BRIEF PAPER

S-Shaped Nonlinearity in Electrical Resistance of Electroactive Supercoiled Polymer Artificial Muscle

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SUMMARY S-shaped nonlinearity is found in the electrical resistance–length relationship in an electroactive supercoiled polymer artificial muscle. The modulation of the electrical resistance is mainly caused by the change in the contact condition of coils in the artificial muscle upon deformation. A mathematical model based on logistic function fairly reproduces the experimental data of electrical resistance–length relationship.

key words: *actuator, supercoiled polymer artificial muscle, twisted and coiled polymer actuator, electrical resistance, mathematical model*

1. Introduction

Artificial muscle is a term to express a class of actuators whose working principle is a reversible change of the shape to generate mechanical force upon some physical stimulation such as electricity, pressure or temperature. The powered exoskeleton, which assists human motions, is recently attracting much attention because it is expected to help to solve many problems arising in super-aging society such as Japan. Although many commercially available powered exoskeletons at present are actuated by electric motors, soft artificial muscles which have designated minimum and maximum sizes seem to be more suitable for powered exoskeletons than electric motors that are rigid and potentially hazardous when they accidentally become uncontrollable [1].

Since the discovery of the supercoiled polymer artificial muscle, which is also known as the twisted and coiled polymer actuator or the nylon muscle, by Haines et al. [2], lots of research efforts have been devoted to the applications of the device such as humanoid hand [3], power-assist system [4], and morphing mechanism for flying robots [5]. The actuation principle of the device is the contraction upon heating, and the device made from conductive sewing thread can be directly driven by electrical power. The electroactive supercoiled artificial muscle seems to be highly attractive compared to other electrically driven artificial muscles based on conducting polymer [6]–[8], ionic polymer-metal composite [9], [10] and dielectric elastomer [11], [12] in numerous key factors such as durability, power density, and cost.

The precise position control is recognized as one of the most important issues in the research community of the device, and thus the modeling of the device is becoming one of the hot topics in this field [13]–[16]. Although thermo-mechanical aspects of the supercoiled artificial muscle are well documented, most researchers assume the constant electrical resistance during the operation. It is frequently pointed out that the resistivity of the electric conductor used has temperature dependence and some authors have assumed a linear relationship between the elongation and electrical resistance [17], [18]. However, little attention has been paid to the electrical resistance of electroactive supercoiled artificial muscle in operation so far.

Previously, we have pointed out that the electrical resistance of the supercoiled polymer actuator shows considerable reduction upon contraction due to Joule heating [19]. This directly invalidates the constant electrical resistance assumption taken in the modeling of the artificial muscle carried out so far. Although we have speculated that the change in the electrical resistance comes from the modulation of the contact condition of neighboring coils in the artificial muscle, no experimental confirmation has been made. This study is intended to give the experimental validation of the speculation as well as a better mathematical model for the length dependence of the electrical resistance.

2. Experimental

The supercoiled artificial muscle used in this study was prepared from Ag-plated multi-filament nylon sewing thread manufactured by Shieldex. The nominal diameter and resistance of the thread are 0.2 mm and 50 Ω/m, respectively. The insertion of twist to a thread 16 cm in length with a suspended weight of 150 g at room temperature resulted in a supercoiled artificial muscle approximately 4 cm in length with approximately 70 coils. It has been confirmed that the success rate of preparation as well as the length of the artificial muscle is seriously affected by the preparation conditions such as temperature and suspended weight [20]. The artificial muscle was annealed at 140°C for 1 h in an oven to fix the shape.

The change in the length of the artificial muscle with a suspended weight of 100 g at room temperature driven by a 1/120 Hz square current wave of 0.5 A, which made the temperature of the artificial muscle 20/70°C at the end of off /on state, was measured by an Optex FA CD22-35 laser displacement sensor and collected by a Graphtec GL240 data logger. The data logger also collected the voltage applied to the artificial muscle.

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In order to measure the dependence of the electrical resistance on temperature, Joule heating of the artificial muscle under fixed length equipped with a thermocouple was employed. The length of the artificial muscle was changed by changing the suspended weight for the measurement of the dependence of the electrical resistance on length at room temperature.

3. Results and Discussion

Figure 1 shows the temporal change of the length and the voltage of the electroactive supercoiled artificial muscle driven by a 1/120 Hz square current wave of 0.5 A. It is noticed that the contraction upon Joule heating takes place quickly, while the relaxation due to cooling is much slower than contraction. In the present case, the contraction ratio is calculated as 9.6%, because the artificial muscle at the relaxed state with 46 mm in length shows a stroke of 4.4 mm. The contraction and relaxation times (10–90% of the final values) are estimated to be 3 and 15 s, respectively.

If the electrical resistance of the artificial muscle in operation is constant as assumed by a number of researchers, the voltage waveform must resemble the current waveform. However, the voltage waveform, which has a peak as high as 2.6 V at initial and gradually decays to be 1.7 V, is obviously different from the rectangular wave. This clearly invalidates the constant resistance assumption. A voltage spike can be induced by a current pulse in an electrical circuit including a coil. However, this does not apply in the present case. Although the shape of the artificial muscle is the coil with 70 turns, it does not carry any magnetic materials inside. Therefore, the inductance of the artificial muscle is too small to explain the observed voltage waveform whose time constant is more than 1 s.

Figure 2 (a) shows the initial part of the temporal change of the length and the voltage. It is observed that the contraction of the artificial muscle is readily started after the application of the current pulse and saturates within 5 s. On the other hand, the voltage remains 2.6 V for approximately 3 s and then, gradually drops. Since the contraction directly reflects the temperature of the artificial muscle, the initial plateau suggests the temperature dependence of the electric resistivity of the conductor; plated Ag in this case, is small. Indeed, the electrical resistance of an artificial muscle fixed at a constant length only has a minor temperature dependence as shown in Fig. 2 (b). The negative slope in this characteristic may come from the semiconducting nature of grain boundaries in the plated Ag.

The electrical resistance of a non-heated artificial muscle as a function of length is plotted in Fig. 3 (a). The electrical resistance monotonically increases with length, and abruptly saturates near 42 mm. The S-shaped characteristic can be explained as follows. When the artificial muscle is free from elongation and in the shortest form, the neighbor-

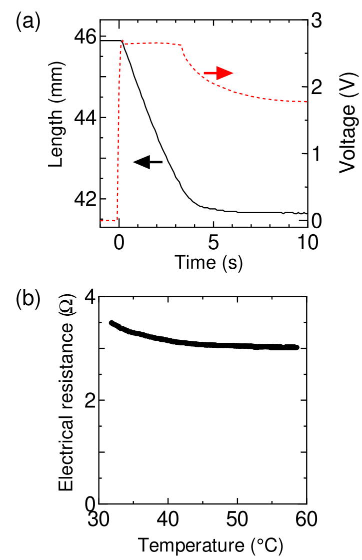

Fig. 2 (a) Initial part of the temporal change of the length and the voltage. (b) Dependence of electrical resistance of an electroactive supercoiled artificial muscle on temperature. The length of the sample was fixed during the measurement.

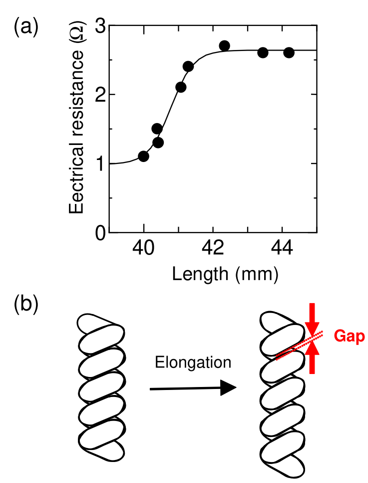

Fig. 3 (a) Dependence of electrical resistance of the electroactive supercoiled artificial muscle on length at room temperature. The line shows the fitting curve using Eq. (1). (b) Schematic model of the electroactive supercoiled artificial muscle. Neighboring coils are in contact before elongation and elongation creates a gap between neighboring coils.

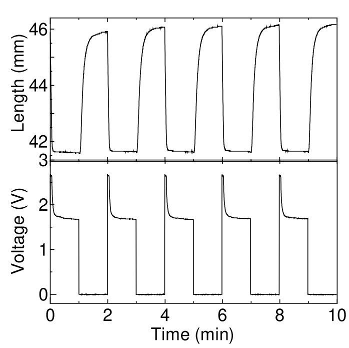

Fig. 1 Temporal change of the length and the voltage of an electroactive supercoiled artificial muscle driven by a 1/120 Hz rectangular current wave of 0.5 A.

ing coils are in maximum contact as shown in the left panel of Fig. 3 (b). In this stage, the artificial muscle can be considered as a rippled cylindrical conductor with a length of the artificial muscle and has minimum electrical resistance. The elongation of the artificial muscle decreases the contact area between the neighboring coils and raises the electrical resistance. The saturation probably corresponds to the creation of a gap between adjacent coils in the artificial muscle as shown in the right panel of Fig. 3 (b), where the artificial muscle becomes a spiral line conductor with a length of the thread and has a maximum electrical resistance. The characteristic with an S-shaped nonlinearity readily invalidates the linear relationship between the elongation and electrical resistance assumed in the literature [17], [18].

The precise modeling of the dependence of electrical resistance on length in the electroactive supercoiled artificial muscle, which must be a complex problem including mechanics of the elastic body, is out of the scope of this study. Instead of that, we have checked whether a simple expression for electrical resistance R as a function of length L using logistic function

$$R(L) = R_0 + \frac{\Delta R}{1 + \exp(-\alpha(L - L_0))} \quad (1)$$

can reproduce the experimental data or not. As shown in Fig. 3 (a), Eq. (1) with $R_0 = 0.986\,\Omega$, $\Delta R = 1.65\,\Omega$, $\alpha = 3.04$ and $L_0 = 40.8$ mm successfully reproduces the experimental data. This compact mathematical model will be useful for the modeling of electroactive supercoiled artificial muscle. Although we have proposed a mathematical model based on softplus function for the R–L characteristics in the previous paper [19], the present expression seems to be better than it because suftplus function does not reproduce the S-shaped characteristics shown in Fig. 3 (a).

In conclusion, S-shaped nonlinearity is found in the electrical resistance–length relationship in an electroactive supercoiled polymer artificial muscle. The phenomenon is attributed to the change in the contact condition of coils in the artificial muscle. A mathematical model based on logistic function is proposed for the electrical resistance–length relationship.

Acknowledgments

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