

Study on the Controllable Characteristics of Electrorheological Valve Using Serial Multielectrode

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Abstract

This paper studies on the controllable characteristics of electrorheological valve using serial multielectrode. We design an electrorheological valve using serial multielectrode and apply to damper for testing the controllable characteristics. From the analysis and experimental results, we show that the electrorheological valve using serial multielectrode has higher controllable characteristics than a single-electrode ER valve. The electrorheological valve using serial multielectrode is suitable for vehicle dampers that especially require short stroke and high damping force.

Key Words: Electrorheological Fluid, Electrorheological Valve, Electrorheological Damper, Multielectrode

1. Introduction

Electrorheological (ER) fluid is one of the intelligent materials whose rheology changes with applied electric field [1]. This fluid consists of micro-powder particles dispersed in a nonconductive liquid. When subject to an electric field, the viscosity and yield shear stress of the liquid increase with the electric field to such an extent that the liquid may become plastic, and once the electric field is removed, the plastic is quickly turned into liquid again. Its response time is about few milliseconds [2]. It is easy to control, fast to respond, simple to install and versatile. The controllable rheological nature of this versatile material has been evaluated for a wide range of application concepts. Hence, ER fluid has a great potentiality for industrial development [3], such as clutches, seals, bearings, chucks, hydraulic control valves [4], couplings, shock absorbers and dampers of vibration

system [5].

The ER valves of the hydraulic control systems have been demonstrated in detailed investigations at the Institute of Fluid Power Transmission and Control [4,6,7]. However, the electrode gap of ER valve is usually rather small about the range of 0.5 to 2 mm, and has very small flow rate [7,8]. Then, some researchers have developed the high reaction rate of volume flow or pressure drop of the ER effect using multielectrodes. The multielectrode in parallel of ER valves can increase the flow rate [9], but decrease the controllable pressure and the pressure drop [10]. The multielectrodes in parallel of ER dampers are also decrease the controllable damping force [11]. The multielectrode [12,13] shows the numerical examples focusing on large-scale dampers, and the simulated dampers can regulate very large forces. He has studied large-scale dampers that aimed at application to civil engineering. Kuo [10] studied multielectrode ER dampers for Vibration Suppression Control. This paper studies on the controllable characteristics of electrorheological valve

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using serial multielectrode. We design an electrorheological valve using serial multielectrode and apply to damper for testing the controllable characteristics for vehicle dampers that especially require short stroke and high damping force.

2. ER Valve Analysis

The flow paths of multielectrode ER valves are composed of one-electrode ER valves, as shown in Figure 1. With the electrode gap of one-electrode ER valve denoted by h_e , its electrode length by L_e , and its electrode width by b , the width of cylindrical electrodes $b = \pi d_e$, its average diameter of electrode gap is d_e . The viscosity of ER fluid is μ . When ER fluid flows through ER valve without electric field applied, the flow throughput law according to Hagen-Poiseuille gives:

$$\Delta P_v = \left(\frac{12\mu L_e}{bh_e^3} \right) Q_e \quad (1)$$

If the electrodes are without the applied electric field, ER fluids would behave like a Newtonian fluid. Under the influence of an electric field, its behavior changes such that they can only begin to flow once they have overcome a yield shear stress. The resistance of flow force is generated by yield shear stress τ_y . The pressure drop ΔP_e , due to the increment in the yield shear stress of the ER fluid is given by

$$\Delta P_e = \left(\frac{2L_e}{h_e} \right) \tau_y \quad (2)$$

Therefore, total pressure drop ΔP of ER valve contains a Newtonian component ΔP_v and an electrorheologically influenced component ΔP_e . When the electric field

is applied to the electrodes, the total pressure drop of ER valve is given by

$$\Delta P = \Delta P_v + \Delta P_e = \left(\frac{C_v}{d_e} \right) Q_e + C_e \tau_y \quad (3)$$

$$\text{where } C_v = \frac{12\mu L_e}{\pi h_e^3} \text{ and } C_e = \frac{2L_e}{h_e}.$$

This relationship is a simple Bingham model [4].

From the following experimental studies: (a) Boyle (1991) [14] experiments that the shear stress versus shear rate of an ER fluid measured in steady-state Couette-flow geometry and oscillating Poiseuille-flow geometry, (b) Wolff-Jesse et al. (1998) [4] measures the pressure drop versus flow rate characteristics of ER valves, and (c) we test the damping force versus velocity of ER dampers. The actual flow behavior of ER fluid in an electric field, E , is analogous to the real Bingham model. The flow field is influenced by the electrode median gap velocity v (m/sec) of ER fluids. Thus the yield shear stress τ_y of ER valve is here modified by a simple function:

$$\tau_y = \tau(E, v) = \alpha E^\beta + \alpha E^\beta (\delta v^\psi) \quad (4)$$

α and β are the coefficients of ER material, ψ is the exponent. δ is constant.

3. Serial Multielectrode ER Valve

Figure 2 is a serial multielectrode ER (SMER) valve which consists of a set of concentric cylindrical electrodes. All electrodes are electrically parallel and the flow paths are arranged in hydraulically series. All concentric cylindrical electrode gap is h_e and the length of

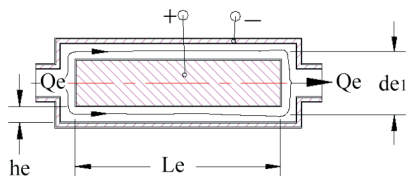


Figure 1. ER valve.

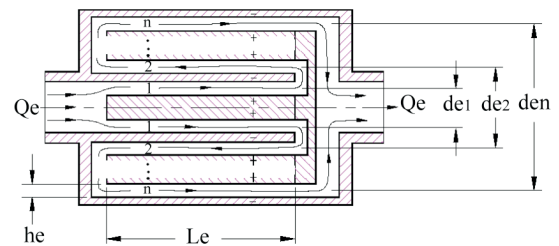


Figure 2. ER valve with serial multielectrode.

electrode of every layer is L_e . The ER fluid flows through every annular electrode gap has pressure drop, ΔP_{vi} , $i = 1 \sim n$. The total pressure drop without applying electric field is ΔP_v which is the sum of the pressure drops ΔP_{vi} along annular gap of every layer,

$$\Delta P_v = \sum_{i=1}^n \Delta P_{vi} \quad (5)$$

The flow rate of every annular electrode gap is Q_{ei} , $i = 1 \sim n$, the total flow rate Q_e in serial flow path is equal to the flow rate of every annular electrode gap Q_{ei} , i.e.

$$Q_e = Q_{ei}, \quad i = 1 \sim n \quad (6)$$

The relationship of the pressure drop ΔP_{vi} and the flow rate Q_{ei} of every annular electrode gap is

$$\Delta P_{vi} = C_v \frac{Q_{ei}}{d_{ei}}, \quad i = 1 \sim n \quad (7)$$

The total pressure drop ΔP_{vn} of n -layer electrode is

$$\Delta P_{vn} = C_v \sum_{i=1}^n \left(\frac{1}{d_{ei}} \right) Q_e \quad (8)$$

The pressure drop ΔP_{ei} of every annular electrode gap under applying electric field due to ER effect is

$$\Delta P_{ei} = \frac{2L_{ei}}{h_e} \tau_y, \quad i = 1 \sim n \quad (9)$$

The total pressure drop ΔP_{en} of n -layer electrode under applying electric field due to ER effect is

$$\Delta P_{en} = \sum_{i=1}^n \Delta P_{ei} = \frac{2 \sum_{i=1}^n L_{ei}}{h_e} \tau_y \quad (10)$$

Every electrode length L_e of n -layer is the same, i.e. $L_e = L_{ei}$, $i = 1 \sim n$, thus

$$\sum_{i=1}^n L_{ei} = nL_e \quad (11)$$

From equations (9), (10) and (11), we can obtain the total pressure drop ΔP_{en} due to ER effect.

$$\Delta P_{en} = nC_e \tau_y, \quad i = 1 \sim n \quad (12)$$

When serial multielectrode ER valve of n -layer electrode is applied to electric field, the total pressure drop ΔP_{ns} is the sum of the pressure drop, ΔP_{vn} due to Newton fluid and the pressure drop ΔP_{en} due to ER effect.

$$\Delta P_{ns} = \Delta P_{vn} + \Delta P_{en} \quad (13)$$

The total pressure ΔP_{ns} of serial n -layer ER valve is

$$\Delta P_{ns} = C_v \sum_{i=1}^n \left(\frac{1}{d_{ei}} \right) Q_e + nC_e \tau_y \quad (14)$$

3. The Damping Characteristics of Serial Multielectrode ER Valve

Assuming that the electrode length and electrode gap of serial multielectrode ER valve are $L_e = 0.1$ m and $h_e = 0.001$ m. The average diameters of every annular electrode gap are $d_{e1} = 0.0185$ m, $d_{e2} = 0.0235$ m, $d_{e3} = 0.0285$ m, $d_{e4} = 0.0335$ m and $d_{e5} = 0.0385$ m. The numbers of electrodes of serial multielectrode ER valve are five electrodes, and change from one to five electrodes with applied electric field.

The ER fluid is mixed by silicone oil and corn starch. The Bingham characteristic of the ER fluid is tested at room temperature (25 °C) and the strain rate is 190 s^{-1} . The viscosity of ER fluid is 200 cPs. The influence of the electric field on the yield stress can be approximated mathematically and described through the following function [10]:

$$\tau_{y0} = 581.5 E^{1.175} \quad (15)$$

We define the controllable pressure drop $\Delta P_{40} = \Delta P_4 - \Delta P_0$ that is the maximum pressure drop difference at 4 kV/mm (ΔP_4) and 0 kV/mm (ΔP_0), i.e. the pressure drop due to the electrorheological effect. Figure 3(a) indicates

the relationships between the pressure drop, number of electrodes and electric field, revealing that $\Delta P_{s5} > \dots > \Delta P_{s1}$. ΔP_{si} , $i = 1, 2, \dots, 5$ denotes i electrodes in series. Figure 3(b) shows that the controllable ratio (CRp) which is defined as $CRp = \Delta P_{40} / \Delta P_0$ increases with increasing the number of electrodes. From the results of the analysis, it can be proved that the number of electrodes can promote the controllable pressure drop and the controllable ratio. Then, we design, fabricate and test ER dampers using serial multielectrode ER valve to prove the above analysis results.

The serial multielectrode ER damper is composed of serial multielectrode ER valve and cylinder. The serial multielectrode ER valve can be designed with innermost type as indicated in Figure 4. The piston of the cylinder forces the ER fluid flowing through serial multielectrode ER valve developed the pressure drop when the piston is in motion. Therefore, the damping force of ER damper is mainly dominated by the serial multielectrode ER valve.

The damping force of damper is almost proportional to the pressure drop (ΔP) of serial multielectrode ER valve, i.e., $F_{ev} = A(\Delta P)$, A is the cross-sectional area of piston. If the ER damper is at compression stroke, $A = A_p$, and at rebound stroke, $A = A_r$, $A_r = A_p - A_{rod}$, A_{rod} is the cross-sectional area of piston rod. Hence, the damping characteristics of ER damper are similar to the pressure drop characteristics of serial multielectrode ER valve. But the total damping force F is the sum of (a) the inertial

force F_a of piston acceleration, (b) the damping force F_{ev} of pressure drop developed by serial multielectrode ER valve, (c) the restricted force F_{ro} due to orifices, (d) the damping force F_g due to the gas compliance of pressure P_a of the gas chamber and the pressure P_c of compression chamber, and (e) the Coulomb friction and viscous resistance force F_{fs} of the piston and piston rod.

$$F = F_a + F_{ev} + F_{ro} + F_g + F_{fs} \quad (16)$$

(a) The inertial force, F_a , is very small comparing the damping force, thus it can be neglected.

(b) The damping force, F_{ev} .

The damping force of pressure drop due to multi-

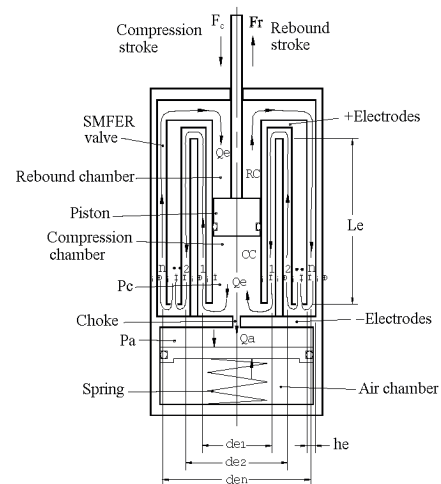


Figure 4. ER damper with serial multielectrode ER valve.

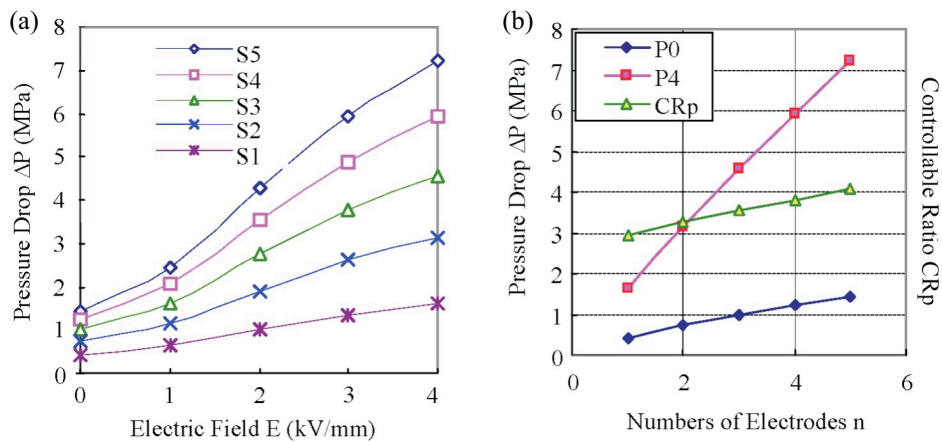


Figure 3. The relationships of controllable pressure drop, controllable ratio and numbers of electrodes of the serial multielectrode ER valve. S_i , $i = 1, 2, \dots, 5$ denotes i electrodes in series.

electrode ER valve is

$$F_{ev} = A(\Delta P_{ns}) \quad (17)$$

The pressure drop, ΔP_{ns} , is the same as Equation (14) for serial multielectrode ER valve, i.e. $\Delta P = \Delta P_{ns}$.

(c) The restricted force, F_{ro}

The restricted force F_{ro} due to the pressure drop of orifice is

$$F_{ev} = A(\Delta P_o) \quad (18)$$

The pressure drop, ΔP_o , developed by orifice, i.e.

$$\Delta P_o = \left(\frac{\rho^* A_r^2}{2(C_d^* A_o)^2} \right) \dot{y}^2 \quad (19)$$

A_o is the orifice area; C_d is the discharge coefficient; and ρ is the density of ER fluid.

(d) The damping force, F_g

The damping force due to the pressure P_a of the gas chamber and the pressure P_c of the compression chamber can adjust the force of piston rod variable volume in the ER fluid chamber.

$$F_g = A_{rod} P_c \quad (20)$$

A_{rod} is the cross-sectional area of piston rod.

When the piston rod goes into the rebound chamber at compression stroke, the volume increment by the piston rod may flow through choke to the gas chamber. As fluid in the compression chamber flows through the narrow diameter and the long length choke to the air chamber, we can obtain the pressure drop equation [15]:

$$\Delta P_{ca} = P_c - P_a = \frac{128\mu l_a}{\pi d_a^4} Q_a \quad (21)$$

where d_a denotes the diameter of choke, l_a is the length of choke, P_a is the pressure of the gas chamber. The flow rate of piston compression stroke, $Q_c = A_c \dot{y}$, is the sum of the flow rate Q_e through all electrode gap and the

flow rate Q_a through the gas chamber.

$$Q_c = Q_e + Q_a = A_c \dot{y}, \quad Q_a = A_{rod} \dot{y}, \quad Q_e = A_r \dot{y} \quad (22)$$

The gas chamber has a floating piston, piston diameter is d_a and floating piston area is A_a . y_a is the compression length of spring compressed by floating piston. Floating piston is supported by a spring. The spring coefficient is k , and pre-compression length of spring is x_0 . From the force balance equation of floating piston:

$$F_{ap} = (y_a + x_0)k = P_a A_a \quad (23)$$

From Equations (21), (22), (23) and the equation of state for gas in the gas chamber $P_i V_i^\gamma = P_f P_f^\gamma$, the pressure P_c of the compression chamber can be derived. Considering the initial pressure P_i and initial volume V_i in the gas chamber, we can obtain the pressure P_c of the compression chamber.

$$P_c = \frac{kx_0}{A_a} + k \left(\frac{A_{rod}}{A_a^2} \right) y + \frac{P_i V_i^\gamma}{[V_i - (y - y_0) A_{rod}]^\gamma} + \left(\frac{128\mu l_a A_{rod}}{\pi d_a^4} \right) \dot{y} \quad (24)$$

The first term of Equation (24) is the pressure due to the pre-compression length of spring x_0 of the spring coefficient k . The second term is the pressure due to the floating piston of the force balance. The third term is the pressure due to the equation of state for gas in the air chamber $P_i V_i^\gamma = P_f P_f^\gamma$. P_i and V_i are the initial pressure and initial volume of gas chamber, and P_f and V_f are the final pressure and volume after floating piston compression, and γ is the specific heat ratio. The fourth term is the pressure due to the ER fluid flowing through the choke to the gas chamber. d_a is the diameter of the choke, l_a is the length of the choke and P_a is the pressure of the gas chamber.

(e) The Coulomb friction and viscous resistance force,

$$F_{fs}$$

The Coulomb friction and viscous resistance force are developed by the piston and piston rod. The damping force F_{ns} of serial multielectrode ER valve is influenced

by the viscosity of fluid μ the piston velocity $\dot{y}$ and the ER effect τ_y .

$$F_{fs} = f_{fs} |\dot{y}|^\phi \quad (25)$$

where f_{fs} is the frictional force constant; ϕ is an exponent.

We have designed the ER damper with innermost serial multielectrode ER valve having one to three hydraulically serial electrodes. The primary designing parameters of the ER damper using serial multielectrode valve are (a) electrode gap $h_e = 0.0006$ m, (b) electrode length $L_e = 0.09$ m, (c) diameter of piston rod $d_{rod} = 0.011$ m, (d) diameter of piston $d_p = 0.025$ m, (e) electrode number $n = 3$.

The testing device, a mechanical damper dynamometer, contains (a) actuator units including hydraulic cylinder, servovalve, amplifier, etc. (b) control units including PC, high voltage supply, etc. and (c) data acquisition units including LabVIEW acquisition system, linear transducer and a load cell. Schematic of the experimental setup is shown in Figure 5.

Force measurements from sinusoidal displacement cycles were recorded on the mechanical damper dynamometer. Damping forces and displacements were sampled at 200 samples per second. The sinusoidal input 0.015 m amplitude changes slowly in frequency from 1 Hz to 5 Hz. The electric field was applied from 0 kV/mm to 4 kV/mm. Figure 6 indicates the damping characteristics of ER damper using serial multielectrode valve with electrode number from one to three at exciting frequency 1 Hz. The damping characteristics of ER damper increase with electrode number and electric field. Figure 7 shows the damping characteristics of damper using the serial multielectrode ER valve with 3 layers at exciting frequency 3 Hz, the dot lines are shown in simulation and the other lines are shown in experiment. This damper has the piston using check valve, then the damping force at the rebound stroke is larger than that of the compression stroke. The characteristic is suitable for vehicle damper [16].

The damping coefficient C is defined as the ratio of

the maximum damping force and maximum velocity. C_r and C_c are the damping coefficient of the rebound and compression stroke, respectively. Figure 8 shows that

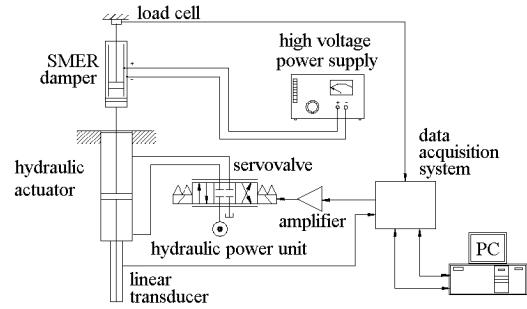


Figure 5. Schematic of the experimental setup.

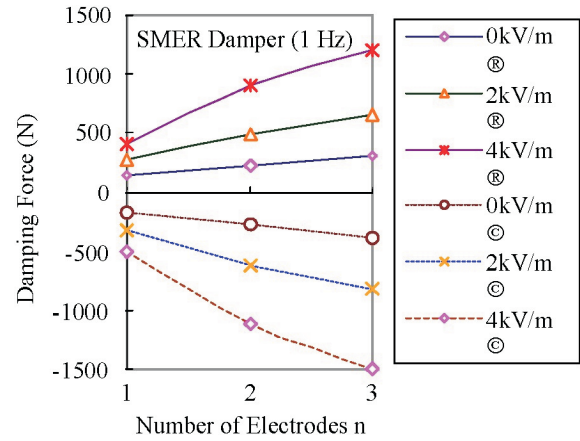


Figure 6. The damping characteristics of ER damper using serial multielectrode valve.

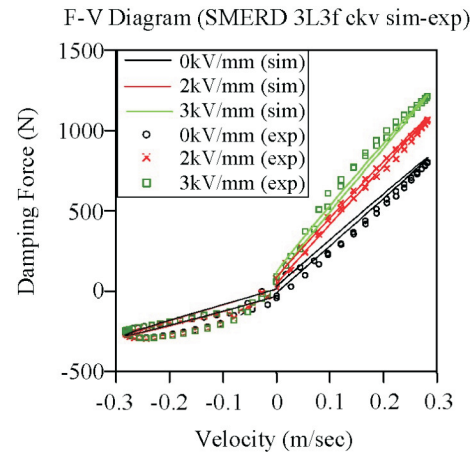


Figure 7. The damping characteristics of damper using the serial multielectrode ER valve and the piston using check valve ($n = 3$ layers, $f = 3$ Hz, sim = simulation, exp = experiment).

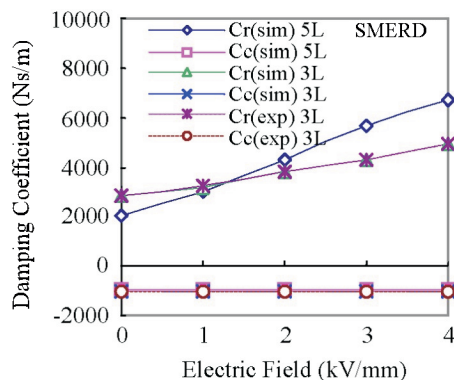


Figure 8. The damping coefficient characteristics of damper using the serial multielectrode ER valve and the piston using check valve at 3 Hz exciting frequency (5L = five electrodes, 3L = three electrodes, sim = simulation, exp = experiment).

the damping coefficient characteristics of rebound stroke increase with increasing electric field and electrode number by simulation and experiment.

To sum up, the ER damper using serial multielectrode valve can be designed to meet the requirements of any dampers. Specifically, the design variables of the electrode length, electrode gap and the number of electrodes can be varied to meet the performance requirements of dampers for vehicle suspension systems.

4. Conclusion

The aforementioned analytic and experimental results can be summarized as follows.

1. The number of electrodes can promote the controllable pressure drop and the controllable ratio.
2. The controllable damping force and the controllable ratio increase with increasing numbers of electrodes using serial multielectrode valve.
3. We can design the appropriate geometric size of electrodes for maximum controllable ratio and required damping force using serial multielectrode valve. This ER damper can produce a relatively high damping force with short stroke damper or using low level of electrorheological effect of ER fluid. It is suitable for vehicle dampers that especially require short stroke, high damping force and variable compression and rebound damping force ratio.

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