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Characteristics Evaluation of PVC Gel Actuators

Naoki Ogawa, Minoru Hashimoto, *Member*, *IEEE*, Midori Takasaki, and Toshihiro Hirai

Abstract— **A poly vinyl chloride (PVC) gel actuator shows great potential for use as an artificial muscle because of such positive characteristics as movement in the air, large deformation, and being lightweight. A bending type actuator using PVC gel was studied previously [4]-[6]. We have proposed the structure of a contraction type actuator to construct an artificial muscle, and we have conducted some experiments using the single-layer PVC gel actuator [8]. In this paper, we investigate the characteristics of the multi-layer PVC gel actuator experimentally and evaluate its specifications in terms of the composition of PVC gel and the structure of the mesh electrode. The experimental results showed that the contraction rate of the actuator was about 14%, the response rate was 7Hz, and the output force was 4kPa. Also, we found that the stiffness of the actuator increased as the applied dc field increased like human muscle. The characteristics of the PVC gel actuator are shown to be very effective for constructing an artificial muscle.**

I. Introduction

Polymeric materials have received special attention as material for artificial muscle because they are flexible, light-weight, and can be easily molded. There have been many studies in this field, however most of the actuators using polymeric materials work only in the water, and they only make the bending type deformation.

We believe the characteristics of the artificial muscle should approximate the characteristics of human muscle. Human muscles include the following characteristics, 30% in contraction rate, 0.3MPa in output force, and 10Hz in response rate [1]. Regarding the practical use, we can consider the following three materials as candidates for an artificial muscle, a polypyrrole[2], a dielectric elastomer[3], and a PVC gel[4]. The conducting polymer polypyrrole has good properties in contraction rate and output force, but not in response rate. Also the dielectric elastomer has noble properties in response rate and output force, however it is necessary to apply a very high dc field to operate. Therefore, the PVC gel is the most promising material for an artificial muscle in terms of the applied dc field and the response rate. Moreover continuous supply of the solvent is necessary for usual gel, but PVC gel including the plasticizer does not need to supply solvent at all, so it is possible to operate in the air. Since the PVC gel deforms by the electric field, it is easy to obtain a fast response. Besides, the electric efficiency is better than that of the conventional soft actuator using polymeric materials.

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N. Ogawa and M. Hashimoto are with Department of Kansei Engineering, Faculty of Textile Science and Technology, Shinshu University, 3-15-1 Tokida, Ueda, Nagano, 386-8567, Japan (corresponding author to provide phone/fax: +81-268-21-5524, e-mail: hashi@shinshu-u.ac.jp) .

M. Takasaki is with Satellite Venture Business Laboratory, Shinshu University, 3-15-1 Tokida, Ueda, Nagano, 386-8567, Japan.

T. Hirai is with Functional Polymer Science Course, Faculty of Textile Science and Technology, Shinshu University, 3-15-1, Tokida, Ueda, Nagano, 386-8567, Japan.

Hirai et al. have studied the bending deformation of the PVC gel actuator [4]-[7], and they found the principle and the characteristics of the bending deformation. However, it is necessary to cause deformation of expansion and contraction for an artificial muscle. Then we have proposed the principle and the structure of the contraction type PVC gel actuator using mesh-type anodes [8]. In this paper, we investigate the characteristics of the contraction type PVC gel actuator experimentally, to examine the validity of the PVC gel actuator as an artificial muscle.

Now we give an outline of this paper. In the next chapter, we describe the preparation of PVC gel, and the principle of deformation mechanism. We introduce the structure of the contraction type PVC gel actuator using mesh-type anodes in chapter III. In chapter IV, we conduct the experiments for investigating the elasticity, the displacement, the output force, the response in terms of the composition of PVC gel and the structure of mesh-type anode. Also, we investigate the thermal influence to the contraction rate and the relationship between output force, displacement and DC filed. In chapter V, we discuss the characteristics of the proposed actuator. Finally, we conclude this paper in chapter VI.

II. Preparation and Principle

A. PVC-DBA Gel Preparation

PVC (degree of polymerization = 3200) was plasticized with Dibutyl adipate (DBA). DBA is a typical plasticizer. PVC was dissolved with DBA in Tetrahydrofuran (THF) solvent. The weight ratios of PVC and DBA were adjusted to 10:40, 10:60 and 10:80. We call DBA40 (10:40), DBA60 (10:60) and DBA80 (10:80).

B. Principle of operation

Both sides of the PVC gel is sandwiched by electrodes (Fig.1). Electric charges (electrons) are injected from the cathode of the electrode into the gel, and it migrates toward the anode. The accumulation of the electric charges promotes the electrostatic adhesiveness of gel onto the anode, and creeping deformation appears on anode surface [4]. When the electric field is discharged, the PVC gel is returned to its original shape. The explanation of operation that described above is an estimation. In the present stage the principle of operation of the PVC gel actuator has not been completely clarified yet.

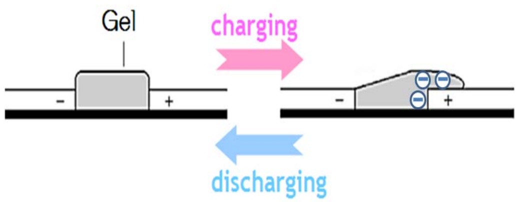

Fig.1 Transforming mechanism of PVC gel

III. STRUCTURE OF A CONTRACTION TYPE ACTUATOR

We proposed the structure of a contraction type PVC gel actuator using mesh type electrode [8]. The PVC gel is sandwiched between a stainless mesh as an anode and a cathode. Figure 2 shows the deformation of the PVC gel when the DC field is applied. A cathode is located under the PVC gel, and an anode is above the gel. When the DC field was applied, the PVC gel creeps up the anode and moves into the mesh hole.

Based on properties of the PVC gel, we propose a structure of the PVC actuator which allows the deformation of expansion and contraction. The gel is sandwiched between an anode and a cathode, and it shrinks when the DC field is applied. When the DC field is removed, it returns to former shape by its elasticity. The displacement is increased by stacking up the layers and it is operated as an expansion and contraction type actuator (Fig.3).

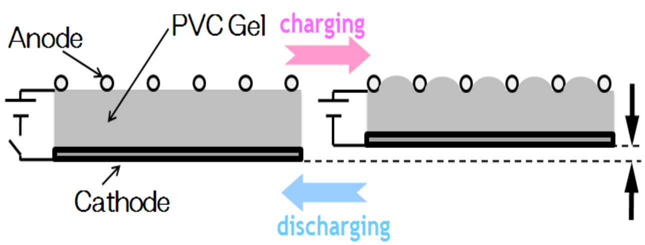

Fig.2 Cross section of the deformation of actuator
(a) discharge, (b) charged

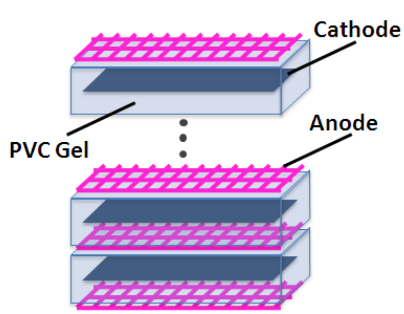

Fig.3 An illustrative diagram of electrodes arrangement

IV. CHARACTERISTICS OF THE PVC GEL ACTUATOR

A. *Prototyping of the PVC gel actuator*

In order to examine the characteristics of the proposed PVC gel actuator, we made each actuator with ten-layer. Figure 4 shows the structure of the actuator sample. The mesh electrodes (20 × 20mm) were used as anodes, either mesh electrodes or foil electrodes were used as cathodes. The anode was fixed on the base, the anode and the cathode enclosed with PVC gel were stacked up. Figure 5 shows the overview of the PVC gel actuator.

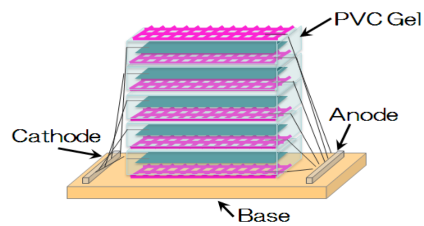

Fig.4 Schematic drawing of the PVC gel actuator

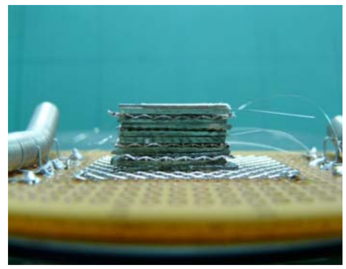

Fig.5 Overview of the Multilayer-type PVC gel actuator

B. *Elasticity of actuator without DC field*

We measured the longitudinal elasticity of the actuators with various compositions of the PVC gel to find the dependency on the composition. The elasticity was measured by a force sensor (LMA-A-5N, KYOWA) without the applied voltage. DBA80 (20 × 20mm, 0.68mm in thickness a sheet), DBA60 (20 × 20mm, 0.55mm in thickness a sheet), DBA40 (20 × 20mm, 0.50mm in thickness a sheet) were utilized in this experiment. The mesh size of anodes was 20. The mesh size means the number of wires per inch.

Figure 6 shows the relationship between longitudinal elasticity and composition of the PVC gel. The modulus of longitudinal elasticity increases as the amount of the plasticizer decreases.

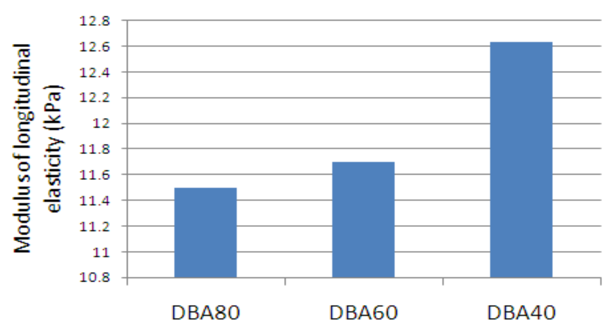

Fig.6 Modulus of longitudinal elasticity

C. *Displacement*

We measured the displacement of the actuator with the various applied DC fields to find the dependency on the applied DC field. The displacement was measured by a laser displacement meter (LB-02, KEYENCE). The measurement began after applying a DC voltage (600V) to the PVC gel for 3 minutes. The various data were recorded for 15s. The DC field was applied from 5s to 10s. The various data were taken at sampling intervals of 0.05s, and the output from the displacement sensor was converted through the analog to digital conversion machine.

Figure 7 shows the results of the displacement. DBA80 was utilized in this experiment. The mesh size of the anode was 20. In the case of an applied DC field of 1324V/mm, the maximum displacement was about 1.3mm. This displacement is about 14% in the contraction rate.

We measured the displacement of the PVC gel actuator with gels of various compositions to investigate the relationship between composition and displacement. DBA80 (20×20mm, 0.68mm in thickness), DBA60 (20×20mm, 0.55mm in thickness), DBA40 (20×20mm, 0.50mm in thickness) were utilized in this experiment. The applied DC voltage was 900V, the mesh size was 20.

Figure 8 shows experimental results. The displacement of DBA80 is largest, and that of DBA40 is smallest. The displacement of actuator becomes small when the amount of plasticizer decreases. It is supposed that the displacement depends on amount of plasticizer.

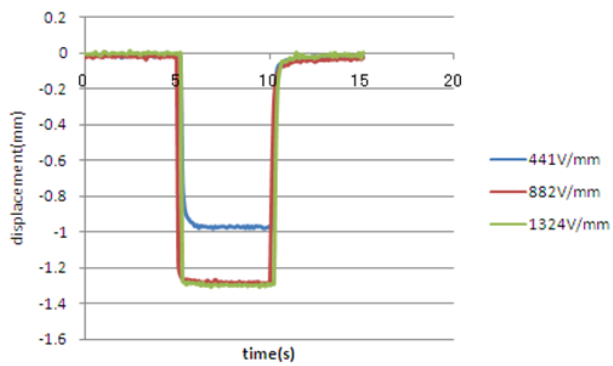

Fig.7 Displacement of actuator (DBA80)

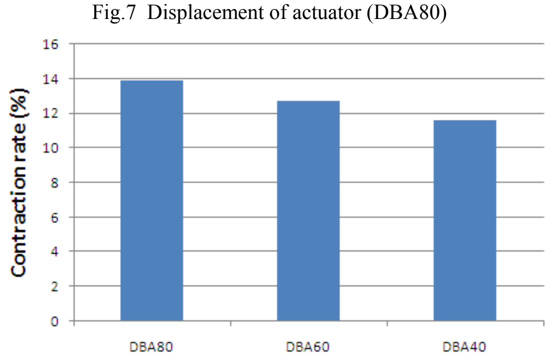

Fig.8 Relationship between displacement and composition

D. Force

The output force of the PVC gel actuators were measured with various applied DC fields. Figure 9 shows the schematic drawing of the actuator that we used in the output force measurement. The actuator has a plastic plate and a resin stick to connect with a force sensor. The various data were recorded for 5s while the various DC fields were applied. The force was measured by a force sensor (T1-1000-240, A&D). The resin stick was fixed to the force sensor and the roof of actuator by the coupling connecter to transmit the output force directly.

Figure 10 shows the experimental results of DBA40 with various DC fields. The generation force increases with the applied DC field. Maximum generation force of DBA40 was approximately 3kPa when the applied DC field was 1800V/mm. Figure 11 shows the relationship between output force and composition of PVC gel. The force of the actuator becomes strong when the amount of plasticizer decreases. It is found that the output force depends on the amount of plasticizer, and we can get larger output force by decreasing the amount of the plasticizer.

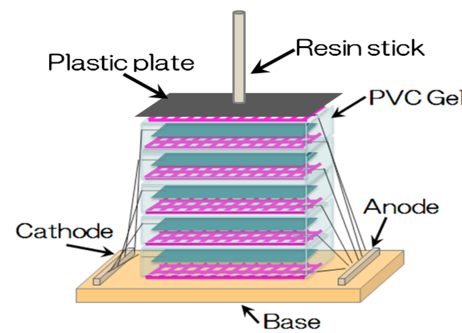

Fig.9 A schematic drawing of the PVC gel actuator

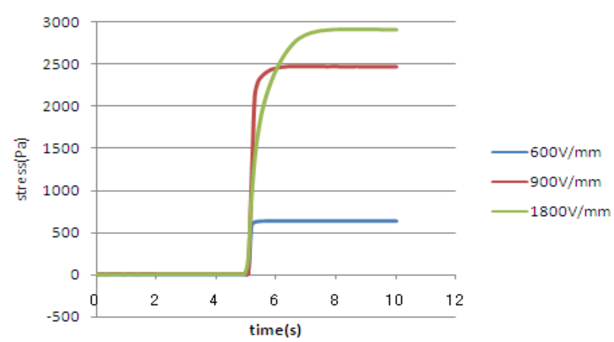

Fig.10 Output force of actuator (DBA40)

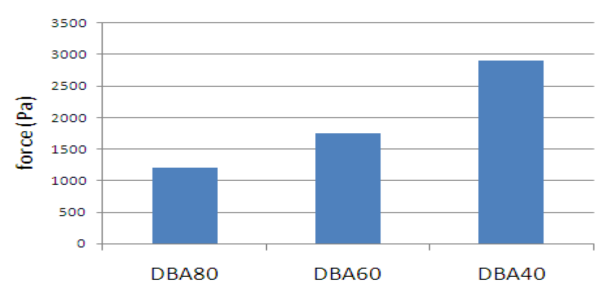

Fig.11 Relationship between force and composition

E. Response

We measured the response rate of the actuator to find the dependency on the composition of the PVC gel. The response rate was investigated by the frequency response method. The input signal to the actuator was rectangular pulses with the various frequencies from 0.1Hz to 10Hz. The voltage of the rectangular pulse was 500V. Bode diagram of the displacement, DBA40, DBA60 and DBA80, were shown in Fig.12.

The response of the actuator using DBA40 was better than those of the other actuators. The elasticity of the PVC gel is related to the response speed of the actuator, since the ratio of the plasticizer to PVC relates the elasticity of the PVC gel as shown in Fig.6. The band width of the actuator using DBA40 was 7Hz.

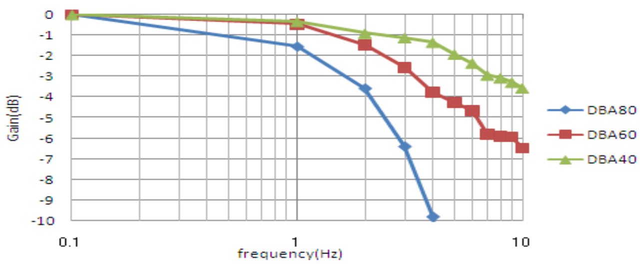

Fig.12 Bode diagram in displacement (DBA40, DBA60 and DBA80)

F. Dependency of Elasticity on the applied DC field

We measured the longitudinal elasticity of the actuator to find the dependency of the elasticity on the applied DC field. The elasticity was measured by a force sensor (KYOWA LMA-A-5N). The measurement was performed pushing a force sensor onto the actuator roof until the required displacement was applied on the actuator, and measuring the force of the actuator. We utilized a DBA40 actuator for this experiment.

Figure 13 shows the relationship between longitudinal elasticity and applied DC field. The modulus of longitudinal elasticity increases in proportion to the applied DC field, there are dramatic changes caused by the applied DC field. The elasticity of the actuator with the applied DC field of 1200V/mm is ten times bigger than that of the actuator with no applied DC filed. We supposed that this change of elasticity was caused by increasing the contact area between mesh anodes and gels when the DC field was applied.

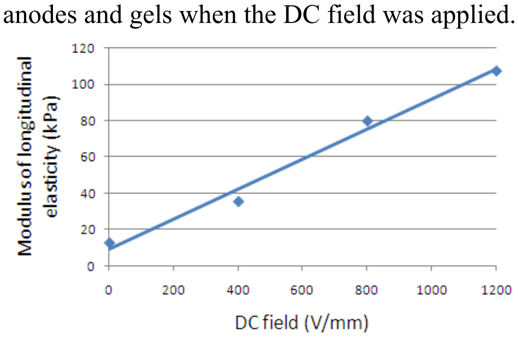

Fig.13 Relationship between longitudinal elasticity and DC field (DBA40)

G. Thermal influence

We investigated the displacement of the actuator with various temperatures. DBA40 was utilized in this experiment. We applied the windy oven (WFO-451SD, EYELA) to keep actuators warm at various temperatures. The displacement was measured by a laser displacement meter (LB-02, KEYENCE) in the atmosphere. We adjusted the normal point of laser displacement meter on actuator's roof at 25 degrees Celsius, and started to measure the displacement after the temperature had fixed.

Figures 14 and 15 show the experimental results of the displacement on various temperatures. The displacement increases around 70 degrees Celsius, and then it is held constant. We supposed that the change of displacement was caused by the elasticity change of PVC gel. Figure 16 shows the height change of the actuator caused by the temperature. The PVC gel expanded with heat, and the height increased about 1% around 70 degrees Celsius.

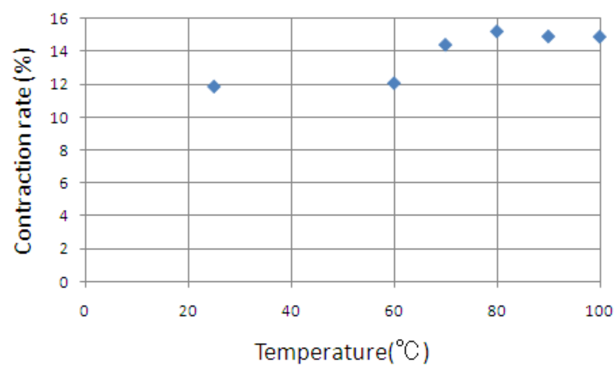

Fig.14 Transition of displacement (DBA40)

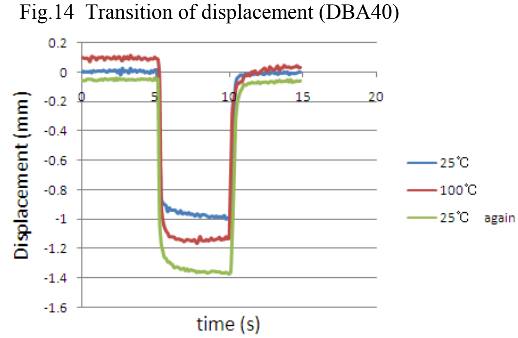

Fig.15 Representative results of experiments about displacement

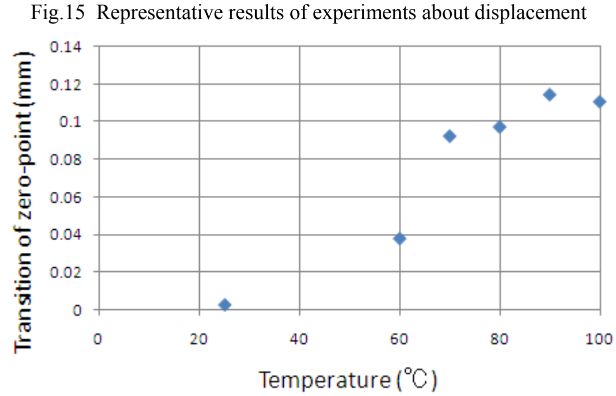

Fig.16 Height changes of the actuator caused by the temperature

H. Effect of anode shape

So far we investigated characteristics of a contraction type actuator using 20mesh anodes. However we did not consider that the dependencies of the characteristics on the mesh shape of the anode.

Thus, we investigated the influence of the structure of the mesh anode. We prepared 5 anode types which vary in mesh-size and wire diameter. Figure 17 shows overviews of the mesh anodes, and Table 1 shows details of them. DBA40 was utilized in this experiment.

Figures 18 and 19 show experimental results. Concerning these figures, we note that error bars in Fig.18 and 19 mean the standard error of the mean (SEM).

We found that when the mesh size was enlarged, the displacement decreased. But, the output force was largest, 4kPa, in the case of sample B (the mesh size is 30). When the wire-diameter of the mesh anode increased, the displacement decreased and the output force increased. According to Figs. 18 and 19, the actuator with 30mesh anodes includes the following characteristics, 1.1mm in the displacement approximately, 4kPa in output force approximately when the applied DC field was 1800V/mm.

From the experimental results shown in Fig.18, we can find that the actuator with the anode B generates larger output force than those of the anodes A and C. The output force increases with the lager contact area between the gel and the anode and the larger displacement. When the mesh size of the anode increases, the total contact area increases, but the displacement of the actuator decreases. Therefore, we may consider that the anode B whose mesh size is between those of A and C generates the larger output force than those of A and C.

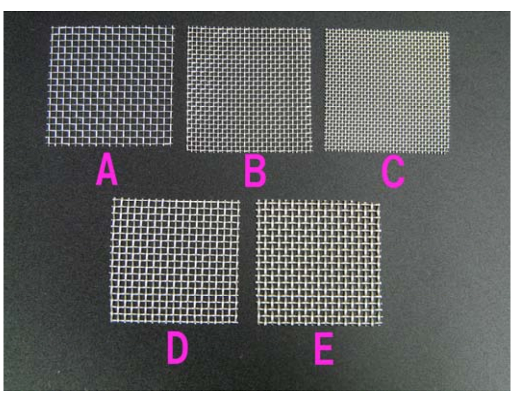

Fig.17 Overview of anodes (A, B, C, D and E)

Table 1 Mesh size and wire diameter of anodes

Anode	Meshsize	Thickness(mm)	Wire diameter(mm)
A	20	0.40	0.20
B	30	0.40	0.20
C	40	0.40	0.20
D	20	0.74	0.37
E	20	1.00	0.50

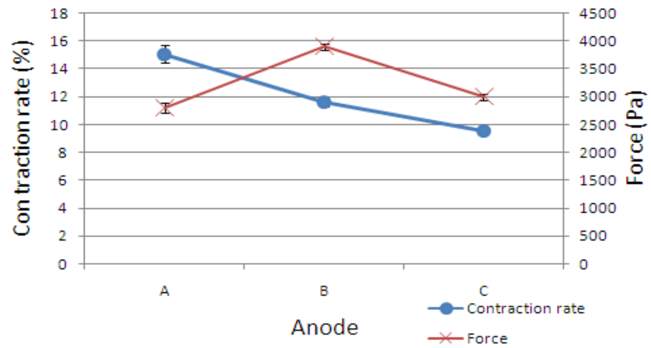

Fig.18 Experimental results about anode A, B and C

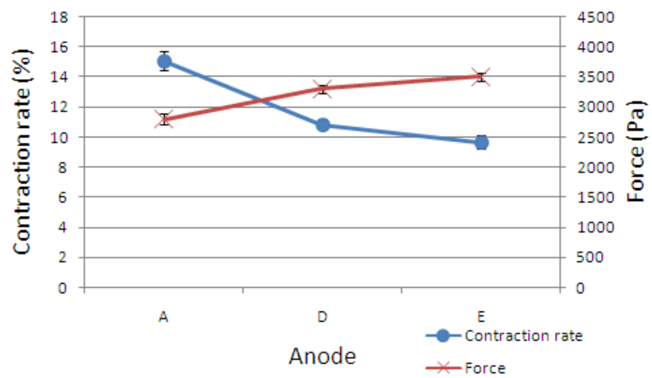

Fig.19 Experimental results about anode A, D and E

I. Relationship between output force, displacement and DC filed

As a summary of characteristics of the PVC gel actuator, we want to show the relationships between output force, displacement and DC field. From experimental results, we found that a property of this actuator is represented by three physical quantities, DC field, displacement, and output force. We examine the relationships with these three quantities. In these experiments, we utilized a DBA40 actuator.

Figure 20 shows the relationship between contraction rate and DC field with SEM error bars, and Fig. 21 shows the relationship between force and DC field. We found that there is a little hysteresis. Figure 22 shows relationship between contraction rate and force in continuous change. We found that there is a little hysteresis.

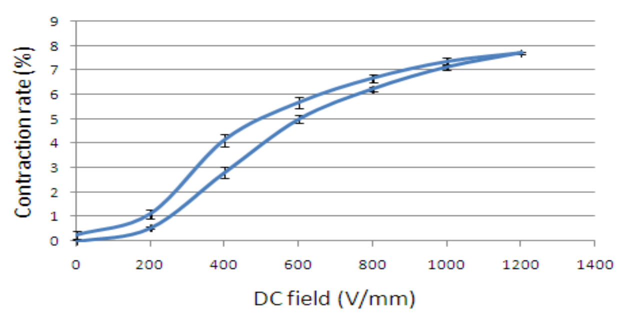

Fig.20 A static characteristic between displacement and DC field

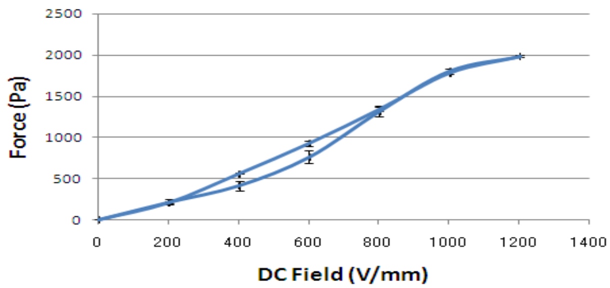

Fig.21 A static characteristic between force and DC field

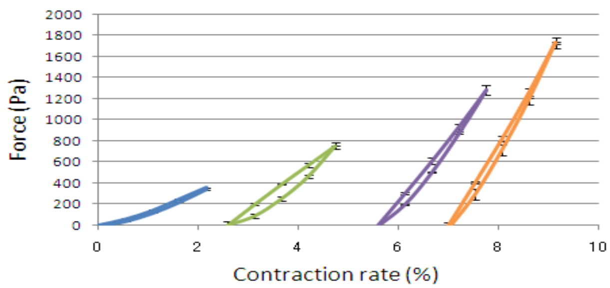

Fig.22 A static characteristic between displacement and force

From each of the examinations about relationships between two quantities, we found that a static characteristic of this actuator is almost linear, although there is a little hysteresis. Figure 23 shows a static characteristic in a three dimensional space.

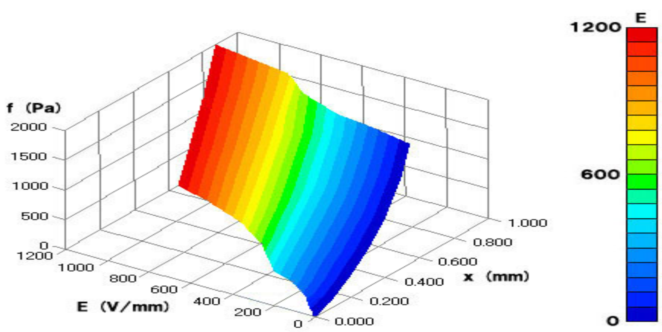

Fig.23 A static characteristic (3D visualized)

V. Discussion

Based on the experimental results, we found that proposed PVC gel actuators includes the following characteristics, 14% in contraction rate, 4kPa in output force, and 7Hz in response rate. We appreciate that characteristics of the proposed PVC actuators are so unique. The proposed actuator will open the doors of next-generation actuator, smart actuator, and artificial muscle. However, the output force is smaller than that of human muscle. We plan to conduct further research to improve the characteristics of output force.

We believe that unique characteristics of the proposed actuator may lead it to be used in many applications such as a micro pump, a micro valve, a relay circuit and so on.

VI. Conclusion

We have investigated the characteristics of a contraction type PVC gel actuator in which PVC gel is sandwiched between an anode using a stainless mesh and a cathode. The mesh type anode attracts the PVC gel when the dc field is applied, then the actuator contracts. From the experimental results, we found that the contraction rate was 14%, and the output force was 4kPa, the response rate was 7Hz. Also, the contraction rate and the output force depended on both of the composition of gel and the applied dc field. The PVC gel actuator had good performances such as good response rate, large displacement, and being light in weight. And we found the dependencies of the elasticity on the applied dc field, and the stability on the thermal influence. Moreover, we found that mesh shapes of anode influenced on the characteristics of the actuator much.

The PVC gel actuator can be operated in the air, and has the characteristics of flexibility and lightness, so various applications are expected.

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References

[1] K. Kaneto, “macromolecule actuator”, polymer, vol.55, no.12, pp. 956, 2006

[2] S. Hara, T. Zama, W. Takashima, K. Kaneto, ‘Free-standing gel-like polypyrrole actuators doped with bis (perfluoroalkylsulfonyl) imide exhibiting extremely large strain”, Smart Materials and Structures, vol.14, pp1501-1510, 2005

Y. Osada, “Soft Actuators,” NTS, 2004 (in Japanese)

Md. Zulhash Uddin, Masashi Watanabe, Hirofusa Shirai, and Toshihiro Hirai, “Creeping and Novel Huge Bending of Plasticized PVC”, Journal of Robotics and Mechatronics, vol.14, no.2, pp.161-166, 2002

K. Fujii, T. Ogiwara, T. Hirai, T. Kinoshita, “Influence of the plasicizer on the electrical deformation of PVC”, Polymer Preprints, Japan, vol.55, no.2, pp.4557-4558, 2006

[6] T. Ogiwara, K. Fujii, T. Hirai, T. Kinosihita, “Artificial pupil using the creep deformation of DBP containing PVC gel”, Polymer Preprints, Japan, vol.55, no.2, pp.4559-4560, 2006

[7] M. Watanabe, N. Wakimoto, H. Shirai, T. Hirai, “Bending electrostriction and space-charge distribution in polyurethane films”, Journal of applied Physics, vol.94, no.4, pp.2494-2497, 2003

[8] M. Yamano, N. Ogawa, M. Hashimoto, M. Takasaki, T. Hirai, “A Contraction Type Soft Actuator Using Poly Vinyl Chloride Gel”, Proceedings of IEEE International Conference on Robotics and Biomimetics (ROBIO 2008), Bangkok, Thailand, pp.745-750, 2009