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PROPOSITION OF AN ER MICROACTUATOR WITH INHERENT POSITION FEEDBACK MECHANISM

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ABSTRACT

The paper proposes and develops a novel smart ER microactuator with inherent position feedback mechanism. The microactuator consists of a pair of movable and fixed parallel plate electrodes with variable gap length and an upstream restrictor, and ERF (electro-rheological fluid) is supplied as a working fluid. By applying voltage to the electrodes, with the increased pressure drop due to ERF viscosity increase, the electrode gap length i.e. the output displacement increases. Also the microactuator can suppress the displacement due to external force by the inherent position feedback mechanism. The mechanism utilizes increase of the flow resistance between the electrodes for decrease of the electrode gap length. In this paper, the structure and working principle are revealed and the mathematical model is derived. Then, a microactuator is fabricated and the characteristics are experimentally clarified. Furthermore, a mechanism to magnify the output displacement is proposed and the validity is confirmed through experiments.

KEY WORDS

Microactuator, ERF (electro-rheological fluid), Functional fluids, Position feedback, ER valve

INTRODUCTION

A smart actuator having built-in position sensor has been required to realize a position control system in compact size without additional sensors [1].
A fluid microactuator connected with an ER microvalve [2]-[4] is one of ER microactuators. By applying electric field to the ERF (electro-rheological fluid) in the ER microvalve, the pressure of the fluid actuator is controlled. Such an ER microactuator features simple and miniaturizable structure. Furthermore, utilizing the functionality of the ERF, a simple and compact smart actuator will be realized as a microactuator.
In this paper, a novel smart ER microactuator is proposed and developed, which can not only control the output displacement / force by the applied voltage but also suppress the displacement due to external force using the inherent position feedback mechanism. First, the structure and working principle are revealed and the mathematical model is derived. Second, a microactuator is fabricated and the characteristics are experimentally investigated. Furthermore, a mechanism to magnify the output displacement is proposed and tested.

PROPOSITION OF FB TYPE ER MICRACTUATOR

Proposed FB Type ER Microactuator

The proposed microactuator consists of a pair of movable and fixed parallel plate electrodes with variable gap length and an upstream restrictor as shown in Figure 1. The electrodes are disks and the ERF flows from the outside inlet port to the central outlet port on the fixed electrode. The movable electrode is supported by an elastic element such as a bellows. The ERF is supplied at pressure P_s as the working fluid.
When the applied voltage v increases / decreases, the control pressure p_c increases / decreases due to viscosity

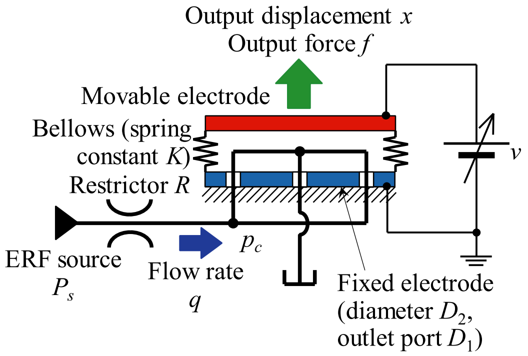

Figure 1 Proposed FB type ER microactuator

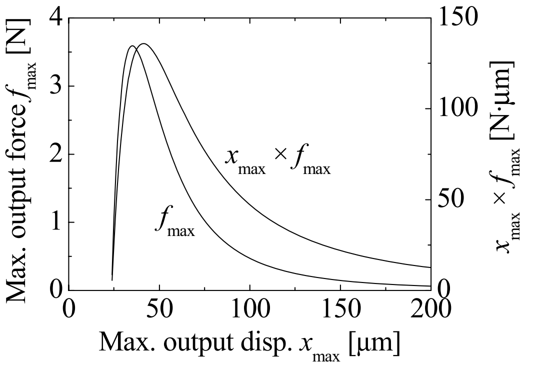

Figure 2 Analyzed characteristics of the FB type ER microactuator

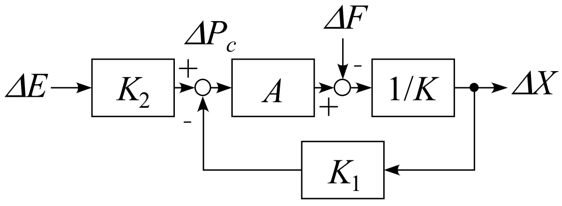

Figure 3 Block diagram of the FB type ER microactuator

change of the ERF and the output displacement x increases / decreases. Also, with constant applied voltage v, when external force to increase / decrease the gap length is applied, due to decrease / increase of the electric field strength and flow resistance between the electrodes, the control pressure p_c and hence the output force f decreases / increases. As a result, the displacement due to external force is suppressed with the inherent position feedback mechanism.

Mathematical Model

For theoretical investigations, the mathematical model of the microactuator was derived assuming flow between the electrodes to be isotropic flow. Let D_1=1.0 mm, D_2=8.8 mm, the base viscosity without electric field μ_0=24 mPa·s and the ER effect index [3] κ_{ER}=5 of the ERF, P_s=200 kPa and q_{max}=0.1 cm^3/s, the maximum output force f_{max} and $x_{max} \times f_{max}$ were calculated as shown in Figure 2. It is found that $x_{max} \times f_{max}$ becomes maximum at x_{max}=41 μm. With linearization at the driving point, the block diagram can be expressed as in Figure 3. The microactuator is proved to have a feedback loop and the actuator rigidity is derived as follows:

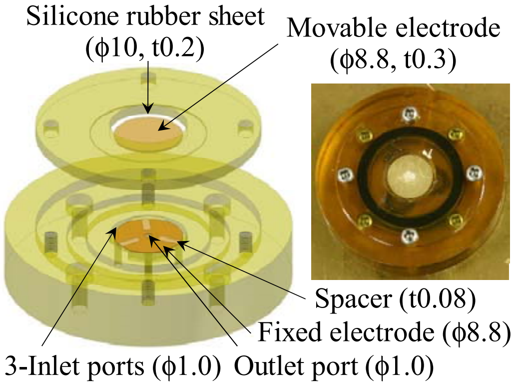

Figure 4 Fabricated electrode part of the FB type ER microactuator

$$K_a = -\frac{\Delta f}{\Delta x} = K + AK_1, \qquad (1)$$

which means the microactuator has the actuator rigidity higher than K without additional feedback loop and the microactuator can suppress the displacement due to external force.

FABRICATION AND CHARACTERIZATION OF FB TYPE ER MICRACTUATOR

Fabricated FB Type ER Microactuator

Based on the derived results, a microactuator was designed and fabricated. The fabricated electrode part is shown in Figure 4. The disk electrodes are divided by three parts with independent hydraulic circuits and slant of the movable electrode is suppressed. The movable electrode is supported by a silicone rubber sheet instead of a bellows. The homogeneous ERF used here is a nematic liquid crystal (MLC-6457-000, Merck Ltd., Japan) whose base viscosity μ_0=24 mPa·s and ER effect index κ_{ER}=5.4 [3].

Experiments

The static characteristics were measured with supply pressure P_s=200 kPa. The output displacement x under no load was measured by a laser displacement sensor and the control pressure p_c (average of three pressures) was measured by semiconductor type pressure transducers.

Figure 5 shows the measured results. The origin of the output displacement x is corresponding to the output displacement without supply pressure and voltage. It is found that the output displacement x has nonlinearity, however there is few hystereses. The output displacement range is 52 μm. The output displacement x at v=0 is not zero due to the initial stretched length error of the silicone rubber sheet.

The output force f was measured through the deflection of a brass beam (50×10×1.4 mm^3, spring constant 7.6 kN/m) for the output displacement x to be the value without voltage. Figure 5 shows the measured results. The maximum output force f_{max}=1.5 N was obtained.

Based on the control pressure p_c and the mathematical

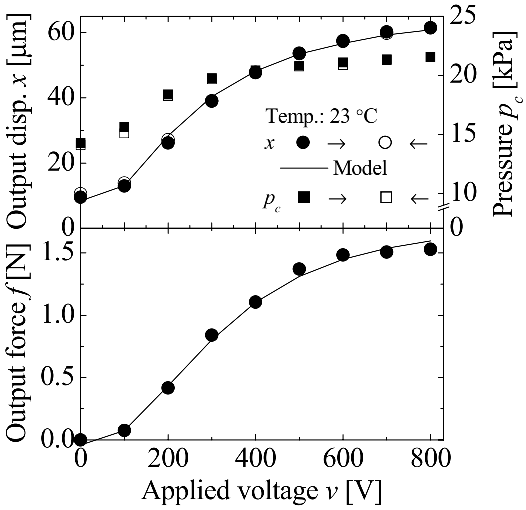

Figure 5 Measured static characteristics of the FB type ER microactuator

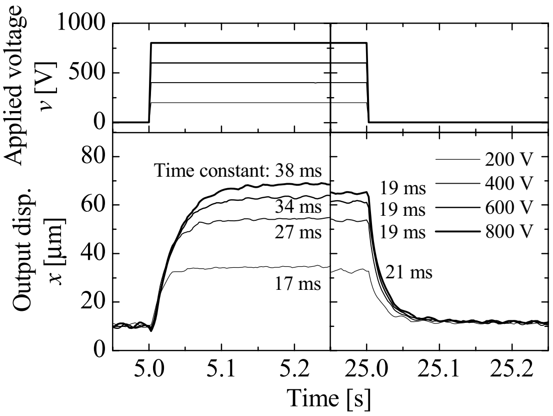

Figure 6 Measured step responses of the FB type ER microactuator

model, the parameters were identified. The solid lines in Figure 5 show the results of output displacement x and the output force f. It is ascertained that the results agree well with the measured values. Differences between the identified and the measured parameters are due to different flow from the isotropic flow due to the three inlet ports.

The actuator rigidity at the maximum output displacement was measured using the beam at the applied voltage v=800 V. As a result, K_a=16 kN/m was obtained. The value is 3.7 times higher than the value without feedback loop and the validity was confirmed. The value of the mathematical model is 18 kN/m that agrees well with the measured value.

Figure 6 shows the measured step responses of the microactuator. The step down responses are higher than step up, which is due to the mechanism difference; for step up, the liquid crystal molecules make domains; for step down, the domains collapse by the flow [4]. The identified time constants of the first order lag responses are also shown in Figure 6. As for the effect of the applied voltage amplitude, there are few differences for step down and the step up responses decrease with higher voltage amplitude, which are the same as the previous ER microactuators [3]. The bandwidth of 4 Hz or more was confirmed.

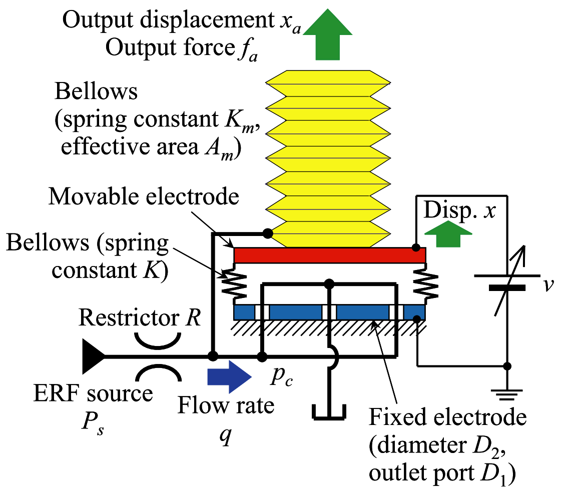

Figure 7 Proposed FB type ER microactuator with displacement magnification unit

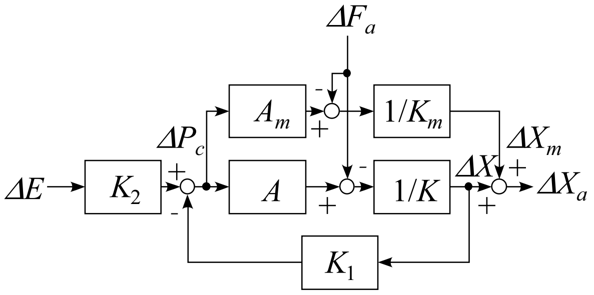

Figure 8 Block diagram of the FB type ER micro-actuator with displacement magnification unit

PROPOSITION OF DISPLASEMENT MAGNIFICATION UNIT

Proposed Displacement Magnification Unit

To extend application fields of the FB type ER microactuators, the output displacement range is required to enlarge. In this paper, a displacement magnification unit utilizing the control pressure p_c is proposed as shown in Figure 7.

The unit is a bellows that is attached on the movable electrode and is connected to the control pressure p_c port in hydraulic circuit. The output displacement x_a is the sum of the movable electrode displacement x and the bellows extension / contraction x_m. When the applied voltage v increases / decreases, the control pressure p_c increases / decreases like the electrode part only. Hence, gap length of the electrodes and length of the bellows of the unit increase / decrease. The output displacement x_a can be controlled by the applied voltage v.

With the constant applied voltage v, when the external force is applied to increase / decrease the output displacement, flow resistance of the electrode unit decreases / increases due to the large / small gap length

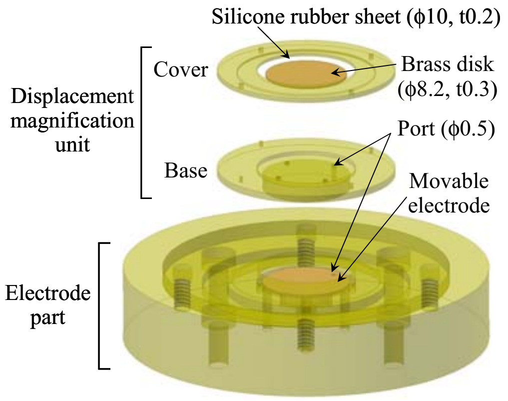

Figure 9 Fabricated FB type ER microactuator with displacement magnification unit

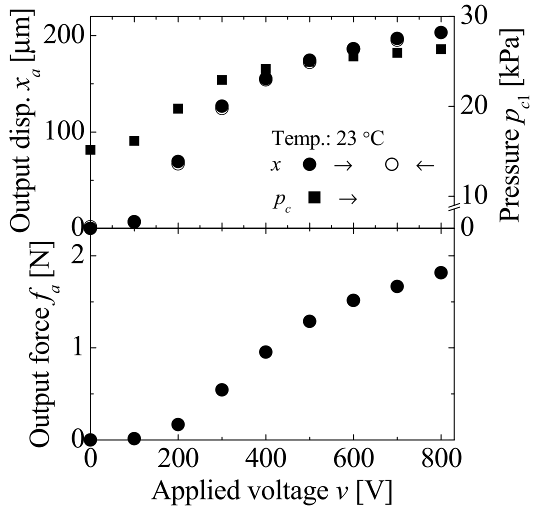

Figure 10 Measured static characteristics of the FB type ER microactuator with displacement magnification unit

and low / high electric field strength, so the control pressure p_c and hence the output force f_a decreases / increases. The microactuator can suppress the displacement due to external force. As can be seen in Figure 8, the derived block diagram of the microactuator has a feedback loop.

The output displacement x_a under no load, the output force f_a without displacement and the actuator rigidity K_{am} at the maximum output displacement are calculated as follows:

$$
\begin{aligned}
&x_a = \left(1 + A_m K / A K_m\right) x, \\
&f_a = \begin{cases} \left\{1 - \left(A - A_m\right) K / \left(K + K_m\right)\right\} f & \left(A \geq A_m\right) \\ \left(A_m / A\right) f & \left(A < A_m\right) \end{cases}, \qquad (2) \\
&K_{am} = \left(K + A K_1\right) K_m / \left\{K + K_m + \left(A - A_m\right) K_1\right\}.
\end{aligned}
$$

Experiments

The FB type ER microactuator with displacement magnification unit was fabricated as shown in Figure 9. Dimensions of the electrode unit is the same as Figure 4. Instead of the bellows, a diaphragm using silicone rubber sheet was used.

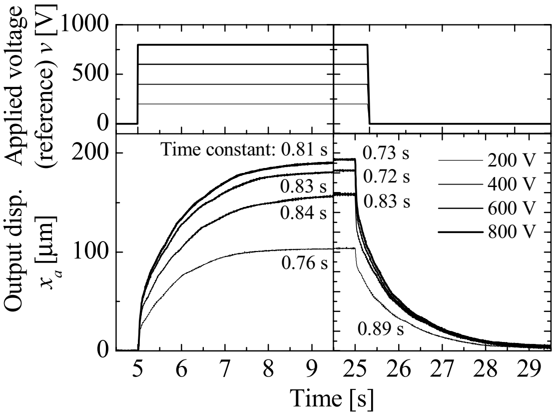

Figure 11 Measured step responses of the FB type ER microactuator with displacement magnification unit

The static characteristics of the microactuator were measured using the same method as the electrode part. Figure 10 shows the measured results. The output displacement range of 203 μm and the maximum output force of 1.8 N were obtained. The measured actuator rigidity at the maximum output displacement was 6.3 kN/m. Figure 11 shows the measured step responses of the microactuator. Due to flow saturation, the responses were lower than values of the electrode unit. Based on the identified time constant of the first order lag responses, the bandwidth is 0.2 Hz.

CONCLUSIONS

In order to realize a smart microactuator, the FB type ER microactuator was proposed and the basic investigations were conducted. The main results are summarized as follows:

1) The FB type ER microactuator was proposed and the mathematical model was derived.
2) An FB type ER microactuator was fabricated and the validity was confirmed experimentally.
3) A displacement magnification unit was proposed and the basic characteristics were experimentally clarified.

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