1996 ASME International Congress and Exhibition
November 17-22, 1996
Atlanta, GA
(with 1/6/97 corrections)

STATE FEEDBACK CONTROL OF ELECTRORHEOLOGICAL FLUIDS

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ABSTRACT

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 ER fluids under on-off control of high electric fields. Successful applications will require fast, precise control of the response of ER fluids, independent of application at low field strengths.

This study presents a new approach to the control of ER fluids that overcomes the problems of imprecise, slow, nonlinear response and high electric fields. An optical sensor was used to indicate the ER fluid state in a layered composite window. Feedback control of ER fluid state was developed and compared to conventionally actuated ER fluids. Feedback control employs the state sensor and high initial electric field strength to speed ER state response, then lowers the field strength to the minimum level required to achieve the desired ER fluid state. Predicted responses were compared to experimentally measured responses and showed excellent agreement. Laboratory measurements showed that a proportional state feedback control system yielded an electrorheological fluid which responded 35 times faster and 21 times more accurately than possible with a conventional open-loop fluid control system. Although the use of ER fluids in feedback control systems have been proposed in the past, this work is the first application of feedback control to the fluid itself.

INTRODUCTION

As early as the 19th century (Duff 1896; Quinke 1897), scientists began studying electrorheological (ER) response, although it was not until research by Winslow (1947) that electro-viscous phenomena gained prominent attention. He introduced the concept of controlling the viscosity of an electro-viscous fluid by 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 these field induced particle chains increased the viscosity of the fluid.

An ER fluid consists of fine polarizable particles suspended in a fluid of lower dielectric constant. Typically such fluids are assembled with a continuous hydrophobic liquid phase (e.g. silicone oil) containing hydrophilic particles (e.g. Zeolite). The density of the particles is matched as closely as possible with that of the oil to ensure good dispersion upon mixing of the ER fluid (Stangroom 1978, 1983). An applied electric field aligns the dipoles of water molecules trapped in particles, thus polarizing the particles. Particle polarization changes their organization in the fluid and causes changes in fluid rheological properties (Fig. 1). When particle chains are subjected to fluid shearing forces, the particles still attract even though they may be pulled away from each other (Duclos et al 1988). Higher electric field strength increases polarization and causes particle chains to pull together tighter and to lengthen the chains through the addition of more particles (Klingenberg et al, 1989). These longer, stronger particle chains result in higher fluid viscosity and stiffness. At

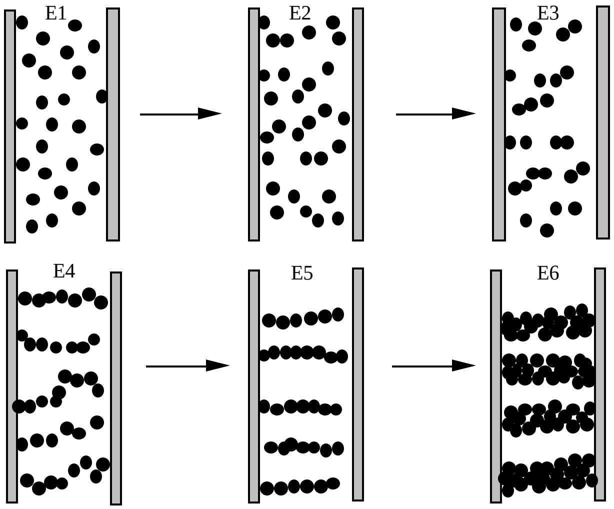

Figure 1: Particle polarization and single sphere width chain formation with increasing field, E. Particle chaining changes fluid properties

higher electric field levels (e.g. 3-4 kV/mm), destructive arcing can occur through the particle chains in the fluid.

Engineers and scientists have identified possible applications including vehicle suspensions, hydraulic valves and soft clutches that would utilize the special properties of ER fluids. Development of commercial applications of devices using ER fluids has been hampered by the inability to quickly and precisely control the ER fluid state. Electrorheological fluids have not responded with precision and accuracy, which suggests that a new 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. 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). Despite progress in these areas of research, precise control of ER fluid response has eluded investigators.

Investigators turned their attention to modeling the ER phenomena in an effort to better understand fluid response precision and speed. 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).

Current devices such as ER fluid based valves, clutches or hydraulic mounts typically do not react quickly or precisely enough to meet needs of the applications (Duclos 1987; Ushijima et al 1988, Arguelles et al 1973). Stangroom (1983) recognized the importance that feedback would add to the control of devices. 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.

Greater control of the speed and precision of ER fluid response was the objective of this study. Laboratory and analytical comparisons were made between state feedback and conventional open-loop control of a low particle volume concentration ER fluid. Analytical models for the ER fluid and control systems were developed which predict ER fluid state responses to the application of both conventional and state feedback control of the fluid. Effective and efficient control of an ER fluid is necessary in order to achieve the benefits of their controllable properties and successful application

ELECTRORHEOLOGICAL FLUID SYSTEM CONTROL

The traditional method for controlling an ER fluid's response is through the open-loop actuation of the fluid with an applied field (Fig. 2). In this "open-loop" control, the response of the ER fluid system is assumed to be both predictable and to have sufficient speed for the application. To achieve the desired output, a controller $D(s) = G^{-1}(s)$ is designed based on knowledge of the relationship $G(s)$ between field input and fluid response output. The presence of any external disturbance or noise $N(s)$ disrupts the controlled system's accuracy. The total system output, $C_{ol}(s)$, is the sum of the outputs due to the control and external disturbances .

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

Accurate feed-forward control requires both exact knowledge of the controlled system $G(s)$ and minimal disturbance $N(s)$. It is apparent that either changes from the nominal values of the controller $D(s)$ and the ER fluid $G(s)$ or the presence of noise $N(s)$ in the open-loop system will cause proportional errors in the response, $C_{ol}(s)$. Conventional open-loop fluid control also requires sufficiently fast, predictable response. Unfortunately, ER fluids have not proven to be either sufficiently fast or adequately predictable.

"Closed-loop" (feedback) control uses measured system output in the control system (Figure 3). The actuating error signal is the difference between desired and measured system output signals. The objective of feedback control is a controller design $K(s)$ which systematically reduces the actuating error $E(s)$ to drive the output $C_{cl}(s)$ to the desired value $R(s)$.

$$\begin{aligned} C_{cl}(s) &= \frac{G(s)[K(s)R(s) + N(s)]}{1 + K(s)G(s)H(s)} \\ &= R(s) \text{ iff } K(s) \to \infty \text{ and } H(s) = 1 \end{aligned} \tag{2}$$

Accurate feedback control does not require either exact knowledge of the controlled system $G(s)$ or minimal disturbance $N(s)$. Accurate feedback control does require both a strong controller $K(s)$ and accurate feedback sensing $H(s)$. Electrical amplifiers easily provide strong controllers $K(s)$. The missing element in previous work has been an accurate and precise sensor of ER fluid state.

Both the viability of an ER fluid state sensor and the variability in ER fluid response are indicated in Figure 4. Normalized optical transmittance T of an ER fluid composed of a low volume fraction (1%) Zeolite in silicone contained between glass plates is shown for a sequence of constant amplitude applied AC field applications. Increasing ER fluid chaining state (Fig. 1) is indicated by an increase in optical transmittance T parallel to the orientation of particle chains as they form along the lines of applied AC field. The figure shows that the particle response is very different for the first AC field application as compared to the last.

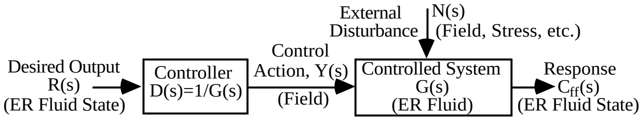

Figure 2: Feed-Forward Control System

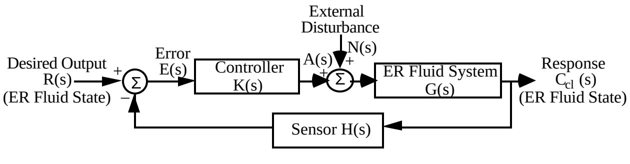

Figure 3: Feedback Control System

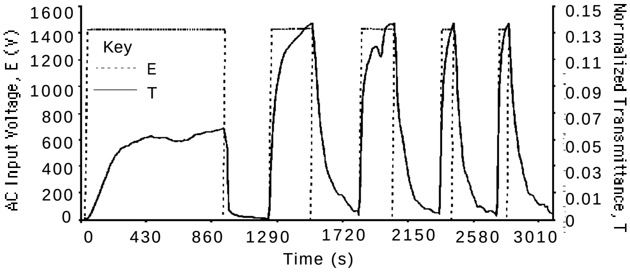

Figure 4: Laboratory Measurement Of Zeolite ER Fluid State Using A Prototype Optical Sensor (1% Zeolite Vol. Fraction) (Tabatabai, 1993)

The ER fluid state response can be modeled in the Laplace domain as a first order system where $T(s)$ is the output ER fluid state measured by transmissibility, $V(s)$ is the input electrical field, k is the system gain, and τ is the system time constant.

$$G(s) = \frac{k}{1+\tau s} = \frac{T(s)}{V(s)} \tag{3}$$

The ER fluid state gain k and the associated time constant τ vary widely (Fig. 4).

FEEDBACK CONTROLLED ER FLUID TEST SYSTEM

An ER fluid prototype control system was designed and used to compare the responses of open-loop and closed-loop feedback control of ER fluid state. Measurements for both precision and speed of feedback control of an ER fluid state response were compared with open-loop responses. The experimental apparatus (Fig. 5) consisted of 4 distinct components: an ER fluid state sensor, ER fluid window, an amplifier, and a computer controller.

The ER fluid state sensor detected changes in ER fluid chaining state. Particle chaining in the ER fluid (Fig. 6) permits greater passage of light, so that the extent of chaining can be measured by light transmissibility. When little or no electric field is applied, the particles are randomly dispersed (Fig. 6a), and only a small amount of light passes through the fluid. With increased field (Fig. 6b), the increased chaining state of the particles allows more light to pass through the window.

The prototype optical sensor design consisted of two silicon solar cells (Radio Shack) and an Edmund Scientific beam splitter. A M1650 Toshiba laser diode (λ=650nm) provided the light source. The ratio of the laser light transmitted to the detector A versus the laser light detected by reference B was used to evaluate the transmittance of the ER fluid layer and to indicate chaining state independent of the laser beam amplitude (Fig. 7). This transmittance sensor was calibrated for the nominal transmittance of the glass enclosing the ER fluid, the ratio (A/B) used to measure the ER fluid chaining state.

The ER fluid measurement window (Fig. 8) held a sample of ER fluid, applied a uniform field across the window and allowed transmission of light. The window walls were constructed from two rectangular glass spectrophotometer cells (38mm x 19mm) and insulated from the aluminum frame by silicon rubber and sulfur-cured styrene butadiene rubber sections which permitted the placement of a type T thermocouple to monitor fluid temperature. The glass spectrophotometer cells were plated with electrically conductive intium tin oxide on one side in a manner similar to glass used to contain liquid crystals in electronic displays. A small gap for insertion of the dispersed ER fluid was left at the center of the top, sulfur-cured styrene butadiene rubber insulator. 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.

Electrorheological fluid was prepared by letting anhydrous crystalline Zeolite particles adsorb water molecules. A particle moisture content of 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. 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 interstitial 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 stirring had risen to the surface. The ER

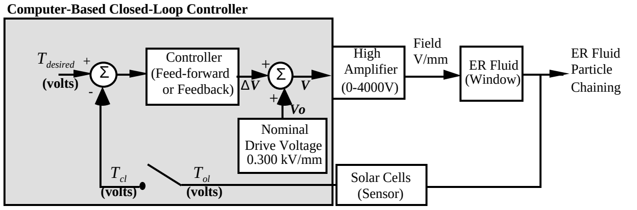

Figure 5: Experimental Apparatus Schematic

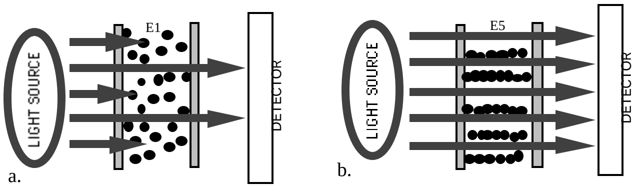

Figure 6: Conceptual design of an optical ER fluid state sensor when light penetrates the ER fluid state. (a)Light penetrating dispersed particles; (b)Light penetrating chained particles

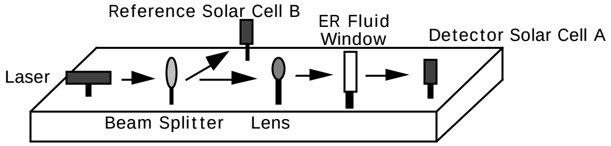

Figure 7: ER Fluid State Sensor and Window Setup

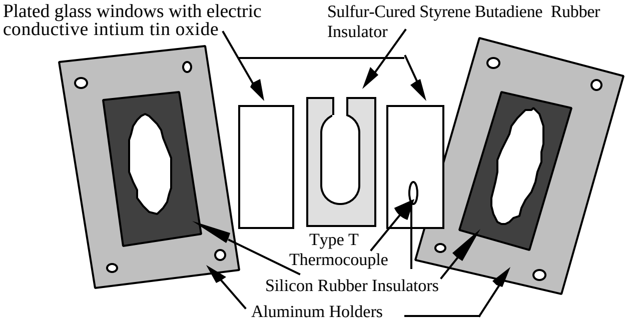

Figure 8: ER Fluid Measurement Window Schematic

fluid could then be inserted by syringe into the ER Fluid test window.

The ER Fluid State 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.

$$V = V_0 + K\left(V_{des} - V_{act}\right) \tag{4}$$

The nominal drive voltage V_0 provides an operating point around which deviations were proportionally controlled. The 0.30 kV/mm operating point was chosen for the tests described in this work. The controller was written in the data acquisition programming language LabVIEW.

Integration of the ER fluid state control test system is shown in Figure 9 which indicates direction of light, passage of signals, and transfer of information . The Trek 609C-6 high voltage amplifier (0-4000V) provided the ER fluid electric field. A 10MΩ carbon resistor and 175VDC metal-oxide varistor were included to protect equipment. A computer displayed data collected by the Fluke Hydra data logging system while the Hewlett-Packard E3630A DC power supply provided 3 volts to operate the laser diode. In contrast to some previous studies, DC fields were used in the tests described here because they were more easily implemented. During system operation, observations of the same time sequence of experimental conditions typically resulted in measurements which differed by less than 5% including hysteretic effects.

ER Fluid State Tests, Experimental Procedure

Experimental trials used a systematic approach to maintain consistency. Each open-loop (feedforward) or closed-loop (feedback) run included 2 segments: control and relaxation. At the start of each trial, the nominal drive voltage was 0.30kV/mm. The data logger monitored actual transmission level to both solar cells, current through the window, applied DC electric field, desired ER fluid state, and temperature °C. For open-loop (feed-forward) trials, feedback gain was set to zero, and the nominal drive voltage was changed to observe the ER fluid response. For closed-loop (feedback) trials, the desired ER fluid state and a non-zero proportional constant were set, and the ER fluid response was observed. A single sample of ER fluid in the window was used over a period of approximately 12 hours for all experiments in the trials discussed here.

Each trial began at steady measured state. Between the feedback and feed-forward runs the ER fluid had all field removed and was permitted to relax from the chained state for at least an hour. The maximum electrical field on the ER fluid sample was limited to a level which would not form body-centered cubic chains. Experience showed that the body-centered cubic chains did not relax when the field was decreased.

Measured Open-Loop Control Response

In the feed-forward trials, the initial nominal field voltage V_0 = 0.30kV/mm. Once a steady value of measured ER fluid state was established , the field voltage was increased to V = 0.50kV/mm (Fig. 10). After steady measured ER fluid state was again reached, the drive voltage was lowered to V = 0.40kV/mm. State sensor output T_{ol} was used to provide a reading of the ER fluid state C_{ol}. gain, k_{equ}, and time constant, τ_{equ}, for open-loop, feed-forward rise and fall were determined using

$$k_{equ} = \frac{\Delta T_{ol}}{\Delta V} \tag{5}$$

where ΔT_{ol} is change in the measured ER fluid chaining state, and
ΔV is the change in the ER Fluid Field

By establishing steady state at each level the time constant τ_{equ}, could be calculated. Time constants τ_{equ}, for the open-loop and feedback rise and decrease were determined using

$$\tau_{equ} = \Delta t \text{ for 63.2\% of the rise/fall to steady-state} \tag{6}$$

Representative open-loop rise parameters for the data were determined to be k_{equ} = 0.39 and τ_{equ} = 44 minutes. For other

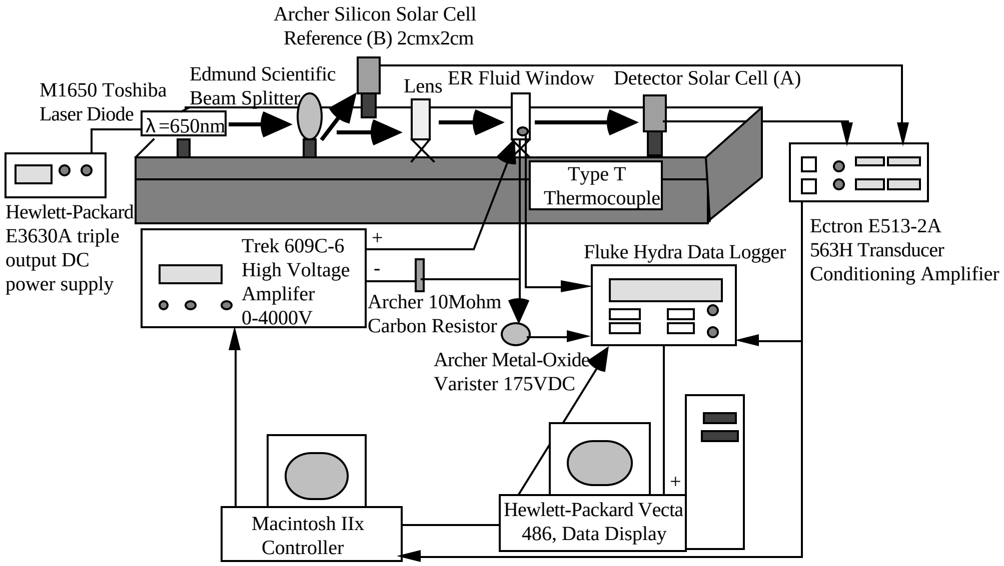

Figure 9: Laboratory Configuration

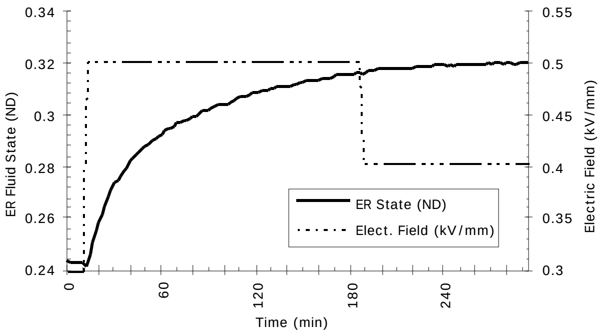

Figure 10: Open-Loop Response of the ER fluid State and Field. Note slow ER fluid response.

electric field variation amplitudes and directions, the ranges of open-loop parameters observed were -0.09 <k_{equ}<0.5 and 4 minutes <τ_{equ}=45 minutes. Note both the significant variation in open-loop gain and the slow speed of response. In fact, Fig. 10 includes an instance of no measureable response to changes in field. Other cases included incremental decreases in transmissibility with incremental increases in field yielding the negative gains reported above.

Measured Closed-Loop Control Response

The feedback trial with gain, K_p = 0.5, began at steady-state fluid response for a desired ER state $T_{desired}$ = 0.47 Volts with a nominal drive of V_0 = 0.30kV/mm. After steady state was achieved, the desired ER state was raised to $T_{desired}$ = 0.56 Volts (Figure 11). The gain, k_{equ}, and time constant, τ_{equ}, for the feedback rise and decrease were determined using (3) where

$$k_{equ} = \frac{\Delta T_{cl}}{\Delta T_{desired}} \tag{7}$$

where ΔT_{cl} is the change in measured ER fluid chaining state,
and $\Delta T_{desired}$ is the change in desired ER fluid state measurement

The feedback trial equivalent system parameters for K_p = 0.5 were computed as

$$k_{equ} = (0.524\text{-}0.481)/(0.566\text{-}0.481) = 0.48 \tag{8a}$$

$$\text{and } \tau_{equ} = 10.8 \text{ minutes} \tag{8b}$$

For closed-loop (feedback) controlled decrease in ER fluid response, the same method calculated k_{equ} = 0.05 and τ_{equ} = 20 minutes. With low feedback gain K_p=0.5, steady state error varied between 7.5% and 12% for the first two segments in the trial, however, when the desired ER state was lowered, the measured state did not change significantly. This observation indicated large hysteresis in the fluid. To test hysteresis in the ER fluid chaining state response, the feedback was removed in the third trial segment, and the field was lowered to the nominal drive of 0.30kV/mm with negligible effect on the measured ER fluid chaining state. Only in trial segment 4 when the ER fluid's field was completely removed, did the measured ER fluid chaining state change with a drop to a relaxed state with a time constant similar to previous open-loop results. The low-gain closed loop trial again demonstrated the large variation in system gain and time constant associated with the highly non-linear, hysteretic, open-loop response of the ER fluid chaining state.

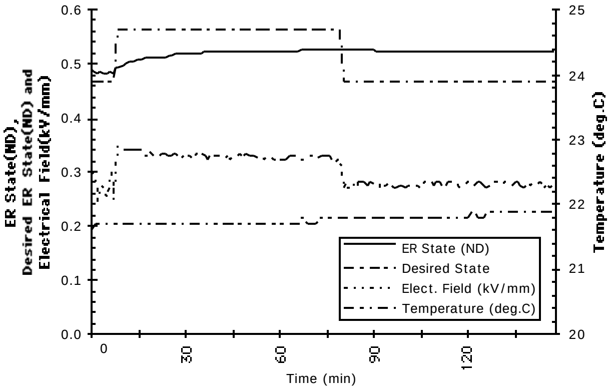

Figure 11: Feedback response of K_p = 0.5, of the desired ER fluid state, ER fluid state, and field. The ER fluid state changed only negligibly when the field was lowered. Removal of the field forced the ER fluid state to fall. Measured temperature change was negligible

The monitored temperature remained relatively constant. Temperature increase during the experiments was negligible, and remained just above room temperature at about 22 °C (Fig. 11). These temperature measurements indicated that the trial's other measurements had not been adversely affected by significant temperature variation.

The closed-loop feedback trial with feedback gain K_p = 5.0 repeated the previous schedule of desired ER state measurements (Fig. 12). For the rise from $T_{desired}$ = 0.566-0.488, the closed-loop system gain

$$k_{equ} = (0.556\text{-}0.448)/(0.566\text{-}0.488) = 0.872 \text{ and} \tag{9a}$$

$$\tau_{equ} = 0.99 \text{ minutes} \tag{9b}$$

Using the same method for the fall from $T_{desired}$ = 0.566-0.488 resulted in k_{equ}=0.85 and τ_{equ}=1.8 minutes. With larger feedback gain, the percent error between desired and actual ER fluid state was 1.7% on increasing desired state, and 2.7% on decreasing desired state. The larger feedback gain K_p = 5.0 tracked the desired ER fluid state with very small steady state error as the feedback control was both raised and lowered to the desired level.

Changes in DC electric field reflect the effective closed-loop feedback control action (Fig. 12). The initial high field strength forced the ER fluid state to rise quickly. As it approached the desired level, the field was reduced by the proportional control. Response of the fluid to the desired ER fluid state was faster than if the field had been raised with a fixed excitation level. Although the field strength was initially larger with feedback control, the reduction in field strength as the fluid state approached the desired level is expected to prevent potential damage to the ER fluid system.

Accuracy and response time were both improved with the strong closed-loop feedback. Addition of feedback improved precision by a factor of 5 times at K_p = 0.5 and by factors over 21 with K_p = 5.0. The feedback controlled system response time

Table 1: Computed vs. Measured Gains and Time Constants. With increasing control gain K_P, system gains k approached one, and the time constant τ decreased

System Type	Measured		Computed	
	k	τ (sec)	k	τ (sec)
Open-Loop	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.	----	----	0.94 - 0.997	116. - 0.94

constant with K_p = 0.5 was 11 times faster than for the open-loop system, and 35 times faster with K_p = 5.0. The oscillations apparent in the response are due to amplification of noise introduced by the amplifier. This phenomenon will be discussed in detail in the next section.

Settling of particles did not appear to 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 affect 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 affect settling.

ER Fluid State Feedback Model Validation

Measured gains and time constants (3) of the open-loop system were used to predict closed-loop system responses. These *Computed* closed-loop response predictions were subsequently compared with *Measured* closed-loop response (Table 1). The non-linear, hysteretic nature of the ER fluid yielded considerable variations in *Measured* open-loop gain and time constants. When a first order open-loop ER fluid model (3) is substituted into the closed-loop feedback model (2), the range of *Computed* closed-loop gain k_{cl} and time constant τ_{cl} can be predicted assuming noise $N(s) = 0$, $K(s) = K_P$, and $H(s) = 1$.

$$G_{cl}(s) = \frac{T_{cl}(s)}{T_{desired}(s)} = \frac{K_P G_{ol}(s)}{1 + K_P G_{ol}(s)} = \frac{K_P k}{1 + \tau s + K_P k} = \frac{k_{cl}}{1 + \tau_{cl} s} \quad (10)$$

where $k_{cl} = K_P k / (K_P k + 1)$ and $\tau_{cl} = \tau / (K_P k + 1)$

Computed gain and time constants were determined from the analytical model (10) using control gain K_P and measured ranges of open-loop gain k and time constant τ. Ranges of *Measured* open-loop, *Computed* closed-loop, and *Measured* closed-loop gain and time constants are given in Table 1. The measured values of k and τ under feedback control fell into the ranges computed from the analytical model.

Desirable performance for an electrorheological fluid control system is gain $k = 1$ with a short time constant τ. The experimental results show both trends as proportional feedback K_P increases. 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 $k \to 1.0$ and $\tau \to 0$. Although the feedback response at K_P = 50 was not measured, the computed range for predicted closed-loop gain k and time constant τ should follow the analytical model.

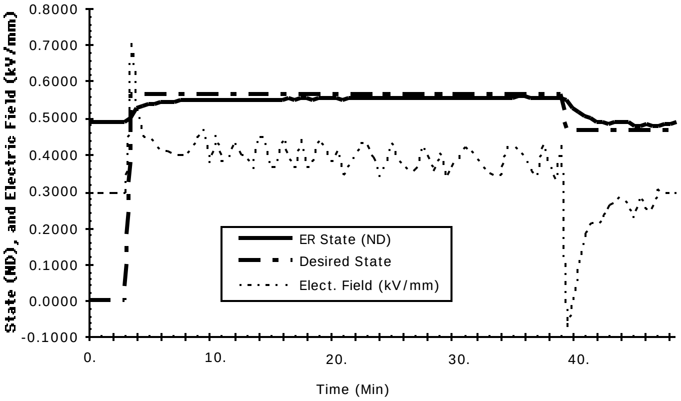

Figure 12: Feedback response of K_p = 5.0, of the desired ER fluid state, ER fluid state, and field.

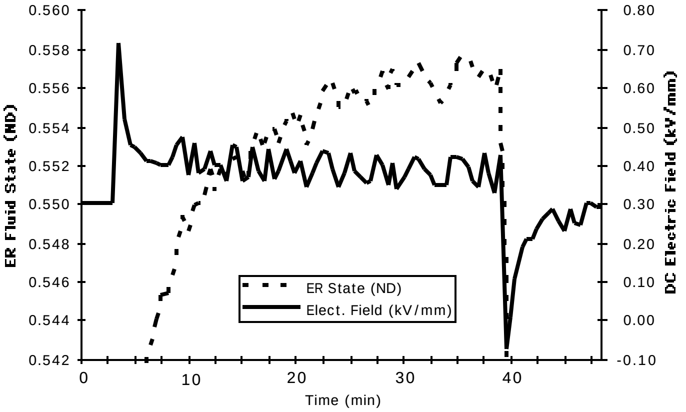

Figure 13: Enlarged section from Fig. 12, feedback response K_p = 5.0, Desired ER fluid state V_{des} = 0.57 Measured Oscillations in ER Fluid state T_{cl} are due to noise in applied field.

Apparent control system instability limited possible improvements in both the precision and speed of ER fluid response. Oscillations in the measured ER fluid state and applied field were observed, and the closed-loop system began to exhibit oscillation (Fig. 12) for feedback $K_P > 5.0$. An enlarged section from Figure 12 makes the oscillations more apparent (Fig 13). Because the ER fluid response is first order and the control proportional, classical feedback initiated instability is unlikely and sources of noise were investigated. The source of state sensor oscillations could have been either noise injected at the state sensor T or at the amplifier supplying the electric field ΔE. In each case, the effect of these two signals on each other can be readily predicted. For the results shown at K_P = 5.0, the effect of sensor noise on the field is

$$\Delta E = K_p \Delta T \to \frac{\Delta E}{\Delta T} = K_p = 5 \quad (11)$$

The effect of external noise injected at the amplifier is

$$\frac{\Delta T}{\Delta E} = G(j\omega) = \frac{k_{equ}}{\tau_{equ} j\omega + 1} \quad (12)$$

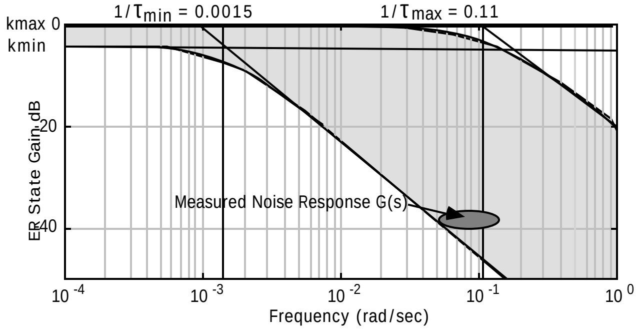

Figure 14: Frequency response of the predicted gain range of the analytical model. Shaded area indicates predicted ER fluid state response range. The ellipse indicates the actual measured frequency response due to noise.

Comparison of the ER fluid state and field shows $\Delta E / \Delta T \neq 5$, therefore the oscillations must be due to noise injected at the electric field amplifier. The actual ratio of sensed state oscillation to electric field oscillation amplitude measured

$$(0.001/0.1) < \Delta T / \Delta E < (0.002/0.1) \qquad (13)$$

This oscillation occurs over periods between 50 and 125 seconds.

The range of possible frequency response magnitudes was predicted (Figure 14) for the measured ranges of predicted closed-loop gain k_{cl} and time constant τ_{cl} using the analytical model (9). The shaded ellipse in the figure indicates actual measured noise oscillation ratio and frequency range, and lies within the range of frequency responses predicted. This ellipse ranges from 0.05 to 0.13 (rad/sec) and -37. to -40. dB. The measured ER fluid state and field were in the range of frequency responses predicted from the analytical model confirming the source of the noise in the amplifier. This noise analysis further confirms the validity of the ER fluid state feedback model. Noise reduction in future system prototypes will allow the increased gain needed to further improve performance of the ER fluid system.

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 open-loop control was tested and was shown to be ineffective in precise control of ER fluid response. A novel closed-loop feedback control based on optical measurement of ER fluid chaining state more effectively controlled the ER fluid response. The remarkable improvement on controlled response precision and speed was demonstrated over a range of control gains for simple proportional control. The simple proportional feedback control improved precision and decreased ER fluid 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.

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