as rheological and thermal transport properties can be changed reversibly, through the application of an externally applied magnetic field [1–3].

The property changes of MR fluids result from alignment of micron sized iron/magnetic particles into long columns within the fluid along the lines of the magnetic field in response to an application of a magnetic field. The stronger the field the greater the effect on the properties of the MR fluid such as viscosity. Current commercial applications of MR fluids include controllable damping elements using the variable rheology of these fluids [4], jet finishing of ultra smooth surfaces [5], and in torque transfer devices [6].

The physical properties of an MR fluid change as a nonlinear time-varying function of applied field driven particle alignment with the typical hysteresis of magnetic materials. The external magnetic field applied to the MR fluid causes changes in all physical properties of the fluid, e.g. electrical conductivity, thermal conductivity [2,3], permeability [7], as well as viscosity [1]. If the MR fluid response can be sensed electrically, then changes in physical properties can be precisely controlled. This strategy has been followed by the authors for Electrorheological fluids in 1996 [8,9],

Winslow [10] is generally credited as the first person to recognize the potential of controllable fluids in the 1940s. The first electrorheological (ER) fluids patent paper describing the ER effect. MR fluid discovery can be credited to Jacob Rabinow [11,12] at the US National Bureau of Standards. Interestingly, this work was almost concurrent with Winslow‘s ER fluid work. The late 1940s and early 1950s actually saw more patents and publications relating to MR fluids than to ER fluids. While Rabinow's work is largely overlooked today, Winslow discussed the work on MR fluids going on at the National Bureau of Standards in his seminal paper on ER fluids [10].

The transient and steady-state behavior of MR fluids has been investigated extensively. Fluid viscosity is very sensitive to changes on external magnetic fields [13–15]. Viscosity dependence on particle concentration, particle shape, size, and material in combination with several carrier fluids have been evaluated. Because MR fluid viscosity changes are large, most applications exploit these changes to produce various designs of controllable damping or torque conversion devices [4,6].

Control of the viscosity in current MR devices is performed by direct excitation of the external magnetic field. The nonlinear, hysteretic, time-varying response of the fluid is an obstacle to precision viscosity control despite the fast response time. Controlling the external magnetic field yields a fast but imprecise response of the fluid. To design for high-speed precise control, a more sophisticated strategy for the control of the fluid response is required.

The MR fluid organizational state is the level of geometrical organization of particles in the fluid. The magnetorheological effect was demonstrated in the view of an optical microscope with a low concentration (3% estimated). MR fluid suspension under a magnetic field applied from 0 kA/m to 40 kA/m was observed. The nonenergized state of the fluid (Fig. 1(*a*)), shows a random orientation and positioning of particles. When energized with a magnetic field, H, the MR fluid shows particle organization patterns parallel to the flux lines of the magnetic field (Figs. 1(*b*)–1(*f*)). The particle organizational state of the fluid is indicative of the induced interparticle magnetic forces generated by the applied magnetic field. An important fact is that for MR fluids, the ability to physically observe the chaining process is reserved only for low concentrations of particles, which we do. To date, no experiments have been devised to directly observe chaining of MR fluids when high particle concentrations are present. We will therefore relate our work directly to low concentration applications, but direct observation towards what is expected at high concentrations based on our experiences with ER controllable fluids.

The physical properties of the fluid are functions of the particle organizational state of the fluid, physical properties of the particles, and the magnetically induced forces between them. Conceptually, the particle organizational state, x, of the MR fluid combined with the applied field input, B, governs the time rate of change of organizational state, dx/dt, of the particles in the fluid. The resulting combination of organizational state and applied field then governs all of physical property values, y

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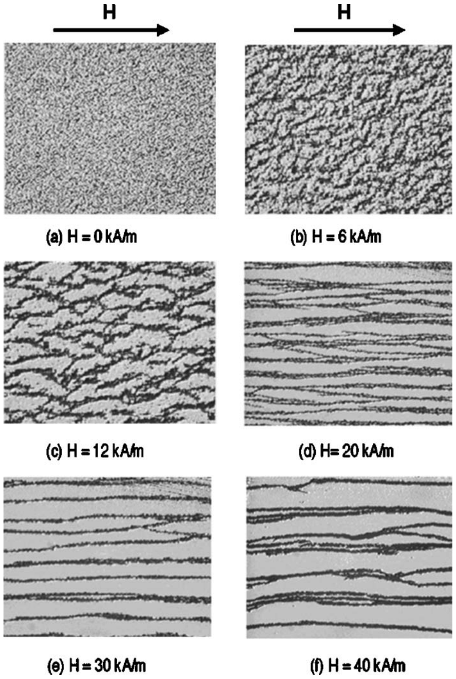

(a) H = 0 kA/m (b) H = 6 kA/m (c) H = 12 kA/m (d) H = 20 kA/m (e) H = 30 kA/m (f) H = 40 kA/m

Fig. 1 Visualization of particle organization of a magnetorheological fluid as a function of applied magnetic field strength, *H*

$$\dot{x} = f(x,B)$$
$$y = g(x,B) \tag{1}$$

A measurable effect representative of the state of the fluid must be identified to implement a sensor of particle organizational state. The state descriptor property should be sensitive to changes in internal particle organizational state and easy to implement in real devices. Sensitivity of three magnetoelectric properties: resistance, inductance, and capacitance will be tested and their suitability for use in describing other properties will be evaluated.

Experimental Apparatus

Three properties that react to the external field were considered for evaluation in the present study: inductance, capacitance, and resistance. The first property studied was the inductance because it would give the possibility of using the same electric circuit that generates the field, thus avoiding the need for an additional secondary circuit. Capacitance and resistance of a secondary circuit connecting the MR fluid in series was used to test their response to changes in applied field.

The device used to generate the magnetic field for all experiments was a magnetic core with a MR fluid gap (Fig. 2). The magnetic core was made of laminated ferromagnetic material and had a reduced cross section at the MR fluid gap to concentrate the field. The fluid was located in thin wall plastic reservoirs to perform static fluid measurements. A plastic duct was located through the gap to carry out measurements with MR fluid flow. A dc powered positive displacement pump was used to pump the MR fluid. A dc voltage was applied to the winding to generate the external magnetic field. The MR fluid used on all the experiments was the VersaFlow MRX-135CD manufactured by Lord Corporation. The MR fluid was mechanically mixed before every experiment to ensure homogeneity.

Inductance Testing

To measure magnetic permeability, μ, the inductance change in the drive circuit was evaluated as a function of magnetic field strength. The inductance of a magnetic circuit is a function of the permeability of the materials that make up the magnetic circuit, the number of turns of the winding and of the geometric characteristics of each part of the core. The magnetic circuit includes the ferromagnetic core and the MR fluid gap. Ohm's law for magnetic circuit provides a formula for the total magnetic circuit inductance

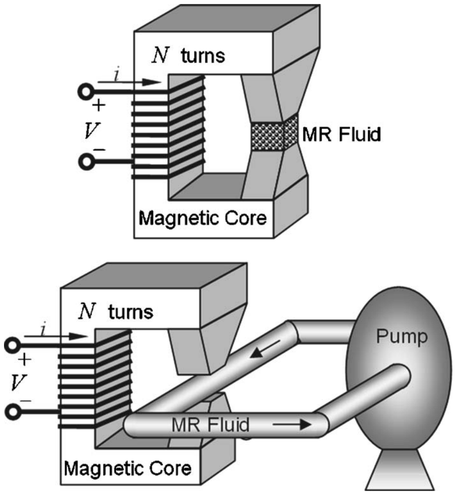

Fig. 2 MR fluid experimental facilities for measurements of properties in static and moving fluids

$$L = \frac{N^2}{\dfrac{l_1}{\mu_c \cdot A_1} + \dfrac{l_2}{\mu_c \cdot A_2} + \cdots + \dfrac{l_{n-1}}{\mu_c \cdot A_{n-1}} + \dfrac{l_{\mathrm{MR}}}{\mu_{\mathrm{MR}} \cdot A_{\mathrm{MR}}}} \tag{2}$$

For constant geometric parameters and number of turns, the inductance is a function of the permeability only. If the permeability of the MR fluid, μ_{MR}, is sensitive to changes in particle organization state, a measurable change in inductance would indicate a change in the state of the fluid, and a measure of the organizational state of the fluid.

The electromagnetic circuit works as both an actuator and as a sensor in the above system. The complete circuit includes the winding (inductance and resistance) and a known resistance resistor (Fig. 3). A small ac voltage is superimposed on the dc voltage.

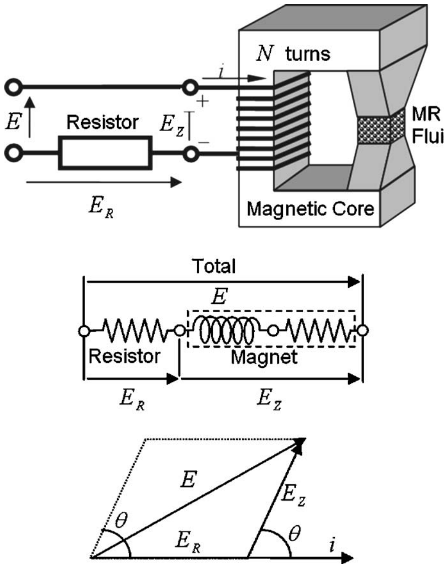

Fig. 3 Schematic diagram of the three voltmeter method to compute inductance: experimental system, equivalent circuit diagram, and vector diagram

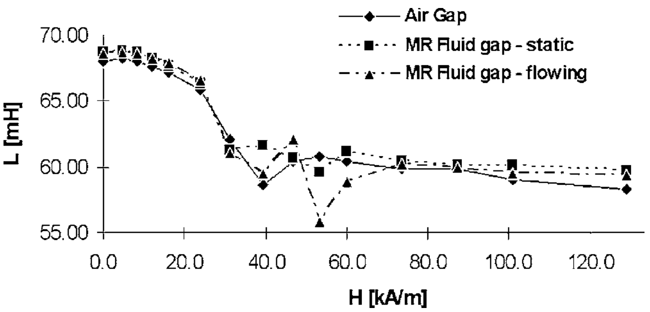

Fig. 4 Initial measured inductance versus applied field results showing an external, indirect, sensor yields small measured changes in inductance

This small ac voltage was used only to sense the impedance of the electrical signal, and it was kept small enough to have discernible effect on the fluid state. The measurement method used to measure inductance was the three voltmeter method applied to the ac component amplitudes [16]. A typical result is the relationship for inductance

$$L = \frac{R_1 \cdot E_Z \cdot \cos\theta}{E_R \cdot 2 \cdot \pi \cdot f} \tag{3}$$

where

$$\cos\theta = \frac{E^2 - E_R^2 - E_Z^2}{2E_R E_Z}$$

This method (Fig. 3) uses three ac amplitudes to compute inductance L, capacitance C, and/or resistance R accurately because it does not require a difficult direct measurement of phase angle θ.

A LabVIEW program was written to acquire the ac measurements required to compute inductance. A Wavetek 12 MHz synthesized function generator and an HP bipolar power supply–amplifier were used to generate the input voltage. Two Hewlett Packard 3478As and one Keithey 175 Multimeter were used to acquire the voltage measurements. All instruments were connected to the computer by general purpose interface bus (GPIB) connections.

Steady-state inductance measurements were taken with the gap filled with MR fluid. The dc voltage was increased from 0 to 20 V to generate magnetic dc fields that ranged from 0 to 128 kA/m. A 100 Hz ac voltage frequency was applied and the amplitude of the source was kept constant at 0.25 V. This ac amplitude represented only 1.25% of the full scale dc applied field. This measurement methodology used small ac field only to monitor changes in inductance as large variations in the dc field resulted in changes in magnetorheological state.

Inductance measurements were performed with the gap occupied by the static MR fluid, the flowing MR fluid, and air only (Fig. 4). The total measured value of inductance is dominated by the inductance of the ferromagnetic core itself, which showed a typical saturation curve. The data revealed a 16.7%, 15.0%, and 15.6% decrease in inductance for the air gap, static MR fluid gap, and flowing MR fluid, respectively, over the entire change of magnetic field. The measurements for low field regions (0–30 kA/m) were stable and repeatable. The higher field region (>30 kA/m) produced unstable results. The difference associated with the fluid state in the core's gap represented only a 16.7%–15.6%=1.9% change in measured inductance due to MR fluid particle chain formation. This small change in inductance indicates that magnetic permeability is not a strong candidate for organizational state sensing. The results below were obtained with a more direct method that demonstrated higher sensitivity to applied field.

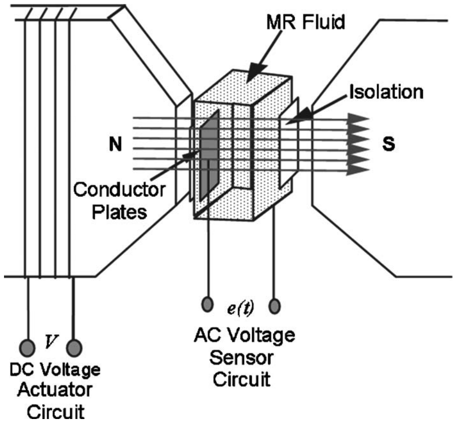

Fig. 5 Schematic diagram of experimental facility for capacitance and resistance measurements

Capacitance and Resistance Testing

The MR fluid properties of permittivity, ε, and resistivity, ρ, were evaluated simultaneously as candidates for state sensor effectiveness using the same laboratory test system (Fig. 5). Permitivity and resistivity change of the MR fluid as a function of a magnetic field was evaluated between two parallel conductor plates applied directly to the fluid in the MR fluid gap. The plates and MR fluid formed a parallel plate resistor/capacitor.

Steady state permittivity, ε, change affects capacitance of a secondary circuit as a function of the magnetic field strength. The capacitance values for a parallel plates capacitor is a function of the area of the conductors, the distance between them, and the permittivity of the material filling that space. Capacitance changes for constant geometry are functions of the permittivity, ε, of the material only

$$C = \frac{\varepsilon * A}{d} \tag{4}$$

The resistance value between the plates is a function of the area of the plates, the distance between plates, and the resistivity of the MR fluid between the plates

$$R = \rho \cdot \frac{d}{A} \tag{5}$$

Two electrical circuits (Fig. 6) were used to perform these measurements: the actuator circuit and the sensor circuit. The actuator circuit was an HP power supply that produced a dc actuation field. A Wavetek function generator and another HP power supply/amplifier generated the ac actuation fields. The sensor circuit connected the two parallel plates located in the MR fluid with a constant separation between them. The sensor circuit was connected to a Fluke RCL meter used to measure series and parallel equivalent capacitance and resistance. The Fluke RCL meter applied a

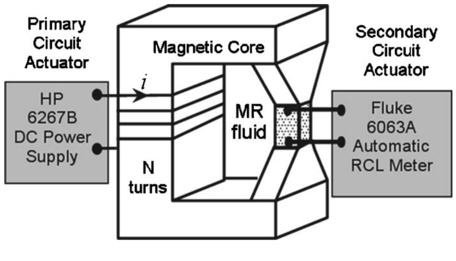

Fig. 6 Schematic diagram of equipment setup for MR fluid capacitance and resistance measurements

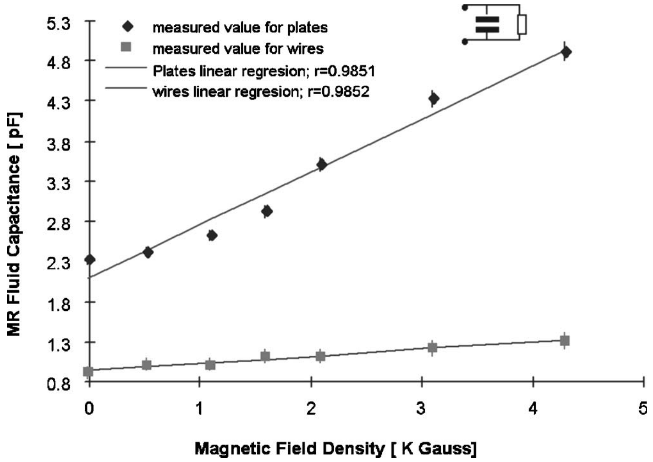

Fig. 7 Measurements of parallel equivalent capacitance of the MR fluid as a function of applied field

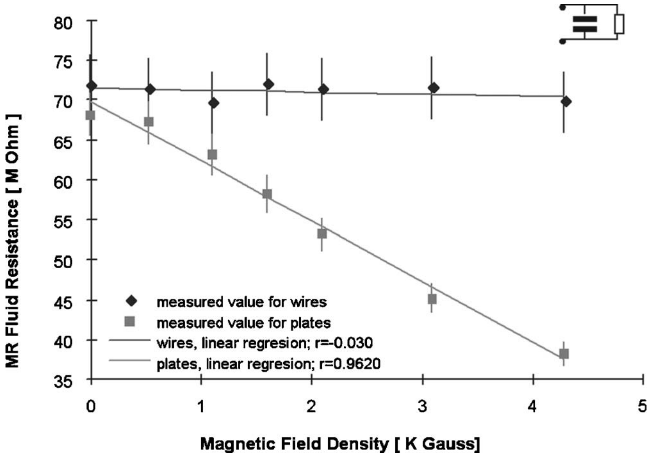

Fig. 9 Measurements of parallel equivalent resistance of the MR fluid as a function of applied magnetic field

small ac field to the secondary circuit and used this ac circuit to measure changes in capacitance and resistance across the plates.

Capacitance Measurements

As stated previously measurements were taken with the plates inside the MR fluid. The plates were carefully positioned parallel to each other and perpendicular to the field lines. 20 mm plates and 28 gage wires were tested. Using a parallel equivalent capacitance model, measurements (Fig. 7), showed an increase of 44.4% and 113% for a total increase of 340 kA/m of the applied field for the wires and plates, respectively. A correlation factor of 0.9852 and 0.9851 for a linear regression analysis belong to the two corresponding sets of data although the plate data show a saturation curve trend. Using a series equivalent capacitance model, measurements (Fig. 8) showed no change in capacitance for the wire capacitor and a 28.2% increment for the plate capacitor. Linear regression on these showed 0.030 and 0.9620 correlation factors, respectively. It should be noted that in this work correlation factors are employed to provide information on both repeatability and reproducibility. As expected, the larger cross sectional area made plate capacitance measurements more sensitive to changes in magnetorheological fluid response.

Resistance Measurements

Measurements using a parallel equivalent resistance model for the MR fluid with the plates placed along the magnetic field (Fig. 9), showed a 1.4% resistance decline between 28 AWG wires and a 44.1% resistance decrease between 20 mm plates over the 340 kA/m variation on the applied magnetic field. Correlation factors of 0.381 and 0.993 were computed for the linear regression of both sets of data, respectively. Measurements using a series equivalent resistance model (Fig. 10) showed a 17.2% decrease between 28 AWG wires and a 40.5% decrease between the 20 mm plates over the 340 kA/m increase of the applied field. Correlation factors of 0.995 and 0.992 were computed for the linear regression of both sets of data, respectively.

Resistance measurements with the plates placed across the field showed no change over the a 340 kA/m increase in the applied field in either parallel or series equivalent circuits. Capacitance with the plates across the field showed no change for a parallel equivalent measurement and showed a 2.8% increase over the 340 kA/m change on the applied field for a series equivalent measurement. These measurements demonstrate the ability to measure the directional orientation of field induced internal structure and hence the directionality of the internal organization state of MR fluids.

Sensitivity of Inductance, Resistance, and Capacitance

Sensitivity of the three measured electric properties as a function of the applied field was investigated. Sensitivity was com-

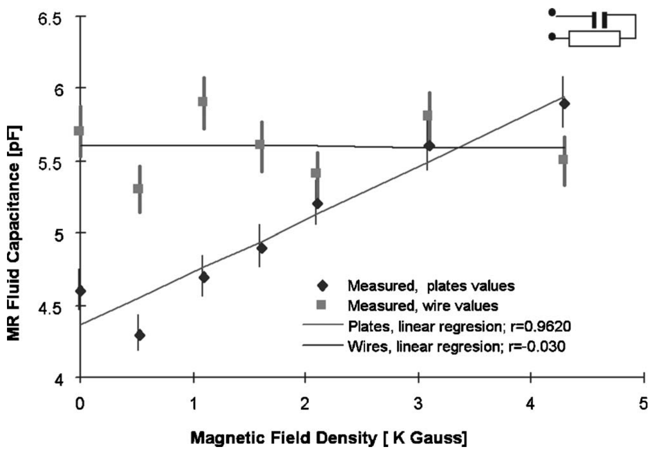

Fig. 8 Measurements of series equivalent capacitance of the MR fluid as a function of applied field

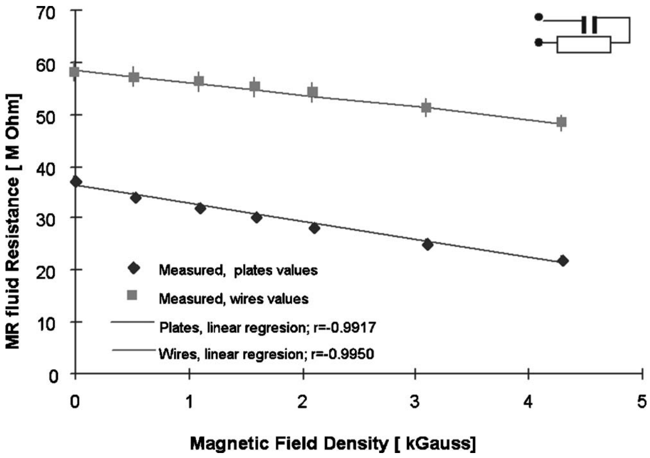

Fig. 10 Measurements of series equivalent resistance of the MR fluid as a function of applied magnetic field

Table 1 Sensitivity of magnetic and electric properties of the MR fluids to strength of applied magnetic fields

Property	Range	Applied field H (kA/m)	Sensitivity S_H^*	Correlation
Inductance (mH)	4.84–4.88	0–30	0.004	0.953
Relative permeability	31.5–31.8			
Resistance (M Ω)	37–22	0–340	−0.254	0.992
Resistivity (kΩ m)	148–88			
Capacitance (pF)	2.3–4.9	0–340	0.361	0.985
Relative permittivity	65–139			

puted as the ratio of the total increment of every one of these properties over its average value to the total variation in applied field over its average value

$$S_H^Q = \frac{(Q_2 - Q_1)\cdot(H_2 + H_1)}{(H_2 - H_1)\cdot(Q_2 + Q_1)} \tag{6}$$

The measured sensitivity for inductance measurements showed the lowest sensitivity to applied field, $S_H^L=0.004$ (Table 1). The MR fluid resistance connected in series showed sensitivity to applied field, $S_H^R=-0.2542$. The sensitivity of the capacitance to applied field, $S_H^C=0.361$, was the highest. Although the highest correlation factor for a linear regression analysis of all sets of data belongs to the resistance, the repeatability of the measurements is demonstrated by the correlation factors above 0.95 for all measurements in the table.

Permeability, permittivity, and resistivity are the material properties sensed by the inductance, resistance, and capacitance changes, respectively. These changing properties reflect changes in the particle state organization. Using inductance measurements, the computed relative permeability increased from 31.5 to 31.76. Using resistance measurements, the resistivity was larger and decreased from 148 kΩ m to 88 kΩ m. Using capacitance measurements, the relative permittivity was the largest and increased from 65 to 138.

Conclusions and Recommendations

Sensitivity of inductance, resistance, and capacitance of a VersaFlow MRX–153CD MR fluid to changes in magnetic field was investigated in order to determine their suitability for use as an MR fluid state sensor. Changes in inductance, resistance, and capacitance reflect associated changes in the material properties: permeability, resistivity, and permittivity. Sensitivities to field variation for these properties were demonstrated for fields up to 340 kA/m. Large dc magnetic fields were applied to excite changes in magnetorheological fluid properties while small ac magnetic fields were used to sense the changes in the electrical properties of the fluid. The Inductance of the MR fluid core under magnetic fields in the range of 0–30 kA/m showed a very low sensitivity of $S_H^I=0.004$ Unstable and unpredictable inductance values were obtained for higher fields. These results indicated that inductance is a poor candidate for a magnetorheological state sensor.

Resistance and capacitance measurements showed a stronger sensitivity to applied field. Resistance sensitivity was of $S_H^R=-0.254$. Capacitance showed highest sensitivity of $S_H^C=0.361$. The applied field ranged from 0 to 340 kA/m for capacitance and resistance measurements. The relative magnitudes of these measured changes (Fig. 11) demonstrate that permittivity is most strongly affected by particle organization and is the most likely candidate for a state sensor, followed closely by resistivity.

Inductive sensing is not attractive because inductance change has a small sensitivity to both internal particle organization and low applied fields. Under higher fields unstable measurements were obtained. Real MR fluid devices will always have an electromagnetic circuit with a very small MR fluid gap. Because of this geometry, the total inductance measured will be dominated by the inductance of the non-MR fluid portion of the electromagnetic circuit, i.e., the ferromagnetic core, making changes in MR fluid permeability even more difficult to detect.

Resistance and capacitance sensor circuits are highly sensitive to both applied magnetic field and particle organization, and provide an accurate measure of MR fluid internal state. Parallel conductor plates placed normal to field lines gave the most predictable signal and had the highest sensitivity. Resistance and capacitance sensors have a big advantage over traditional shear rate sensing used to compute viscosity where fluid movement is required because they provide accurate measures of particle organization state for both static and moving fluid. The correlation factors found over a large number of independent measurements (Table 1) varied between 0.953 and 0.992 indicating the reproducibility and repeatability of the measurements.

As has been demonstrated in many studies of controllable fluids, most notably ER fluids (e.g., Refs. [14,17]), the organizational state of the controllable fluid is directly related to physical transport properties. While viscosity is the most observed transport property, thermal conductivity is also significantly controlled by the organizational state. It is not unreasonable to expect the same general behavior of non-Newtonian behavior in viscosity and a strong increase in thermal conductivity resulting from an increase in particle chaining or organizational state. The yield stress in the viscosity measured by many does not reveal any significant change in the properties directly measured in this study. This suggests that the transport properties such as thermal conductivity exhibit a similar smoothness or change in property as a result of flow. Thus, the present study suggests the need for confirming experiments to confirm this, no matter how difficult the experiment may be.

In concluding, it is important to discuss application of the

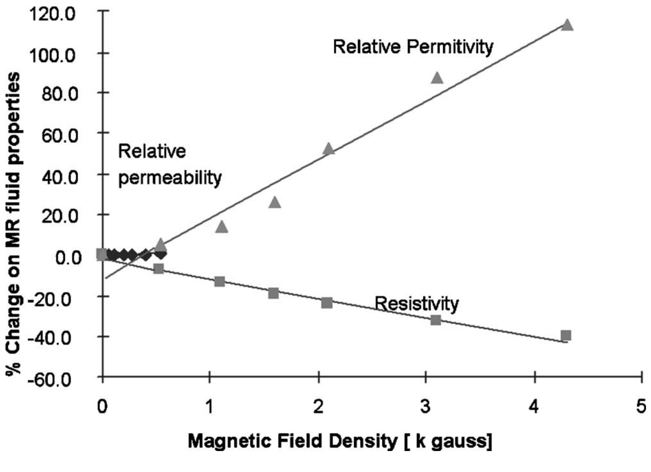

Fig. 11 Relative property changes in permeability, permittivity, and resistivity of the MR fluid as a function of applied magnetic field

knowledge presented in this paper. MR fluids have found an important market in fluid clutches for automotive and sports equipment applications. In automotive applications especially, where the clutches operate at 4000 rpm or more, the application of a strong magnetic field across the plates of the clutch creates the chain structures, and the apparent "viscosity" of the MR fluid increases until it effectively becomes a solid link with no slippage. There is a very high yield stress for the non-Newtonian fluid at this state. As a result of the "viscous" work done on the fluid in the clutch, the temperature of the fluid reaches very high values. This energy must be transferred from the clutch if it is to continue effective operation. The fact that the chains have formed also increases the effective thermal conductivity of the clutch fluid several times its nonstructured value, and the energy is transported away from the clutch gap more effectively. Without the increase in effective thermal conductivity resulting from the chaining of the magnetic particles, the magnetic fluid clutch would not be successful. The knowledge provided in this paper provides effective, direct methods for measurement of MR fluid chaining state allowing accurate electrical measurement of the fluid properties resulting from the formation of those particle chains.

Nomenclature

x = particle state
S_H^Q = sensitivity of Q with respect to H
μ = magnetic permeability (H/m)
θ = phase angle (deg)
ε = permitivity (F/m)
ρ = resistivity (MΩ m)
A = cross section (m^2)
B = magnetic field density (G)
C = capacitance (F)
d = distance (m)
E = system potential amplitude (V)
E_r = potential amplitude across the resistor (V)
E_z = potential amplitude across the magnet (V)
f = frequency (Hz)
H = magnetic field strength (kA/m)
L = inductance (mH)
l = length (m)
N = number of turns on the winding
R = resistance (Ω)

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