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DEVELOPMENT OF PISTON TYPE LINEAR ACTUATORS USING ELECTRO-CONJUGATE FLUID

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ABSTRACT

An Electro-Conjugate Fluid (ECF) is considered as a functional fluid like electro-hydro dynamics fluid, and it has a remarkable property that a jet flow is generated between two electrodes when a high voltage is applied to the electrodes. In this study two types of linear actuators consisting of the pistons and cylinders using an ECF are proposed. The one has a structure of a coil type electrodes, and the other a structure of mesh type electrodes. The proposed actuators are fabricated, and their basic characteristics such as piston velocities vs. applied voltages to electrodes and the load characteristics are examined in the experiment. The experimental results show that the proposed linear actuators have the possibilities to be used as the functional linear actuators.

KEY WORDS

Linear Actuator, ECF, Jet Flow, Static Characteristics, Load-Velocity Characteristics

INTRODUCTION

An actuator is an essential component of robots and many other mechanical devices. There has been a growing demand for increasingly miniaturized and versatile actuators in recent years. This has spurred great interest in R & D for these components, both in solid-state actuators such as piezoelectric and electrostatic devices, and devices based on functional fluids, such as electro-rheological and magnetic fluids. Sumoto discovered that a dielectric fluid will rise against the pull of gravity along an electrode submerged in the fluid if a sufficiently high voltage is applied to the electrodes, a phenomenon subsequently called the Sumoto effect. More recently, Ohtubo et al. have reported that application of a high voltage to electrodes submerged in certain types of dielectric fluids such as di-n-butyl dodecandioate causes an intense jet between the electrodes. The mechanism of this flow has yet to be explained, but since the jet effect is considerably more intense than those observed in other electrohydro-dynamic (EHD) fluids, these dielectric media have been given their own designation, “electro-conjugate fluids” (ECF)[1]. ECF may enable construction of actuator systems with much simpler structures and driving circuits than conventional electric motors. There has been much research into different kinds of rotary motors based on ECF[2][3][4], pump modules employing EHD fluids[5], flow analysis of jets in opposed ring electrodes[6][7], and related topics.

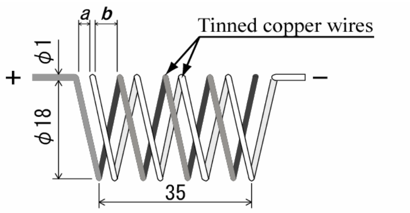
This report describes the concept, fabrication and observed operating characteristics of a linear actuator based on ECF, a type of actuator which has received almost no attention from other researchers to the best of our knowledge. Piston-operated linear actuators of two configurations were fabricated using coil and mesh type electrodes. Operating characteristics were observed for both actuators, namely, the piston velocity with respect to applied voltage, static characteristics of current in the actuator at no load, and load-piston velocity. Future issues in the development of these actuators are also discussed.

CONCEPT AND FABRICATION OF LINEAR ACTUATOR

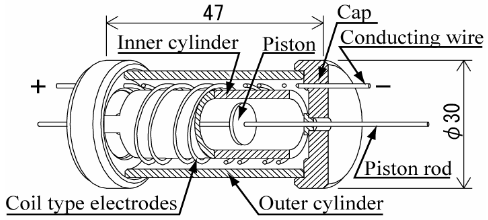
Since, in addition to rotary actuators, linear actuators have been widely used in industry, two types of ECF-based actuators were designed and constructed in this research. Both a coil and a mesh construction can be used for the electrodes in generating an ECF jet as the power source for a piston-operated linear actuator; accordingly, a coil-electrode linear actuator (coil-type actuator) and a mesh-electrode linear actuator (mesh-type actuator) were created.

Coil-Type Actuator

Figure 1 presents the coil-type actuator fabricated in this research. Let us consider the results of applying a voltage across the pair of helical coil-type electrodes shown in (a) with differing gap sizes of *a* and *b*. To simplify, let us assume here that $a < b$. In this model, an ECF jet is generated from the black coil toward the white coil in the gap *a* in Figure 1(a), from left to right, while an opposite jet is generated, from right to left, in the gap *b*. Since the gap *a* is smaller than the gap *b*, however, the strength of the jet in the gap *a* is greater than that in the gap *b* and therefore, the net effect is the excitation of an ECF jet from right to left. Applying an opposite voltage will cause a jet from left to right. Thus, controlling the polarity and intensity of the voltage applied to the helical coil pair controls the direction and intensity of the ECF jet. As shown in (b), directing the ECF jet into the cylinder inside the coil drives the piston in the cylinder. The number of turns in the fabricated coil was 4, the diameter was 18 mm, the length was 35 mm, and the material was tin-plated 1-mm wire. The electric power supplied to the coil was produced by a high voltage DC source through leads into caps placed at each end of the coils. The effective area of the piston was made of propylene and measured 12mm in diameter and 0.8 mm in thickness. The piston rod was made of 1-mm piano wire. The overall piston weight was 0.75g and the maximum stroke was 16 mm. Transparent polyvinyl chloride resin was used for the structure of the coil-type actuator. To examine the effect of the *a*:*b* gap ratio on actuator performance, three coils were fabricated with gaps of *a* =1, 2 or 3mm and *b* =4 mm.

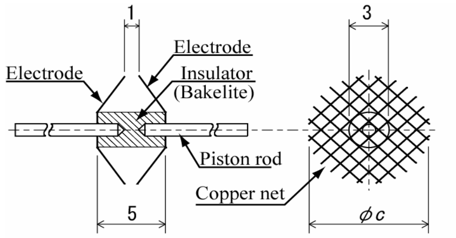


(a) Structure of coil type electrodes

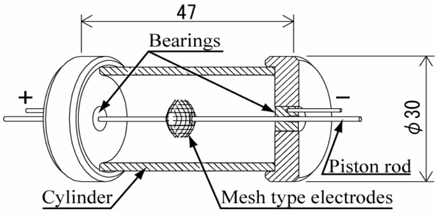


(b) Structure of coil type actuator

Figure 1 Configuration of coil type actuator



(a) Structure of mesh type electrodes



(b) Structure of mesh type actuator

Figure 2 Configuration of mesh type actuator

Mesh-type Actuator

Figure 2 is a diagram of a mesh-type actuator. The electrodes shown in (a) were two opposed bowl-shaped meshes of 0.2-mm-diameter copper wire, woven at a spacing of 1 mm. A Bakelite rod 3 mm in diameter held the meshes in position while also insulating them from each other. Piston rod pieces were inserted along the axis at each end of the Bakelite rod and were electrically connected to each mesh. The piston rods were connected at their tips to a high-voltage source through a bearing (Figure 2(b)). The ECF jet was generated by charging the electrodes with the voltage through the piston rods. As shown in Figure 2(b), the mesh electrode structures also serve as pistons, driven directly by the jet.

In this research, meshes with three diameters (ϕ_c in Figure 2(a)) were used: 10, 13 or 15 mm. A preliminary experiment showed that a pair of flat meshes standing in parallel yielded almost no driving force to the pistons; the bowl-shaped electrodes were then fabricated and tested. This configuration has the advantage of a simpler construction than the coil-type actuator.

EXPERIMENTAL APPARATUS

Figure 3 shows the apparatus used for examining the basic operating characteristics of the linear actuators fabricated for this research. Each actuator was set in a vertical position in the cylinder. The base of the cylinder was placed in a container of ECF (not shown in the figure) in order to prevent leaks of the ECF from the bearing race of the piston. When the actuator was charged with a high voltage by the DC source, the piston, positioned at the floor of the cylinder by gravity, was raised by the action of the ECF jet under the influence of the electrodes. The speed of the piston was observed with a laser-based displacement/speed sensor. Also, the ground side of the electrode was connected in series with an exterior electric resistor (10 kΩ) in order to estimate the current by measuring the voltage drop across the resister. Table 1 displays the principal physical characteristics of the ECF used in the experiment.

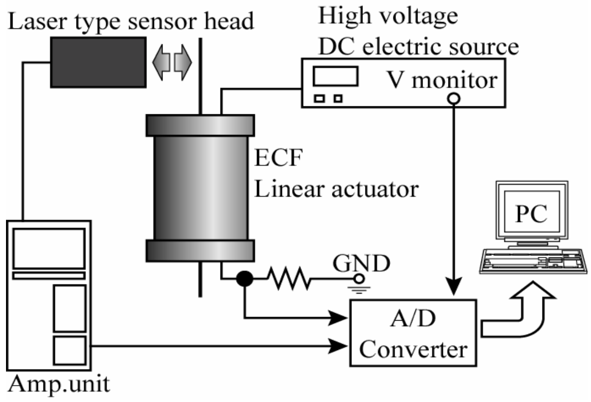


Figure 3 Experimental apparatus

Table 1 Properties of ECF

Boiling temperature	78 [℃]
Surface tension	0.014 [N/m]
Kinetic viscosity	0.4×10^{-6} [m²/s]
Density	1430 [kg/m³]
Firing point	None

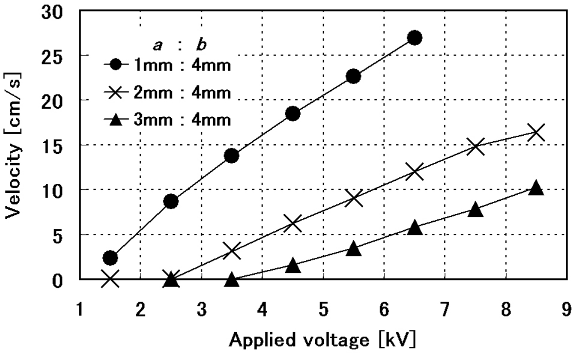


Figure 4 Static characteristics between piston velocity and applied voltage in coil type actuators with no load

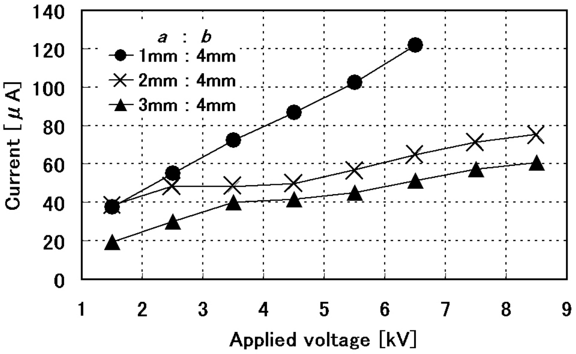


Figure 5 Static characteristics between current and applied voltage in coil type actuators with no load

STATIC CHARACTERISTICS OF THE ACTUATORS (NO LOAD)

Coil-Type Actuator

A coil-type actuator (see Figure 1(b)) was placed in the apparatus shown in Figure 3 and a DC voltage was applied to the helical coils. The speed of the piston forced upward by the operated ECF jet was recorded once it had reached a constant rate. The results are given in Figure 4. The symbols ●, ×, and ▲ represent the results for electrode spacing of 1, 2 and 3 mm, respectively. All cases showed a nearly proportionate increase in piston speed with applied voltage. Also, the smaller the dimension of the gap *a*, the greater the piston speed. This is consistent with the increase in ECF jet speed of the gap *a* shown in Figure 1(a). When the gap *a* was 1 mm and the voltage 6.5 kV, the piston speed was a considerable 27 cm/s. No results were recorded for higher voltages for the gap a = 1 mm because at high voltages, the piston speed did not become constant within the maximum stroke distance (about 16 mm) before the piston struck the top of the cylinder. It is reasonable to anticipate that higher piston speeds would be attained at higher voltages.

It should also be noted that the minimum voltage necessary to initiate piston displacement diminished with gap size; at the gap a = 1 mm, this was 1.5kV. This voltage is expected to be greatly affected by the weight of the piston and the piston-cylinder friction.

The piston speed characteristics were found to be strongly affected by the gap ratio (a:b) and thus it will be necessary to identify the optimal electrode distance, given coil shape and dimensions. Figure 5 shows the observed current flow between the electrodes with applied voltage and electrode gap a. As seen in the piston speed characteristics in Figure 4, the current between the electrodes increased both with applied voltage and with diminishing electrode gap a.

Mesh-Type Actuator

The mesh-type actuator (see Figure 2(b)) was placed in the apparatus in Figure 3. The same experiments were performed as with the coil-type actuator, using the three mesh diameters (ϕ_c) 10, 13 and 15 mm. Figure 6 displays the observed relation between applied voltage and piston speed, and Figure 7, that between applied voltage and current flow between the electrodes. Figure 6 shows quite similar results to those for the coil-type actuator in Figure 4, i.e., all electrodes show a roughly linear increase in piston speed with voltage. However, in terms of the minimum voltage necessary to obtain starting, the mesh-type actuator required a higher voltage, and its results showed a greater scatter. As described later, this was attributed to the lower driving force generated by the present mesh-type actuator compared to the coil-type actuator; friction in the bearings and at other locations is expected to exert a relatively larger effect. The piston speed was highest when the ϕ_c = 13 mm mesh was used; the speed was about equal to that observed with the 1-mm electrode spacing in the coil-type actuator. For mesh with ϕ_c = 10 or 15 mm, no clear tendencies were observed in the relation between piston speed and electrode size. Figure 7 shows the current through the mesh structure between the electrodes; the current generally increases with electrode diameter. However, even though the current through the 13-mm-diameter electrodes was about midway between the levels at 10 and 15 mm, the piston speed at this diameter was highest, as shown in Figure 6. Further study is necessary into the relation of the electrode size to the current flow and piston speed. As the mesh electrode size increases, the electrode current and piston speed are also expected to increase, but piston mass and fluid resistance to the piston motion must also increase. The piston speed is determined by the equilibrium among all these factors. These interrelationships will have to be clarified before this actuator can be applied to real-world uses.

Time-Based Changes in Static Characteristics

We have discussed the characteristics of piston speed and current between the electrodes with respect to applied voltage in coil-type actuators and mesh-type actuators. For practical application of these actuators, however, it is also important to examine how these characteristics change with time. Therefore, a coil-type

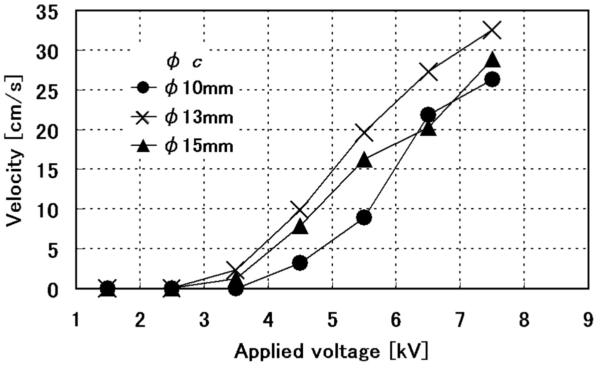


Figure 6 Static characteristics between piston velocity and applied voltage in mesh type actuators with no load

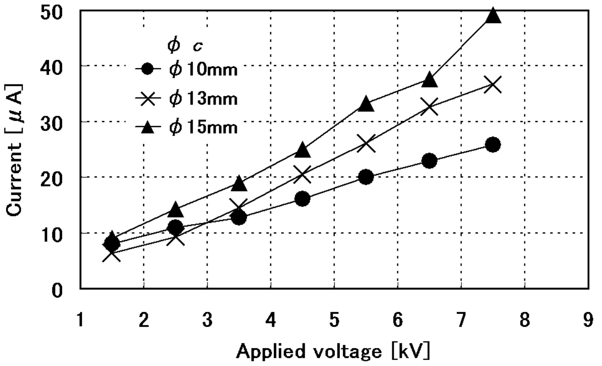


Figure 7 Static characteristics between current and applied voltage in mesh type actuators with no load

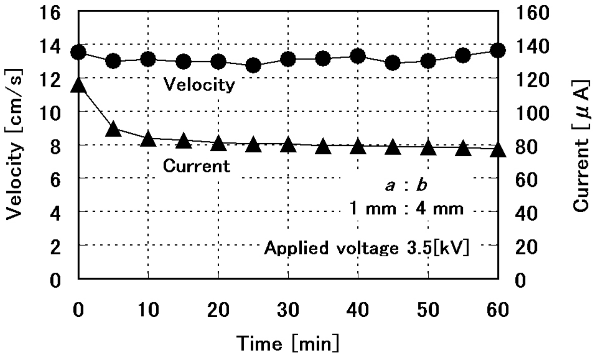


Figure 8 Static characteristics of piston velocity and current against elapse of time in coil type actuator with no load

actuator with electrode spacing *a* = 1 mm and a mesh-type actuator with mesh diameter of 13 mm were subjected to voltage square waves of intensity 0 – 3.5 kV at a frequency of 0.1 Hz, causing reciprocating motion of the pistons, continuously for 60 min. Every 5 min, the piston speed and the current were observed, as shown for the coil-type actuator in Figure 8. The values of the piston speed hold constant. However, the current decreased somewhat during the 0-5 min period and subsequently became approximately constant. The mesh-type actuator exhibited the same pattern.

CHARACTERISTICS OF PISTON SPEED WITH ACTUATOR LOADING

The piston speed was again measured using the same method as described for the unloaded actuators in section 4, but this time, a range of weights were attached to the upper tip of the piston axle on the vertically displacing actuator (see Figure 3) The models tested were the coil-type actuator with a 1-mm electrode gap and the mesh-type actuator with 13-mm mesh, as these produced the highest piston speeds in the unloaded condition. The relations between piston speed and loading are shown in Figure 9 (coil-type actuator) and 10 (mesh-type actuator). The loads and piston speeds indicated by ▲, ×, and ● in Figure 9 represent voltages of 2.5 kV, 3.5 kV and 4.5 kV, respectively. Overall, these figures show the same drooping characteristic as seen in the torque-speed curve of a typical DC motor. It is easy to control the load by adjusting the voltage; this is a desirable trait for the purpose of control. In Figure 10, the ▲, ×, and ● symbols represent voltages of 4.5 kV, 5.5 kV and 6.5 kV, respectively. The mesh-type actuator showed the same trend for piston speed under load as the coil-type actuator did. The characteristics in Figures 9 and 10 were approximated by the broken lines, and then, the maximum power efficiency (mechanical power output/electrical power input, %) was calculated for each voltage. The coil-type actuator showed maximum power efficiencies at 2.5 kV, 3.5 kV, and 4.5 kV of 0.5%, 0.9% and 1.2%, respectively; the corresponding figures for the mesh-type actuator at 4.5 kV, 5.5 kV, and 6.5 kV were 1.3%, 1.5% and 1.7%, respectively. The maximum power efficiencies in both actuators improved with increased applied voltage. Also of interest, the electrical energy levels supplied to the coil-type actuator and mesh-type actuator at 4.5 kV were 400 mW and 90 mW, respectively. As mentioned above, the power efficiencies at this voltage were similar at 1.2% and 1.3%, respectively. ECF-based micromotors have attained experimental efficiencies as high as 17%. One of the issues for future models of these linear actuators will be to establish design guidelines for improving the power efficiency.

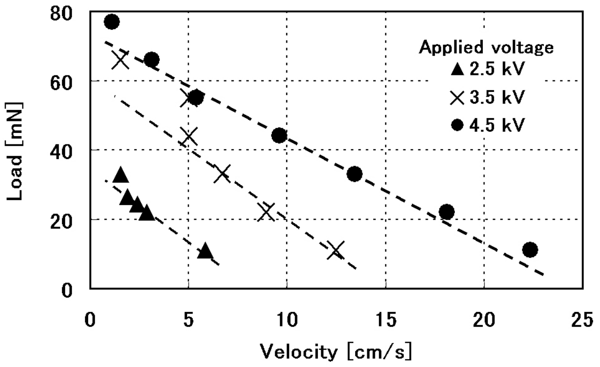


Figure 9 Static characteristics between load and applied velocity in coil type actuator (*a* : *b* = 1[mm] : 4[mm])

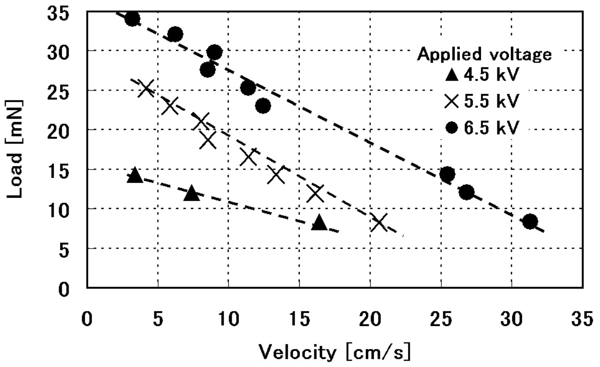


Figure 10 Static characteristics between load and velocity in mesh type actuator (ϕ 13)

CONCLUSIONS

This report presents two linear actuators based on jet flows of electro-conjugate fluids (ECF), which have attracted interest as new functional fluids. Piston-type actuators were constructed using two different structures for the exciting ECF jets: a coil-based structure and a mesh-based structure. The basic static characteristics of these actuators were investigated. The main findings are as follows:

(1) Both of the proposed linear actuators displayed fairly good static characteristics and potential for functional improvement.

(2) In the coil-type actuator, the piston speed and the electric current flow between the electrodes grew approximately in proportion to the applied voltage. The mesh-type actuator showed similar characteristics. The coil-type actuator produced an unloaded piston speed of 27 cm/s when the electrode spacing was 1 mm and the applied voltage was 6.5 kV, at a current flow of 120 μA. This represents a moderately high piston speed.

(3) No large changes in function were noted in continuous cycling of either actuator for 60 min.
(4) Both actuators showed load-piston speed characteristics closely resembling the well-known torque-speed curve for a DC motor.
(5) The maximum power efficiencies were 1.2% at a supplied electrical power of 400 mW for the coil-type actuator and 1.7% at a supplied electrical power of 90 mW for the mesh-type actuator.
Future research on these linear actuators should aim to improve speed, and power efficiency. In particular, more detailed design data is required in order to optimize the coil and mesh electrode structures of the actuators and to investigate methods to prevent leakage of ECF.

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