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FEEDBACK CONTROL OF ELECTORHEOLOGICAL FLUIDS

By

Ruth Marie Andersland

A THESIS

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

MASTER OF SCIENCE

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ABSTRACT
FEEDBACK CONTROL OF ELECTORRHEOLOGICAL FLUIDS

By
Ruth Marie Andersland

Electrorheological (ER) fluids have electrically controllable stiffness, viscosity, and heat transfer properties. Since the 1940s researchers have attempted to model the properties of ER fluids and have proposed applications which attempt to utilize their special characteristics in the operation of hydraulic valves, soft clutches, and active suspension systems. Early attempts to make these applications commercially successful were hampered by the relatively slow, nonlinear response of these fluids to the application of an electric field. These problems in response were attributed to the influence of particle volume concentration and moisture content, and to ER fluid temperature. In contrast, successful applications will require fast, precise control of the response of ER fluids, independent of those properties.

This study presents a new approach to the control of ER fluids that overcomes the problems of imprecise, slow, nonlinear response. A feedback-based approach to the control of ER fluid response was developed and compared to the conventional feed-forward control approach. A sensor was used to indicate the ER fluid state in a layered composite window. Feedback control employs the sensor and high initial electric field strength to speed ER state response, then lowers the field strength to the level required to achieve the desired ER fluid state. Predicted responses were compared to experimentally measured responses and showed excellent agreement. In fact, it was demonstrated for the first time that the proportional feedback control system responded 35 times faster and 21 times more accurately than the feed-forward system.

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NOMENCLATURE

Arabic Symbols

C	=	ER fluid state
C_{fb}	=	ER fluid state of the feedback system
C_{ff}	=	ER fluid state of the feed-forward system
C_N	=	output due to input N
C_R	=	output due to input R
D	=	controller
E	=	error
G	=	system or plant (ER fluid)
H	=	ER fluid state sensor
k	=	system gain
K_{equ}	=	equivalent gain K
K_p	=	feedback proportional gain
N	=	external system disturbance
R	=	desired ER fluid state
s	=	Laplace transfer variable
T	=	transfer function
U	=	input electrical field
V_{actual}	=	actual measured voltage level
$V_{desired}$	=	desired voltage level
V_o	=	nominal drive voltage
W	=	nominal drive voltage
Y	=	output from controller

Greek Symbols

ΔC = ER fluid state signal

λ = wavelength

τ = system time constant

τ_{equ} = equivalent time constant

INTRODUCTION

As early as the 19th century (Konig 1885; Duff 1896; Quinke 1897), scientists began studying electrorheological (ER) response, though it was not until research by Willis M. Winslow that electro-viscous phenomena gained prominent attention. He introduced the concept of controlling the viscosity of an electro-viscous fluid by the use of an electric field (Winslow 1947, 1949). Flow resistance of these fluids increased with field strength when exposed to AC electric fields on the order of 4kV/mm. He observed a fibrous structure composed of particle chains generally aligned with the applied electric field. Winslow hypothesized that the field increased the viscosity of the fluid.

An ER fluid consists of fine polarizable particles suspended in a fluid of lower dielectric constant. The fluid consists of a continuous hydrophobic liquid phase which contains hydrophilic particles. It is desirable that the density of the particle should be

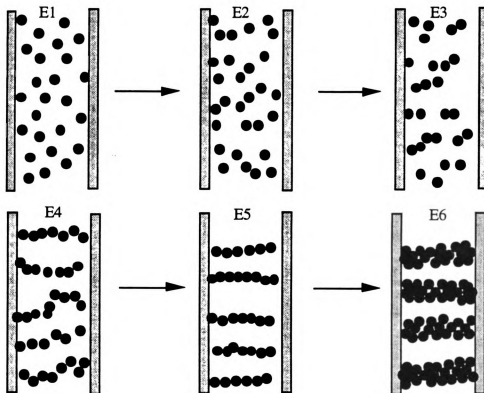


Figure 1: Particle polarization and single sphere width chain formation with increasing field, E. Particle chaining changes fluid properties.

matched as closely as possible with that of the oil to ensure good dispersion upon mixing of the ER fluid (Stangroom 1978, 1983). In the presence of a high voltage electric field, particle chains are formed due to polarization changing fluid properties (Figure 1).

Higher field strength causes the chains to pull together tighter and to increase in length (Klingenberg et al 1989). At very high field strengths (e.g. 2000 V/mm), the lowest energy state for the chains, ER fluid develops into a body centered cubic (Figure 1-E6) (Tao and Sun 1991a, 1991b). Arcing will occur at higher field levels. When the chains are subjected to a shearing force, the particles still attract even though they may be pulled away from each other (Duclos et al 1988).

Engineers and scientists have identified possible applications that would utilize the special properties of ER fluids. The sensitivity of properties of ER fluids to an electric field means that microprocessors can be used to control dynamic mechanical systems whose response is determined by that of the ER fluid. The systems would be connected directly to computers in order to control response in a rapid and precise manner. Possible applications include vehicle suspensions, hydraulic valves and soft clutches.

Development of commercial applications of devices using ER fluids has been hampered by the fact that (Butters 1995) science and industry have not been able to quickly and precisely control the ER fluid state to capture the full potential of the ER controllable properties. Electrorheological fluid applications have not responded accurately, which suggests that a new control strategy is necessary for successful commercialization to occur.

Previous studies have focused on varying essential aspects of ER fluids including ER effect, preparation of an ER fluid, particle temperature range, yield strengths, shear stress, and the control of systems harnessing ER fluid properties. Despite some progress in these areas of research, precise control of the variable ER fluid has eluded investigators. In this investigation we studied the basic problem of control of the state and the properties of an ER fluid so that all applications could benefit from the results.

Many previous studies focused on the development of new fluid types. The basic ER fluid consists of a suspension of hydrophilic particles in a hydrophobic fluid (Winslow 1962). Polymeric materials have been extensively investigated for use as particles and are often chosen for enhanced viscosity performance and specific mechanical applications (Stangroom 1977, 1978, 1980, 1984; Block and Kelly 1986). Environmentally safe fluids that more readily transform from a Newtonian material to a Bingham plastic have also been examined (Stangroom 1982; Block and Kelly 1986). Filisko and Armstrong (1988) were able to prepare particles at very high temperatures ($>100\text{ }^{\circ}\text{C}$ @ atmospheric pressure) without releasing water. The resulting ER fluid is particularly useful in automotive and other high temperature applications.

Other individuals turned their attention to modeling the ER phenomena. A simulation method was developed to describe structure formation in electrorheological suspensions (Klingenberg et al 1989). Tao and Sun (1991a, 1991b) examined the ground state and the various phases that exist in the ER fluid. The dynamic stress-strain behavior of an ER fluid was investigated by Yen and Achorn (1991). Properties were determined for an ER fluid consisting of 20% vol. zeolite particles, and a model was proposed to explain the mechanical response in terms of the dielectric mismatch between particles, carrier fluid, and field (Conrad et al 1991).

The issue of control of response in ER fluid applications has continued to perplex engineers. ER fluids of high volume concentration are usually considered fast to respond to the application of a field. Low particle volume concentrations are typically thought to be slow. However, even high particle volume fraction ER fluids may be too slow in some applications where very fast response is necessary. In both cases the precision of response may be a concern.

Devices such as ER fluid based valves, clutches or hydraulic mounts typically do not react quickly enough to meet needs of the application even with their enhanced performance over those of conventional oil fluids. These devices use high particle

volume concentrations, but the physical problem requires faster responses (Duclos 1987; Ushijima et al 1988, Arguelles et al 1973). Stangroom (1983) recognized the importance that feedback would add to device control system applications. The ER fluid responded quickly, but the intended control was of the mechanical device rather than of the fluid. On the other hand, Lloyd and Zhang, (1994) and Zhang and Lloyd, (1992a, 1992b) used low particle volume fluids to control transport of thermal energy by a feed-forward control method and found very slow ER fluid response. They reported that response time was several minutes as compared to fractions of seconds with high particle volume concentrations. In either way fast, precise response was not possible; this fact prevented success of application. Control of the ER fluid response controls the success of the application.

The control level within the ER fluid application is important. Three types of ER fluid control are possible: ER fluid device, ER fluid properties, and ER fluid state. The response of ER fluid devices is dependent on the properties of the ER fluid contained in them. The properties of the ER fluid are dependent on the chaining state of the ER fluid. The chaining state is dependent on the applied electrical field. Past work has concentrated on device and fluid property control (Arguelles et al 1973; Stangroom 1983; Duclos 1987; Ushijima et al 1988; Zhang and Lloyd 1992a, 1992b; Lloyd and Zhang 1994). The following work focuses on control of the ER fluid chaining state which alters ER fluid properties effecting successful device control.

In this study, a comparison is made between feedback and feed-forward control of low particle volume concentration ER fluid state. Analytical models for the ER fluid and control systems were developed which predict ER fluid state responses to the application of a varied DC field drive and were compared to experimentally measured responses. Greater control of the accuracy and speed of ER fluid response was the objective. Effective and efficient control of an ER fluid is necessary in order to achieve the benefits

of polarized ER fluid particles. This will lead directly to commercially successful applications, which were here-to-fore not possible.

FEED-FORWARD AND FEEDBACK CONTROL SYSTEMS COMPARED

There are two traditional methods for controlling an ER fluid state response: feed-forward, and feedback. In feed-forward control, sometimes called "open-loop" control, the response of a system is controlled by manipulating system input based on knowledge of the relationship between system input and system output. In feedback control, sometimes called "closed-loop" control, the desired system output is compared to the measured output and the difference is used to drive the controlled system. This use of feedback allows more precise control of system response in the presence of noise and variations in controlled system behavior than is possible with feed-forward methods.

Successful feed-forward control (Figure 2) requires invariant system behavior and limited noise to precisely control system response. Though the ER fluid system is nonlinear, it is assumed the system can be modeled linearly. To achieve a desired output, an input value is selected using knowledge of the relationship between input and output, $G(s)$. Feed-forward control design involves inversion of that relationship, $D(s)=1/G(s)$.

$$C_R(s) = D(s)G(s)R(s) = G^{-1}(s)G(s)R(s) \quad (1)$$

The accuracy of the control system is defined by the accuracy of the known relationship between input and output. The presence of any external disturbance disrupts the controlled system's accuracy.

$$C_N(s) = G(s)N(s) \quad (2)$$

Here, the disturbance is modeled as an additional system input. The total system output,

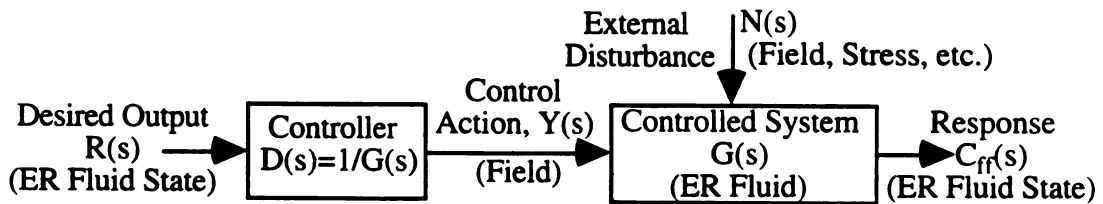


Figure 2: Feed-Forward Control System

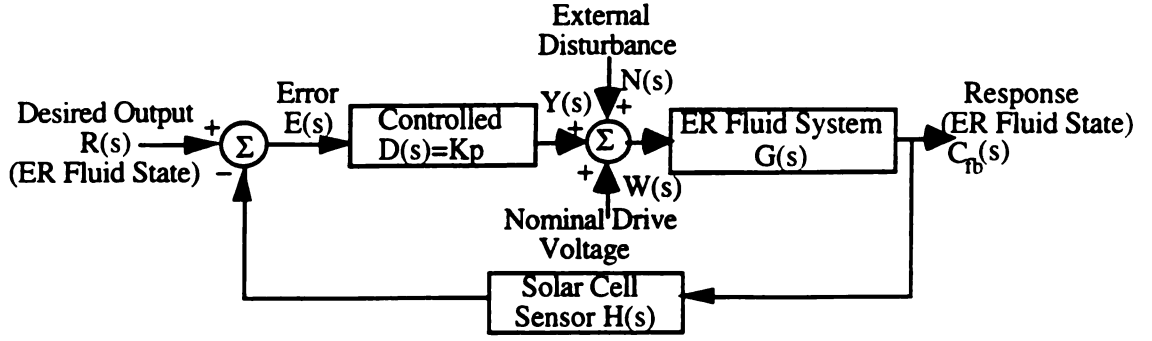


Figure 3: Feedback Control System

$C_{ff}(s)$, is the sum of the outputs due to the control (1) and external disturbances (2).

$$\begin{aligned} C_{ff}(s) &= G(s)[D(s)R(s) + N(s)] \\ &= R(s) \text{ iff } D(s) = G^{-1}(s) \text{ and } N(s) = 0 \end{aligned} \quad (3)$$

Accurate feed-forward control requires both exact knowledge of the controlled system, $G(s)$, and minimal disturbance, $N(s)$. It is apparent that any changes from the nominal values of either the controller $D(s)$ or the controlled system, $G(s)$, (Figure 2) for the feed-forward system will cause proportional errors in the response, $C_{ff}(s)$.

Feedback control uses measured system output to drive the control system (Figure 3). The actuating error signal is the difference between desired and measured system output signals. The objective of feed-back control is a design, $D(s)$, which systematically reduces the actuating error. Proportional control, K_p , is the simplest form of feedback design between the controller output, $Y(s)$, and the actuating error signal, $E(s)$.

$$D(s) = K_p = \frac{Y(s)}{E(s)} \quad (4)$$

System error, $E(s)$, for the feedback controlled system is driven by desired output, $R(s)$, and measured system output, $C_{fb}(s)$.

$$E(s) = R(s) - H(s)C_{fb}(s) \quad (5)$$

The nominal input, $W(s)$, maintains the controlled system at its nominal output value when system error, $E(s)$, becomes zero. External noise, $N(s)$, nominal input, $W(s)$, and control action, $Y(s)$, add to form the control system input.

$$C_{fb}(s) = G(s)[N(s) + W(s) + K_p E(s)] \quad (6)$$

Combining (5) and (6) yields an expression for feedback controlled system output, $C_{fb}(s)$.

$$\begin{aligned} C_{fb}(s) &= \frac{G(s)[W(s) + K_p R(s) + N(s)]}{1 + K_p G(s)H(s)} \\ &= R(s) \text{ iff } K_p \rightarrow \infty \text{ and } H(s) = 1 \end{aligned} \quad (7)$$

Accurate feedback control requires both accurate gain k , and feedback sensing, $H(s)$.

The primary objective of implementing feedback is to reduce the sensitivity of the system to parameter variations and disturbances. Applications of feedback to, $G(s)$, of ER fluids is ideal since it is inherently non-linear, fluid, and hysteretic. The hysteretic, non-linear nature of ER fluids (Figure 4) has been previously observed (Tabatabai 1993) at low particle concentrations. Feedback reduces sensitivity to the system by using a high quality sensor and implementing high gain.

Feed-forward and feedback control systems are both advantageous for particular, but different situations. The feed-forward control system (3) is ideal when external disturbances, $N(s)$, are small and when there is an exact knowledge of the controlled system response, $G(s)$, because the expense of an external sensor is not required. Past work has clearly shown that accurate models of ER fluid state are unavailable and

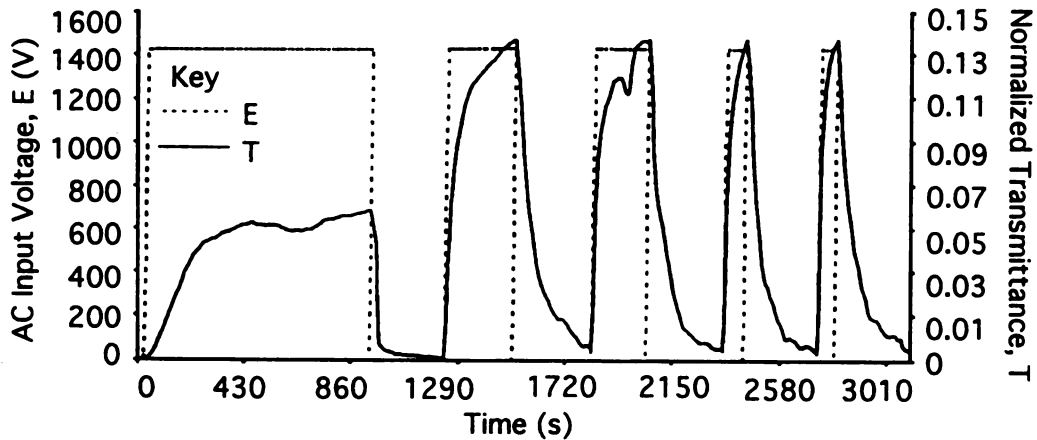


Figure 4: Laboratory measurement of zeolite ER fluid response using a prototype optical sensor feed-forward control, pulse train zeolite-fluid (1% Vol. Fraction, Dry) (after Tabatabai, 1993).

elimination of noise is difficult. The feedback control system (7) is ideal when a high quality sensor, $H(s)$, is available and the expense of implementing high gain K_p , is justified. Even when the ER fluid state response model changes dramatically with time, the feedback controlled ER fluid state responds accurately.

The ER fluid state response can be modeled as a first order system where $C(s)$ is the output ER fluid state, $U(s)$, is the input electrical field, k is the system gain, and τ is the system time constant. The ER fluid state gain k , and the associated time constant τ have been observed to vary widely (Figure 4).

$$G(s) = \frac{k}{1 + \tau s} = \frac{C(s)}{U(s)} \quad (8)$$

Assuming the availability of sensor, $H(s) \neq 0$, and substituting (8) into (7),

$$\begin{aligned} T(s) &= \frac{C_{fb}(s)}{R(s)} = \frac{kK_p / (1 + \tau s)}{1 + [H(s)kK_p / (1 + \tau s)]} \\ &= \frac{kK_p / (1 + H(s)kK_p)}{1 + [\tau / (1 + H(s)kK_p)]s} = \frac{k_{equ}}{1 + \tau_{equ}s} \end{aligned} \quad (9)$$

where

$$\begin{aligned} \tau_{equ} &= \frac{\tau}{1 + H(s)kK_p} \rightarrow 0 \text{ as } K_p \rightarrow \infty \\ k_{equ} &= \frac{kK_p}{1 + H(s)kK_p} \rightarrow \frac{1}{H(s)} \text{ as } K_p \rightarrow \infty \end{aligned}$$

For a large K_p , τ_{equ} approaches zero, and the system will have a faster response time.

A response time is considered fast if it is significantly shorter than the previous response times. For example, if K_p is increased by an order of magnitude and the response time decreases from 11 minutes to 1 minute, that would be a fast response time with increasing K_p . Similarly, an increasing K_p forces the steady state error to become small. Steady state error occurs when the output of a system's steady state does not exactly agree with the input. Steady state error could be caused by any number of reasons, such as hysteresis, amplifier drift, or aging or deterioration of system components. Model predictions of τ_{equ} approaching zero and k_{equ} approaching one with increasing K_p , were demonstrated in the experiment.

The effects of the sensor, $H(s)$, are minimized with an increasing K_p , as long as $H(s)$ remains non-zero. The sensor has a greater influence on the gain k_{equ} . By increasing K_p , $k_{equ} = 1/H(s)$, the inverse of the sensor transfer function. The system requires a high quality sensor with near unity gain for precise feedback response. The sensor transfer function, if constant, reduces steady state error because increasing K_p decreases the steady state error.

The accuracy and speed of feedback control are determined by the response measurements of k_{equ} and τ_{equ} respectively. Feed-forward fails to provide the accuracy and speed necessary for ER fluid state response systems with variable behavior (Figure 4) and inevitable external disturbances. In fact, the feed-forward system will cause proportional errors in the response to changes in the system, $G(s)$, (Figure 2). Feedback control retains more precise control of system response in the presence of noise and variation in system behavior. By design, feedback systematically reduces the actuating error (Figure 3). Transient feed-forward system measurements will determine both the ER fluid state gain k and time constant, τ . These calculated values are used as the basis for the model predicted values of k_{equ} and τ_{equ} with feedback to be compared with measured feedback response.

PROTOTYPE CONTROLLED ER FLUID TEST SYSTEM

An ER fluid prototype control system was designed and tested using feed-forward and feedback control of the ER fluid state response. Measurements for accuracy and speed of feedback control of an ER fluid state response were compared with model predictions. The experiment (Figure 5) consisted of 4 distinct features: an ER fluid state sensor, ER fluid window, an amplifier, and a computer controller.

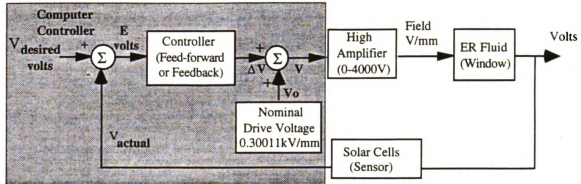


Figure 5: Experiment Schematic

ER Fluid State Sensor

To implement an ER fluid state sensor it must detect and respond to small or large changes in the ER fluid state in a measurable way. A sensor must be reliable, its results reproducible. Light will pass through a thin layer of ER fluid having low particle concentrations. Particle chaining in the ER fluid (Figure 6) permits greater passage of

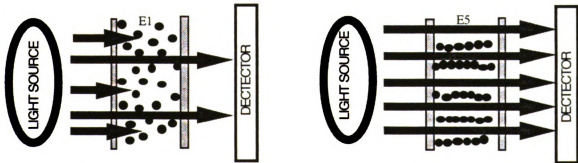


Figure 6: Conceptual design of an optical ER fluid state sensor when light penetrates the ER fluid state. E1-Light penetrating dispersed particles; E5-Light penetrating chained particles.

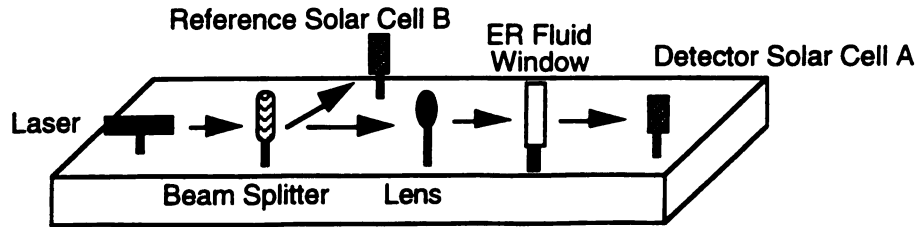


Figure 7: ER Fluid State Sensor and Window Setup

light, so that the extent of chaining can be indirectly measured by the concentration of light reaching a detector. When little or no electric field is applied, the particles are random and dispersed, (Figure 6-E1) and only a small amount of light passes through the window. With increased field (Figure 6-E5), the particles form parallel chains and the ER fluid state response allows more light to pass through the window. Two difficulties in choosing an appropriate sensor and light source are the extended time of the experiment, and the effects of small changes in the surrounding room light on the sensor. A steady light source capable of functioning for the length of the experiment is essential.

The sensor design consisted of two Archer silicon solar cells and an Edmund Scientific beam splitter. A M1650 Toshiba laser diode ($\lambda=650\text{nm}$) provided the light source. Detector solar cell A, used in coordination with reference solar cell B, permitted evaluation of the true transmittance regardless of the light beam steadiness (Figure 7). A fifty-fifty light split to the two solar cells was provided by the beam splitter. A gain of 1000 and 100 was used on solar cells, A and B respectively. This was to compensate for the nominal transmittance of the window glass. The ratio (A/B) of the amplified signals from the detector, A, and reference, B, determined the transmittance T , of the ER fluid state. The transmittance permitted the determination of the level of chaining in the ER fluid state.

ER Fluid Window

The ER fluid window must be capable of holding fluid, applying an even field across the window and allowing transmission of light. A well sealed, electric conductive

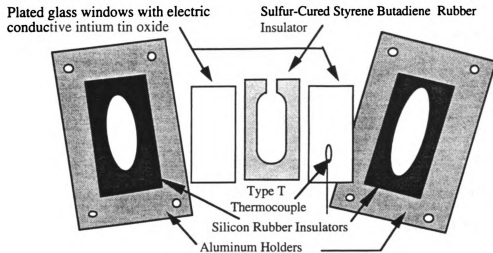


Figure 8: Composite Window Schematic

plated clear glass composite window meets these requirements (Figure 8). The seal is important, to keep the ER fluid in place and to last the length of the experiment. The ER fluid window was also insulated, had replaceable sections and permitted the placement of a type T thermocouple to monitor fluid temperature. Insulating materials require good surface and bulk dielectric strength and resistivity, as well as chemical and mechanical stability (Stangroom 1983). The sections permitted easy cleaning and replacement of damaged layers. The window, two rectangular glass spectrophotometer cells (38mm x 19mm), was insulated from the aluminum frame by silicon rubber and sulfur-cured styrene butadiene rubber sections. The glass spectrophotometer cells were plated with electrically conductive antimony tin oxide on one side. The conductive coating permitted an even spread of electric field across the windows. To the naked eye the thin coating looked like an oil across the transparent glass. The coating's thickness was negligible. A small gap was left at the top of the center, sulfur-cured styrene butadiene rubber insulator, for insertion of the dispersed ER fluid. Once the window had been set in place, the thermocouple was placed between one side of the insulation and the glass cell to monitor

temperature. Since several of the characteristic fluid parameters are temperature dependent (Stangroom 1978), especially the current, temperature was monitored.

Electrorheological fluid was prepared by letting anhydrous crystalline zeolite particles adsorb water molecules. A moisture content of approximately 17.1% was measured by thermogravimetric analysis. This moisture content is consistent with preparations used by Winslow (1962). The average particle diameter was less than 10 microns of the agglomerate particle size, and the average crystal size was 1.0 to 4.0 microns (UOP, 1990). Particles (specific density 1.1 kkg/m^3) were mixed to a weight fraction of 3% with phenylmenthyl polysiloxane silicon oil (specific density 1.11 kkg/m^3). At low temperatures the intentional presence of adsorbed water is critical (Winslow 1962; Stangroom 1977, 1978, 1984) and mechanistically necessary in achieving the desired changes in viscosity during the presence of an applied electric field (Filisko and Armstrong 1988). To insure good random dispersion of particles, a magnetic stirrer was used for a period of 5-10 minutes. The solution was then left undisturbed until the majority of bubbles created from the stirring had risen to the surface. The ER fluid could then be inserted by syringe into the window arrangement (Figure 8).

ER Fluid Controller

The ER fluid controller was capable of performing both feed-forward and feedback control designs. The feedback controller was designed for proportional control and produced a change in output voltage proportional to the measured error in ER fluid state. User inputs included desired state, nominal drive voltage, and control gain K_p .

The nominal drive voltage provided a standard base above zero to start the two control approaches. This allowed comparison of the increase or decrease in change of field strength due to the desired ER fluid state. The 0.30 kV/mm nominal value was chosen only because it was a low non-zero voltage that still provided an upper range of change in electric field within equipment safety specifications. The controller was

written in the virtual instrument program language LabVIEW (Appendix B) for ease of use.

System Integration of Equipment

Arrangement of the ER fluid state control test system is shown in Figure 9. Direction of light, passage of signals, and transfer of information are displayed between each equipment item. The Trek 609C-6 high voltage amplifier (0-4000V) amplified signals from the controller to the ER fluid. Due to the possibility of voltage surges, an Archer 10M Ω carbon resistor and Archer metal-oxide varister 175VDC were included to protect equipment. The Hewlett-Packard Vectra 486 was implemented merely for convenience of data display. The Hewlett-Packard E3630A triple output DC power supply was chosen over batteries to operate the laser diode, because of the length of the experiment.

Accuracy of the ER fluid system was improved by experimental design and precision equipment. Errors associated with signal transmission from the controller to the

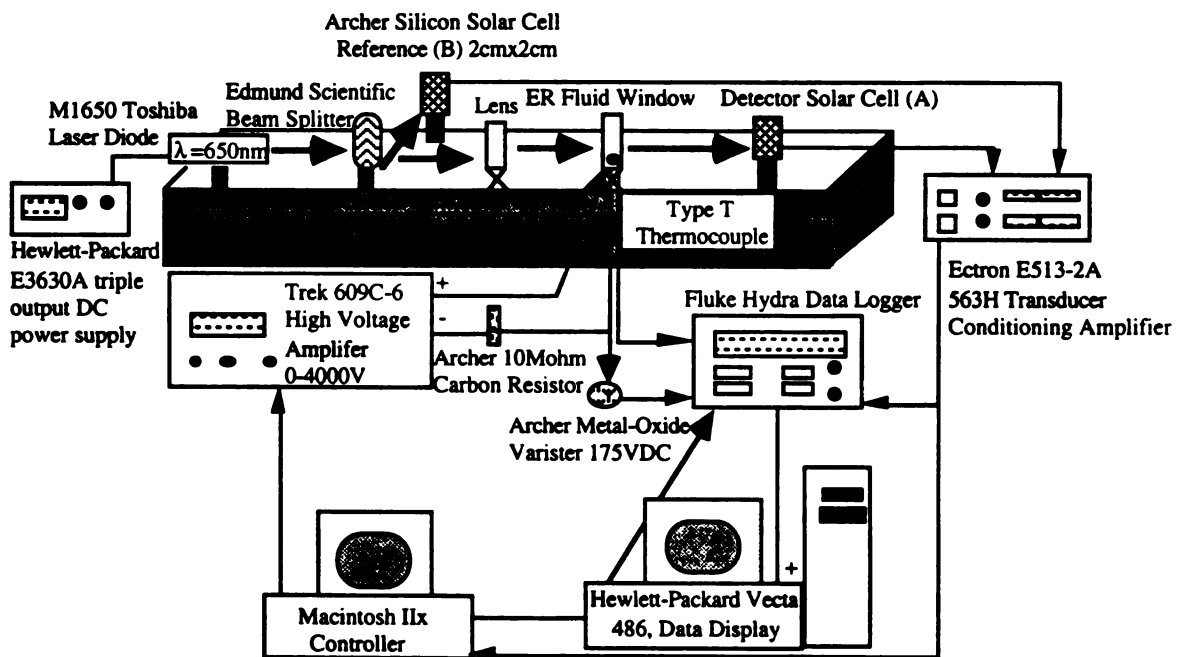


Figure 9: Laboratory Configuration

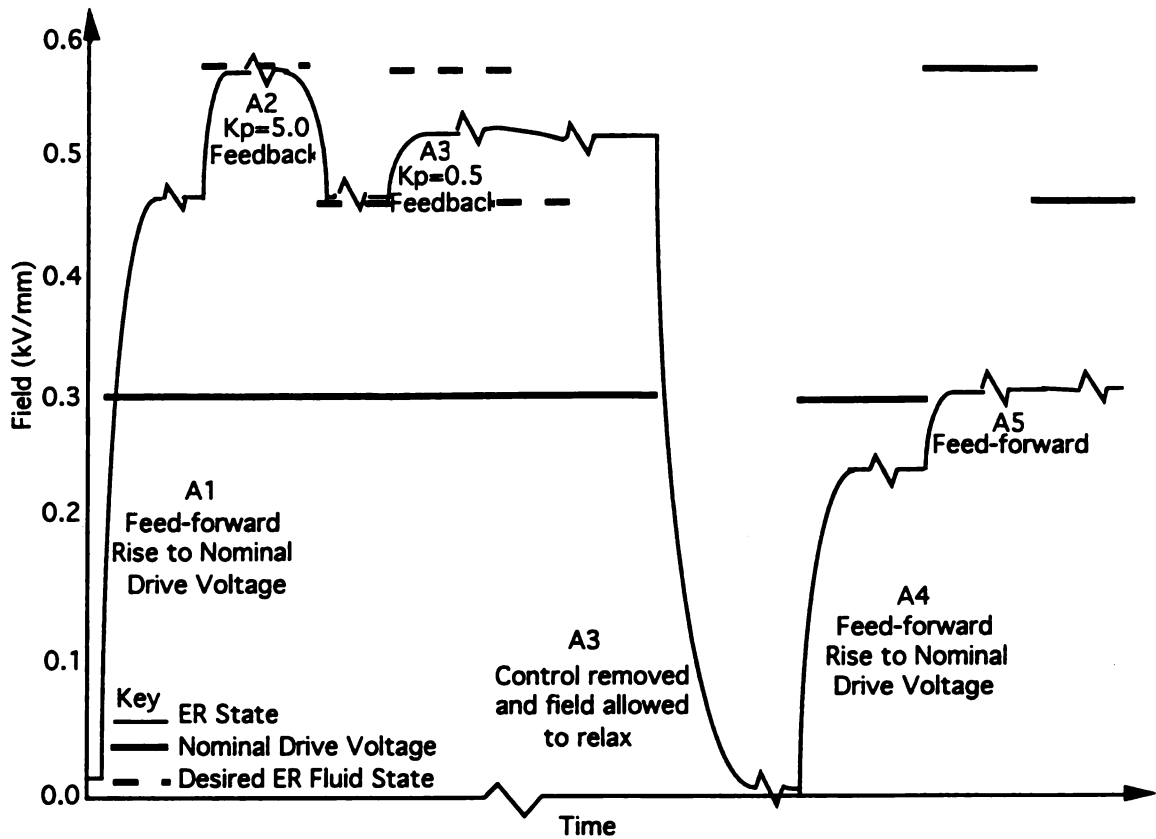


Figure 10: Experiment Sequence

Fluke Hydra data logger were observed to be less than 1%. Errors associated with output of the laser beam were eliminated by determining the measured state from the ratio of reference and detector solar cells signals. Observations of the same time sequence of experimental conditions resulted in measurements which differed by less than 5% including hysteretic effects.

ER Fluid State Tests, Experimental Procedure

Experiments were run using a systematic approach to maintain consistency between runs (Figure 10). The feed-forward and feedback runs each included 2 segments, the control and relaxation periods. At the start of each trial, the nominal drive voltage was 0.30kV/mm. The data logger monitored actual transmission level of both solar cells, current, DC electric field, desired ER fluid state, and temperature °C. The desired ER fluid state and proportional constant were then entered and the experiment would

commence. The ER fluid initially inserted into the window was used for all experiments in the sequence discussed here.

Each experiment began at steady measured state. A large change in field strength was followed by a small change in field strength in each run. Between the feedback and feed-forward runs the ER fluid state had all field removed and was permitted to relax from the chained state. The period of relaxation of the ER fluid state continued for 1.3 hours. The range of K_p and desired state values were limited to avoid a body-centered cubic state whereupon the particle chains would become locked and a decrease in DC field level would be unable to relax the chains.

Measured Feed-forward Control Response

In the feed-forward experiment the nominal drive voltage was equal to 0.30kV/mm. It was increased from a steady value of ER fluid state, as measured by transmittance T , to 0.50kV/mm, a large change in field strength (Figure 11). After steady ER fluid state was again reached, the nominal drive voltage was lowered to 0.4026kV/mm to reflect a small change in field strength. With feed-forward, the state sensor was used to provide a reading of the ER fluid state C_{fb} . The gain, k_{equ} , and time constant, τ_{equ} , for the feed-forward rise and decrease were determined using

$$k_{equ} = \frac{\Delta Y}{\Delta R} \quad (10)$$

where

ΔY = steady ER fluid state - rise to nominal ER fluid state

ΔR = desired ER fluid state - nominal ER fluid state

By establishing steady state at each level the time constant τ_{equ} , could be calculated.

The time constant τ_{equ} , for the feed-forward and feedback rise and decrease were determined using

$$\tau_{equ} = \text{to the corresponding time of 63.2\% of the steady ER fluid state} \quad (11)$$

The feed-forward rise for k_{equ} and τ_{equ} , were determined as

$$\begin{aligned}
 \frac{k_{equ}}{\tau_{equ}s + 1} &= \frac{(\Delta Y / \Delta R)}{\tau s + 1} \\
 &= \frac{(0.068 / 0.20008)}{2089.44s + 1} = \frac{0.340}{2089.44s + 1}
 \end{aligned} \tag{12}$$

where

$$\Delta Y = 0.311 - 0.243 = 0.068$$

$$\Delta R = 0.5002 - 0.30012 = 0.20008$$

and

$$\tau_{equ} = 0.632(0.147) = 0.093 \rightarrow 35 \text{ min.}$$

The same method was used in calculating k_{equ} and τ_{equ} of the feed-forward decrease.

The feed-forward decrease resulted in $k_{equ} = -0.09$ and $\tau_{equ} = 36$ minutes.

Measured Feedback Control Response

The feedback experiment with gain, $K_p = 0.5$, set the desired ER state to 0.47 kV/mm with a nominal drive of 0.30 kV/mm. After steady state was achieved, the desired ER state was raised to 0.56 kV/mm (Figure 12). The gain, k_{equ} , and time constant, τ_{equ} , for

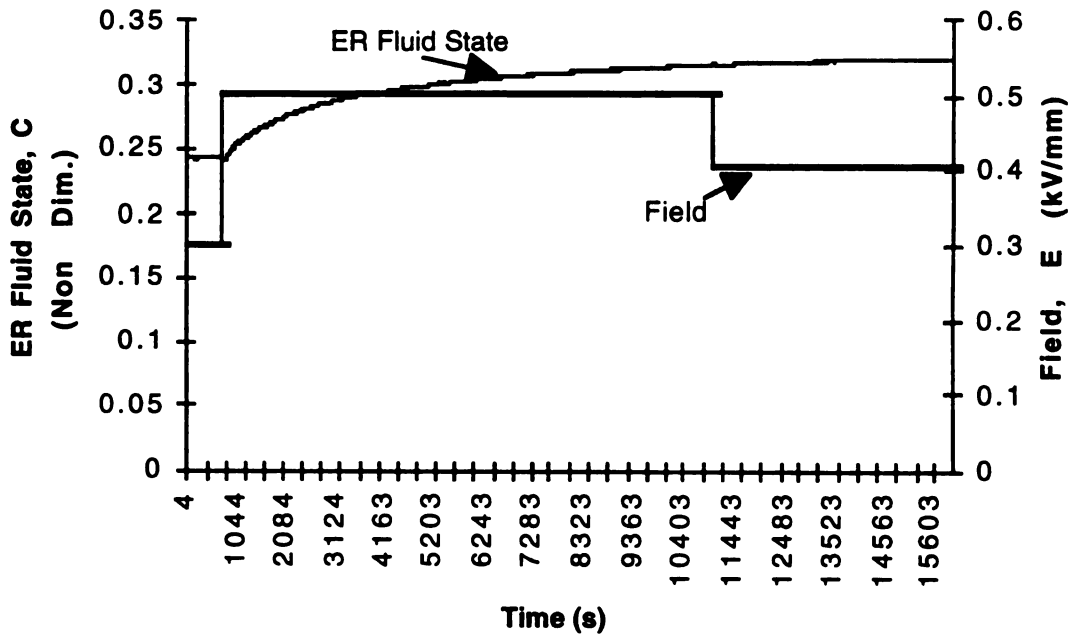


Figure 11: Feed-forward response of the ER fluid state and field. Relatively slow response by the ER fluid state.

the feedback rise and decrease were determined using (10) where

$$\Delta Y = \text{ER fluid state} - \text{steady ER fluid state}$$

$$\Delta R = \text{desired ER fluid state} - \text{steady ER fluid state}$$

(13)

and (11). The feedback rise for k_{equ} and τ_{equ} , were determined as

$$\begin{aligned} \frac{k_{equ}}{\tau_{equ}s + 1} &= \frac{(\Delta Y / \Delta R)}{\tau s + 1} \\ &= \frac{(0.042 / 0.085)}{672.2s + 1} = \frac{0.500}{672.2s + 1} \end{aligned} \quad (14)$$

where

$$\Delta Y = 0.524 - 0.481 = 0.042$$

$$\Delta R = 0.566 - 0.481 = 0.085$$

and

$$\tau_{equ} = 0.632(0.0447) = 0.0283 \rightarrow 11 \text{ min.}$$

The same method was used in calculating k_{equ} and τ_{equ} of the feedback decrease. The feedback decrease resulted in $k_{equ}=0.05$ and $\tau_{equ}=4.5$ minutes. The percent error from the desired ER fluid state was 7.5% for the rise, and 12% for the decrease. The decrease

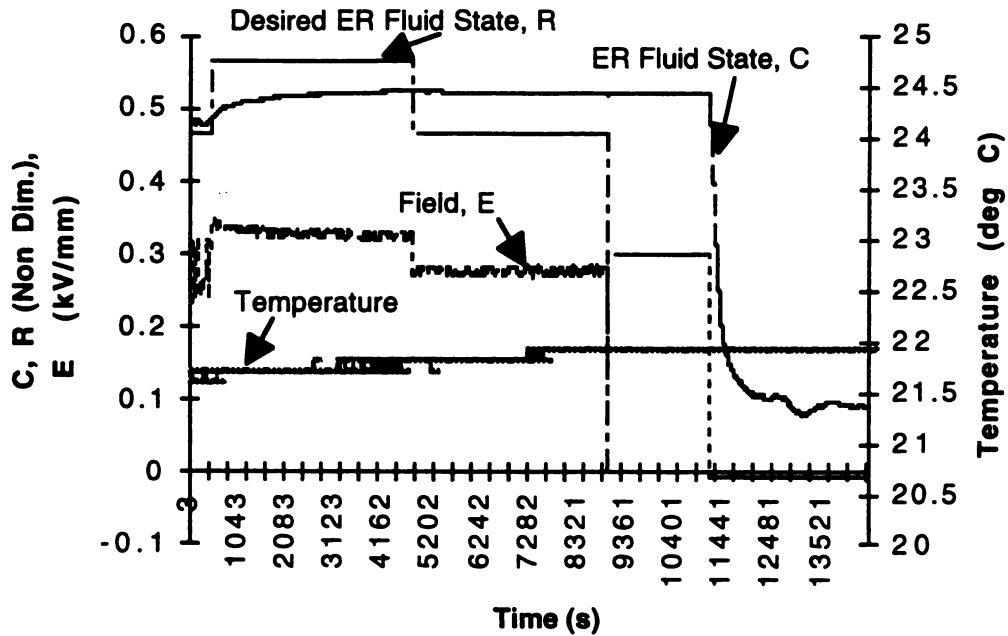


Figure 12: Feedback response of $K_p=0.5$, of the desired ER fluid state, ER fluid state, and field. The ER fluid state changed only negligibly when the field was lowered. Removal of the field forced the ER fluid state to fall. The temperature change was negligible.

had a larger difference because the forced maximum drop of ER fluid state would remove the field completely. The time constant τ for the decrease was misleading. The amount of change in the rise from the steady state point was negligible, therefore reached steady state faster, resulting in the faster time constant. The small gain was not strong enough to force the ER fluid state to the desired level. In addition, even when the field was lowered to the nominal drive of 0.30kV/mm, the gain was not large enough to overcome the effects of hysteresis and lower the ER fluid state.

The monitored temperature remained relatively constant. Temperature increase during the experiments was negligible, and remained just above room temperature at about 22 °C (Figs. 12, A1-A5). This validated that the other readings had not been adversely affected by temperature.

The feedback experiment with gain, $K_p=5.0$, repeated the desired ER state values (Figure 13). The gain k_{equ} , and time constant τ_{equ} , for the feedback rise and decrease were determined using (10) with (13) and (11). The feedback rise for k_{equ} and τ_{equ} were determined as

$$\begin{aligned} \frac{k_{equ}}{\tau_{equ}s + 1} &= \frac{(\Delta Y / \Delta R)}{\tau s + 1} \\ &= \frac{(0.068 / 0.078)}{59.1s + 1} = \frac{0.872}{59.1s + 1} \end{aligned} \quad (15)$$

where

$$\Delta Y = 0.556 - 0.488 = 0.068$$

$$\Delta R = 0.566 - 0.488 = 0.078$$

and

$$\tau_{equ} = 0.632(0.067) = 0.043 \rightarrow 0.99 \text{ min.}$$

The same method was used in calculating k_{equ} and τ_{equ} of the feedback decrease. The feedback decrease resulted in $k_{equ}=0.85$ and $\tau_{equ}=1.8$ minutes. The percent error from the desired ER fluid state and the actual ER fluid state was 1.7% on the rise, and 2.7% on the decrease. Again, the time constant τ for the decrease was misleading. The amount of change in the rise from the steady state point was negligible, therefore reached steady

state faster, resulting in the faster time constant. The field had an initial large field error which then reduces as the ER fluid state increases. A similar negative drop in field strength forced the ER fluid state to the lower desired level. The larger gain tracked the desired ER fluid state with very small steady state error. The desired level was both raised and lowered with the precise tracking relatively unchanged. The sensor in the feedback control system measured the ER fluid state and returned that value to determine the actuating error.

Changes in DC electric field reflect the effective feedback control action (Figure 13). The initial impulse of high field strength forced the ER fluid state to rise quickly. The response of fluid toward the desired ER fluid state was faster than if the field had been raised in slow increments. This impulse prevented damage to the ER fluid or equipment from too large a field imposed continuously on the window to force the ER fluid state to rise. The change in field strength is due to the actuating error increase as the desired level is altered. The field strength change becomes K_p times the actuating error. As the actuating error decreases the field decreases. A field variation can be readily

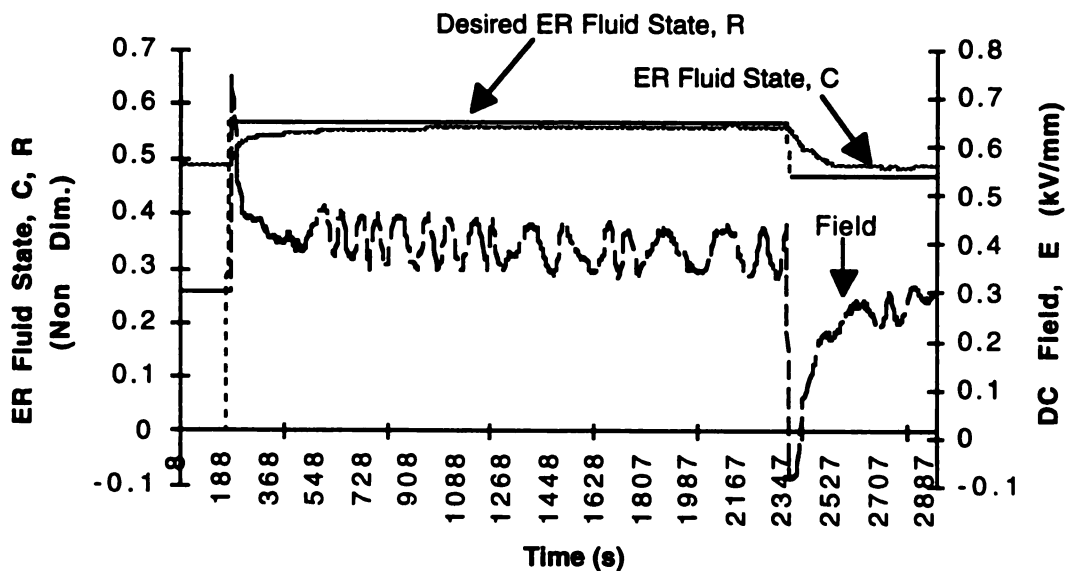


Figure 13: Feedback response of $K_p=5.0$, of the desired ER fluid state, ER fluid state, and field. A large positive and negative change in the field forced the ER fluid state to the desired level.

observed in the feedback response with large gain (Figure 13). These large oscillations effecting the field will be discussed later.

Accuracy and response time were much improved with the added feedback. The addition of feedback improved precision 5 times with the use of $K_p=0.5$ and over 21 times with $K_p=5.0$. As K_p increased, accuracy of the ER fluid state to the desired ER fluid state was increased. The feedback control system rise with $K_p=5.0$ was 35 times faster than feed-forward rise, and 11 times faster than feedback rise with $K_p=0.5$.

Settling of particles did not compromise either accuracy or response time over the experimental period of 13 hours 19 min. This agreed with observations by Goldstein (1990) and Monkman (1991). Settling did not effect control of the system since the field was frequently engaged (Duclos et al 1988; Goldstein 1990; Monkman 1991). The period of relaxation between feedback and feed-forward was of a short enough duration not to effect settling.

Simultaneous monitoring of the current, DC field, and temperature made it possible to detect possible variations that could occur in the ER fluid. The DC field reading was a confirmation of values entered from the control program during the feed-forward experiment. During the feedback experiment, DC field readings became a monitor of window conditions. The current, as previously observed, did not follow Ohm's Law (Scott and Yamaguchi 1983; Stangroom 1983), and reflected changes in the control system ER fluid state as well as external disturbances to the window (Figs. A1-A5).

ER State Feedback Model Validation

The analytical model (3) was used to predict gains and time constants from the measured feed-forward response. Due to the hysteretic nature of an ER fluid, feed-forward responses of the gain and time constant can vary considerably over time. Measurements were taken for feed-forward responses of the gain and time constant at both the beginning and conclusion of experiments. The range of responses, computed

Table 1: Comparison Between Computed and Measured Gains and Time Constants.
With increasing K_p , gains approached one, and the time constant decreased.

System Type	Measured		Computed	
	k	τ (s)	k	τ (s)
Feed-forward	0.34 - 7.5	350. - 2100.	----	----
Feedback $K_p=0.5$	0.51	670.	0.16 - 0.79	1800. - 79.
Feedback $K_p=5.0$	0.87	59.	0.63 - 0.97	770. - 9.2
Feedback $K_p=50.0$	----	----	0.94 - 0.997	116. - 0.94

both the beginning and conclusion of experiments. The range of responses, computed feedback, and actual feedback are given in Table 1. The computed gain and time constants were determined from the analytical model (9) using control gain K_p and measured feed-forward values of k and τ . These measured values of k and τ under feedback control fell into the ranges computed from the analytical model.

The effect of K_p decreases the magnitude and range for both k and τ . This decrease in range improves precision by decreasing the steady state error, and decreases the response time of the ER fluid control amplifier. Since K_p and τ are inversely proportional, the increase in K_p decreases the ratio for gain k and increases the ratio for τ . Increasing K_p forces $k \rightarrow 1.0$ and $\tau \rightarrow 0$. Though we were unable to measure the feedback response of $K_p=50$, the computed range for gain k and time constant τ appears to follow the established pattern of the analytical model.

Oscillations in the measured ER fluid state and applied field were observed. An enlarged section from Figure 12 makes the oscillations more apparent (Figure 14). The source of these oscillations could have been either the state sensor or the electric field

$$\Delta E = K_p H \Delta C \rightarrow \frac{\Delta E}{\Delta C} = K_p H = 5$$

$$\frac{\Delta C}{\Delta E} = G(j\omega) = \frac{k_{equ}}{\tau_{equ} j\omega + 1} \quad (16)$$

where ΔC is the state sensor signal oscillation. Comparison of the ER fluid state and field shows $\Delta E/\Delta C \neq 5$, therefore the oscillations must be due to variations in the electric field amplifier. By examining the frequency response of the predicted gain range from the analytical model, a bandwidth was established (Figure 15). This bandwidth indicates how well the system will track the input. The bandwidth and time constant are inversely proportional to each other, therefore a large bandwidth corresponds to a fast system response. The shaded ellipse indicated the actual measured frequency due to noise, and lies within the bandwidth. This ellipse ranges from 0.07 to 0.09 (rad/sec) and -37. to -40. dB. Even with the amplifier disturbance, the measured ER fluid state and field were in the range predicted from the analytical model. The disturbance from the amplifier limited the increase of gain and proportional constant in this experiment because of possible damage to the equipment at too high electric fields.

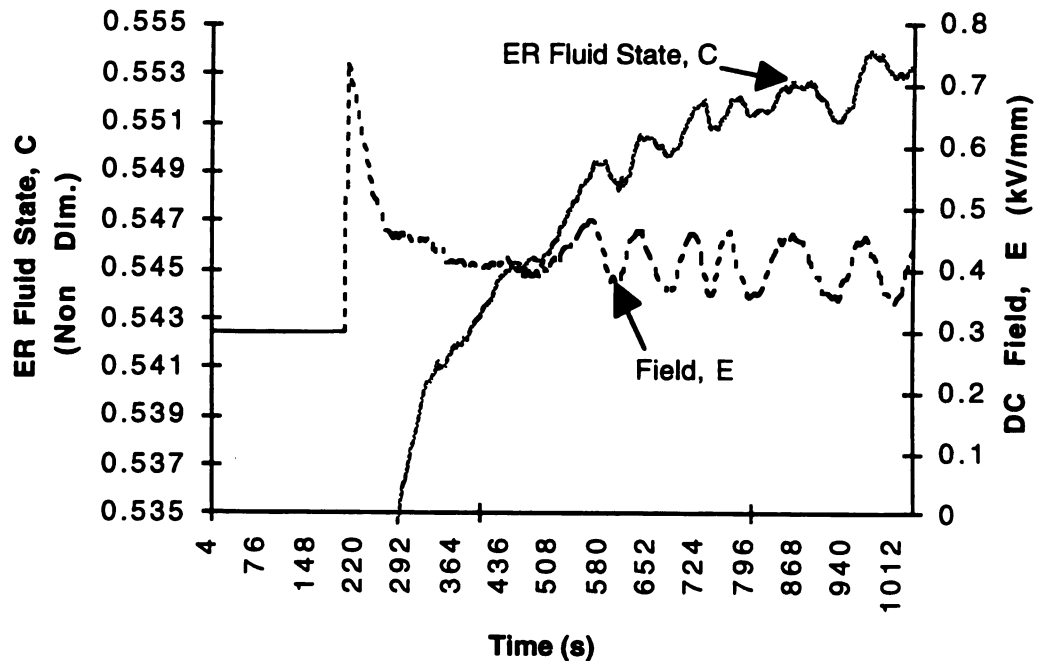


Figure 14: Enlarged section from Figure 12, feedback response $K_p=5.0$, ER fluid state=0.57. Oscillations due to noise in field, E.

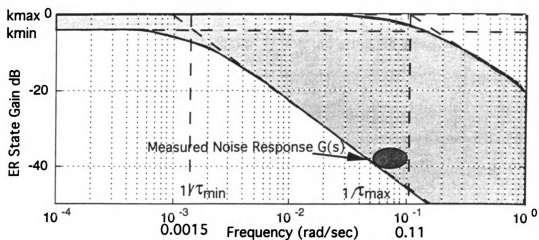


Figure 15: Frequency response of the predicted gain range of the analytical model. Shaded area indicates predicted ER fluid state response range. The ellipse indicates the actual measurable frequency response due to noise.

CONCLUSIONS

Feed-forward and feedback control approaches using nonlinear, hysteretic ER fluids were examined by experimental comparison and the results were compared to an analytical model of the ER fluid state response. Conventional feed-forward control was tested and shown to be inefficient in design and an ineffective control approach of the ER fluid state. It was determined that feedback in comparison to feed-forward more effectively controlled the ER fluid state. This was demonstrated in 3 ways. First, analytical models of the ER fluid and control system were developed which predicted system responses. These predictions improved with an increased proportional constant. Secondly, an ER fluid state sensor was identified that effectively detected and measured chaining within the ER fluid state. Finally, it was demonstrated that feedback control improved precision, and decreased response time. Measured responses fit within the range predicted by the analytical model. These results provide a vehicle of control for stiffness, viscosity, and other heat transfer properties to be employed.

With higher accuracy and speed, an increased number of low temperature applications of ER fluids become available (Hartsock et al 1991; Goldstein 1990). Future work should include examination of more sophisticated control algorithms which provide more accurate and faster response of the ER fluid state as well as improvement in sensor technology to increase overall quality of the response. Effective feedback control of the ER fluid state permits utilization of ER properties formerly hampered by the imprecise, slow, hysteric and nonlinear response of ER fluids. It was demonstrated for the first time that the proportional feedback control system responded 35 times faster and 21 times more accurately than the feed-forward system.

APPENDIX A

APPENDIX A

Graphical representation of the experimental sequence outlined in Figure 10 is as follows (Figs. A1-A5). Each graph, though described as if starting from time zero, follows one after the other. Lapses between data collecting were less than 1.5 minutes, and taken during appropriate steady state intervals.

The simultaneous monitoring of various properties during the experiment helped to maintain consistency between runs. The temperature fell to a steady state during the initial run of the experiment (Figure A1). Large spikes in the current (Figures A2 and A4) may be due to external disturbances. Constants were used in the desired ER fluid state (Figures A2 and A3), and the feed-forward runs (Figures. A1, A4, and A5). Feed-forward control was used in the rise from zero to the nominal drive field (Figures. A1 and A4).

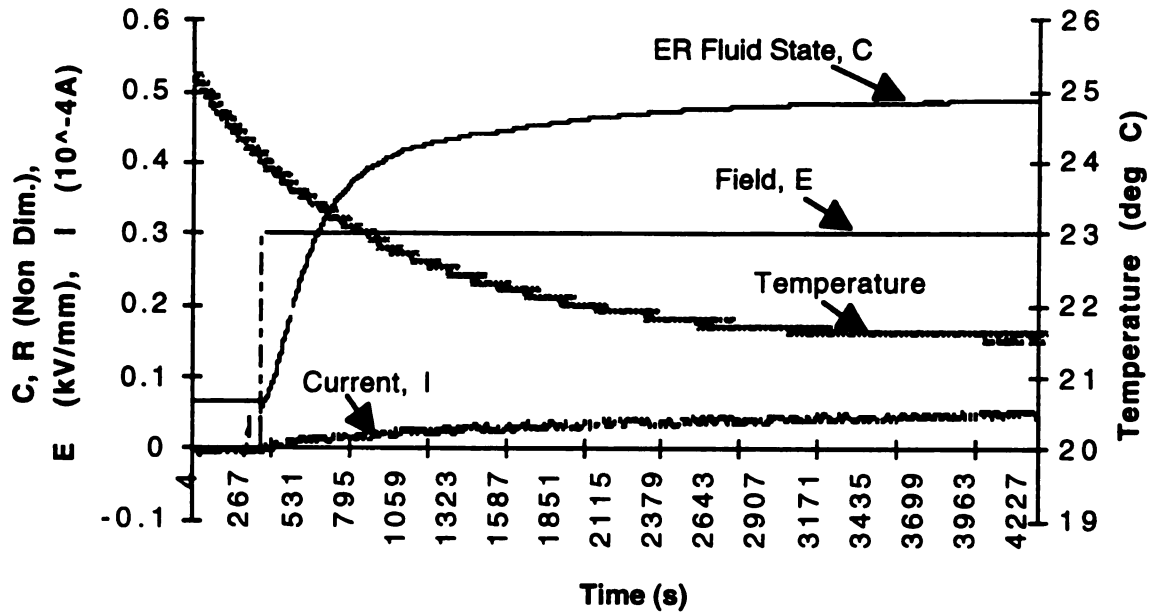


Figure A1: Feed-forward rise response to nominal drive voltage of 0.30kV/mm, displaying current, field, temperature, and ER fluid state. Temperature decreased to a steady state value.

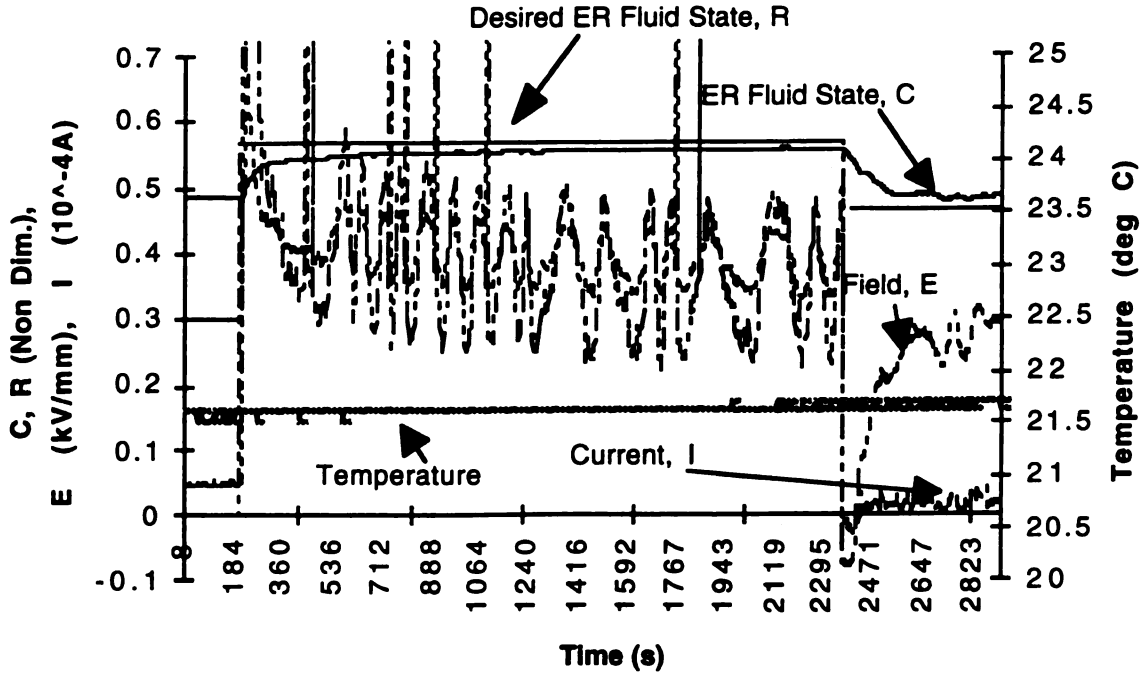


Figure A2: Feedback response with $K_p=5.0$ of current, ER fluid state, field, and temperature. The ER fluid state tracked the changes in field strength. The current exhibited similar behavior to changes in the field strength.

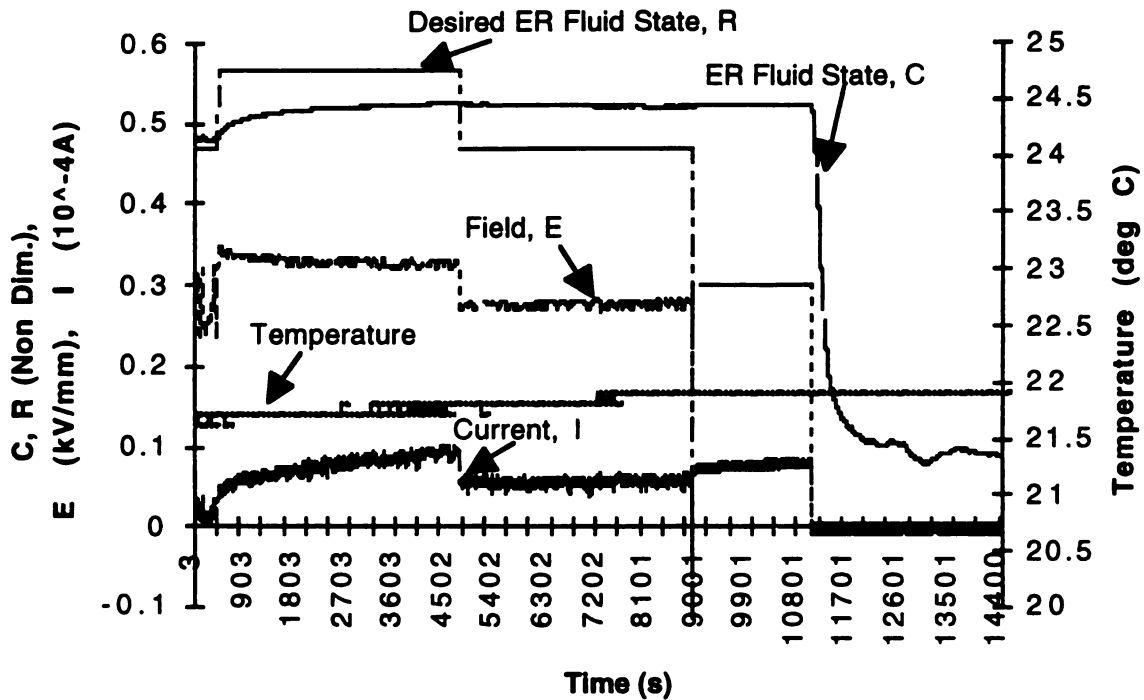


Figure A3: Feedback response with $K_p=0.5$ of current, desired ER fluid state, ER fluid state, field, and temperature. The field was lowered, ER fluid state changes were negligible until the field was removed. The temperature changes were negligible.

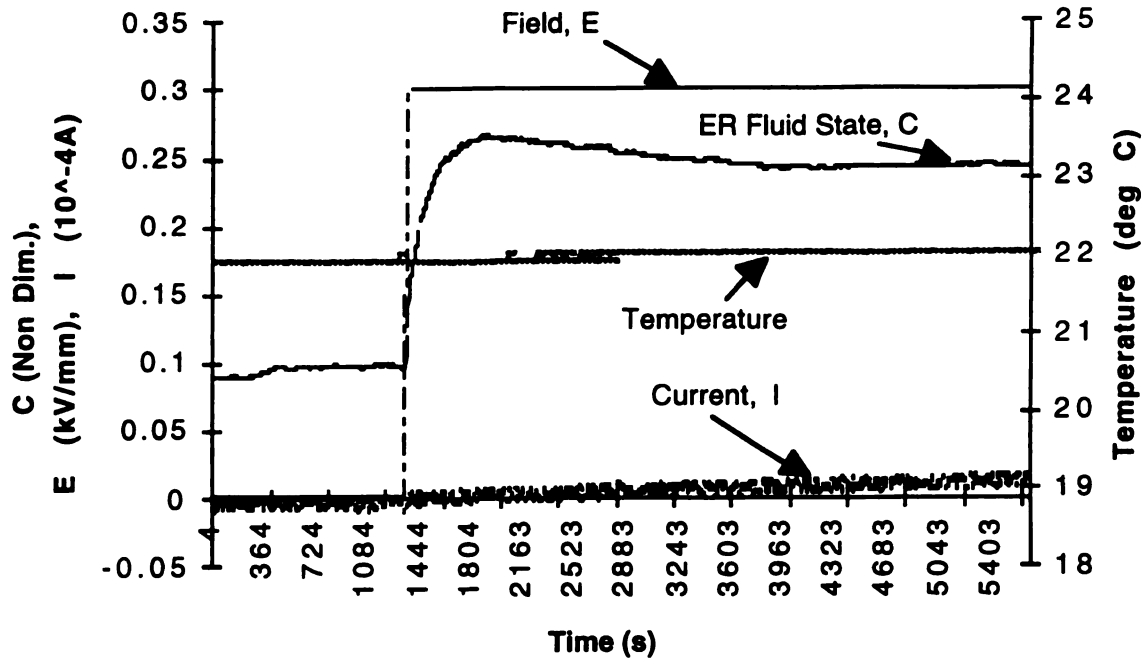


Figure A4: Feed-forward rise response to nominal drive voltage 0.30kV/mm, of current, ER fluid state, field, and temperature.

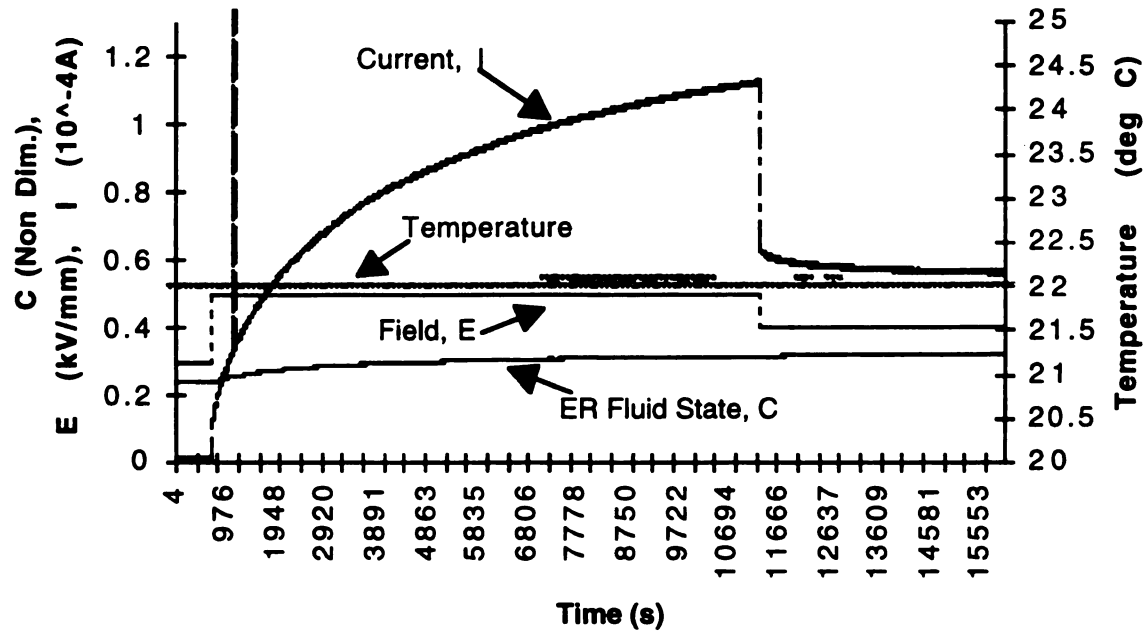


Figure A5: Feed-forward response of current, ER fluid state, field, and temperature. The ER fluid state was negligibly effected by changes in the field, which readily effected the current. The temperature remained relatively steady.

APPENDIX B

APPENDIX B

Experimental Control Systems

The feedback and feed-forward control systems were written in the virtual instrument (VI) program language LabVIEW (Appendix B, Program 1). Programs were set up in 3 stages: (1) configuration, (2) control, and (3) clear and error identifier. This gives easy access and clarity to the program.

The configuration of the program includes input of channels, the device, a NB-MIO-16L card, and the addition of default values for other available VI options (Figure B1). Output channels are provided to feed the measured output to the ER fluid system and desired transmittance to a Fluke Hydra Data Logger Model 2625A. Initially the program was tested with simulated ER fluids. The results were observed on an oscilloscope for accuracy of the feedback control system.

The second or control stage is the heart of the program (Figure B2). It contains the formula node which utilizes entered values from the front user panel and calculates the resulting measured output voltages. The use of a continuous buffer and internal timing of the Macintosh IIx provides a shorter, faster and more efficient program.

The clear and error identifier section describes errors to the user and clears values of the buffer after each run (Figure B3). The error messages aid the user in two ways. First, it can assist in identifying the origin of error, and second, it suggests why the program may have discontinued running. The clear VI prevents previous data from mixing in with the current run.

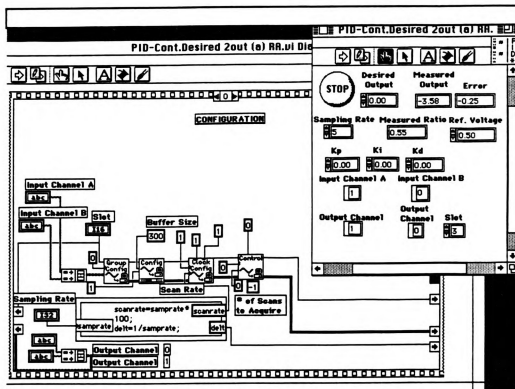


Figure B1: Front panel and configuration section of the control program.

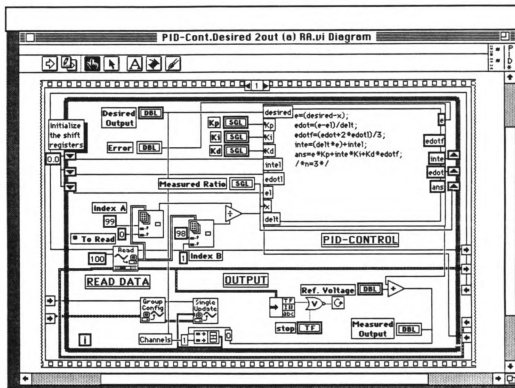


Figure B2: Data reading, control capabilities, and output sections of the control program.

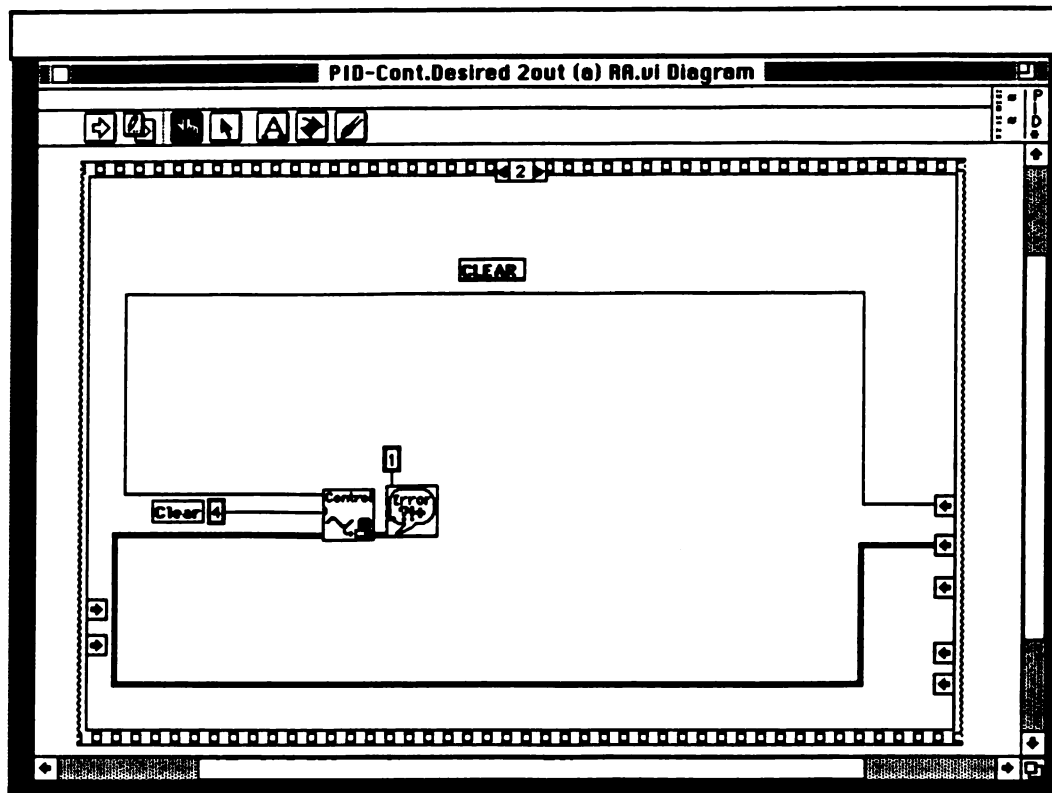


Figure B3: Clear section of the control program.

LIST OF REFERENCES

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- Arguelles, J., Martin, H. R., and Pick, R. J., 1973, "Some Experiments with Electrosensitive Fluids," *Proceedings of the 3rd International fluid Power Symposium.*, May.
- Block, H., and Kelly, J. P., 1986, "Electrorheological Fluids," European Patent 0,191,585.
- Butters, R., March, 1995, Personal Communication, Lord Corporation, Carey, North Carolina.
- Conrad, H., Sprecher, A. F., Choi, Y., and Chen, Y., 1991, "The temperature dependence of the electrical properties and strength of electrorheological fluids," *The Society of Rheology, Inc.*, May, pp. 1393-1410.
- Duclos, T. G., 1987, "An Externally Tunable Hydraulic Mount which Uses Electro-Rheological Fluid," *Proceedings of the 1987 Noise and Vibration Conference.*, April.
- Duclos, T. G., Acker, D. N., and Carlson, J. D., 1988, "Fluids That Thicken Electrically," *Machine Design*, January, pp. 42-45.
- Duff, A. W., 1896, "The Viscosity of Polarized Dielectrics," *Physical Review* , Vol. 4, pp. 23-38.
- Filisko, F. E., and Armstrong, W. E., 1988, U. S.. Patent 4,744,914.
- Goldstein, G. 1990, "Electrorheological Fluids: Applications Begin to Gel," *Mechanical Engineering*, October, pp. 48-52.
- Hartsock, D. L., Novak, R. F., and Chaundy, G. J., 1991, "ER fluid requirements for automotive devices," *The Society of Rheology*, October, pp. 1303-1326.
- Klingenberg, D. J., van Swol, F. and Zukoski, C. F., 1989, "Dynamic Simulation of Electrorheological Suspensions," *Proceedings of the ACS Division of Polymeric Materials Science and Engineering* , September, Vol. 61, pp. 154-155.
- Konig, W. 1885, *Annals of Physics*, Vol. 25, p. 618.
- Lloyd, J. R., and Zhang, C., 1994, "A Discussion on the use of Electrorheological fluids in the control of Heat Transfer Processes," Paper presented at the *1994 Heat and Mass Transfer Conference, Bombay, India, January*.
- Monkman, G. J., 1991, "Addition of solid structures to electrorheological fluids," *The Society of Rheology, Inc.*, October, pp. 1385-1392.

Quinke, G., 1897, "Die Klebrigkeit isolirender Flüssigkeiten im constanten electrischen Felde; Viscous Behavior of Isolated Flows in Constant Electric Fields," *Annals of Physics and Chemistry*, Vol. 62, pp. 1-13.

Scott, D. Y., and Yamaguchi, J. 1983, "Automotive engineering," *International Viewpoints*, Vol. 91, No. 11, pp. 61-66.

Stangroom, J. E., 1977, "Electric Field Responsive Fluids," U. S. Patent 4,033,892.

Stangroom, J. E., 1978, "Electric Field Responsive Fluids," U. S. Patent 4,129,513.

Stangroom, J. E., 1980, "Improvements in Relating to Electric Field Responsive Fluids," U. K. Patent 1,570,234.

Stangroom, J. E., 1982, "Electroviscous Fluids," International Patent WO 82/04442.

Stangroom, J. E., 1983, "Electrorheological Fluids," *Physics Technology*, Vol. 14, pp. 290-296.

Stangroom, J. E., 1984, "Electric Field Responsive Fluids," U. S. Patent 4,483,788.

Tabatabai, Stefan, 1993, "Fakultät Für Maschinenwesen," Studienarbeit at Michigan State University.

Tao, R., and Sun, J. M., 1991a, "Three-Dimensional Structure of Induced Electrorheological Solid," *Physical Review Letters*, July 15, Vol. 67, No. 3, pp. 398-401.

Tao, R., and Sun, J. M., 1991b, "Ground state of electrorheological fluids from Monte Carlo simulations," *Physical Review Letters*, November 15, Vol. 67, No. 6, pp. 44-47.

UOP Molecular Sieve Adsorbents, 1990, "Adsorbents Product Information," August.

Ushijima, T. Takano, K. and Noguchi, T. 1988, "Rheological characteristics of ER Fluids and Their Application to Anti-Vibration Devices with Control Mechanism for Automobiles," Passenger Car Meeting and Exposition, October/November, *Society of Automotive Engineers, Inc.*

Winslow, W. M., 1947, U. S. Patent 2,417,850.

Winslow, W. M., 1949, "Induced Fibration of Suspensions," *Journal of Applied Physics*, No. 20, pp. 1137-1140.

Winslow, W. M., 1962, U. S. Patent 3,047,507.

Yen, W. S., and Achorn, P. J., 1991, "A study of the dynamic behavior of an electrorheological fluid," *The Society of Rheology*, pp. 1375-1384.

Zhang, C., and Lloyd, J. R., 1992a, "Control of Radiation Heat Transfer through a Composite Window Featuring ER Fluid: A Conceptual Investigation: Paper presented at the *Second Minsk International Heat and Mass Transfer Form*, May.

Zhang, C., and Lloyd, J. R., 1992b, "Measurements of Radiation Heat Transfer in Electrorheological Fluid Based composite Materials," Paper presented at the *National Heat Transfer Conference*.

Zhang, C., and Lloyd, J. R., 1993 "Enhancement of Conductive Heat Transfer through an Electrorheological Fluid Based Composite Medium," Presented at the 1993 National Heat Transfer Conference, August, Atlanta, Georgia.

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