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Internal Organizational State Sensing for
Magnetorheological Fluids

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Miguel Omar Hayes Michel

has been accepted towards fulfillment
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~~M.S.~~ degree in ~~Mechanical~~ Engineering

Clark Radcliffe
Major professor

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INTERNAL ORGANIZATIONAL STATE SENSING FOR MAGNETORHEOLOGICAL FLUIDS

By

Miguel Omar Hayes Michel

A THESIS

Submitted to
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ABSTRACT

SENSING OF INTERNAL ORGANIZATIONAL STATE OF MAGNETORHEOLOGICAL FLUIDS

By

Miguel Omar Hayes Michel

Physical properties of MR fluids respond a non-linear, hysteretic, time-varying function to direct magnetic field excitation. Physical properties of MR fluids are a function of suspended particle organization. Precise MR fluid response requires control of the particle organizational state of the fluid through the applied magnetic field. A reliable sensor of the state of the fluid is needed to implement precise MR fluid response.

Permeability, resistivity and permitivity changes of MR fluid were investigated and their suitability to indicate the organizational state of the fluid was determined. High sensitivity of permitivity and resistivity to particle organization and applied field was proved experimentally. The measurable effect of these material properties, capacitance and resistance, can be used to implement a MR fluid state sensor.

To Miguel and Karim

ACKNOWLEDGMENTS

The most sincere thanks to Dr. Clark Radcliffe for given me the opportunity to get into the research world. Tanks to Dr. Clark Radcliffe, again, and Dr. John Lloyd for awarding me with a Research Assistantship to accomplish this theses. Thanks to Charles Birdsong and Brooks Byam, graduates students and Dynamics System Laboratory administrators, for their help and friendship. Thanks to Kara Mc Gregor, Yinxue Su on the cotrollable fluids research group. And special thanks to Yinxue Su, Yihong Zhang, Jae-Man Cho, Chirs House and Polarit Apiwatlanalunggarm for their support and friendship through this two years.

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NOMENCLATURE

$\underset{\sim}{x}$	State variable vector
S_H^Q	Sensitivity of Q respect to H
μ	magnetic permeability [H/m]
θ	Phase angle [°]
ε	permitivity [F/m]
ρ	resistivity [M Ω - m]
A	Cross section [m^2]
B	Magnetic field density [Gauss]
C	Capacitance [F]
d	distance [m]
E	Alternate voltage amplitude [V]
Er	Alternate voltage amplitude across the resistor [V]
Ez	Alternate voltage amplitude across the inductor [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]
R1	constant resistance (1Ω)
u	general input
y	general response

INTRODUCTION

Magnetorheological (MR) fluids, are often called intelligent or smart fluids, because the rheology of this fluids can be changed reversibly, by applying an external magnetic field. An MR fluid is a suspension of micron-sized magnetic particles dispersed in a fluid carrier such as a mineral / silicon oil or an aqueous solution. A broad range of possible applications that would use the rheology property of this fluid to enhance devices performance is the reason for the increasing research interest in these fluids.

The physical properties of an MR fluid change as a non-linear time-varying function of applied field. MR fluids also show the typical hysteretic behavior of magnetic materials. The external magnetic field applied to the MR fluid causes changes of physical properties of the fluid, e.g. electrical conductivity, thermal conductivity, permeability and viscosity. If the MR fluid response can be sensed electrically, the above physical properties can be controlled.

Winslow (1947) is generally credited as the first person to recognize the potential of controllable fluids in the 1940's with the first electrorheological (ER) fluids patent paper describing the ER effect. MR fluid discovery can be credited to Jacob Rabinow (1948) at the US National Bureau of Standards. in the

1940's. Interestingly, this work was almost concurrent with Winslow 's, ER fluid work. The late 1940s and early 1050s 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. In the near past, studies have focused on the viscosity of MR fluids as a function of a induced field.

Viscosity has proved to be very sensitive to changes on external magnetic field (Shulman 1985, Kordonsky 1993). Viscosity dependence on particle concentration, particle shape, size and material in combination with several fluids carriers have been evaluated. Despite the high sensitivity of viscosity, real applications are rare (Rheonetic's linear damper, rotary brake and vibration damper).

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

The state of the fluid is defined by the level of organization of the particles in the fluid. The nonenergized state of the fluid (Figure 1(a)), shows a random orientation and positioning of particles. When energized with a magnetic field, the MR fluid shows particle organization patterns parallel to the magnetic field (Figure 1(b)). The particle organization state of the fluid is indicative of the interparticle forces generated by the magnetic field.

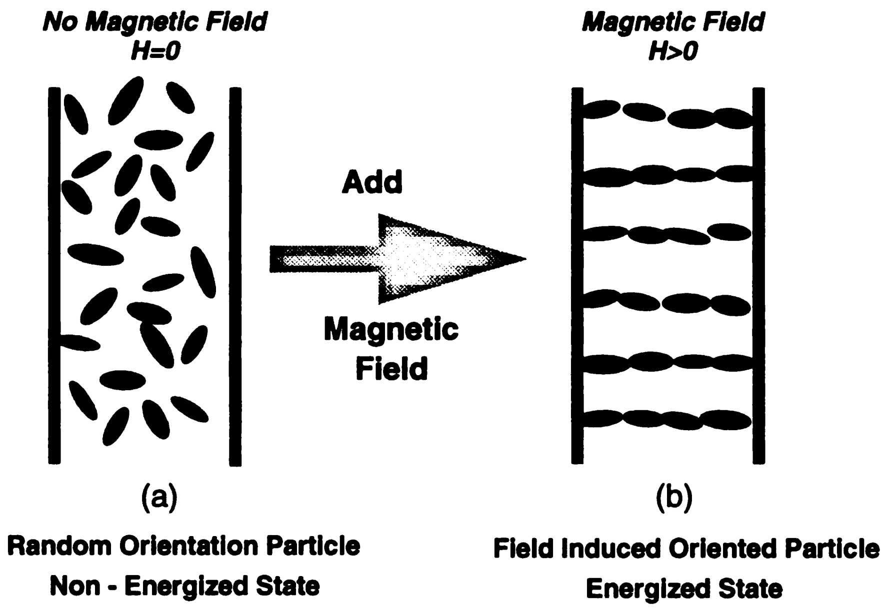


Figure 1.- Non energized and energized particle orientation and positioning.

The physical properties of the fluid are functions of the organization state of the fluid, particles and the forces between them. To control the physical property response of the MR fluid it is necessary to control the state of the fluid through the applied magnetic field. The particle state of the MR fluid combined with the applied field governs all physical properties (1). This generates the non-linear, hysteretic, time-varying characteristic behavior of MR fluids and makes the relationship of the external field with a given property not unique. To maintain a desired value for a property of the fluid is necessary to control the particle state of the MR fluid.

$$\begin{aligned} \dot{\underset{\sim}{x}} &= f(\underset{\sim}{x},u) \\ y &= g(\underset{\sim}{x},u) \end{aligned} \tag{1}$$

A measurable effect representative of the state of the fluid has to be found. This effect will be used to implement a particle state sensor. The accurate state sensor would enable precise response control. The sensing property should be sensitive to changes in internal particle organization state. Another desired characteristic of this effect is easy to be easy to implement in real devices. Sensitivity of three magneto-electric properties: resistance, inductance, and capacitance will be tested and their suitability will be evaluated.

Magnetorheological effect

The internal organizational state of MR fluids change in response to the presence of a magnetic field. Particle alignment that takes place under an applied field is called the magnetorheological effect. The magnetorheological effect was demonstrated in the view of an optical microscope with a low concentration (3% est.) MR fluid suspension under a magnetic field applied from 0 to 40 kA/m. The results of the observations show a change of internal organization as a function of the applied field and time. Particles are dispersed and randomly oriented (Figure 2(a)) in a non-energized state. An applied magnetic field of 6 kA/m. produces chaining of particles that show a classical "worm" pattern (Figure 2(b)). Increasing the field to 12 kA/m produces wider chains that tend to locate parallel to the magnetic field (Figure 2(b)), separation between particles and the carrier medium becomes evident. Thin chains totally aligned to the field (Figure 2(d)) were formed when a 20kA/m field was applied. Increasing fields produced a movement and breaking apart of chains to form wider chains called aggregates, alignment was kept and greater areas of pure carrier medium were shown (Figures 2(e) and 2(f)).

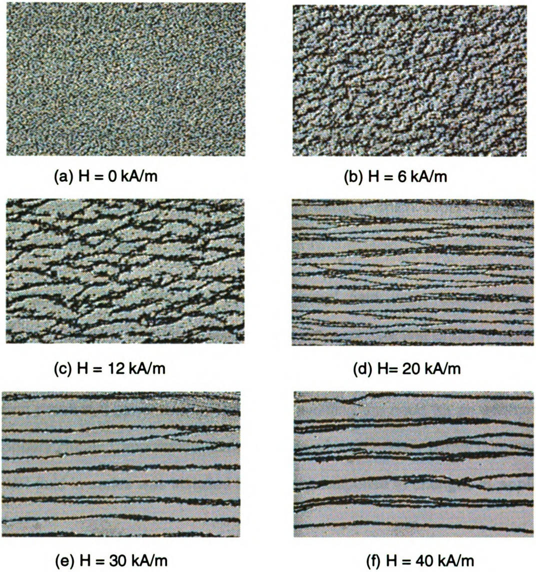


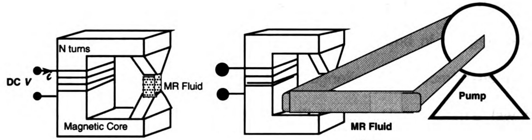
Figure 2.- Internal particle organization of MR Fluid as a function of applied field.

Sensor Development

The Magnetorheological fluid has an inherent non-linear and time varying response. The time response for MR fluids has been reported not to exceed 10^{-4} sec (Kordonsky,1993), which is considerably faster than the time response of electromagnetic transient processes in a magnetic system and all hydro-mechanical processes. Despite the small time constant , to get a precise response it is necessary to develop a state sensor which could be used to control the response.

Three properties that react to the external field were considered for evaluation: 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 connected the MR fluid in series was installed 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 an MR fluid gap. (Figure 5). 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 flowing. A DC powered positive displacement pump was used to pump the MR fluid. The external magnetic field was produced by applying a DC voltage to the connectors of the winding.



(a) (b)

(a) (b)

Figure 3.- MR Fluid Device for measurement of (a) static and (b) moving fluid.

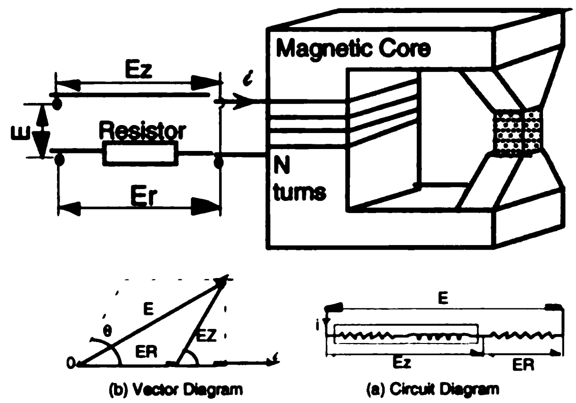
The MR fluid used on all the experiments was the VersaFlow MRX - 135CD manufactured by Lord Corporation. The MR fluid was mechanically mixed before every experiment to ensure homogeneity and to prevent sedimentation, and magnetic particles of the fluid were also believed to be treated to avoid settlement.

Inductance Testing

The inductance change on the electric driven circuit as a function of a change on magnetic field strength has been evaluated. 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 comprises every part of the ferromagnetic core and the MR Fluid gap. Using Ohm's law for magnetic circuit a formula for the inductance can be obtained (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 is sensitive to changes in particle organization state, a measurable change in inductance would indicate a change in the state of the fluid, and it could be used to measure the state of the fluid.

$$L = \frac{N^2}{\frac{l_1}{\mu_c \cdot A_1} + \frac{l_2}{\mu_c \cdot A_2} + \dots + \frac{l_{n-1}}{\mu_c \cdot A_{n-1}} + \frac{l_{MR}}{\mu_{MR} \cdot A_{MR}}} \qquad (2)$$

The electrical circuit works as a actuator and a sensor at the same time. The complete circuit includes the winding (inductance and resistance) and a known resistance resistor (Figure 4). A DC voltage plus a small AC voltage are applied to the terminals of the circuit .The measurement method used to measure inductance was the three voltementer method (Electrical Circuits, Siskind).



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

$$\cos\theta = \frac{E^2 - E_R^2 - E_Z^2}{2E_R E_Z} \qquad (4)$$

Figure 4.- Three voltmeters method to compute Inductance.

Experimental Setup for Inductance measurements.

The experimental set up used to measure the sensitivity of the inductance respect to changes on the applied DC field is shown in the figure 7.

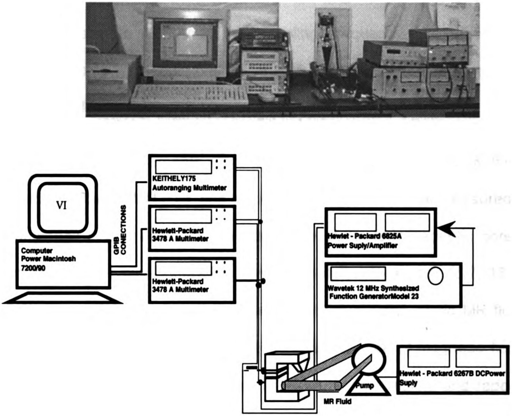


Figure 5.- Experimental setup for inductance measurement.

A LabView program was written to acquire the AC measurements required to compute inductance. A Wavetek 12 MHz synthesized function generator Model 23 and a Hewlett - Packard 6825A Bipolar Power Supply - Amplifier were used to generate the input voltage. Two Hewlett Packard 3478A and one Keithey 175 Multimeter were used to acquire the voltage measurements. All instruments were connected to the computer by GPIB connections.

Inductance Measurements

Inductance measurements were taken with the gap filled with MR fluid. All measurements are for steady state given the fast response of the fluid . The DC voltage was increased from 0 to 20 Volts to generate magnetic DC fields that ranged from 0 to 128 kA/m . The AC voltage frequency was 100 Hz, and the amplitude source was kept constant at 0.25 Vpp which represents only 1.25% of the full scale DC applied field.

Inductance measurements were taken with the gap occupied by the static MR fluid, the flowing MR fluid and air only (Figure 9). 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 % decreasing change on 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 fields regions (0 - 30 kA/m) were stable and repeatable. The higher field (>30 kA/m) region 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 signal.

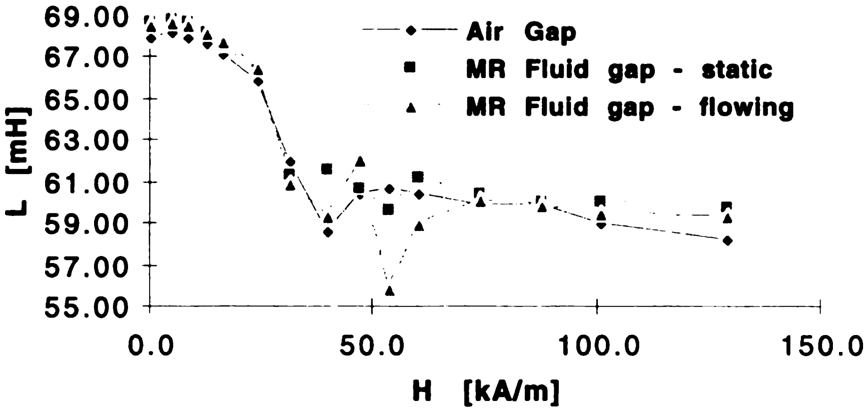


Figure 6.- Inductance vs. applied field.

The inductance value for the MR fluid flowing through a duct placed in the gap at several power inputs also showed a small change (less than 0.25%) with respect to the static fluid value (Figure 10). The magnetic field was kept at zero for this experiment. The inductance of the MR fluid as a function of a magnetic field independent of the inductance of a ferromagnetic or other material core can be obtained if an MR fluid core is used. A core of this kind was built and inductance measurements as a function of time for increasing magnetic fields (0 to 80 kA/m) were taken. Measured data (Figure 11) shows stable and repeatable values for lower fields (H<30kA/m) and unstable and unpredictable values for higher fields (H>30kA/m). The inductance of the MR fluid only increased 0.83% over a 30kA/m increment on the applied field.

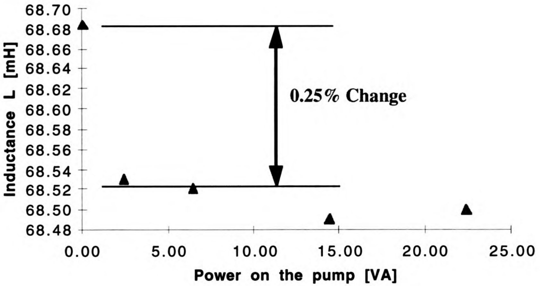


Figure 7.- Inductance vs. MR fluid flow.

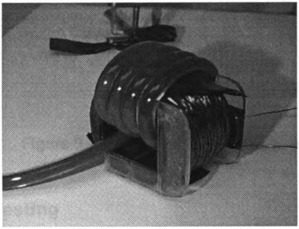


Figure 8.- MR fluid core inductor.

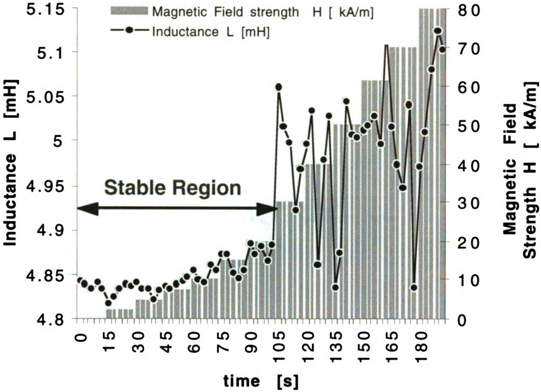


Figure 9.- MR fluid core Inductance vs. time

Capacitance Testing

The steady state capacitance change of a secondary circuit as a function of the magnetic field strength was evaluated. The capacitance values for a parallel plates capacitor is a function of the area of the conductors, the distance between them and the permitivity of the material filling that space. Capacitance changes for constant geometry are functions of the permitivity of the material only (3). Under a magnetic field the particle organization on the MR fluid changes.

$$C = \frac{\varepsilon * A}{d} \tag{3}$$

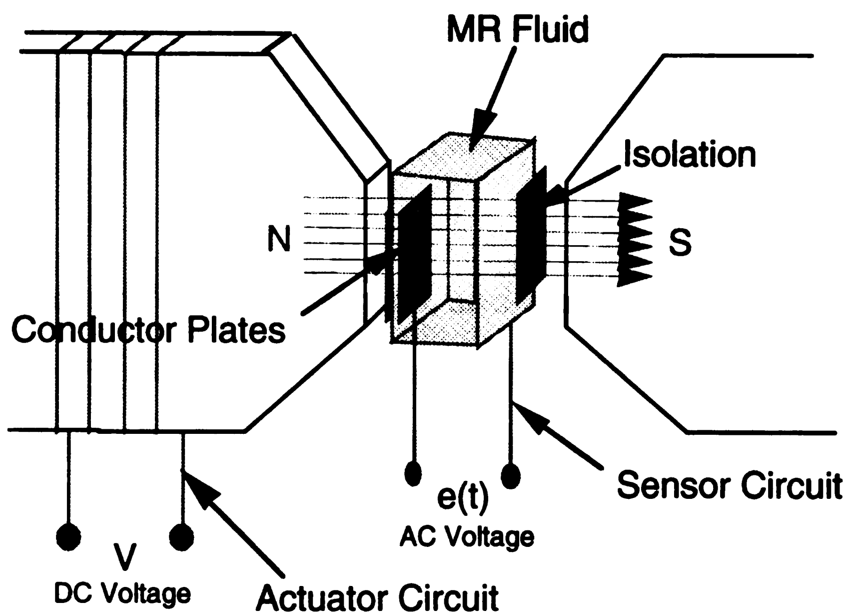


Figure 10.- Experimental setup for Capacitance and Resistance measurements.

Resistance Testing

Resistance change of an MR fluid resistor as a function of a magnetic field was evaluated with two parallel conductor plates inside the MR fluid gap. The plates and MR fluid formed a parallel plate resistor. The resistance value of such a resistor is a function of the area of the plates, the distance between plates and the resistivity of the material (MR fluid) between the plates (8).

$$R = \rho \bullet \frac{d}{A} \tag{8}$$

If the permitivity and/or resistivity of the MR fluid are sensitive to the internal organization of the particles, then a measure of the change of capacitance and/or resistance would reflect a change in the state of the fluid, and therefor capacitance and/or resistance could be used as a state sensor.

Experimental setup for Capacitance and Resistance Testing

Two circuits (Figure 10) were used to perform these measurements: the actuator circuit and the sensor circuit. The actuator circuit was connected to Hewlet Packard 6267B power supply to produce DC actuation fields. A Wavetek function generator model 23 and a Hewlet Packard 6825A power supply / amplifier were used to generate AC actuation fields. The sensor circuit connected two parallel plates located in the MR fluid with a constant separation between them. Good contact between plates and the MR fluid was assured at all times. The sensor circuit was connected to a Fluke 6063A RCL meter and was used to measure series and parallel equivalent capacitance and resistance.

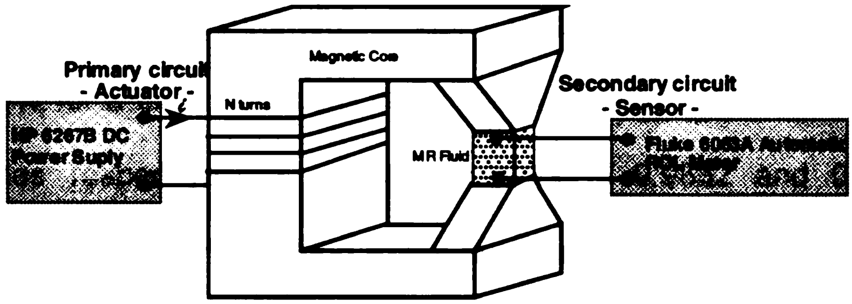


Figure 11.- Equipment setup for MR fluid capacitance measurements.

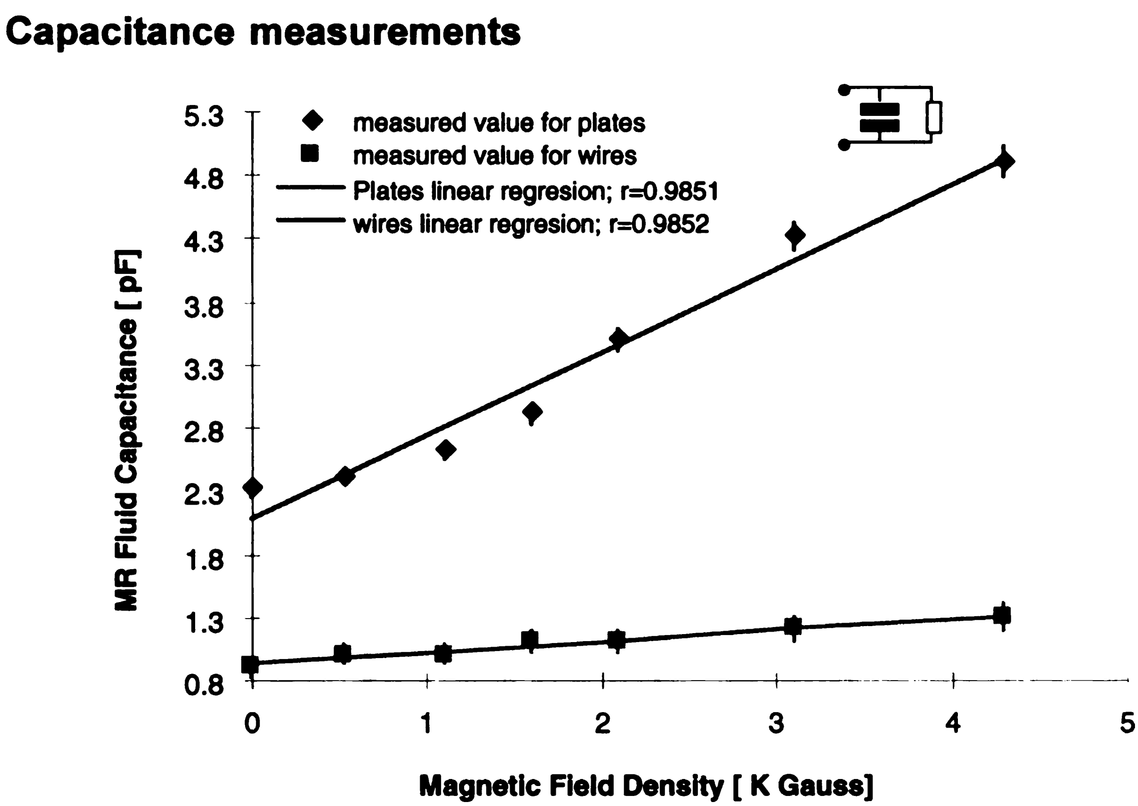


Figure 12.- Parallel equivalent capacitance as a function of applied field.

Measurements were taken with the plates inside the MR pool. The plates were positioned parallel and also perpendicular to the field lines. Plates of 20mm and wires 28 AWG were also tested. The parallel equivalent capacitance measurements (Figure 19), showed an increment of 44.4% and 113% for a total increment of 340kA/m on 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 plates data show a saturation curve trend. Series equivalent capacitance measurements (Figure 20) showed no change for the wires capacitor and a 28.2% increment for the plates capacitor. Linear regression on these show 0.030 and 0.9620 correlation factors respectively.

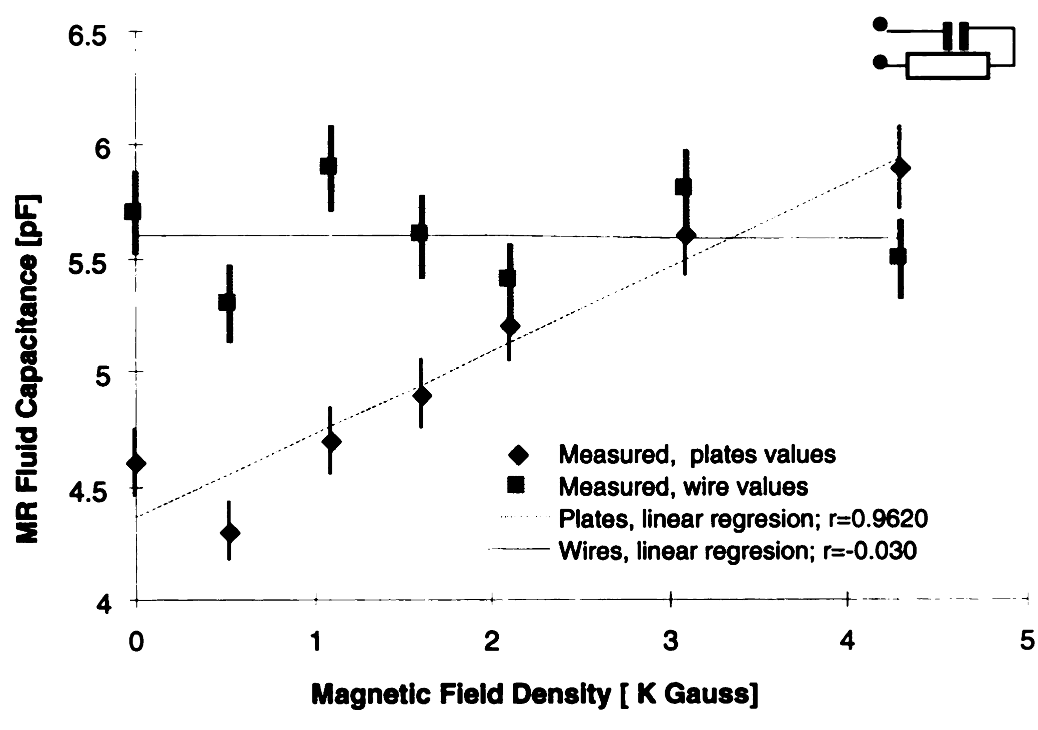


Figure 13.- Series equivalent capacitance as a function of applied field.

Resistance measurements

Parallel equivalent resistance measurements for the MR resistor with the plates placed parallel to the magnetic field (Figure 21), showed a 1.4% decline for the wire resistor and a 44.1% decrease for the plate resistor over a 340 kA/m increment on the applied magnetic field. Correlation factors of 0.3811 and 0.9933 were computed for the linear regression of both sets of data respectively.

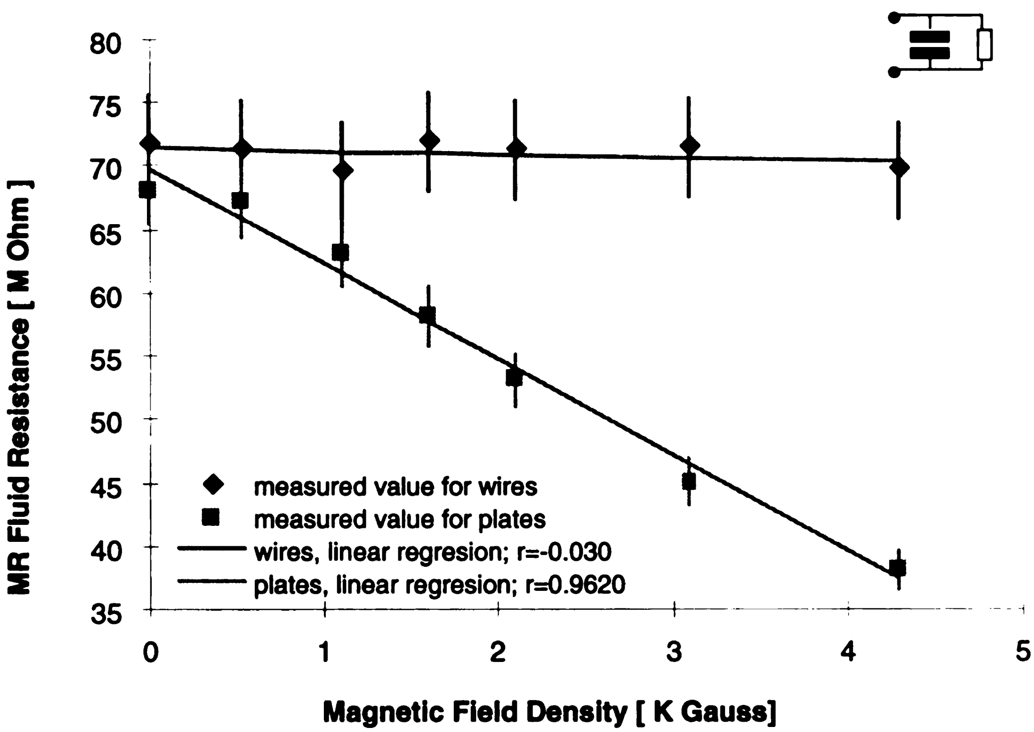


Figure 14.- Parallel equivalent Resistance as a function of applied field.

Series equivalent resistance measurements (Figure 22) showed a 17.2% decrease for the wires resistor and a 40.5% decrease for the plate resistor over a 340 kA/m increment on the applied field. Correlation factors of 0.9950 and 0.9917 were computed for the linear regression of both sets of data respectively.

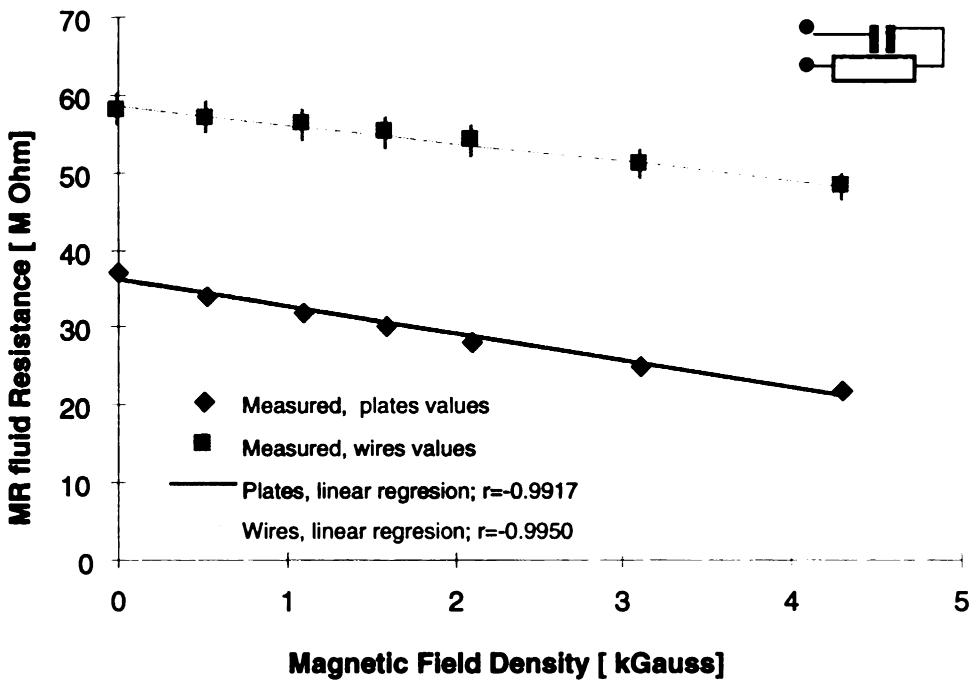


Figure 15.- Series equivalent resistance as a function of applied field.

Resistance measurements with the plates placed parallel to the field showed no change under a 340 kA/m increment on the applied field in either parallel or series equivalent circuits. Capacitance with the plates placed parallel to the field showed no change for a parallel equivalent measurement and showed a 2.8% increment over a 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.

AC fields were applied to measure resistance and capacitance of an MR fluid. Under a low frequency AC field, a changing MR effect was observed. during an field change at approximately 0.1 Hz., no MR effect was observed for zero field value of while maximum MR effect occurred at maximum wave amplitude. Change in field sign produced a fluid motion perceptible when holding the field probe. High AC field frequencies caused immediate unchaining independent of AC field amplitude.

Sensitivity of Inductance, Resistance and Capacitance

Sensitivity of these three measured electric properties as a function of the applied field was investigated. Sensitivity was computed as the ratio of the total increment of every one of these properties over its average value to the total increment on applied field over its average value (11).

$$S_H^Q = \frac{(Q_2 - Q_1)\bullet(H_2 + H_1)}{(H_2 - H_1)\bullet(Q_2 + Q_1)} \tag{11}$$

Computed sensitivity for inductance measurements showed the lowest sensitivity to applied field, 0.0041 (Table 1). The MR fluid resistance connected in series showed a sensitivity of -0.2542. The sensitivity of the capacitance to applied field was the highest, 0.3611. The highest correlation factor for a linear regression analysis of all sets of data belongs to the resistance.

Permeability, permitivity and resistivity are the material properties which changes are been sensed by the inductance, resistance and capacitance respectively. It is important to state that the changing properties are the material properties which are a function of the particle state organization. The computed relative permeability increased from 31.5 to 31.76. The resistivity decreased from 148 to 88 KΩ m. The relative permitivity increased from 65 to 138.5.

Table 1.- Sensitivity of magnetic and electric properties.

Property	Range	Applied Field H [kA/m]	Sensitivity	Correlation factor for linear regression
Inductance [mH]	4.84 - 4.88	0 - 30	0.0041	.9531
Relative Permeability	31.5 - 31.76			
Resistance [M Ω]	37 - 22	0 - 340	-0.2542	.9917
Resistivity [KΩ • m]	0.148 - 0.088			
Capacitance [p F]	2.3 - 4.9	0 - 340	0.3611	.09851
Relative Permitivity	65.0 - 138.5			

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 on inductance, resistance and capacitance showed actually changes in permeability, resistivity and permitivity. Sensitivity values of these properties were obtained for fields up to 340 kA/m. The Inductance of the MR fluid core under magnetic fields in the range of 0 - 30 kA/m showed a very low sensitivity 0.0041. Unstable and unpredictable inductance values were obtained for higher fields. Resistance sensitivity was of -0.2542. Capacitance showed highest sensitivity of 0.3611. The applied field ranged from 0 to 340 kA/m for capacitance and resistance measurements.

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 have always 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, eg. 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 highest sensitivity. Resistance and capacitance sesors have is 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.

APPENDIX

Inductance Measurement LabView Program

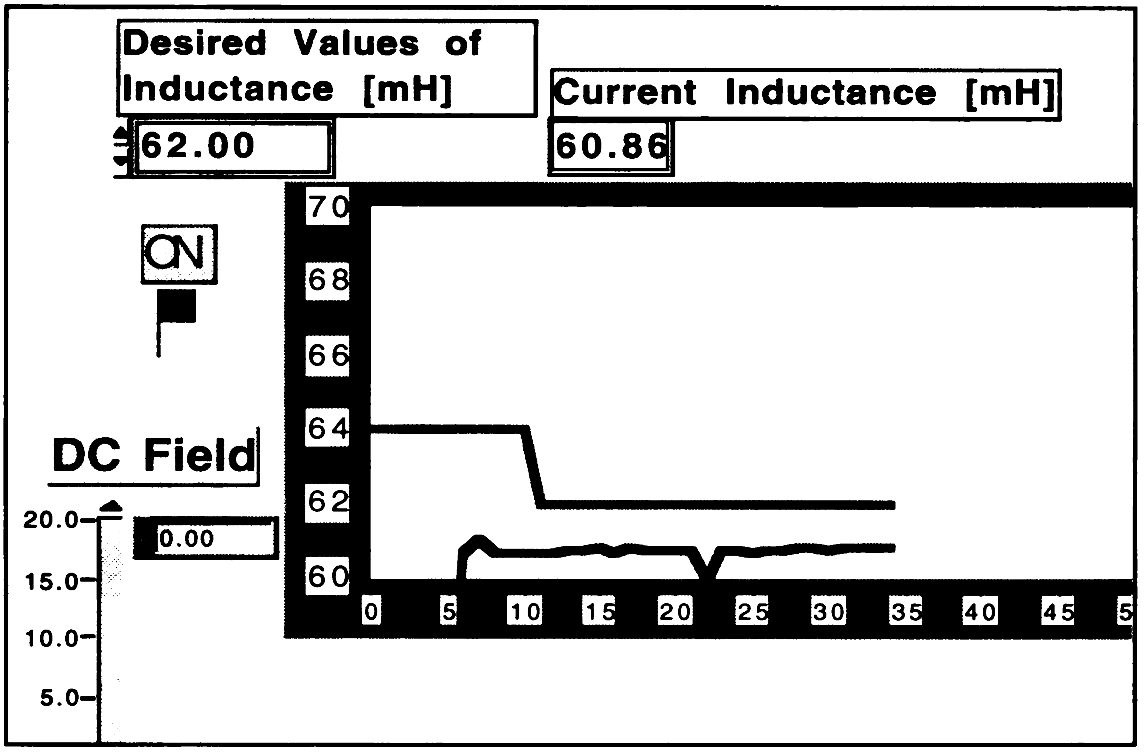


Figure 16.- Front Panel. LabView Inductance measurement program.

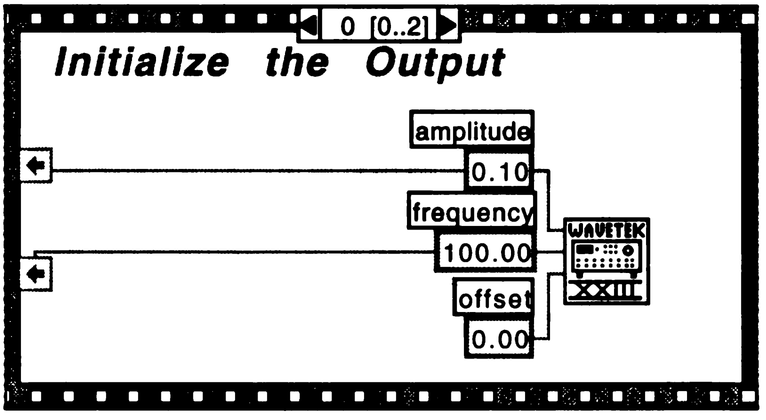


Figure 17.- First Frame. LabView Inductance measurement program.

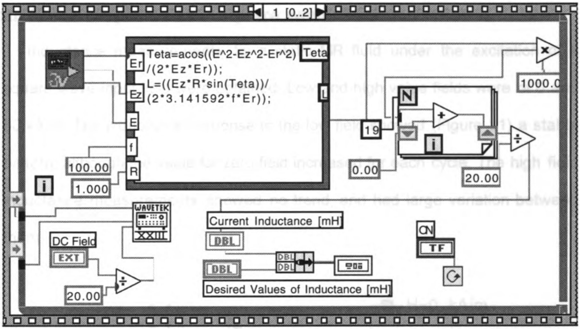


Figure 18.- Second Frame. LabView Inductance measurement program.

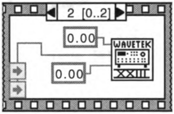


Figure 19.- Third Frame. LabView Inductance measurement program.

Inductance response to a square wave field excitation

Inductance measurements for a static MR fluid under the excitation of a square wave input field were obtained. Low and high value fields were of 0 and 60 kA/m. The inductance response to the low field showed (Figure 21) a stable pattern, although the value for zero field increased for each cycle. The high field inductance measurements showed no trend, and had large variation between them.

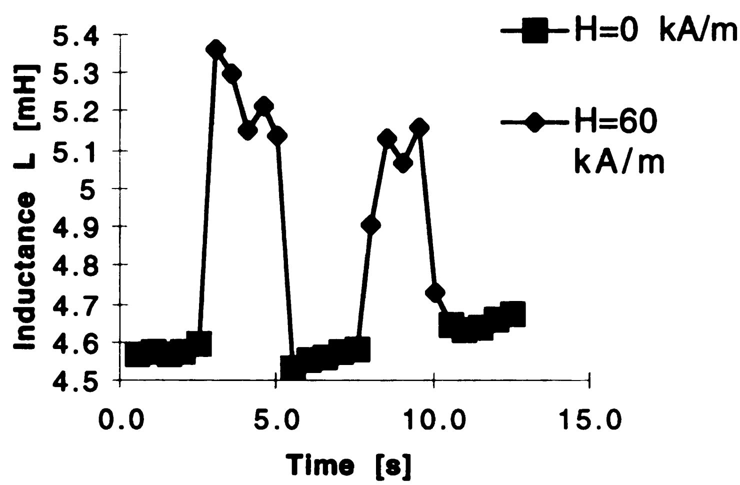


Figure 21.- MR fluid response to a magnetic field square wave

Relative properties change as a function of applied field.

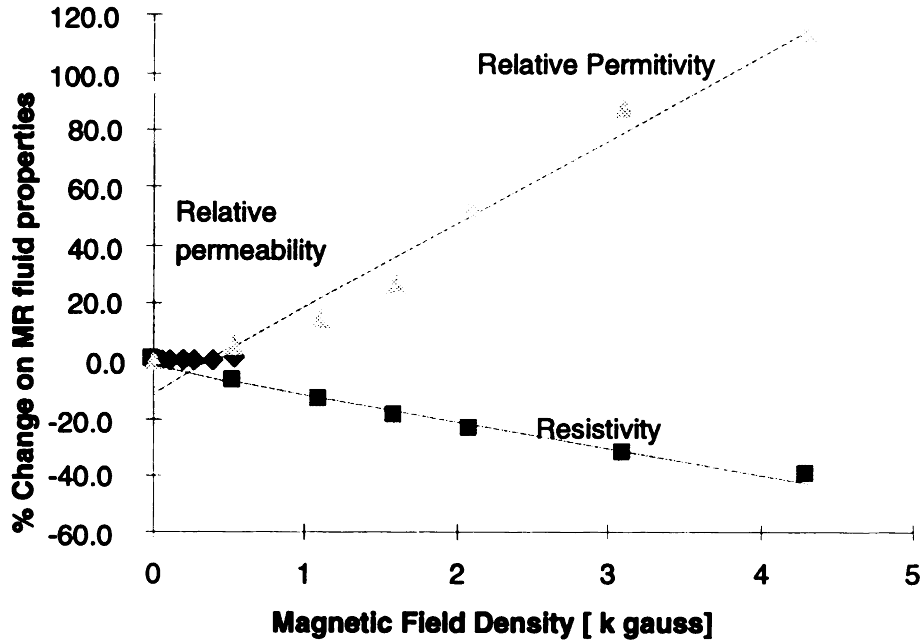


Figure 21.- Relative properties change as a function of applied field.

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