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FLUID POWER CONTROL UNIT USING ELECTRORHEOLOGICAL FLUIDS

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Abstract

Electrorheological (ER) fluids can change their rheological properties when subjected to an electrical field. By using ER fluids as the working medium in fluid power systems, direct interface can be realized between electric signals and fluid power without the need for mechanical moving parts in fluid control unit. The pressure drop and flow rate can be directly controlled through the change of applied electric fields. This paper investigates the design and controllability of ER fluid power control system for large flows. The design criterion for an ER valve is proposed and four ER valves are manufactured based on this criterion. A fluid control unit consisting of an ER valves bridge circuit is constructed, the characteristics of which are theoretically and experimentally investigated. The results show that the ER fluid control units have better controllability for fluid power control.

Keywords: electrorheological (ER) fluids, ER valve, fluid control unit, design criterion

1 Introduction

Electrorheological (ER) fluids consist of fine polarizable particles suspended in a liquid of low dielectric constant and low viscosity. When an electric field is applied, the particles are polarized and form chains between the electrodes. This chain structure is held in place by the field, and hence resists fluid flow. The apparent viscosity is changed. The resulting behaviour is analogous to the class of fluids known as Bingham Plastics fluids capable of developing a yield stress, which is a function of the applied electric field (Sims et al, 2000). Moreover, this phenomenon is completely reversible. Upon electric field cut-off, the fluid almost immediately resumes its original liquid state. The time-scale for the transition is of the order of millisecond. Because of their fast response and low power requirement, ER fluids provide the possibility of rapid-response coupling between mechanical devices and electronic control (Wang et al, 2001). These unusual properties enable ER fluids to be used in various technical applications, such as shock absorbers (Sims et al, 2000; Lindler and Wereley, 2000), clutch/brake systems (Nakamura et al, 2002), intelligent structures (Li, 2002) and valves (Kondoh and Yokota, 2000; Wang et al, 2001).

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By employing ER fluids as the working medium in fluid power systems, direct interface can be realized between electric signals and fluid power without the need for mechanical moving parts in control valves (Kondoh and Yokota, 2000). The pressure drop and flow rate can be directly controlled by changing the applied electric field. The ER fluid control units are characterized by simple construction without moving parts and high response rate caused by the short reaction time of the ER fluids (Lindler and Wereley, 2000).

Simmonds (1991) proposed a plate-type ER valve and investigated the pressure drop responses of the ER valve with respect to the electric field. Tsukiji et al (1993) observed the microscopic behavior of the ER fluids structure in a fixed electrode valve and the effect of the electric field on pressure drop and flow rate. Peel and Bullough (1994) discussed the prediction of ER valve performance in steady flow. They drew on the generalized valve flow characteristic, together with simple static clutch determinations of fluid yield properties, zero volt viscosity and valve dimensions to predict valve pressure/flow performance. Whittle et al (1994) analyzed the pressure response in an ER valve control system. Park et al (1999) fabricated a micro ER valve using homogeneous ER fluids, and experimentally investigated its static and dynamic characteristics. Kondoh and Yokota (2000) proposed a hydraulic actuator with ER fluids and with movable electrodes. Choi et al (2000) presented the position control of a cylinder system using ER valve-bridge with application to a seaport cargo handling system. Yoshida et al (2002) demonstrated and developed a micro ER valve using micromachining technologies. Georgiades and Oyadiji (2003) studied the voltage control characteristics of ER fluids valve.

In this work, the design method and working performance of an ER fluid power control unit under large flows is discussed. The design criterion of an ER valve is first put forward, according to which four ER valves are designed and manufactured. An ER fluid control unit composed of a valve-bridge circuit is described. Finally, a fluid control test rig is introduced to investigate the characteristics of ER fluid power control unit.

2 ER Valve

2.1 Design Criterion of ER Valve

The ER fluids are near Newtonian flow in the absence of an electric field. Assuming their initial viscosity coefficient is η_0.Upon the application of an electric field, the ER fluids are changed to Bingham plastic in which particles are aligned in a chain (Choi et al, 2000). Then their apparent viscosity becomes

$$\eta_A = \eta_0 + \tau_y(E)/\dot{\gamma} \tag{1}$$

where η_0 is the initial viscosity in absence of electric fields, $\dot{\gamma}$ is shear rate, τ_y is yield stress of the ER fluids and a function of the electric field E.

When the flow rate flowing through valve Q is constant, the pressure drop between inlet and outlet of valve ΔP is

$$\Delta P = \frac{12\eta l}{bh^3} Q \tag{2}$$

In the absence of an electric field, $\eta = \eta_0$, then

$$\Delta P = \frac{12\eta_0 l}{bh^3} Q \tag{3}$$

While applying an electric field to the fluid domain, then $\eta = \eta_A = \eta_0 + \tau_y(E)\big/\dot{\gamma}$, the pressure drop is

$$\Delta P = \frac{12 l}{bh^3} Q(\eta_0 + \frac{\tau_y(E)}{\dot{\gamma}}) \tag{4}$$

Assuming the flow pattern for the Bingham plastic flow is plug flow (Peel et al, 1994) and $\dot{\gamma} = \frac{6Q}{bh^2}$, we get the fluid control equation for the ER valve as (Zhu et al, 2002)

$$\Delta P = \frac{12\eta_0 l}{bh^3} Q + 2\frac{l}{h}\tau_y(E) \tag{5}$$

where ΔP is pressure drop, Q is the flow rate through the valve, b is electrode width of flow aperture, h is electrode separation gap, l is electrode length in the flow direction.

For the ER valve under plug flow, the yield stress of ER fluids can be expressed as (Zhu, 2001)

$$\tau_y(E) = 2k_{re}\varepsilon_0\varepsilon_f(\frac{\varepsilon_p - \varepsilon_f}{2\varepsilon_f + \varepsilon_p})^2 E^2 \qquad 6)$$

where k_{re} is a coefficient that depends on the geometry and operating conditions of ER valve, and k_{re}=16.67, ε_0 is vacuum dielectric constant, ε_f and ε_p are relative dielectric constants of the continuous liquid phase and the suspension particles of ER fluids, respectively.

Substitution Eq. 6 into Eq. 5 yields the pressure drop

$$\Delta P = \frac{12\eta_0 l}{bh^3} Q + 2\frac{l}{h} K_E E^2 \tag{7}$$

where $K_E = 2k_{re}\varepsilon_0\varepsilon_f(\frac{\varepsilon_p - \varepsilon_f}{2\varepsilon_f + \varepsilon_p})^2$.

Assuming E is large enough, ER fluids will stop flowing and Q = 0. The pressure drop of valve under the maximum control electrical signal is

$$\Delta P = 2(\frac{l}{h})K_E E^2 \tag{8}$$

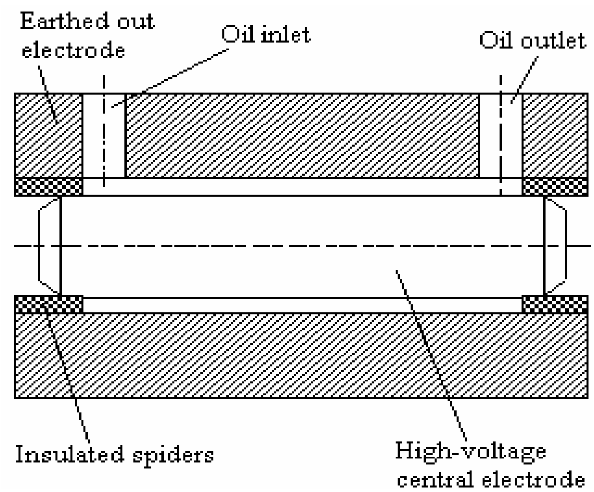
When the control signal E=0, Eq. 7 can be rewritten as

$$\Delta P = \frac{12\eta_0}{bh^2}(\frac{l}{h})Q \text{ or } \Delta P = \frac{12\eta_0}{h^3}(\frac{l}{b})Q \tag{9}$$

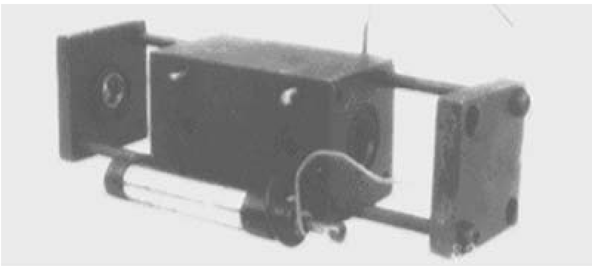
Comparing Eq. 8 with Eq. 9, we can find that the damping length (l/h) is the scale that defines both viscous power loss and ER power loss. The ER power loss indicates that there is an energy consumption to overcome electrical field force between particles in addition to viscous friction. Equation 8 and 9 also show that the ER valve still belongs to a type of typical damping control unit. The controllable range of pressure drop can be raised effectively if the damping length is properly increased. While at the same time, the viscous power loss will be increased and a negative effect on control precision will be produced as well. So the damping length $l/h \geq 1$ should be satisfied when an ER fluid control unit is designed. Meanwhile, the dimension l/b <1 should also be satisfied in order to reduce the viscous power loss and relatively enhance the ER power loss. These are the design criterions of ER valve.

2.2 Configurations of ER Valve

The annular structure is chosen for the construction of the ER valve because it has no edge effects due to its finite width (Zhu et al, 2002). According to the design criterion of the ER valve, the dimensions of ER valve are determined as follows: Mean annular diameter D = 20mm ($D = b/\pi$), Electrode separation gap h = 1mm, Electrode length in flow direction l = 61mm. The configuration for the ER valve is shown in Fig.1



a) Configuration



b) Photograph

Fig. 1: *ER valve*

3 ER Fluid Control Unit

As shown in Fig. 2, the fluid control unit is a valve bridge loop that consists of four ER valves. The ER valves ER1 and ER3 are electrically connected, while valves ER2 and ER4 are connected. The control electric field to be applied to the valves ER1 and ER3 is denoted by E_1, while E_2 denotes the valves ER2 and ER4.

In Fig. 2, the load pressure drop is $P_L = P_1 – P_2$. Assuming that the dimension and configuration of each valve are identical, then $Q_1 = Q_3$ and $Q_2 = Q_4$ by the law of bridge circuit.

Valves ER1 and ER3 have an applied electric field of

$$E_1 = E_0 - \Delta E \tag{10}$$

and similarly valves ER2 and ER4 have an electric field of

$$E_2 = E_0 + \Delta E \tag{11}$$

where E_0 is the electric field applied in static equilibrium position, and ΔE is control signal.

In Eq. 7, let $R_\mu = \dfrac{12\eta_0 l}{bh^3}$ which is defined with viscous hydraulic resistance, and $R_{er} = \dfrac{2l}{h} K_E$ which is defined with ER hydraulic resistance, we can get the flow rate through valves ER1 and ER3 as

$$Q_1 = Q_3 = R_\mu^{-1}[\Delta P_1 - R_{er}(E_0 - \Delta E)^2] \tag{12}$$

and the flow rate through valves ER4 and ER2 as

$$Q_4 = Q_2 = R_\mu^{-1}[\Delta P_4 - R_{er}(E_0 + \Delta E)^2] \tag{13}$$

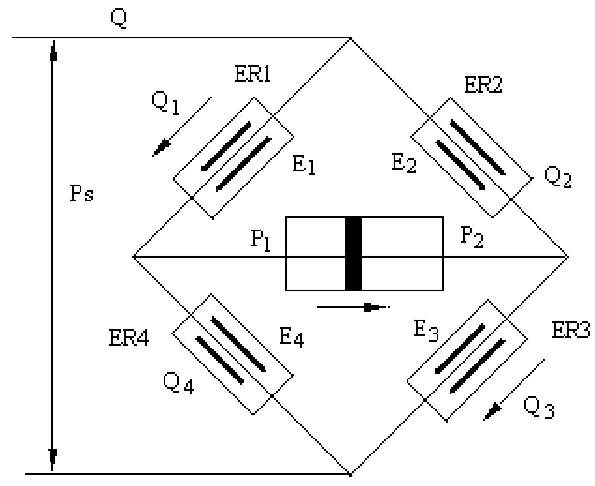


Fig. 2: *ER fluid control unit*

Then the load flow rate through the hydraulic cylinder is

$$\begin{aligned} Q_L &= Q_1 - Q_4 \\ &= R_\mu^{-1}[(\Delta P_1 - \Delta P_4) + 4R_{er}E_0\Delta E] \end{aligned} \tag{14}$$

As $\Delta P_1 = P_s - \Delta P_4$, $P_L = P_s - 2\Delta P_1$ (Lou et al, 1991), the load pressure drop is $P_L = \Delta P_4 - \Delta P_1$. So the load flow rate can be rewritten as

$$Q_L = 4R_\mu^{-1}R_{er}E_0\Delta E - R_\mu^{-1}P_L \tag{15}$$

Equation 15 shows that the load flow rate of the ER fluid control unit is linear in load pressure drop and electric field strength. By changing the magnitude and direction of electric field control signal ΔE, the flow rate and direction of flow through the hydraulic cylinder can be easily adjusted. Thus the velocity and position of the actuator can be linearly controlled.

4 Experimental Program

4.1 Characteristics of ER fluids

The ER fluids are of the suspension type with silica-gel particles dispersed in silicone oil. The dielectric coefficient of the continuous liquid phase is ε_f =2.0, while that of the suspension particles is ε_p = 4.7. The volume fraction of suspension is 0.25, and the initial viscosity in absence of electric fields is $\eta_0 = 0.16$ Pa·s. The rheological characteristic of ER fluids measured with HAAKE Rheometer (model number CV20) is shown in Fig. 3.

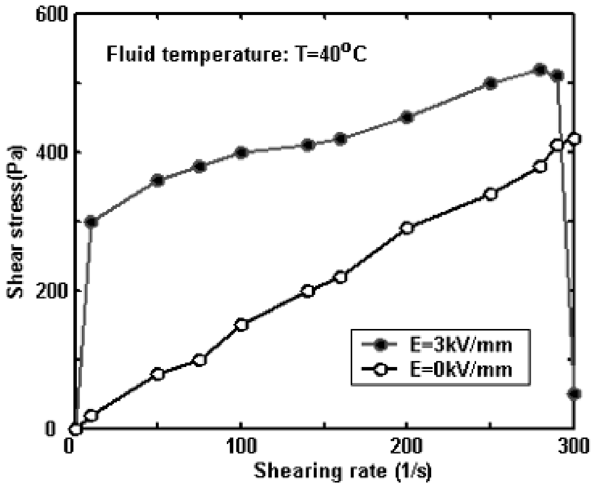


Fig. 3: *Characteristic of ER fluid*

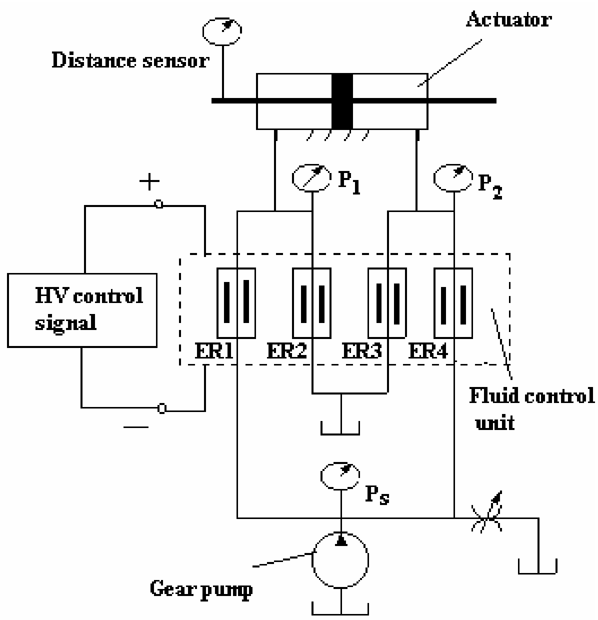


Fig. 4: *Configuration of experimental apparatus*

4.2 Experimental Configuration

The design of this experiment system is consistent with actual engineering applications as far as possible. Figure 4 displays schematically the experimental configuration. The working medium is the ER fluids (suspension), which are circulated using an electrically driven gear pump (model number CB306) out of a tank through the ER fluid control unit back into the tank. HV control unit outputs two voltage signals to valves ER1 & ER3 and valves ER2 & ER4. The valves ER1 and ER3 are electrically connected, while valves ER2 and ER4 are connected. The actuator is hydraulic cylinder type with model number 34Y-100BZ. The piston diameter is 12 mm with a maximum displacement of 32 mm. The pressure drop over the actuator is measured by two pressure meters (P_1 and P_2). The flow rate across the hydraulic cylinder is calculated using the measured piston displacement of the actuator.

5 Results and Discussions

Figure 5 is the characteristic curve of flow rate with electric field strength under no load. The flow rate of the ER fluid control unit increased in proportion to the electric field strength. The proportional relationship obtained experimentally was in good agreement with the theoretical value that was calculated by Eq.15 subject to a few points. The differences between theoretical and experimental value were likely to be caused by variation of output flow of power source. The output flow of gear pump was not always stable. This instability caused the variation of flow rate of the ER fluid control unit.

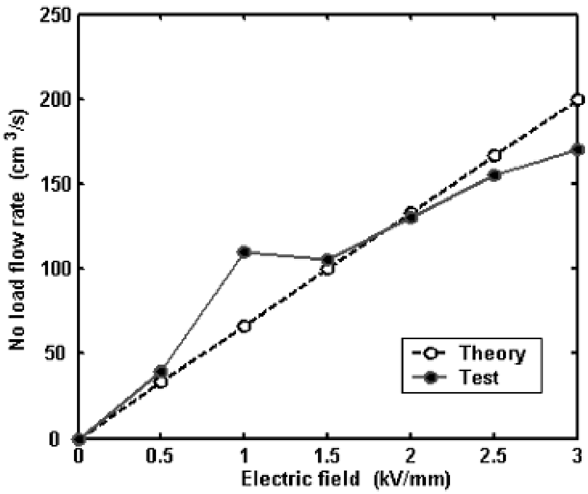


Fig. 5: *The relationship between no load flow rate and electric field strength*

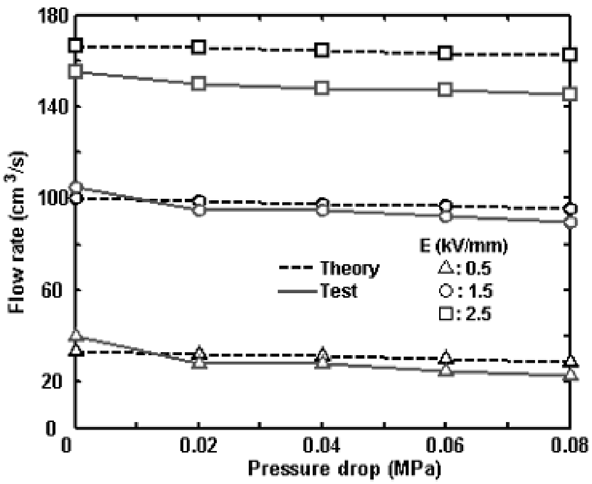


Fig. 6: *Flow–pressure characteristic of fluid control unit*

Figure 6 illustrates the flow-pressure characteristics of the ER fluid control unit. When the applied electric field was low (0.5 kV/mm and 1.5 kV/mm), the experimental curve was close to the theoretical curve. However, as the electric field strength increased to 2.5 kV/mm, experimental values were less than the theoretical values. This error might be due to two reasons: One is that the coefficient k_{re} in Eq. 6 needs to be adjusted for different applied electric fields because it depends on the geometrical parameters and operating conditions for the ER valve as mentioned previously. Better agreement between theoretical with experimental values have been achieved if different values for the coefficient k_{re} were used for the low and high electric fields. The other reason is that we derived the yield stress equation for the ER valve based on the dependence of the yield stress $\tau_y(E)$ on E^2. Atten et al (1997) found that the yield stress $\tau_y(E)$ varies as E^2 at low applied electric fields and as E at high fields. When the applied electric fields are high, the actual flow rate should be lower than is calculated by the dependence on E^2. Figure 6 also shows that the flow rate changes very slightly when pressure drop is increased, and the ratio of flow rate with pressure drop is almost constant upon different electric field strengths.

However, there are also some additional problems with the ER valves apparent in the preceding figures, i.e. their control pressure drop or load flow rate (around 180 cm^3/s when E = 3 kV/mm) is too small for the practical application. Nevertheless, they would have a very promising application in the micro system such as micro ER valve (Park et al, 1999; Yoshida et al, 2002).

6 Conclusions

An ER fluid control unit composed of four ER valves has been designed and constructed. The characteristics of the ER fluid control unit have been analyzed. The results of theoretical and experimental studies show that the flow rate or pressure drop of ER fluid control unit can be directly controlled by applied electric fields, and the flow–pressure characteristics are nearly constant under different electric field strength. But its control pressure drop or load flow rate is too small for practical application. In order to achieve practical engineering application, the parameters and configurations of ER fluid control unit need to be further optimized besides improving the ER effect of ER fluids in the next research.

Nomenclature

b	electrode width of flow aperture	[mm]
h	electrode separation gap	[mm]
l	electrode length	[mm]
D	mean annular diameter in valve	[mm]
E	electric field strength	[kV/mm]
E_0	electric field strength applied in static equilibrium position	[kV/mm]
Q	flow rate flowing through the valve	[cm^3/s]
ΔE	controllable electric field signal	[kV/mm]
ΔP	pressure drop	[MPa]
k_{re}	coefficient	
$\dot{\gamma}$	shear rate	[1/s]
τ_y	yield stress of the ER fluids	[Pa]
ε_0	vacuum dielectric constant ($8.85 \cdot 10^{-12}$)	[F/m]
ε_f	relative dielectric constants of the continuous liquid phase	
ε_p	relative dielectric constants of the suspension particles	
η_A	apparent viscosity of ER fluids	[Pa·s]
η_0	initial viscosity in absence of electric fields	[Pa·s]

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