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PRECISE CONTROL OF ELECTORHEOLOGICAL
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Kara R. McGregor

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of the requirements for

MS degree in ME

Clark Radcliffe
Major professor

Date May 8, 1997

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**PRECISE CONTROL OF ELECTORRHEOLOGICAL FLUIDS
IN COMPOSITE STRUCTURES**

By

Kara R. McGregor

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

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1997

ABSTRACT

**PRECISE CONTROL OF ELECTORRHEOLOGICAL FLUIDS
IN COMPOSITE STRUCTURES**

By
Kara R. McGregor

Electrorheological (ER) fluids have variable viscosity, heat transfer and electrical properties based on an internal organizational state which can be changed with the application of an electric field. ER fluids have not attained widespread use due to relatively slow, nonlinear, and unpredictable response. Fast, linear and predictable response is needed for applications to systems such as variable shock absorbers and controllable heat exchangers. It is imperative that simple and accurate methods be developed to control ER fluids.

This study presents a new method for the remote measurement of fluid activation state and a control strategy to provide fast and precise control in a graphite-epoxy composite structure. Electrical conductivity changes are used here for an accurate sensor of fluid activation state. Laboratory results clearly showed the conductivity of the system rose to levels consistent with the state of the fluid. The precision control strategy used conductivity feedback to adjust the electric field input to achieve the level of chaining desired in any fluid. Response speed was increased by over 170% while decreasing system error from 100% to 0.2% after 60 seconds.

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NOMENCLATURE

Arabic Symbols

C	=	ER fluid state/conductivity
C_{des}	=	desired conductivity
C_{fb}	=	ER fluid state of the feedback system
C_{ff}	=	ER fluid state of the feed-forward system
D	=	feed-forward controller transfer function
E	=	error
G	=	system or plant (ER fluid) transfer function
H	=	ER fluid state sensor
I	=	current
K	=	feedback controller transfer function
K_I	=	feedback integral gain
K_P	=	feedback proportional gain
k	=	system gain
k_{fb}	=	feedback system gain
N	=	external system disturbance
s	=	Laplace transfer variable
T	=	transfer function
F	=	field level
Y	=	output from controller

Greek Symbols

ΔC	=	ER fluid state signal
ΔF	=	Input voltage change
τ	=	system time constant
τ_{fb}	=	feedback system time constant

INTRODUCTION

Electrically controlled components are essential technology because static mechanical parts have limited to zero adjustability and designs must be carefully constructed to meet a variety of conditions. For example, a car suspension system is designed for a range of loads, as well as road and weather conditions. Heat transfer systems use fins designed from different materials to conduct heat away from the primary system. It is impossible, with standard spring and damper combinations and materials with constant heat transfer properties, to construct a system that will handle all feasible conditions optimally. To do this we must build systems that are able to dynamically adjust as the existing conditions change. In a world where technology increases every day, systems must be increasingly dynamic and adjustable.

Engineers are currently working to develop "smart materials" whose properties can change over a range of values. One such material is an electrorheological fluid first recognized by Winslow in 1947. An electrorheological (ER) fluid is a mixture composed of conducting particles suspended in a non conducting fluid whose rheology changes with applied electrical field (Winslow, 1962; Klass and Martinek, 1967a). When an electric field is applied to the fluid the conducting particles link together to form chains parallel to the field. This chaining results in variable viscosity (Russel, 1980), heat transfer (Zhang and Lloyd, 1992, Hargrove, 1997) and electrical properties (Klass and Martinek, 1967b; Hass, 1993) which can be changed with the strength of the electric field.

Progressive particle chaining can be viewed microscopically (Figure 1). An ER fluid is a substance composed of zeolite particles suspended in silicon oil. The zeolite

particles act as microscopic sponges and trap water molecules in their pocketed surfaces allowing the particles to form dipoles (Davis, 1992b). Chains of particles develop over time under a constant electrical field (Figure 1(a) to (c)). The particle distribution is uniform before the field applied with increasing degrees of chaining after the field application. The electrodes are composed of 1 mm and 2 mm gaps, allowing 2 separate field strengths to be viewed, 1000 VDC/mm and 500 VDC/mm. In figures (b) and (c) it can be seen that the chains in the lower portion are much more clearly defined and thicker than those formed in the upper region. This demonstrates that chains are both organized more quickly and become more concentrated in stronger fields. The difference in the gaps also produces an area where it is possible to verify that the chains form parallel to the local field. Therefore, time, field strength and orientation affect the degree of chaining.

Non repeatable and slow response has hindered the use of the changes exhibited in the field (Lloyd and Zhang, 1994). When activated, the fluid reaches steady state over a large range of times and values, as indicated by the transmission of light through the ER fluid under a varying field (Figure 2). With each new field application, the fluid both responds more quickly and to a greater degree. One can never be sure exactly how quickly, or to what degree the fluid will respond, making any precision devices impossible. A method of precisely controlling the fluid and increasing the speed of the

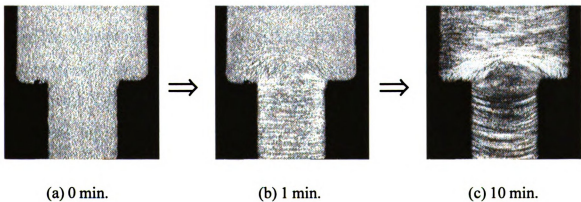


Figure 1 - Microscopic views of particle chaining over time under a voltage of 1000 VDC (Elliott, 1997)

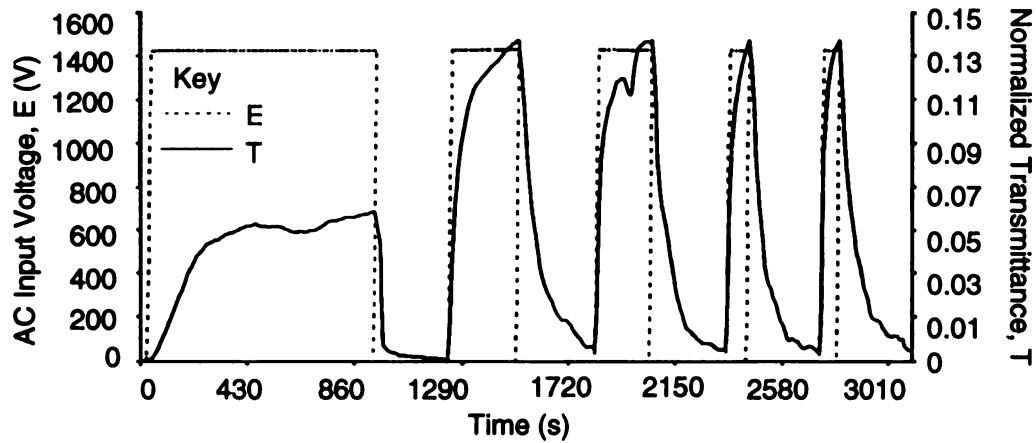


Figure 2 -Laboratory measurement of zeolite ER fluid response using a prototype optical sensor feed-forward control, pulse train zeolite-fluid (1% Vol. Fraction, Dry) (after Tabatabai, 1993).

response are under development.

Previous work (Andersland, 1995; Radcliffe et al, 1996) demonstrated control of the ER fluid using light transmissivity as a measure of the chaining state (Figure 2). A simple proportional feedback controller based on this sensor was developed which produced a faster and more precise response. The proportional controller, however, was limited by a signal to noise ratio in the sensor of about 10:1 which in turn limited both the speed and precision of the system to gains of less than 5. In addition, light transmissivity is measured through a transparent containment unit that most mechanical applications could not allow. This investigation continues previous work with two major distinctions. First, electrical conductivity was used as the state sensor. This sensor allowed a more representative graphite-epoxy composite structure and generated less noise than exhibited in the transmissivity sensor. Second, proportional-integral controllers were investigated to improve the precision of the response.

The internal state of the fluid can be measured directly by the amount of chaining present, or how well organized the particles are. The chaining state can be qualitatively identified (Figure 1) as zero to high in microscopic views. The fluid has been described in closed systems in terms of the viscosity, which is a derived property only obtained when

the fluid is flowing, however, a more direct measurement, dependent only on chaining is needed.

Past studies of "conductivity effects" have focused on the conductivity of the particles and the suspending fluids, particularly in relation to one another (Davis, 1992a; Khusid and Acrivos, 1996). They have used these conductivities and the ratio between them as one of the main factors for mathematically describing the mechanics behind particle chaining. This paper uses the electrical conductivity of the ER fluid mixture and its change over time after the application of an electric field as a measure of particle chaining state. This investigation equates the change in conductivity with the change in the state of the fluid much the same as changes in viscosity have been used.

The objective of this study is to demonstrate that 1) electrical conductivity is an effective measurement of the state of the ER fluid and that 2) a feedback control method can produce a faster and more predictable response. It will be shown, through the use of electrical conductivity measures, that the standard or feed forward control of the fluid reacts too slowly to be useful commercially. Feedback control using conductivity as a measure of the state of the fluid will adjust the applied field to achieve the desired state more quickly and accurately than previously possible.

FEED-FORWARD AND FEEDBACK SYSTEMS COMPARED

Feed-forward is the most common method for the activation of any system (Figure 3). The controller, $D(s) = G^{-1}(s)$, is based upon knowledge of the relationship between the output and the input of the system, $G(s)$. The total output of the system, $C_{ff}(s)$, is represented in the Laplace domain by the system's response to both the controller action, $D(s)$, and external disturbances, $N(s)$.

$$\begin{aligned} C_{ff}(s) &= G(s)[D(s)C_{des}(s) + N(s)] \\ &= C_{des}(s) \text{ iff } D(s) = G^{-1}(s) \text{ and } N(s) = 0 \end{aligned} \quad (1)$$

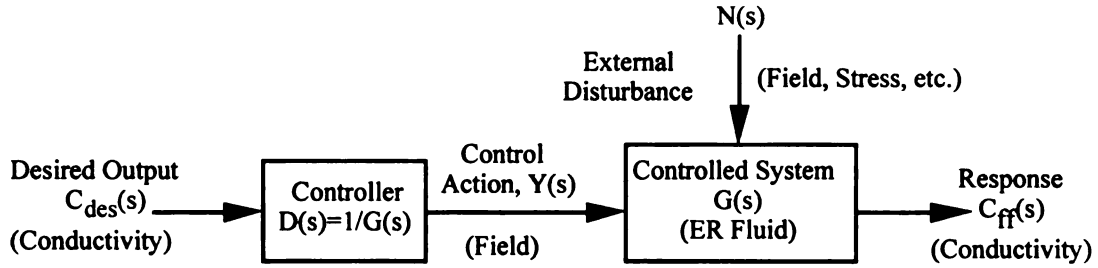


Figure 3 - Feed-forward control system

The precision of the feed-forward controller is dependent upon having an accurate, invertible model of the system and negligible external disturbances. Any noise, $N(s)$, or imprecision in the model, $G(s)$, will result in proportional errors in the output. The input/output function must be both known exactly and invertible to allow precise feed-forward control.

The unpredictable and slow response of ER fluids is well known. For any given input, a large range of outputs can be expected, affecting both the speed and the accuracy of the desired response. Perturbations in the field activating an ER fluid showed a response that varied in terms of the magnitude as well as the time required to reach steady state (Figure 2). This indicates the non-linear nature of the system which has yet to be sufficiently modeled. Without an invertible model of the system, it can easily be seen that the method of feed-forward control is not effective and a more complicated, precision control theory is required to attain the desired state. Therefore, we must consider the other alternative.

Feedback control uses a sensor to measure the system's output, compares it to the desired output and compensates for any difference by adjusting the input (Figure 4). The controller, $K(s)$, responds to the error, $E(s)$, which is the difference between the desired output, $C_{des}(s)$ and the actual system response, $C_{fb}(s)$.

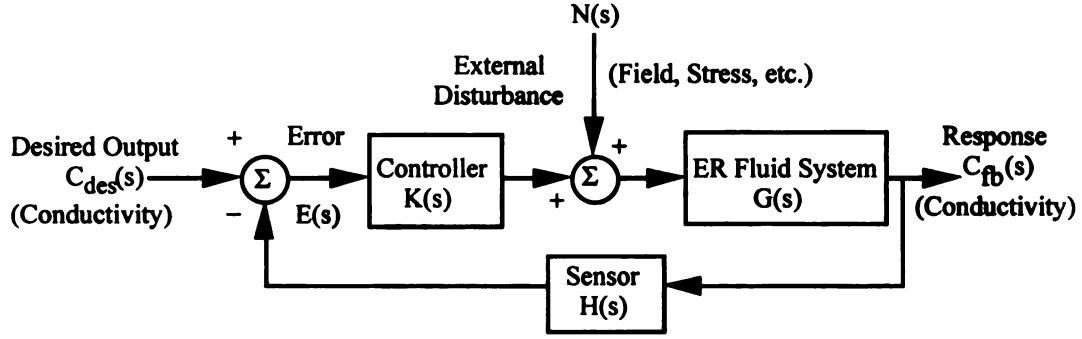


Figure 4 - Feedback control system

$$C_{fb} = \frac{G(s)[K(s)C_{des}(s) + N(s)]}{1 + K(s)G(s)H(s)} = C_{des}(s) \text{ iff } K(s) \rightarrow \infty \text{ and } H(s) = 1 \quad (2)$$

The equation for $C_{fb}(s)$ shows that the accuracy of response no longer requires any knowledge of the physical system or the disturbances. Only a strong controller, $K(s)$, and an accurate sensor, $H(s)$ are required to attain the desired response quickly and precisely. Feedback or precision control is adjustable throughout the activation period, relying on information gathered from system sensors to adjust the level of input as needed. Constant and accurate monitoring of the system through sensors is essential to precision control under changing conditions.

ELECTRICAL CONDUCTIVITY SENSOR DESIGN

The first goal of this study is to establish a fast, simple and accurate electrical conductivity based sensor of the state of the fluid. The material property, the electrical conductivity,

$$C = \frac{I}{V} \quad (3)$$

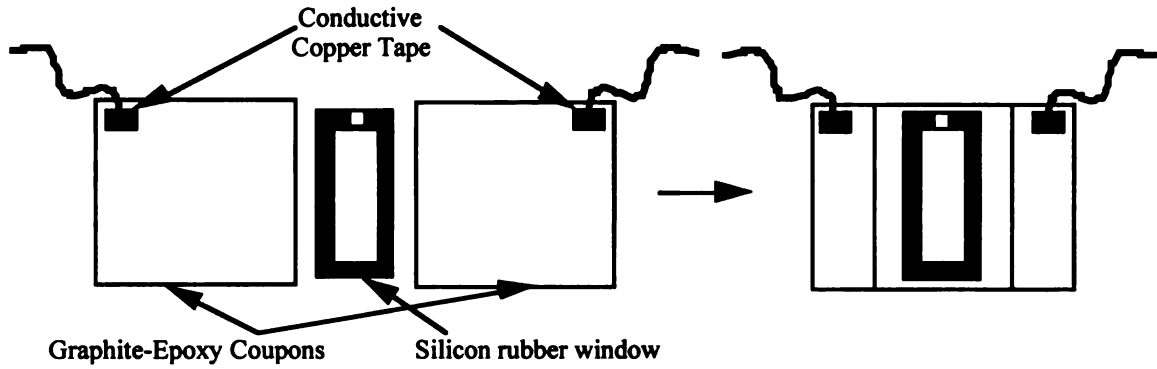


Figure 5 - ER fluid composite structure

ER Fluid Preparation

The manufacture of the ER fluid was accomplished in the laboratory by mixing the silicon oil and zeolite particles according to the percent by weight chemistry standard.

This equation is given by

$$\text{Percent by weight} = \frac{m_{\text{zeolites}}}{m_{\text{zeolites}} + m_{\text{silicon}}} \quad (4)$$

Laboratory conditions did not provide the constant humidity environment required to produce a consistent water content in the zeolite particles. This produced a noticeable difference in the response of some mixtures. All the solutions in the following experiments were a ten percent by weight mixture.

ER Fluid Composite Structure

The ER fluid composite structure was composed of two unidirectional graphite-epoxy composite panels measuring 9 cm x 9 cm separated by a 2 mm thick silicon rubber insulating material enclosing a space 6.5 cm by 4.5 cm filled with the ER fluid (Figure 5). This is the first investigation to use of this type of electrode on the ER fluid.

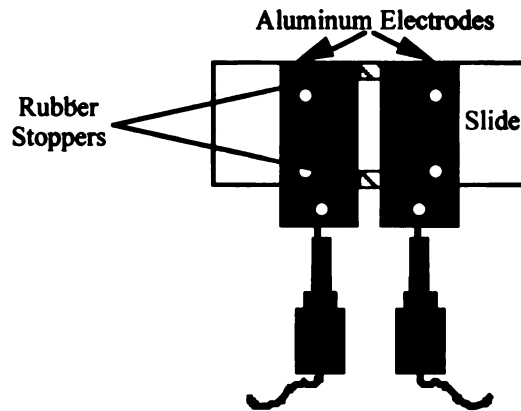


Figure 6 - ER fluid slide assembly for the microscope (Elliott, 1997 and Hargrove, 1997)

ER Fluid Video Slide Assembly

The video device (Figure 6) was a set of aluminum electrodes bolted to a viewing slide forming a gap of 1 mm. The fluid occupied the space between the electrodes and was contained by the silicon insulating material. A microscope with a camera attached was used to record visual images simultaneously with conductivity data.

ER Fluid State Sensor

The state sensor was composed of data acquisition and control algorithms which were programmed in a Power Macintosh 7100/80AV using National Instrument's LabVIEW to create virtual instruments. To activate the system, the desired field was output to a NB-MIO-16 L board connected to the computer, the output was amplified 200 times by a Trek Model 677A Supply/Amplifier. This field was then applied directly to the structure to activate the fluid.

The direct measurement of both the field and the resulting system current was allowed by the amplifier through the back panel of the main device. The NB-MIO-16L board externally monitored the field and the current and the data was taken via the LabVIEW Programs. The data was sampled over a specified time and the data was

averaged over discrete time intervals to remove some noise and reduce the number of data points produced. The conductivity was then computed from the data.

The video apparatus had such a small contact area that a large voltage divider was used to allow the measurement of a very small current (on the order of nAmps). Therefore, the voltage across a $10\text{ M}\Omega/1\text{ M}\Omega$ resistor was measured using LabVIEW programs and converted into a conductivity value.

ELECTRICAL CONDUCTIVITY AS A STATE SENSOR

Chaining can be visually linked with a distinct rise in conductance (Figure 7). With zero electric field, the particles are randomly distributed in all cases. This initial state was the same for the three field strengths shown. The same mixture was used in each trial, but the fluid in the apparatus was changed to provide a consistent starting

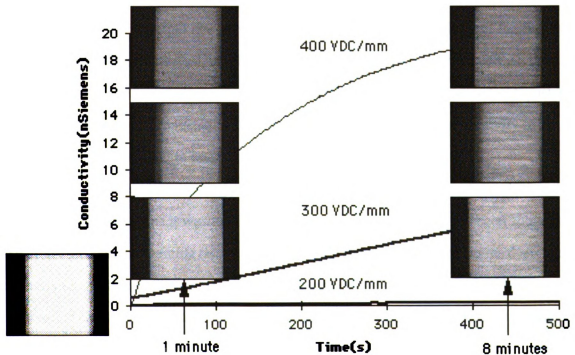


Figure 7 - Transient electrical conductivity of the ER fluid in the video slide assembly under increasing field strengths (10% by weight)

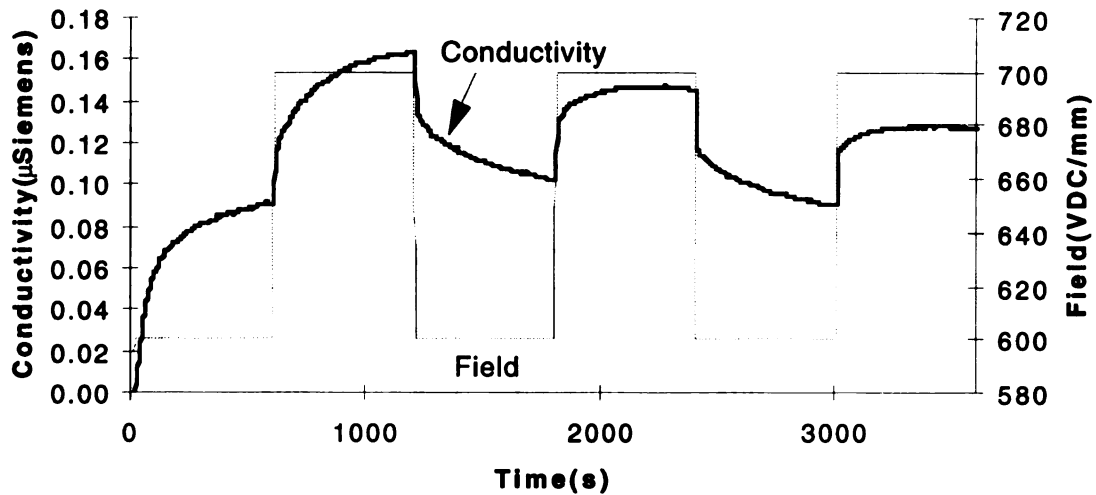


Figure 8 - Transient electrical conductivity measurements of the ER fluid under a varying field (10% by weight)

point. Within one minute of activation, the particles aligned in varying strengths according to the strength of the applied field. These three slides can also be seen to follow the corresponding electrical conductivity measurements. As time proceeds, for each field there was a distinct rise in conductivity. At eight minutes, slides of the fluid are again shown. Closely observed, the chains appear heavier or more developed than the previous slides. There was also a distinct difference between the successive fields just as there is in the levels of conductance. The results show the electrical conductivity of the ER fluid to be proportional to internal chaining in the fluid.

The non repeatable chaining response is demonstrated by means of the electrical conductivity (Figure 8) as it was with transmissivity (Figure 2) which has been shown to be a direct measure of chaining (Hargrove, 1997). The gains and time constants decreased for each perturbation in the electric field. Every application of an electric field had a direct effect on all subsequent applications, making the entire activation history essential to determining fluid behavior.

The level of electrical conductivity decreased over time, rising less and less. This seems to oppose earlier work regarding light transmissivity, which increased over time

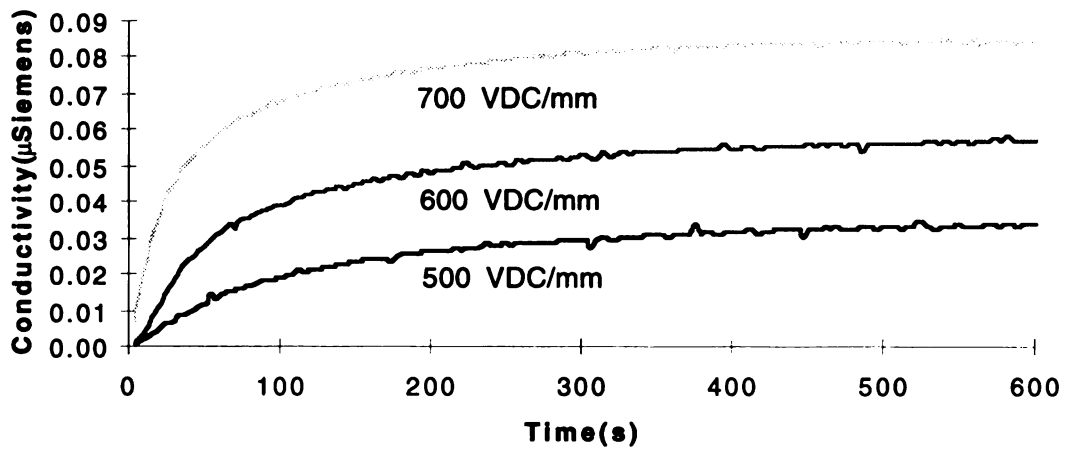


Figure 9 - Transient electrical conductivity measurements of the ER fluid under increasing field strengths (10% by weight)

(Figure 2). Both responses may be due in some part to a small degree of settling. The video data clearly shows that when the field is removed, the chains break from the electrodes and fall without complete disintegration (Elliott, 1997), this would tend to increase the settling effect if compared to the dispersed particles. While a settled fluid would conduct less readily with the particles concentrated at the bottom, light transmissivity would increase with the majority of the fluid free of particles. This effect requires further study using simultaneous visual and state measurements to determine the exact cause or causes.

The conductivity changes due to the application of an electric field are shown over time for three larger field strengths (Figure 9). The conductivity was low before the application of the field corresponding to zero chaining. As time increased, at all field levels the chaining of the fluid resulted in a noticeable increase in electrical conductivity proportional to the field applied. In each case, formation of the internal particle chains allowed electricity to be conducted more easily across the medium, therefore increasing its conductivity.

Moisture content was a significant factor in the response of the ER fluid. Each mixture, while consistent in percentage, was subject to a range of environmental changes, especially humidity. Humidity produced both very sensitive and reactive fluids that saturated at low field strengths, as well as fluids that did not react measurably. This created an added problem in determining how the fluid would react.

Electrical conductivity can be equated with chain formation for any applied field, therefore, it is clearly a more direct measurements of the state of the fluid than previous properties used. The data also gave further evidence that feed-forward control is not a precision control method for the ER fluid. Conductivity provides an excellent sensor for a feed-back control strategy.

PROPORTIONAL FEEDBACK CONTROL

Now that an fast accurate sensor has been established, specific control strategies can be discussed. Referring back to (2), if the controller $K(s)$ is replaced by a constant, K_P , then the equation for the transfer function can be used to predict the closed loop time constants and gains assuming no noise $N(s) = 0$ and $H(s) = 1$.

$$T(s) = \frac{C_{fb}(s)}{C_{des}(s)} = \frac{kK_P(1 + \tau s)}{1 + [kK_P/(1 + \tau s)]} = \frac{kK_P}{1 + kK_P + \tau s} = \frac{k_{fb}}{1 + \tau_{fb}s} \quad (5)$$

$$\text{where } k_{fb} = \frac{kK_P}{1 + kK_P} \Rightarrow 1 \text{ and } \tau_{fb} = \frac{\tau}{1 + kK_P} \Rightarrow 0 \text{ as } K_P \Rightarrow \infty$$

This feedback controller is referred to as a proportional controller, is linear in nature, and can be directly compared to the linear system response. The gains approach precision and the time constants will become smaller as the proportional controller becomes sufficiently large.

The performance of the feed-forward controller and proportional controller will be compared and evaluated by modeling the ER fluid as a first order system where the gain and the time constant vary widely over a large range of values. These values are

dependent upon the length of time that the fluid has been activated, the strength of the field and other physical factors that have been previously mentioned. The linear model of the fluid can be expressed in standard form as

$$G(s) = \frac{k}{1 + \tau \cdot s} = \frac{C(s)}{F(s)} \quad (6)$$

where

$$k = \frac{\Delta I}{\Delta F} \quad (7)$$

which is the conductivity adjusted by the separation of the composite plates and

$$\tau = \Delta t \text{ for 63.2\% of steady state} \quad (8)$$

where 4τ is the settling time at which the system reaches steady state.

ER FLUID FEEDBACK CONTROLLER SYSTEM

The closed loop algorithm (Figure 10) used the same windows and state sensor as the open loop, but the MB board related the measurements to the Power Macintosh with LabVIEW programming, averaged the signal and adjusted the output as shown by the equations developed in the previous section. The control algorithm worked at a maximum real time speed of 8 Hz. In this medium, this rate is sufficient to get accurate control as the fluid responded slowly to any input change.

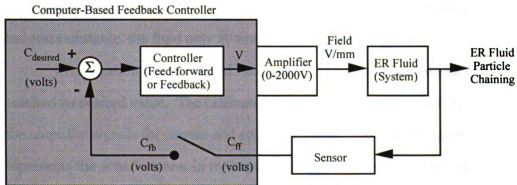


Figure 10 - System Flow Chart

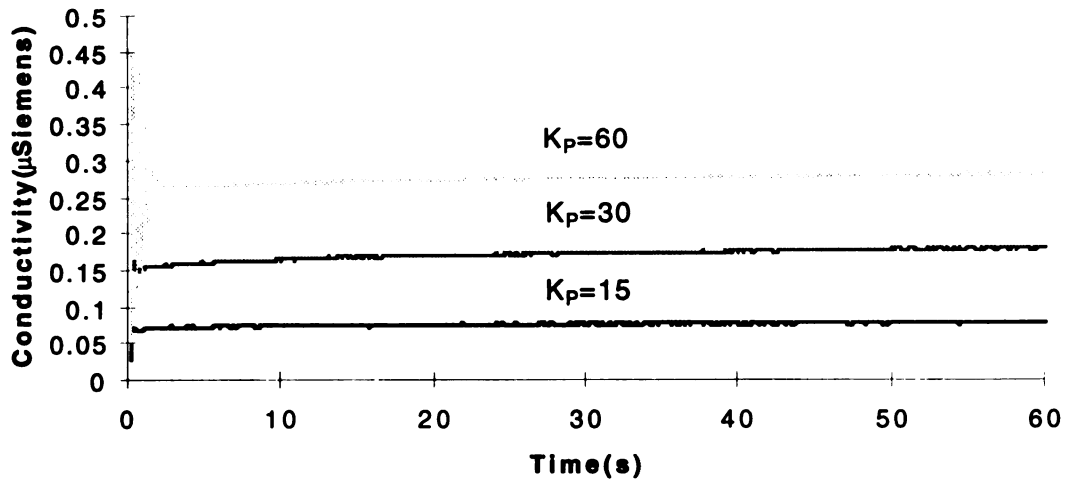


Figure 11 - Proportional control of the ER fluid at a desired electrical conductivity of 0.5 μ Siemens and increasing levels of proportional control (10% by weight)

MEASURED FEEDBACK RESPONSE: PROPORTIONAL CONTROL

Three successively larger levels of proportional control were plotted to determine the ER fluid's response. The desired level of conductivity was 0.5 μ Siemens and as the controller became stronger, or K_p increased, the proximity to the desired value increased as well as the speed of response. Increasing K_p also had a secondary effect, the fluctuations at the beginning of the response increased. Above $K_p = 60$, they continued beyond the first few seconds and the system became unstable. Although the precision increased and the speed of the response increased dramatically, by the time the controller becomes unstable, the fluid only attained 56% of the desired value.

Investigation of the applied field clearly shows why the conductivity never reached its desired value. The calibrated measure of the conductivity is the ratio between the amplifier signals for current and applied voltage. The current signal is a voltage that represents the actual current in mAmps. The applied voltage is a measure of the input to

the amplifier, or the actual applied voltage divided by 200. The signals require a calibration constant of

$$C = \frac{I \cdot 1000}{V / 200} = \frac{I}{V} \cdot 200000 \quad (8)$$

to determine the actual desired conductivity from the actual signals.

$$C_{des} = (200000)(5E - 7 Siemens) = 0.1 \quad (9)$$

At steady state, 60 seconds, the measured current is 0.07 mAmps and the pre-amplified voltage is 1.91.

$$C_{fb} = \frac{0.07}{1.91} = 0.0364 \quad (10)$$

The error signal (Figure 10) is

$$E(s) = (0.1 - 0.0364) = 0.0636 \quad (11)$$

This error was multiplied by the controller gain producing the output to the amplifier in volts,

$$Y = (0.0636) \cdot 30 = 1.91 \quad (12)$$

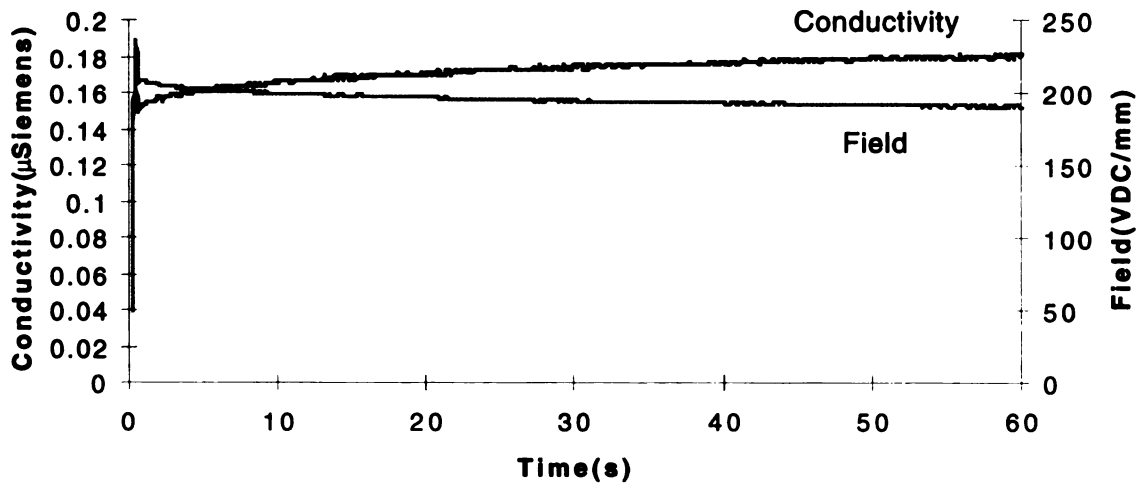


Figure 12 - Proportional controller action and response of the ER fluid at a desired electrical conductivity of 0.5 μ Siemens at $K_p = 30$ (10% by weight)

which corresponds to 382 VDC amplifier output or 191 V/mm field strength as shown (Figure 12). As the system approaches the desired value, the error signal decreases, causing the applied voltage to fall. With proportional control, the conductivity never reaches the desired value because some non-zero error is always required.

Precision, low error, control can only be attained when K_P becomes sufficiently large (6). The proportional controller gain reached its stable limit at about $K_P = 60$. The signal to noise ratio for the sensor was slightly over 60:1, therefore, when amplified by more than 60, the noise generated in the sensor, when amplified at that level, became the driving force in the system, generating random, unstable response. The larger stable gains in this work were a result of this sensor's signal to noise ratio, improved over the transmissivity sensor which had a signal to noise ratio of 10:1 and limited the maximum allowable gain to about $K_P = 5$ in prior work (Andersland, 1995; Radcliffe et al, 1996).

The gains and the time constants for the feed-forward system were computed for all systems that responded at levels that were able to be read by the standard equipment described. These were then used to form a model of computed gains and time constants for the proportional feedback control system (Table 1). The system behaved as predicted by the model for each level of proportional control. The system gains with the feedback controller approached one as the proportional constant increased. Andersland (1995) was

Table 1 - Comparisons of feed-forward and proportional feedback control gain and time constants for ER fluid electrical conductivity measurements (10% by weight)

Controller	Measured		Computed	
	k	τ (s)	k	τ (s)
Feed-forward	0.00458 - 1.13	3. - 119.	-----	-----
Feedback, $K_P = 15$	0.162	0.211	0.0643 - 0.944	0.167 - 111.
Feedback, $K_P = 30$	0.364	0.215	0.121 - 0.971	0.086 - 104.
Feedback, $K_P = 60$	0.564	0.165	0.216 - 0.985	0.044 - 93.
Feedback, $K_P = 600$	-----	-----	0.733 - 0.999	0.004 - 32.

able to achieve about 0.87 gains while this investigation only achieved 0.56 due, in part, to the use of a non-zero operating point about which the desired transmissivity level was specified. The time constants decreased consistently and were still within the predicted range. The measured time constants were over 14-17 times smaller than the smallest feed-forward time constant and were an improvement over Andersland's increase of over 5 times, consistent with the use of higher gains.

The analytical results (Table 1) clearly show that a higher level of control is needed to attain the desirable levels of speed and precision. The controller could approach the desirable level with an acceptable degree of precision if the gains were extremely high, over 600. This control gain would only be possible if the noise in the sensor were less than 0.6% of the signal

PROPORTIONAL - INTEGRAL FEEDBACK CONTROL

A controller design must compensate both for the slowness of response and the lack of precision and the experiments clearly showed the problems encountered with simple proportional control. A controller that provides both speed and precision at lower controller gains than required by the proportional controller is needed. A proportional-integral (PI) controller provides dynamic compensation which will improve both the transient and the steady-state response, providing precision even at the lowest gains. The transfer function for such a controller can be expressed as below with adjustable proportional and integral gains, K_P and K_I respectively.

$$K(s) = \frac{Y(s)}{E(s)} = K_P + \frac{K_I}{s} = \frac{K_P s + K_I}{s} = \frac{K_P(s + K_I / K_P)}{s} \quad (13)$$

The closed loop transfer function of the entire controlled system assuming zero noise $N(s) = 0$, and $H(s) = 1$.

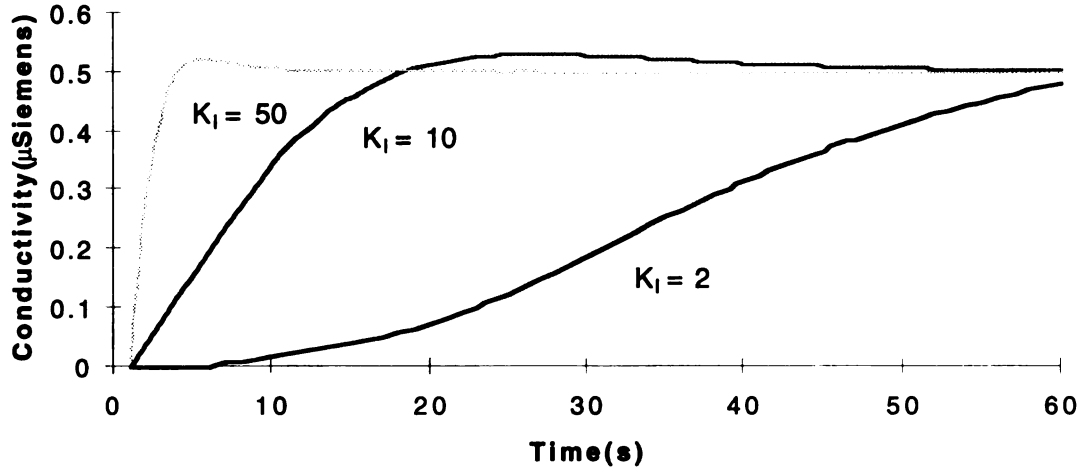


Figure 13 - PI controller response of the ER fluid at a desired electrical conductivity of 0.5 μ Siemens for $K_P = 3$ and increasing levels of integral control (10% by weight)

$$T(s) = \frac{C_{fb}(s)}{C_{des}(s)} = \frac{kK(s)/(1+\tau s)}{1+[kK(s)/(1+\tau s)]} = \frac{k(K_I + K_P s)}{\tau s^2 + (1+kK_P)s + kK_I} \quad (14)$$

where as $s \Rightarrow 0$, $T(s) \Rightarrow 1$

The transfer function $T(s)$ no longer depends on the strength of the controller for precision, at steady state the desired state will be attained. It is also no longer linear, therefore, it can not be compared directly to the system response as with the proportional controller. Simulations that evaluate the transfer function at the feed-forward gains and constants were used to predict the behavior of the ER fluid controller.

MEASURED CLOSED LOOP RESPONSE: PI CONTROL

Proportional-integral control is shown (Figure 13) for constant proportional control held nominally at three and three successively larger integral controls. As the integral constant increased (starting at 1 second) it had two effects, it decreased the time to the desired state while it simultaneously increased the precision. At very low integral control it took a long time to get to the desired state, clearly longer than shown. A slight

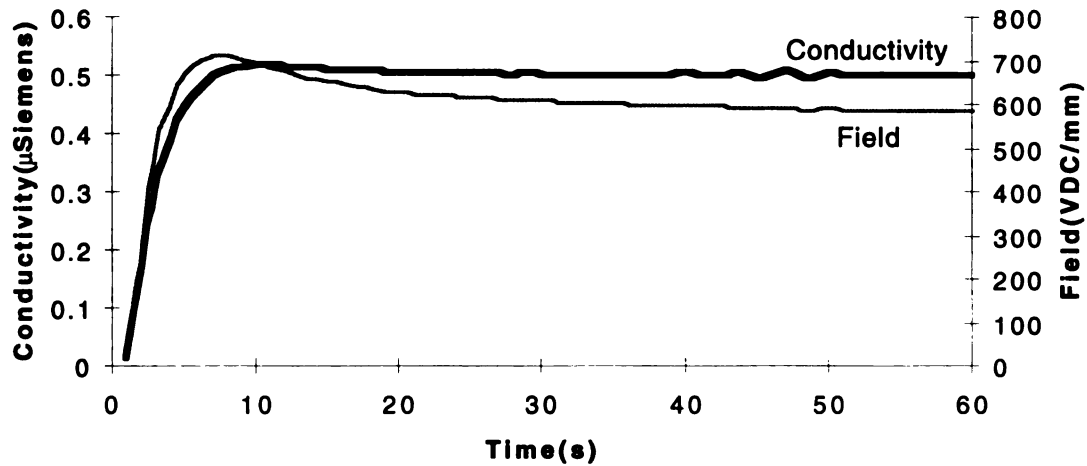


Figure 14 - PI controller action and response of the ER fluid at a desired electrical conductivity of $0.5 \mu\text{Siemens}$ for $K_P = 3$ and $K_I = 30$ (10% by weight)

overshoot was seen at $K_I = 50$, which indicated that the upper limits of the integral portion of the controller had been reached.

The applied field required to obtain the desired response is shown (Figure 14). There was a quick rise then the field began to fall slightly after reaching the desired value of conductivity, in contrast to proportional control (Figure 12). The conductivity rise showed no overshoot and the desired value was reached and precisely held in about 7 seconds. The speed of the response is slower than the those found with proportional control, but still 1.71 times faster than the shortest settling time for feed-forward control. The precision of the response is a significant improvement over both the feed-forward and proportional controls in terms of steady state.

The maximum error attributed to overshoot (after attaining the desired state) ranged from 3.4% to 6.2%. After 60 seconds, the errors ranged from 0.2% to 3.8%, a dramatic improvement over both feed-forward and proportional feedback control. Feed-forward control illustrated the problems in the prediction of the attained state, it was never certain what level of conductivity would be reached. Proportional feedback control was much more predictable, but the error in reaching steady state after 60 seconds was

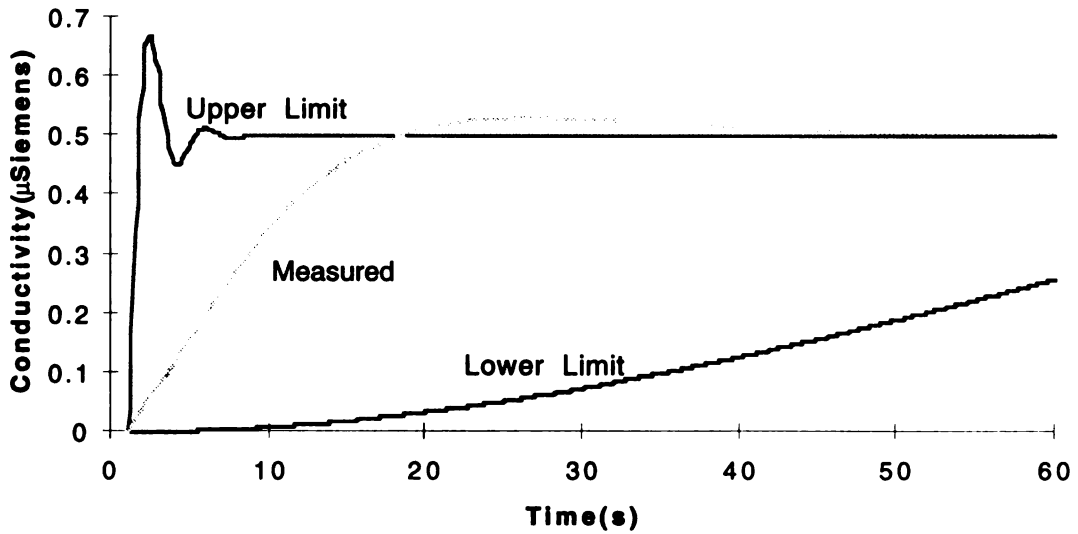


Figure 15 - Comparisons of the measured and calculated responses of the ER fluid at a desired electrical conductivity of $0.5 \mu\text{Siemens}$ for $K_p = 3$ and $K_I = 10$ (10% by weight)

still 44% at the highest level of control. Proportional-integral control provides a combination of speed and precision with little dependence on the size of the error that determined that PI control was the most appropriate method investigated here to control the ER fluid precisely.

The simulated response of the proportional integral controller were found using the open loop gains and time constants (Table 1) to evaluate the transfer function (14). The simulations formed limits between which the measured response for $K_p = 3$ and $K_I = 10$ were found (Figure 15). The upper limit clearly shows an overshoot, while the lower limit is a very slow rise to steady state. The measured response of the PI controller also fell within the predicted limits of the model.

CONCLUSIONS

Feed-forward and feedback controllers for an ER fluid structure were examined experimentally, and the responses were analytically compared using a model of the ER

fluid response. The traditional method of feed-forward control was found ineffective for the ER fluid both analytically and in practice. The experiments clearly showed that neither the level nor the speed of response for feed-forward control was adequate for the fluid to be useful commercially. Electrical conductivity proved to be a more direct method of measuring the internal state of the ER fluid, therefore, a feedback controls approach using an electrical conductivity based sensor produced an effectively controlled ER fluid response. Proportional and proportional-integral feedback control were examined to determine the most effective approach. Proportional control produced a significant decrease in time constants, 1400-1700%, but only attained 56% of the desired electrical conductivity level. The proportional-integral controllers were found to be most effective in terms of precision, they decreased the fastest settling time by up to 170% and attained up to 99.8% of the desired state. All measured results were within the predicted model limits. The conclusions of this study provide a means for the control of viscosity, electrical and heat transfer properties to be used in further applications.

With precise control and increased speed, the ER fluid can be used in commercial applications. Future work should include the investigation of the optimum control strategy for specific fluid concentrations as well as for known water content. It is also important to proceed with simultaneous visual and state measurement techniques to determine the chaining mechanisms behind some of the unusual observed behaviors. Proportional-integral feedback control allows the use of ER fluid properties through increasing the speed of response by at least 170% and an decreasing the system steady state error from 100% down to 0.2%.

APPENDIX A

APPENDIX A

Some of the response trends associated with the ER fluid were seen in experiments with the conductivity. The presence of these trends give further evidence to the validity of conductivity as an ER fluid sensor. These are shown here for reference because they are important to the overall understanding of ER fluids.

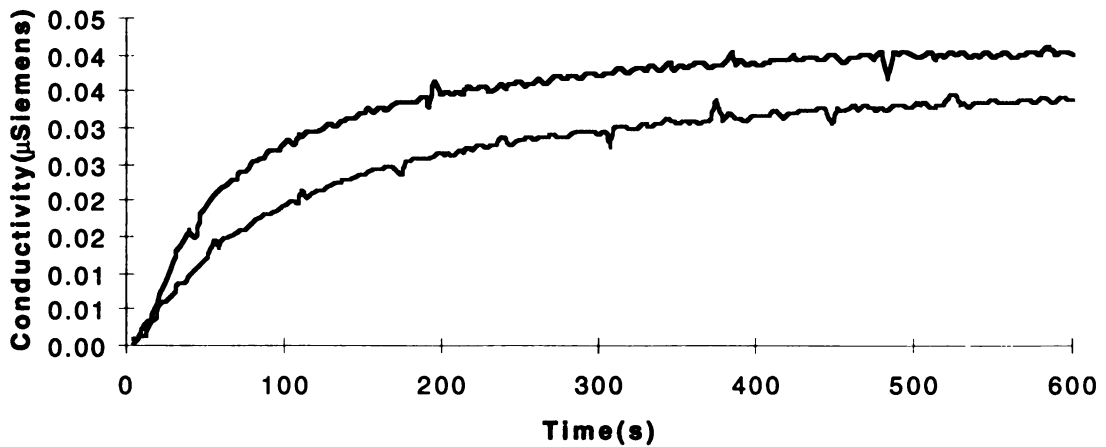


Figure A1 - Comparison of electrical conductivity measurements of two different ER fluid concentrations under a field strength of 500 VDC/mm (10% by weight)

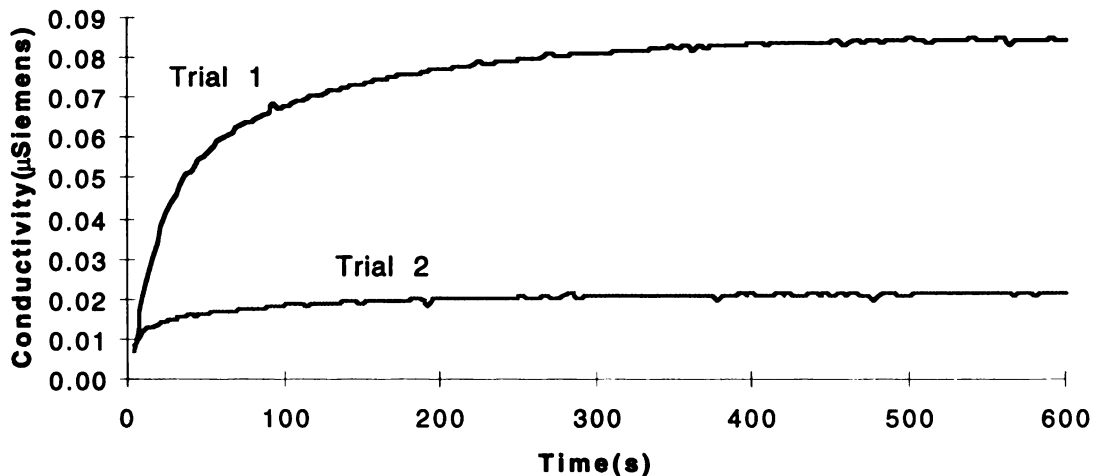


Figure A2 - Comparison of electrical conductivity measurements of the same ER fluid taken under identical field strengths of 700 VDC/mm before and after twenty-four hours of settling (10% by weight)

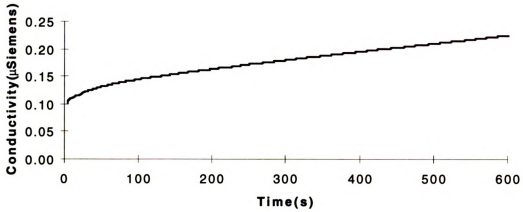


Figure A3 - Saturation of an ER fluid under a field strength of 1000 VDC/mm (10% by weight)

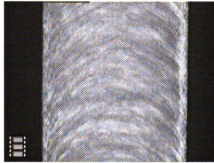


Figure A4 - Microscopic views of broken chains in a previously activated ER fluid

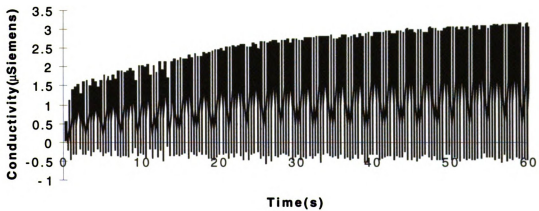


Figure A5 - Proportional controller response of the ER fluid at a desired conductivity of $0.5 \mu\text{Siemens}$ for $K_p = 65$ (10% by weight)

APPENDIX B

APPENDIX B

The programs for both the data acquisition and control are shown here for clarity. The front panels associated with the three devices demonstrate the capabilities of each. Programmed as virtual instruments in National Instruments LabVIEW, they act as mechanical devices with the ability to sent and receive data. Three programs were used: a simple data acquisition program for a constant applied field (Figure B1), a data acquisition program for a step field (Figure B2), and a proportional-integral controller (Figure B3).

The simple data acquisition program first specifies the device(NB-MIO-16 L Board) and the input and output channels on the board. There are channels for the output of a field, and inputs for the current and applied field sensors. Data acquisition is determined by the amount of time the field is to be active and the rate at which the data is sampled. The number of points to be plotted on the graph was included to reduce the data points to a reasonable number and to provide a means to average the data over discrete time intervals. When the program has completed the data acquisition, it polls the user to specify a spreadsheet file to send the data to. When the data has been saved to the file, any error incurred during the program cycle is displayed along with a graph of the data.

The data acquisition program for the step field operated in much the same way with a few exceptions. First, the timing depends on the number of steps taken and the time allowed for each step which are both entered on the front panel. Second, the high and low voltages are also required.

The controller also specifies the input and output channels and the device, and the timing is specified as well as the sampling frequency. In this case, the user is not allowed to dictate the number of points on the graph 100 was designated as the number of points to average. An upper limit was also placed on the sampling rate. These two factors prevented the user from specifying a controller speed beyond the virtual

instruments capacity. The desired conductivity was input in Siemens and there are knobs that allow adjustments for both proportional and integral control. saturation voltage was provided to limit the output field.

Also included here is the program used to simulate the proportional-integral transfer function. This program was written and executed in Matlab. The data was then transferred to an Excel file where the plots were integrated with the measured data.

Data Acquisition for the ER Composite Structure

Device 3	Number of Points on the Graph 200	Sampling Rate 100.00
Field Output Channel 1	Field 200.00	Run Time 10.00
Current Input Channel 0	Error 0	Hours - 0
Field Input Channel 1		Minutes - 0
		Seconds - 0

Conductance (μ Siemens)

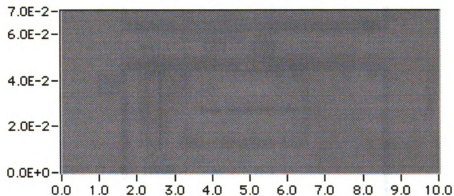
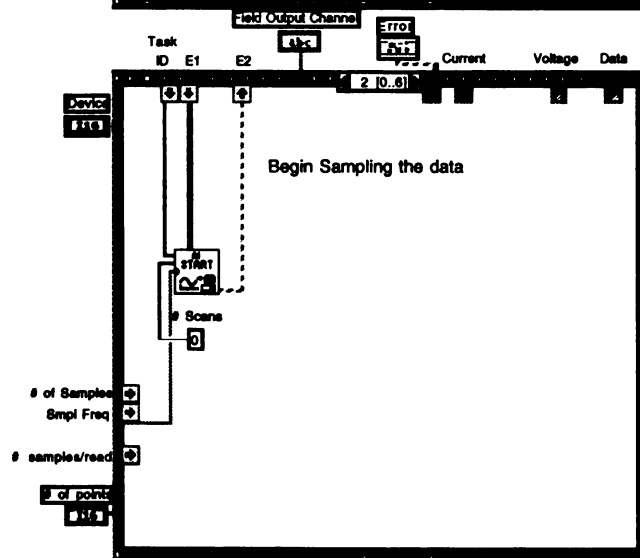
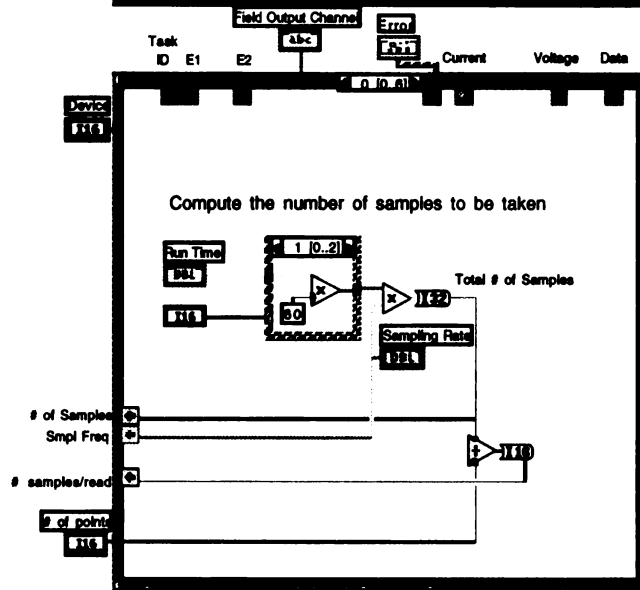
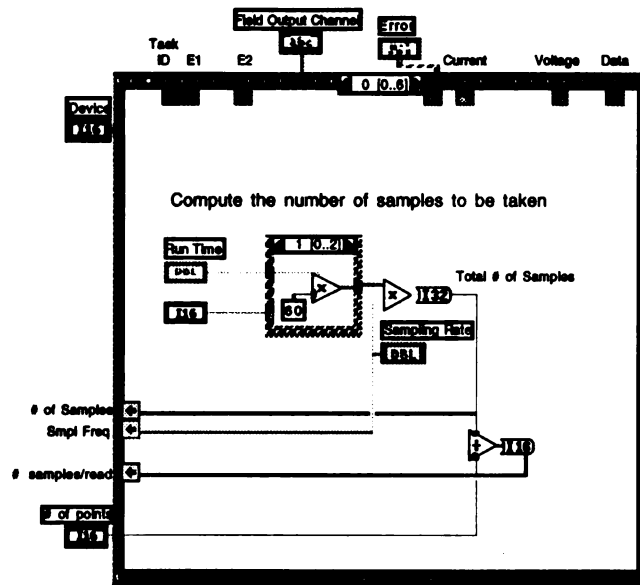
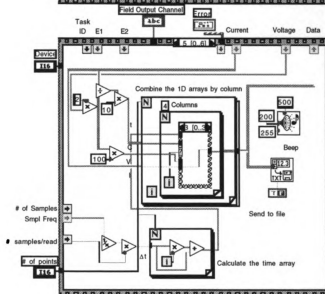
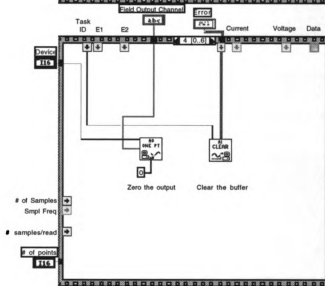
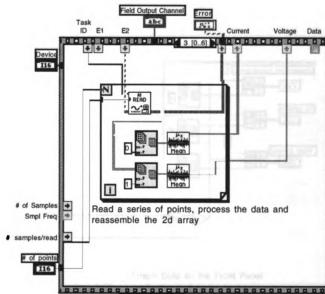


Figure B1 - Virtual instrument front panel for data acquisition of ER fluids composite structure





Data Acquisition for the ER Composite Structure

Device 3	Sampling Rate 100.00	Low Voltage 1000.0
Current Channel 0	Number of Steps 5	500.0 1500.0
Field Input Channel 1	Step Time 10.00	0.0 2000.0
Field Output Channel 1	Run Time Units Hours - 0	High Voltage 1000.0
Error 0	Minutes - 0	500.0 1500.0
	Seconds - 0	0.0 2000.0

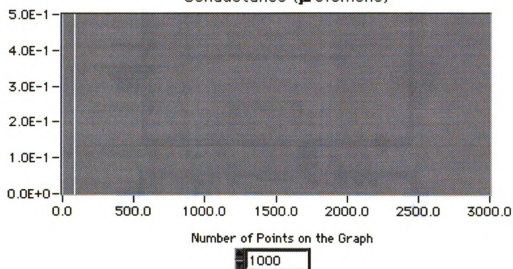
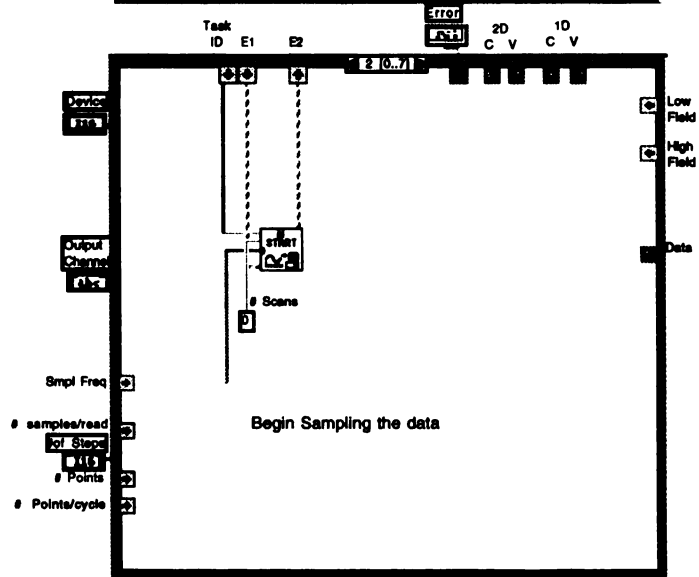
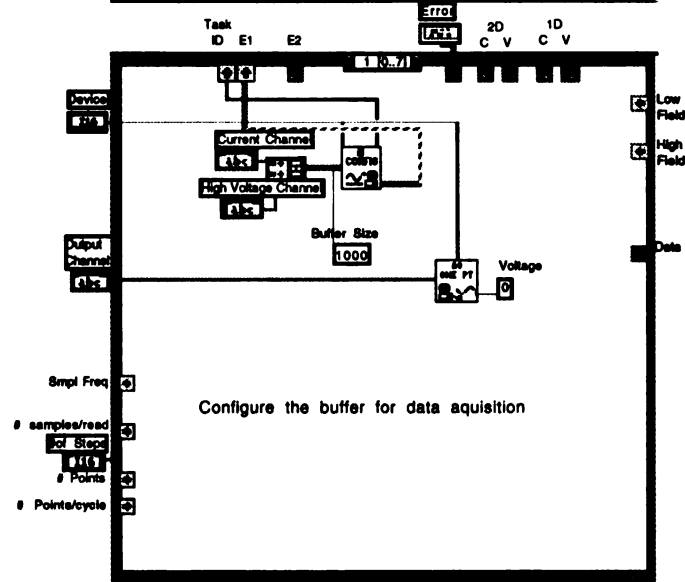
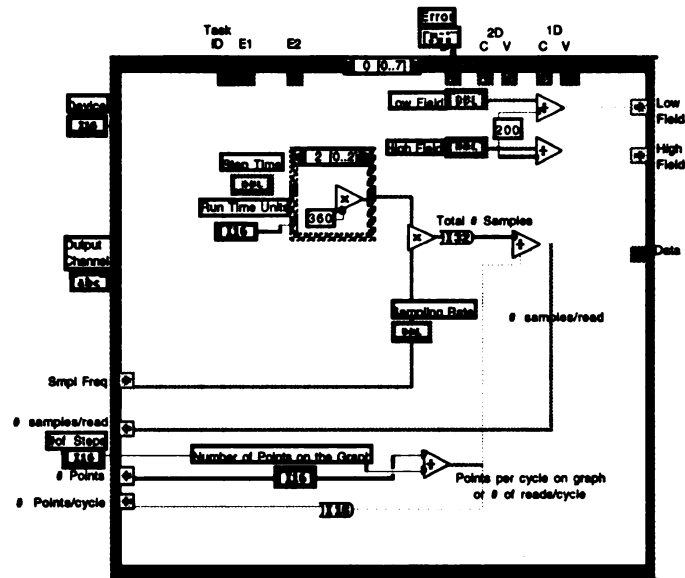
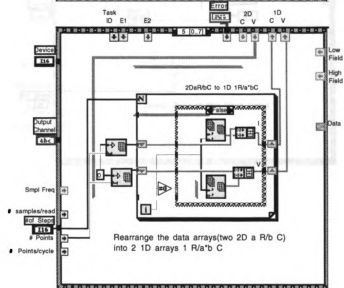
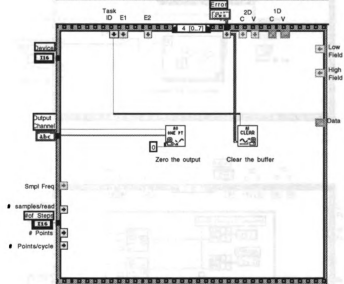
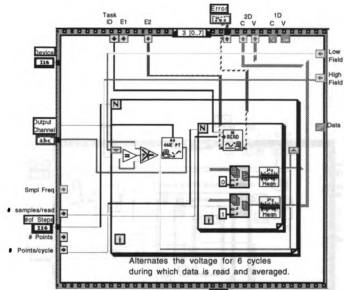
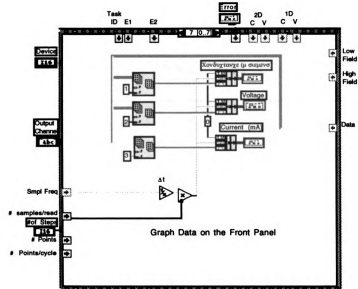
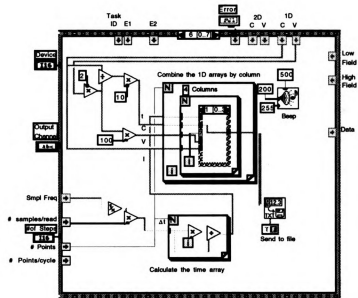
Conductance (μ siemens)

Figure B2 - Front panel for the data acquisition of the field applied in steps for the ER fluids composite structure







PI Controller for ER Fluid Composite Structure

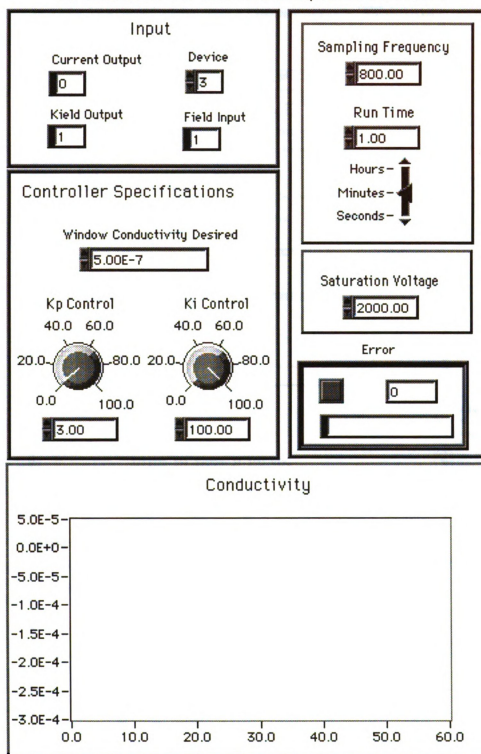
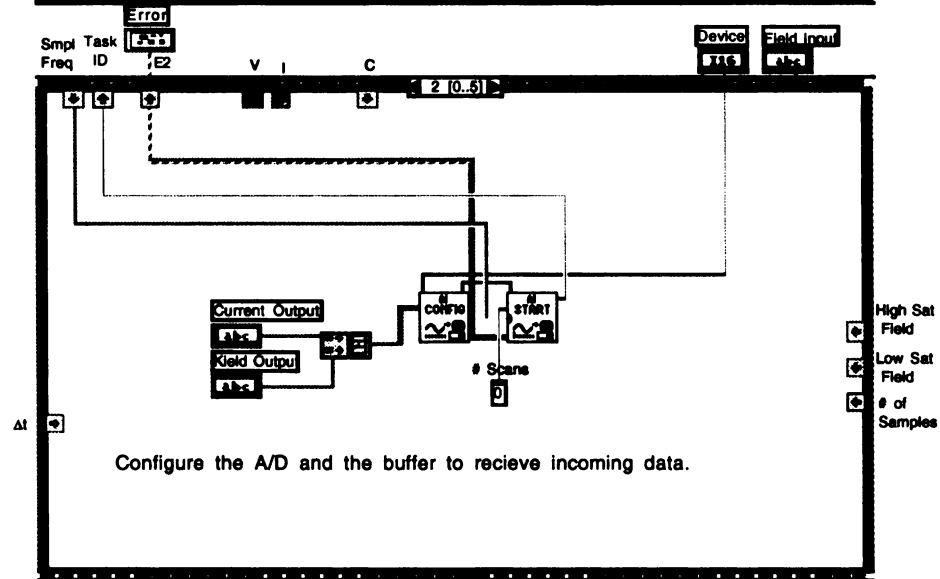
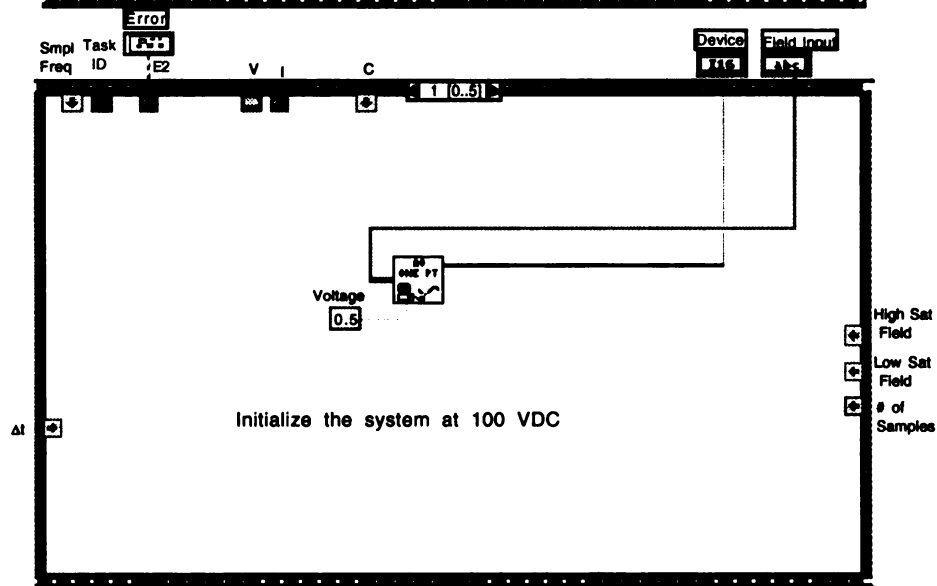
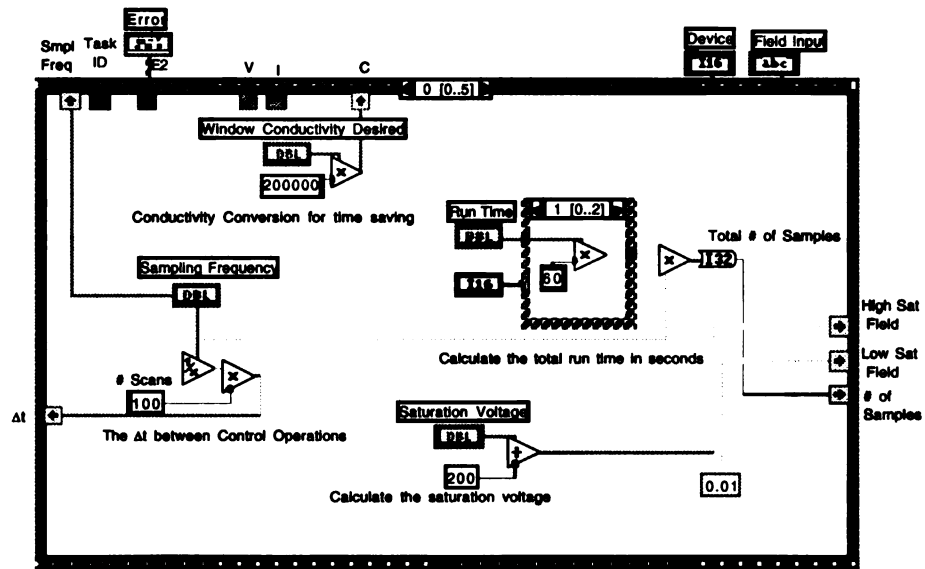
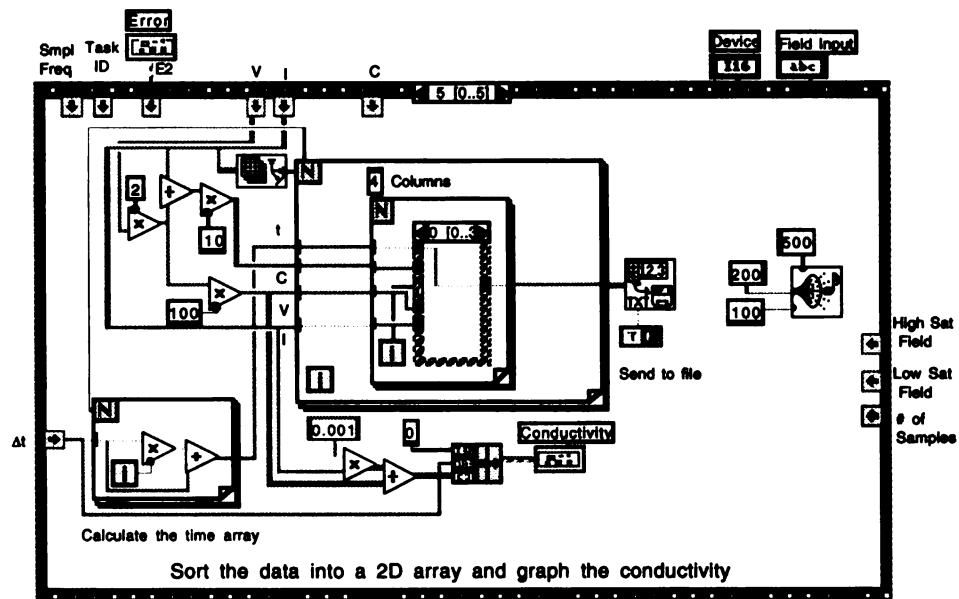
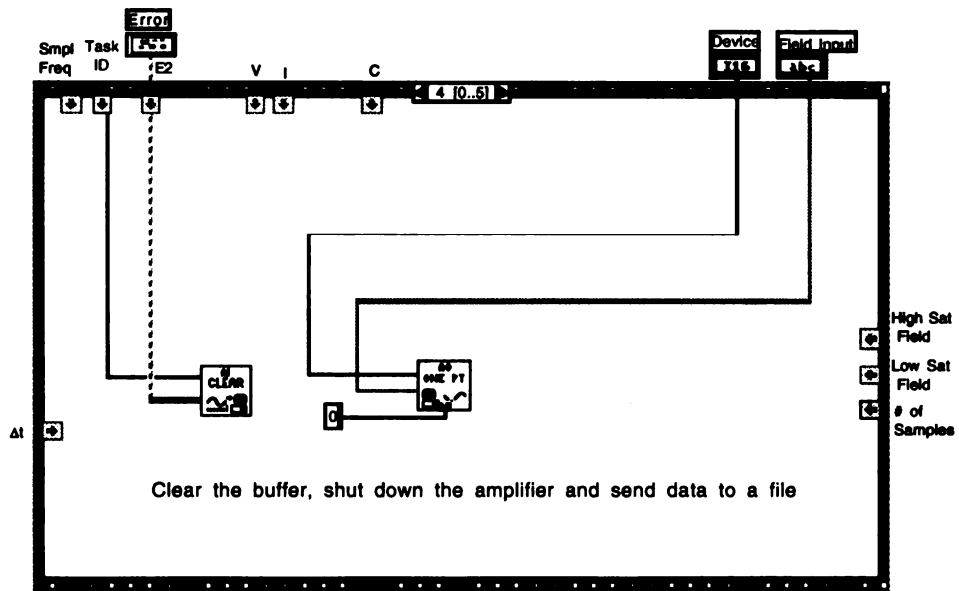


Figure B3 - Front panel for the proportional-integral controller for the ER fluids composite structure





PI Transfer Function Simulator
Written in Matlab

```
%    simulates the transfer function for the proportional integral control
%    with proportional control equal to three and integral control equal to
%    ten. The response will be plotted for the range of values
%    corresponding with the range of gain and time constants shown in
%    experiments with a ten percent ER fluid.
```

```
k1=1.12968;
k2=0.00458;
kp=3;
ki=10;
tau1=3;
tau2=119;
```

```
num1=[k1*kp k1*ki];
den1=[tau1 (1+k1*kp) k1*ki];
t=[0:0.125:60];
[y1,x1,t]=step(num1,den1,t);
y1=y1
```

```
num2=[k2*kp k2*ki];
den2=[tau2 (1+k2*kp) k2*ki];
[y2,x2,t]=step(num2,den2,t);
y2=y2
```

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