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DP-RE type Micromotors using Electro-conjugate Fluid

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Abstract—**This paper presents a new type of micromotor using electro-conjugate fluid (ECF). An electro-conjugate fluid is a kind of dielectric fluid, which works as a smart fluid. The fluid generates a powerful jet flow, which we call an ECF jet, when subjected to high DC voltage with highly non-uniform electric field, which means, it works as a fluid power source for mechanical components without bulky pumps. We introduce this attractive smart fluid to micromotors in this paper. Inside the motor is filled with the electro-conjugate fluid and a rotor has electrode pairs on the surface. By applying high DC voltage to the electrode pairs, the rotor rotates due to the ECF jet. In this paper, we design several types of electrode pairs and examine each influence on motor performances.**

I. INTRODUCTION

MEMS or *millirobot* [1] is one of hot topics in robotics and mechatronics, which has a great potential for expanding an application area of robotic technology. Although there are many issues related to these topics, one of the essential issues is a "micro actuator." The actuator widely used for robot system is an electromagnetic motor, however, they are of disadvantage when the system becomes tiny. Consequently, many researchers have been reported several kinds of power source suitable for micro actuation [2][3][4]. Fig. 1 shows a comparison of energy density of actuators using different kinds of power sources. But still, there is no absolute actuator for MEMS and millirobot, like an electromagnetic motor for general-sized robotic systems.

For this background, we introduce a promising smart fluid, or an electro-conjugate fluid, for micromotors in this study. The electro-conjugate fluid or ECF is a kind of dielectric fluid producing a powerful jet flow (ECF jet) when subjected to high DC voltage [5]. The phenomenon itself is similar to EHD (electrohydrodynamics) effect [6], however, we call particular fluids electro-conjugate fluids, which satisfy a necessary condition we found (*cf.* chapter II). With this attractive fluid, we can develop tiny fluid-driven mechanical components without any bulky pumps [7][8]. In particular, the fluid just needs an extremely tiny electrode pair for generating ECF jet, which means, the fluid is suitable for a power source of micro actuation system.

In this paper, we test several types of electrode pairs for generating ECF jet in order to obtain a high performance micromotor driven by the ECF jet. Chapter II briefly introduces the basics of electro-conjugate fluids. Chapter III proposes a concept of novel micromotor using electro-conjugate fluid (ECF micromotor). Then in Chapter IV, electrode configurations, of the ECF micromotors are designed. Finally, the motor performances are confirmed by experiments in Chapter V.

II. ELECTRO-CONJUGATE FLUID

The electro-conjugate fluid is a kind of dielectric fluid, which works as a smart fluid or functional fluid. Applying high voltage (several kV) between electrodes inserted into the fluid with interelectrode gap of several hundreds micrometers, we can observe a powerful jet flow, which we call an ECF jet, between the electrodes (Fig. 2). Although a high voltage is needed to generate the jet flow, the consumption current is quite low (several μA).

We investigated around 50 dielectric fluids whether the fluids show the above-mentioned effect or not. The fluids plotted by white circles in Fig. 3 showed the effect in the experiments (viscosity and conductivity are experimentally selected as parameters explaining the phenomenon). As can be seen from the figure, the dielectric fluids showing the “ECF effect” are plotted in a particular triangle on the conductivity vs. viscosity relation. That is, this triangle is at least a necessary condition for fluids to show the ECF effect. For this result, we call the fluid satisfying the necessary

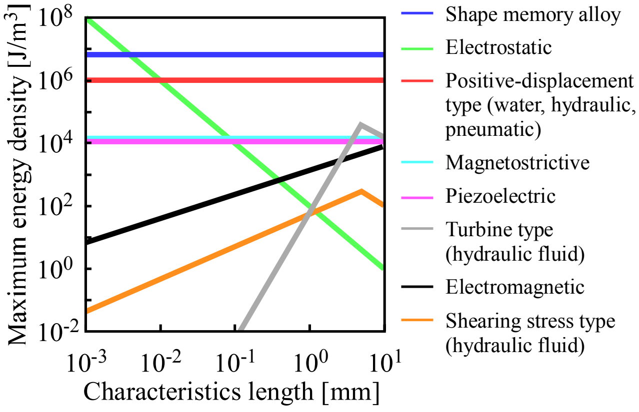

Fig. 1 Maximum energy densities of actuators

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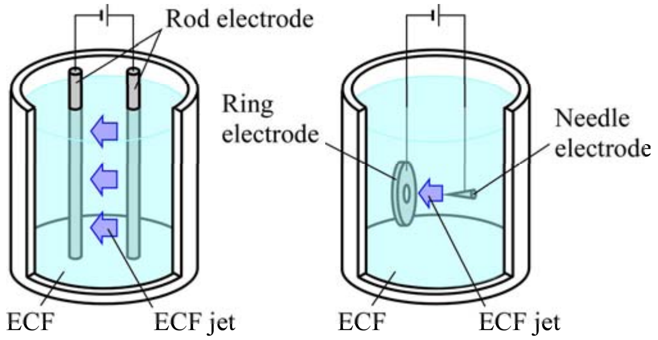


Fig. 2 Schematics of ECF jet

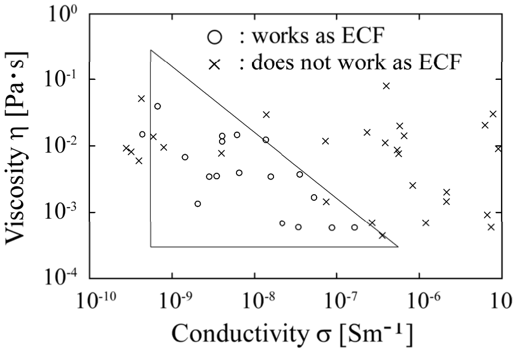
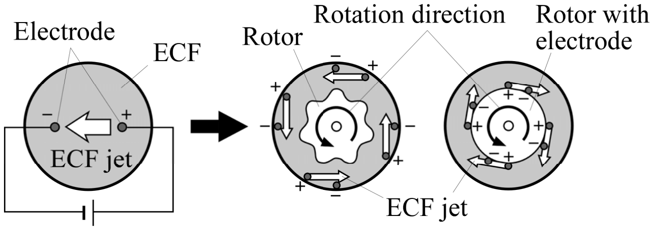


Fig. 3 ECF qualification



(a) SE type (Electrode on stator) (b) RE type (Electrode on rotor)

Fig. 4 Concept of ECF micromotors

TABLE I
CLASSIFICATION OF ECF MICROMOTORS

Rotor shape \ Electrodes	on stator	on rotor
cylinder	C-SE	C-RE
disk plate	DP-SE	DP-RE

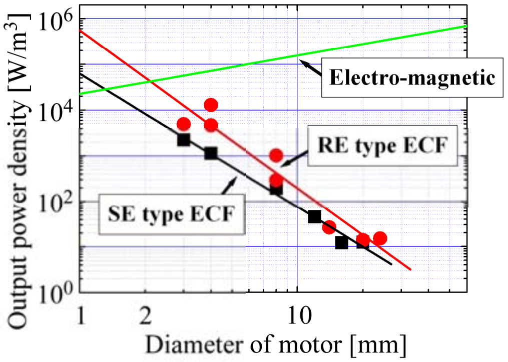


Fig. 5 Comparison between ECF motors and electromagnetic motors

condition an electro-conjugate fluid.

The mechanism of ECF effect has yet to be clarified, however, the effect itself is effective for engineering applications [7][8]. From our previous studies on electro-conjugate fluid, we clarified the attractive following features of electro-conjugate fluids.

- The ECF jet is observed under an extremely nonuniform electric field.
- The ECF jet becomes more powerful as the electrode pair becomes compact, which means, the effect is suitable for micro actuation.
- The fluid plotted closer to the origin of Fig. 3 shows more powerful jet flow.

III. CONCEPT

As mentioned in Chapter II, the electro-conjugate fluid is suitable for micro actuation. Consequently, we proposed several types of ECF micromotors [9][10]. Our concept of ECF micromotor is shown in Fig. 4. There are two possible types of motor configurations, however, both of them are filled with electro-conjugate fluid inside. The first one, which is called SE-type (stator with electrodes) ECF micromotor, is shown in Fig. 4 (a). The electrode pairs on the inner surface of the stator generate a rotational flow inside the stator. Then, a paddle-wheeled rotor rotates according to the rotational flow. The other called RE-type (rotor with electrodes) ECF micromotor is shown in Fig. 4 (b). In this case, the reaction force of ECF jet makes the rotor rotate. In addition, the ECF micromotors are categorized by rotor configuration as well. That is, a motor with cylindrical rotor is called C-type, and a motor with disk plate rotor is DP-type. Accordingly, there could be four types of ECF micromotors, C-SE, C-RE, DP-SE, and DP-RE type (*cf.* Table I).

According to our previous studies [9][10], the DP-RE type ECF micro motor, which is examined in this study, is the most promising from the view point of output power density (Fig. 5 summarizes our previous results).

IV. DESIGN AND FABRICATION

The main purpose of this study is to clarify the effect of electrode configuration for DP-RE type ECF micromotors. Therefore, we designed a four-layer DP-RE type ECF micromotor with inner diameter of 9 mm as a test bench as shown in Fig. 6. The micromotor mainly consists of a stator, a rotor, and a separator. The stator and the separator are of an engineering plastic. The rotor has four disk plates having electrodes on the both sides. An output shaft has bicylindrical structure for power feeding, which means, the electrical power is applied to the electrodes via output shaft and ball bearings located at both sides of the rotor. The separator divides the inside of stator into four thin rooms and cuts off the possibility of unneeded jet generation between the rotor

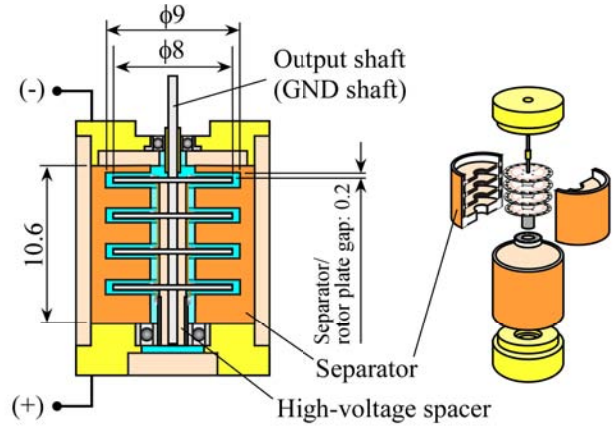
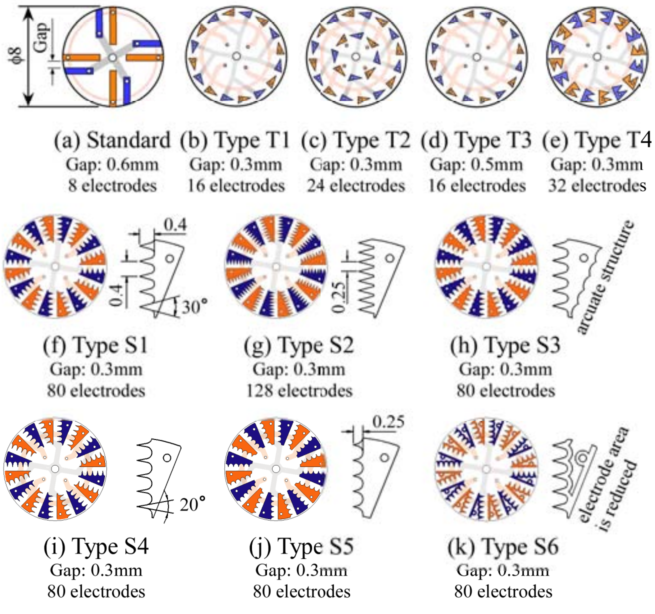


Fig. 6 Four-layer DP-RE type ECF micromotor with inner diameter of 9 mm



(a) Standard Gap: 0.6mm 8 electrodes
(b) Type T1 Gap: 0.3mm 16 electrodes
(c) Type T2 Gap: 0.3mm 24 electrodes
(d) Type T3 Gap: 0.5mm 16 electrodes
(e) Type T4 Gap: 0.3mm 32 electrodes
(f) Type S1 Gap: 0.3mm 80 electrodes
(g) Type S2 Gap: 0.3mm 128 electrodes
(h) Type S3 Gap: 0.3mm 80 electrodes
(i) Type S4 Gap: 0.3mm 80 electrodes
(j) Type S5 Gap: 0.3mm 80 electrodes
(k) Type S6 Gap: 0.3mm 80 electrodes

Fig. 7 Electrode patterns of rotor plates

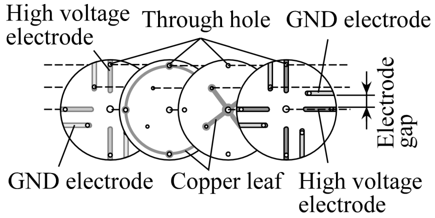


Fig. 8 Configuration of rotor plate (Standard type)

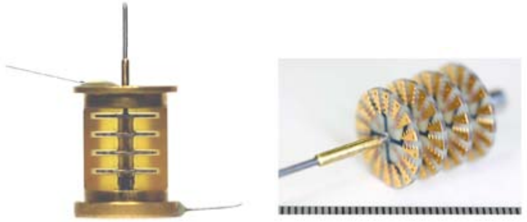

(a) Inner structure (b) Rotor (Type S3)

Fig. 9 Fabricated four-layer DP-RE type ECF micromotor

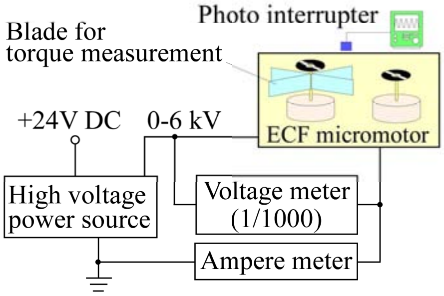


Fig. 10 Experimental setup

plates.

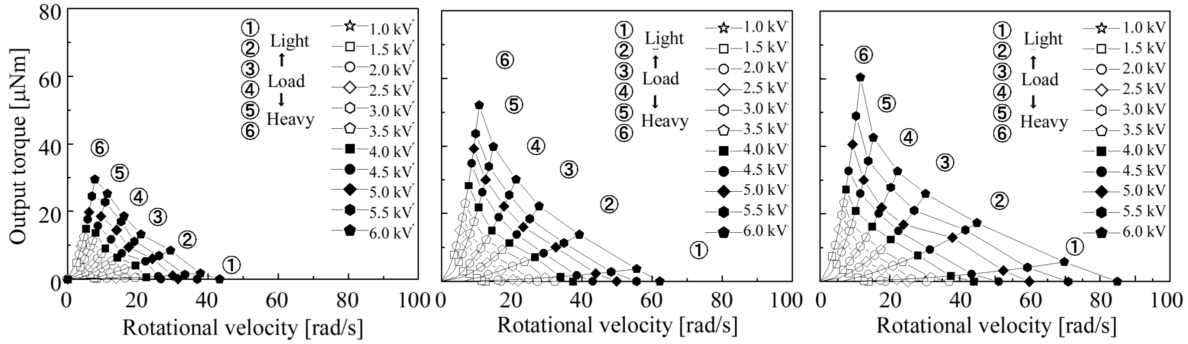
Fig. 7 illustrates several electrode patterns on the rotor plates we designed. Fig. 7 (a) is a standard type developed in our previous study [10]. It has four pairs of linear electrodes on one side of the rotor plate. With this configuration, the ECF jet is generated from the positive electrode to the GND electrode. On the other hand, Fig. 7 (b)-(e) show rotor plates having triangular electrode series, in which the interelectrode gap is constant. According to our previous study [8], the ECF jet is generated from the tip of the triangular electrode to the base of it, without any relations to the polarity. Fig. 7 (f)-(k) have high integrated design of triangular electrode series, resulting in having a saw-toothed electrode series. Basic design of the saw-toothed electrode is the one in Type S1, and the parameters changed in each type are shown in the figure. However, the number of electrode denoted in the figure means the number of the front edge of saw-tooth. The base of the electrode Type S3 (Fig. 7(h)) has an arcuate structure. The surface area of electrode is reduced in the electrode Type S6 (Fig. 7. (k)).

All of the rotor plates are made of glass epoxy board having electrodes on their both sides as shown in Fig. 8 which is illustrating the standard type rotor plate as an example. Fig. 9 shows the fabricated four-layer DP-RE type ECF micromotor and the rotor with saw-toothed electrode series Type S3.

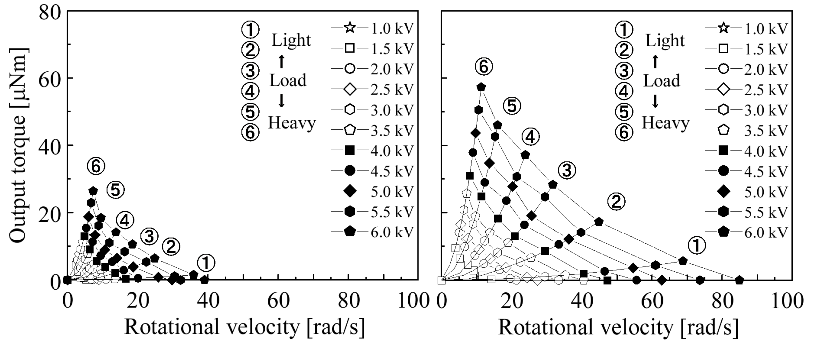
V. EXPERIMENTS

A. Experimental Setup

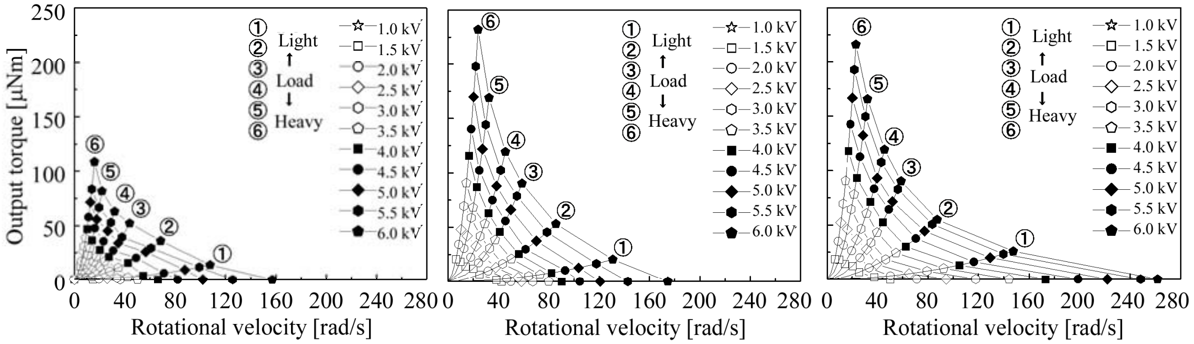
Fig. 10 illustrates an experimental setup we used. We applied up to 6 kV to the micromotors. Rotational velocity was measured using a photo interrupter. Torque was indirectly measured using "load blades." Namely, by measuring the rotational velocity of the rotor with the blades, we can obtain the torque, because the torque vs. rotational velocity relation of each load blade was in advance calibrated. We used dibutyl decanedioate as a working fluid in the following experiments.



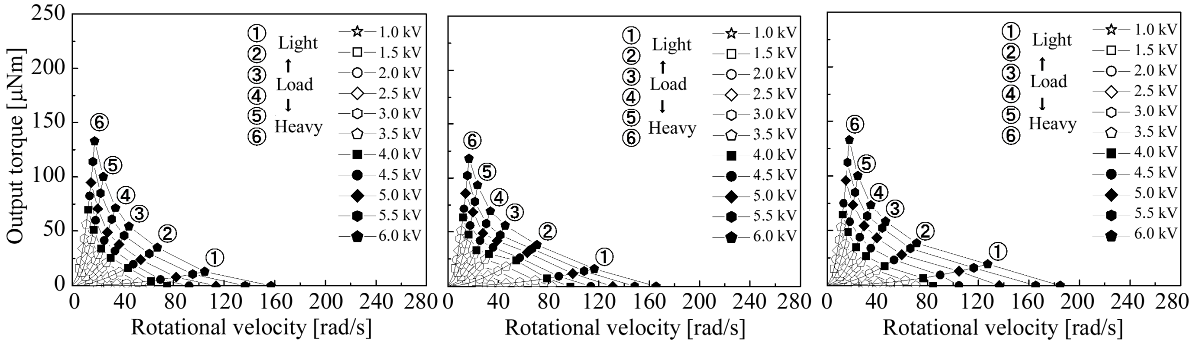
(a) Standard (b) Type T1 (c) Type T2



(d) Type T3 (e) Type T4



(d) Type S1 (e) Type S2 (f) Type S3

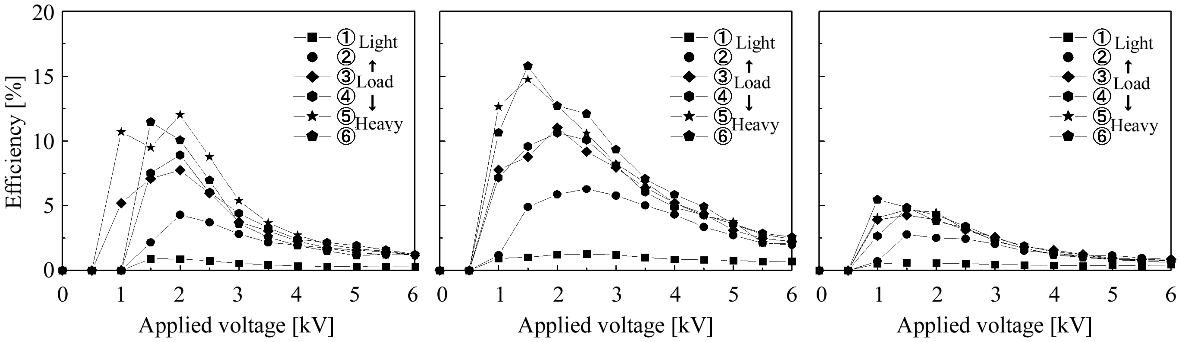


(d) Type S4 (e) Type S5 (f) Type S6

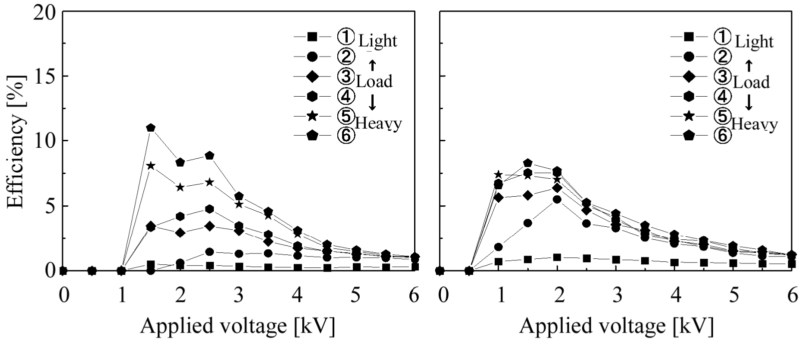
Fig. 11 Torque vs. rotational velocity relation

B. Load Characteristics

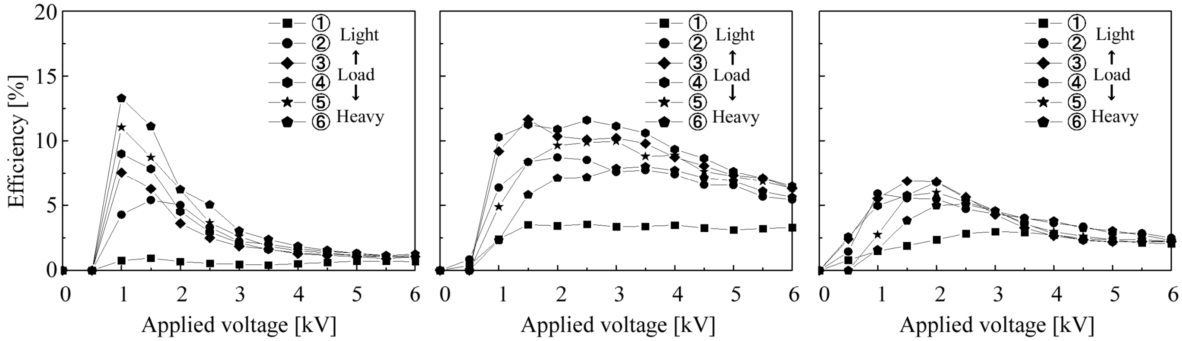
The torque vs. rotational velocity relations are shown in Fig. 11. The range of axis is common in each graph for easy to be compared. Circled numbers in the graphs denotes the load blades number used in the experiments. The blade having larger number has a heavier load. Each result shows a typical drooping characteristic. The motor with saw-toothed electrode Type S2 shows the best performance from the view point of torque.



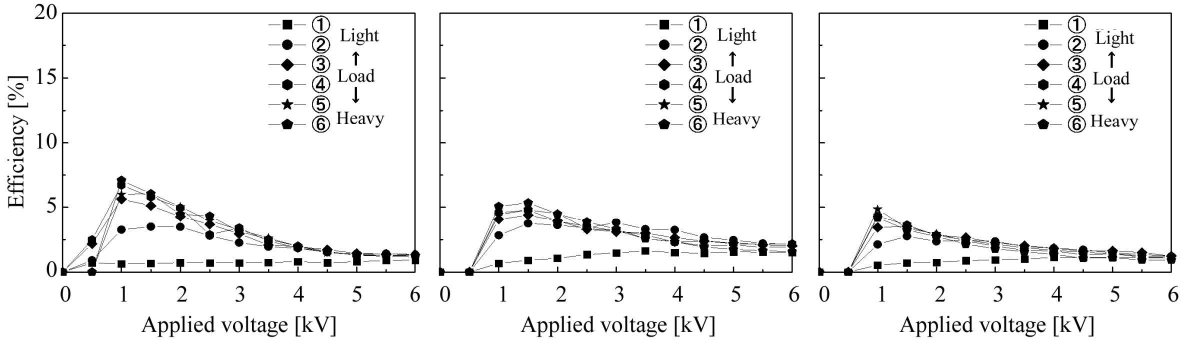
(a) Standard (b) Type T1 (c) Type T2



(d) Type T3 (e) Type T4



(f) Type S1 (g) Type S2 (h) Type S3



(i) Type S4 (j) Type S5 (k) Type S6

Fig. 12 Efficiency

C. *Efficiency*

Fig. 12 denotes the efficiency of each motor. The output power is calculated from the torque vs. rotational velocity relations, and the input power is from the applied voltage and the consumption current. The highest efficiency measured was 15.8 % with triangular electrode Type T1.

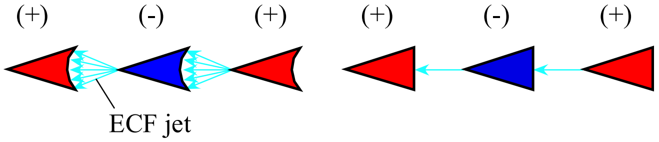
D. *Discussion*

Maximum rotational velocity, output torque, output power, and efficiency of each motor are summarized in Table

TABLE II
COMPARISON OF MOTOR PERFORMANCES

	Electrode type										
	Standard	T1	T2	T3	T4	S1	S2	S3	S4	S5	S6
Rot. velocity [rad/s]	44 (1)	62 (1.4)	85 (1.9)	39 (0.9)	84 (1.9)	157 (3.6)	175 (4.0)	261 (5.9)	157 (3.6)	165 (3.8)	185 (4.2)
Current [μA]	3.2 (1)	5.6 (1.8)	15 (4.7)	6.0 (1.9)	9.0 (2.8)	37 (11.6)	13 (4.1)	38 (11.9)	28 (8.8)	25 (7.8)	40 (12.5)
Torque [μNm]	30 (1)	52 (1.7)	60 (2.0)	26 (0.9)	57 (1.9)	108 (3.6)	232 (7.7)	216 (7.2)	132 (4.4)	118 (3.9)	133 (4.4)
Power [mW]	0.3 (1)	0.64 (2.1)	0.78 (2.6)	0.19 (0.6)	0.9 (3.0)	2.5 (8.3)	5.5 (18.3)	5.4 (18.0)	2.5 (8.3)	2.7 (9.0)	2.7 (9.0)
Efficiency [%]	12 (1)	15.8 (1.3)	5.5 (0.5)	11 (0.9)	8.3 (0.7)	13.3 (1.2)	5.6 (0.5)	6.9 (0.6)	7.1 (0.6)	5.4 (0.5)	4.8 (0.4)

*Round bracket shows the ratio



(a) With arcuate base (b) With linear base

Fig. 13 Estimated ECF jet generation

II. Although there must be an optimal design for triangular/saw-toothed electrodes, the micromotors with saw-toothed electrodes seem to have better characteristics than standard type electrode and triangular electrodes. The main reason for this is the difference in electrode number. An increase of electrode number results in generating much ECF jet. On the other hand, there is no major difference in efficiency. This suggests that the electrode configurations in this study must have the same topological design.

Among the motor with saw-toothed electrode series, the Types S2 and S3 showed better characteristics. From these experimental results, it is clear that the number of the front edge of saw-tooth is effective for improving the motor performance (Type S2), and that the arcuate structure is suitable for realizing high performance ECF micromotors (Type S3). Other design parameters changed in Types S4, S5 and S6 have no influence on motor performance. With the electrode Type S2, it is obvious the total power of ECF jet increases. On the other hand, with the electrode Type S3, the mechanism of improving motor performance is estimated as shown in Fig. 13. Total length of base having the interelectrode gap of 0.2 mm increases with the arcuate structure, resulting in improving the total power of ECF jet generated on the rotor plate. In other words, the ECF jet is assumed to be generated from a point (front edge of saw-tooth) to a line (arcuate base) in Type S3, on the other hand, it is generated from a point (front edge of saw-tooth) to a point (foot of a perpendicular from the front edge to the base) in case of other saw-toothed electrode configuration.

VI. CONCLUSIONS

An influence of electrode shape on DP-RE type ECF micromotor is experimentally clarified in this study. First, we briefly introduced electro-conjugate fluid and concept of ECF micromotors. Then, we designed a four-layer DP-RE type ECF micromotor with inner diameter of 9 mm as a test bench for testing motor performances with different electrode configurations. The experimental results denote the saw-toothed electrodes series proposed in this study is quite effective for improving performance of DP-RE type ECF micromotors. The experimental results also clarify the DP-RE type ECF micromotors are competitive against conventional electromagnetic motors when using for millirobot.

Our future study focuses on improving ECF micromotor performances and applying the motor to millimeter scale robot like micro helicopters.

REFERENCES

[1] R. Fearing, Challenges for Effective Millirobots, Digest of 2006 IEEE Int. Conf. Robotics and Automation, p. xxi, 2006.

[2] T. Morita, T. Kanda, Y. Yamagata, M. Kurosawa and T. Higuchi, Single Process to Deposit Lead Zirconate Titanate (PZT) Thin Film by a Hydrothermal Method, Japan J. Applied Physics, vol.36, part 1, 5B, pp.2998-2999, 1997.micro actuator

[3] A. Fujimoto, M. Sakata, M. Hirano and H. Goto, Miniature electrostatic motor, Sensors an Actuators A, vol. 24, pp. 43-46, 1990.

[4] T. Kanda, A. Makino, K. Suzumori, T. Morita and M. K. Kurosawa, A Cylindrical Micro Ultrasonic Motor using a Micro-machined Bulk Piezoelectric Transducer, Proc. the 2004 IEEE Ultrasonics Symposium, pp.1298-1301, 2004.

[5] Y. Otsubo and K. Edamura, Dielectric Fluid Motors, Applied Physics Letters, vol. 71, no. 3, pp. 318-320, 1997.

[6] Seong-Il Jeong, J. Seyed-Yagoobi, and P. Atten, Theoretical/Numerical Study of Electrohydrodynamic Pumping Through Conduction Phenomenon, IEEE Trans. Industry Applications, vol. 39, no. 2, pp. 355-361, 2003.

[7] K. Takemura, S. Yokota and K. Edamura, Development and Control of a Micro Artificial Muscle Cell using Electro-conjugate Fluid, Sensors & Actuators A, In Press.

[8] W.-S. Seo, K. Yoshida, S. Yokota and K. Edamura, A high performance planar pump using electro-conjugate fluid with improved electrode patterns, Sensors and Actuators A, In Press.

[9] S. Yokota, Y. Kondoh, A Sadamoto, Y. Otsubo, and K. Edamura, A Micro Motor Using Electro-conjugate Fluids (ECF) (Proposition of Stator Electrode-type (SE-type) Micro ECF Motors), Int. J. JSME Ser. C, vol. 44, no. 3, pp. 756-762, 2001.

[10] S. Yokota, K. Kawamura, K. Takemura, and K. Edamura, A High-integration Micromotor using Electro-conjugate Fluid (ECF), J. Robotics and Mechatronics, vol. 17, No. 2, pp. 142-148, 2005.