Chapter 25
Control of Electro-active Polymer Actuators with Considering Characteristics Changes

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Abstract Electro-active polymers (EAPs) are functional polymeric materials which respond to electrical stimuli with shape change. Since EAPs can be activated by electric field, driving equipment and control system are able to be easily implemented. Simple feedback control methods such as PID control and optimal control with identified model are effective; however, actuator characteristics of EAPs are likely to change depending on environmental conditions such as temperature and humidity or on material fatigue by iterative actuation. Therefore, feedback control methods considering the characteristics changes are desired. In this chapter, we explain two effective control methods for characteristics changes. One is a self-tuning control, which is a type of adaptive control, and another is cellular actuator control method for an integrated actuator. As example cases of the applied results, experimental results of feedback control of ionic polymer-metal composite (IPMC) actuators are demonstrated.

Keywords Feedback control · Characteristics change · Ionic polymer-metal composite (IPMC) · Adaptive control · Self-tuning control · Cellular actuator

25.1 Introduction

Electro-active polymers (EAPs) [1, 2] are functional polymeric materials which respond to electrical stimuli with shape change. EAPs have potential capabilities as soft actuators and are sometimes called artificial muscles due to their biotic

This chapter is based on the report of "Control of high polymer actuators with considering characteristics changes," in *Development of Soft Actuators and Application, Control Technologies for Practical Application*, CMC Publishing.

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K. Asaka, H. Okuzaki (eds.), *Soft Actuators*,
https://doi.org/10.1007/978-981-13-6850-9_25

smooth motions. Since EAPs can be activated by electric field, driving equipment and control system are able to be easily implemented.

In the situation that the actuator characteristics remain unchanged, simple feedback control methods such as PID control and optimal control with identified model are effective [3]. In fact, the PID control can be implemented easily and realized the sufficient performance in practical applications. However, the actuator characteristics of EAPs are likely to change depending on environmental conditions such as temperature and humidity or on material fatigue by iterative actuation. The control performance may degrade, or even the system may become unstable with increasing the characteristics changes. Therefore, feedback control methods considering the characteristics changes are desired.

In this chapter, we explain the effective control methods for characteristics changes. As example cases of the applied results, experimental results of feedback control of ionic polymer-metal composite (IPMC) actuators are shown.

25.2 Control of Ionic Polymer-Metal Composite Actuator

An ionic polymer-metal composite (IPMC) is one of the electro-active polymers (EAPs) [4]. It is produced by chemically plating gold or platinum on both surfaces of a perfluorosulfonic acid membrane which is known as an ion-exchange membrane. The IPMC actuator generates large deformation under low applied voltage (0.5–3 V), and it is expected to be applied to biomimetic robots and medical devices [2] due to the advantages of soft actuators such as flexibility and lightweight.

The IPMC actuator can be activated by a simple driving circuit due to low voltage actuation. The IPMC actuator bends in response to electric field. The deformation arises from the internal stress generated according to the movement of ions. Basically, it is possible to drive the actuator with a driving circuit similar to that for the electromagnetic motor. General driving methods such as voltage control, current control, and PWM control are applicable.

In addition, it is able to be controlled by simple controllers such as PID controller. However, individual differences of response characteristics are unavoidable due to the inhomogeneous character of high-polymer materials. The characteristics of the IPMC also vary depending on environmental conditions such as temperature and humidity [5]. To realize stable or precise control of the IPMC actuator, feedback control methods considering the individual differences and characteristics changes are needed.

From these backgrounds, there are many researches for controlling the IPMC actuator such as robust control and adaptive control. The robust control aims to keep the stabilities and performances even with the existence of modeling errors, uncertainties, or parameter variations of the system. As defining the bounds of uncertainties, the robust controller guarantees the control performance as long as the modeling error is within the bounds. Sano et al. indicated the effectiveness of a robust PID controller through force control experiments [6]. Kang et al. indicated that the control performance of a displacement control is greatly improved by H_∞ control [7].

On the other hand, the adaptive control is a control method in which the characteristics changes are successively estimated or controller parameters are adapted online. The adaptive control is applied to systems with parameters which vary over time or are unknown. Brufau-Penella et al. controlled the displacement of the actuator by a model reference adaptive control (MRAC) [8]. Lavu et al. applied the MRAC method with pole placement for the displacement control [9]. Fang et al. applied a direct self-tuning regulator (DSTR) and compared the tracking performance to PID control [10].

From the other viewpoint of problems for practical applications, the output force of the IPMC is very small. To increase the output force or displacement, connection of multiple actuator elements is possible. In this approach, the IPMC actuators connect in serial or parallel, and the output force or displacement of the whole integrated actuator elements is controlled. The integrated actuator is superior in terms of fault tolerance; even if some of the actuator elements fail to the actuation function, the integrated actuator can be activated. However, when using multiple actuator elements, the individual differences affect the control performance. In addition, if the integrated actuator is controlled under observing individual states, design and implementation of the controller become complicated. The control method unaffected by the individual differences or characteristics changes is required for achieving stable behavior and large output.

One of the methods for solving the above problem is a control method for cellular actuators inspired from the structure and control of muscles [11]. It is based on simple structure and stochastic *on/off* control for the integrated actuator with multiple elements.

There are many methods for controller design considering characteristics changes. In this chapter, two methods are introduced. In Sect. 25.3, as an example of the adaptive control, a displacement control by self-tuning control is demonstrated. In Sect. 25.4, a force control by the stochastic *on/off* control for the integrated actuator is demonstrated.

25.3 Self-Tuning Control

In this section, as an example of the adaptive control, the self-tuning control based on generalized minimum variance criterion is demonstrated. The validity of the method is investigated through experiments of displacement control of IPMC.

25.3.1 Controller Design [12]

As a model of the IPMC actuator, a single input-single output (SISO) discrete linear time-invariant model is assumed. The model of the actuator dynamics is expressed by

$$A\left(z^{-1}\right)y_k = z^{-d}B\left(z^{-1}\right)u_k \tag{25.1}$$

where z^{-1} is a time shift operator, u_k is a control input (input voltage), and y_k is an output of the system (displacement). d is a time delay, which is assumed to be known. Polynomials $A(z^{-1})$ and $B(z^{-1})$ are

$$A\left(z^{-1}\right) = 1 + a_1 z^{-1} + a_2 z^{-2} + \cdots + a_n z^{-n} \tag{25.2}$$

$$B\left(z^{-1}\right) = b_0 + b_1 z^{-1} + b_2 z^{-2} + \cdots + b_m z^{-m} \tag{25.3}$$

where orders n and m are assumed to be known.

A generalized output is defined as

$$s_{k+d} = C\left(z^{-1}\right)\left(y_{k+d} - r_{k+d}\right) + Q\left(z^{-1}\right)u_k \tag{25.4}$$

where r_k is a desired value. $C(z^{-1})$ and $Q(z^{-1})$ are weight coefficients for controlled variable and input and given by

$$C\left(z^{-1}\right) = 1 + c_1 z^{-1} + c_2 z^{-2} + \cdots + c_n z^{-n} \tag{25.5}$$

$$Q\left(z^{-1}\right) = q_0\left(1 - z^{-1}\right). \tag{25.6}$$

Equation (25.4) is rewritten as

$$s_{k+d} = G\left(z^{-1}\right)u_k + F\left(z^{-1}\right)y_k - C\left(z^{-1}\right)r_{k+d} \tag{25.7}$$

where $G(z^{-1})$ is

$$G\left(z^{-1}\right) = E\left(z^{-1}\right)B\left(z^{-1}\right) + Q\left(z^{-1}\right) \tag{25.8}$$

and $E(z^{-1})$ and $F(z^{-1})$ are selected to satisfy the Diophantine equation:

$$C\left(z^{-1}\right) = A\left(z^{-1}\right)E\left(z^{-1}\right) + z^{-d}F\left(z^{-1}\right). \tag{25.9}$$

Then, the control input based on the minimum generalized variance control to make $s_{\mathrm{k+d}} = 0$ in Eq. (25.4) is given by

$$u_k = -G\left(z^{-1}\right)^{-1}\left[F\left(z^{-1}\right)y_k - C\left(z^{-1}\right)r_{k+d}\right]. \tag{25.10}$$

25.3.2 Parameters Updating Based on the Recursive Estimation

The self-tuning controller is given by introducing the online estimation of controller parameters in Eq. (25.10).

The estimated equation of the controller polynomials $F(z^{-1})$ and $G(z^{-1})$ is defined as

$$\hat{F}\left(z^{-1}\right) = f_0 + f_1 z^{-1} + \cdots + f_{n-1} z^{-(n-1)}, \tag{25.11}$$

$$\hat{G}\left(z^{-1}\right) = g_0 + g_1 z^{-1} + \cdots + g_{m+d} z^{-(m+d-1)}. \tag{25.12}$$

Let ϕ_k be a data vector containing output and input signals:

$$\phi_k = \left[y_k, \cdots, y_{k-n+1}, u_k, \cdots, u_{k-m-d+1}\right]^T \tag{25.13}$$

and $\hat{\theta}_k$ be an estimated vector containing controller parameters:

$$\hat{\theta}_k = \left[f_0, \cdots, f_{n-1}, g_0, \cdots, g_{m+d-1}\right]^T. \tag{25.14}$$

The controller with estimated parameters is given by

$$u_k = -\hat{G}^{-1}\left(z^{-1}\right)\left[\hat{F}\left(z^{-1}\right)y_k - C\left(z^{-1}\right)r_{k+d}\right]. \tag{25.15}$$

The updating laws of the controller parameters and covariance matrix to assure the system stability are given by

$$\hat{\theta}_k = \hat{\theta}_{k-1} + \frac{\Gamma_{k-1}\varphi_{k-d}}{1 + \varphi_{k-d}^T \Gamma_{k-1}\varphi_{k-d}}\left[s_k + C\left(z^{-1}\right)r_k - \varphi_{k-d}^T \hat{\theta}_{k-1}\right], \tag{25.16}$$

$$\Gamma_k = \Gamma_{k-1} - \frac{\Gamma_{k-1}\varphi_{k-d}\varphi_{k-d}^T \Gamma_{k-1}}{1 + \varphi_{k-d}^T \Gamma_{k-1}\varphi_{k-d}}. \tag{25.17}$$

By using past estimate and measuring data in time k, the online estimation of controller parameters can be realized.

25.3.3 Results

The validity of the self-tuning control is demonstrated though experiments. The experimental setup is shown in Fig. 25.1. The samples of the IPMC actuator with rectangular shape are fixed in a cantilever with the electrode. The displacement at a pint near the tip is measured by using a laser displacement meter. The measuring data of the displacement is fed into the computer. In the computer, the control law is calculated, and the calculated control input (driving voltage) is applied to the actuator through a driving amplifier.

The IPMC used in the experiment was fabricated by gold plating on the surface of the ion-exchange membrane (DuPont: Nafion® 117) with electroless plating method and was cut into the rectangular shape of 1 mm width and 30 mm length. The cation in the IPMC was sodium ion (Na^+). The sampling time was set to 10 ms. The order of the actuator model was determined from the step response of preliminary experiment as $n = 2$ and $m = 1$, and the time delay was also determined as $d = 1$. Parameters for controller design were set as $C(z^{-1}) = 1 + 40z^{-1} + 40z^{-2}$ and $Q(z^{-1}) = 800(1 - z^{-1})$, and the initial settings of the controller parameters were set as $F(z^{-1}) = 1 + z^{-1}$ and $G(z^{-1}) = 1 + z^{-1}$.

First, we conducted the control experiment in water, under the condition that the actuator characteristics are unchanged. The experiment result is shown in Fig. 25.2. In the interval of constant reference signal, the displacement tracked to the reference signal. The controller parameters, which were initially set to one, were tuned adequately with time, and the displacement control was realized.

Next, we conducted the control experiment in air, under the condition that the actuator characteristics are changing. The response characteristics in air are greatly different from that in water due to the difference in fluid resistance. In addition, the water in the IPMC is evaporating in air, and the response with characteristics changes can be demonstrated. The experimental results are shown in Fig. 25.3. After taking the IPMC sample from the water, the control experiments were conducted every 5 min. The parameters of the controller design are the same as in

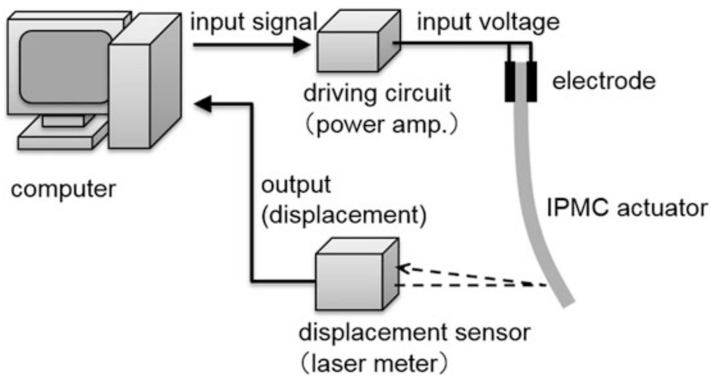
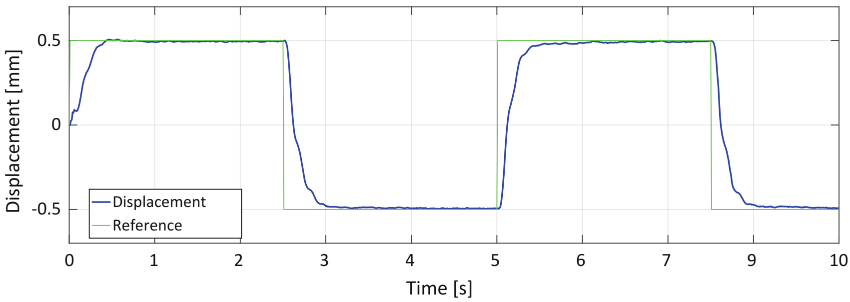
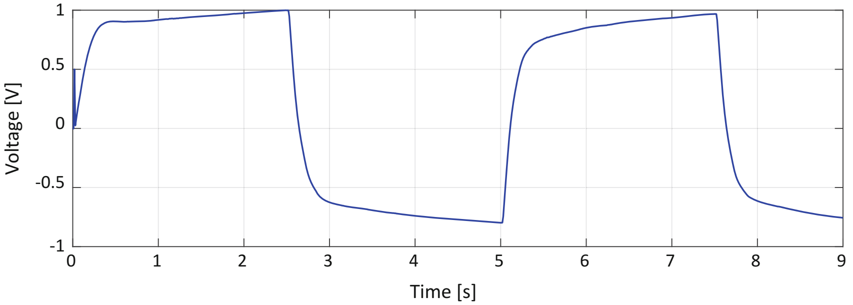


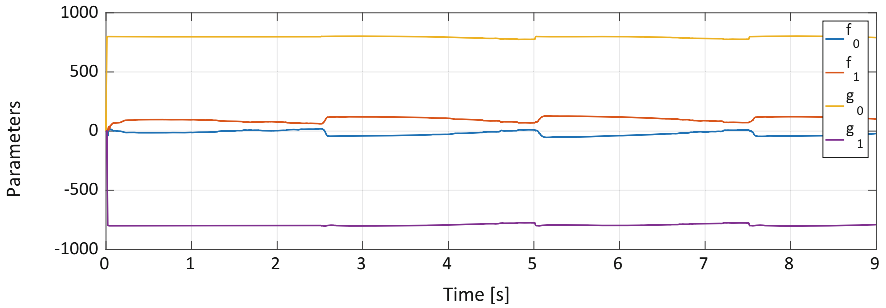
Fig. 25.1 Experimental setup



(a) Displacement



(b) Input voltage



(c) Estimated Parameters

Fig. 25.2 Experimental result of self-tuning control (in water). (**a**) Displacement, (**b**) input voltage, (**c**) estimated parameters. (Adapted with permission from Ref. [13]. Copyright 2017 The author)

the experiment in Fig. 25.2. From the results in Fig. 25.3, it is observed that the displacement control was realized in air. Although the tracking error and variation became large compared to the result in water, the tracking control was realized in each case. It is possible to achieve performance improvement by adjusting the design parameters. By the effect of online tuning of the controller parameters, stable control is realized under the situation that the actuator characteristics are unknown or changing with time.

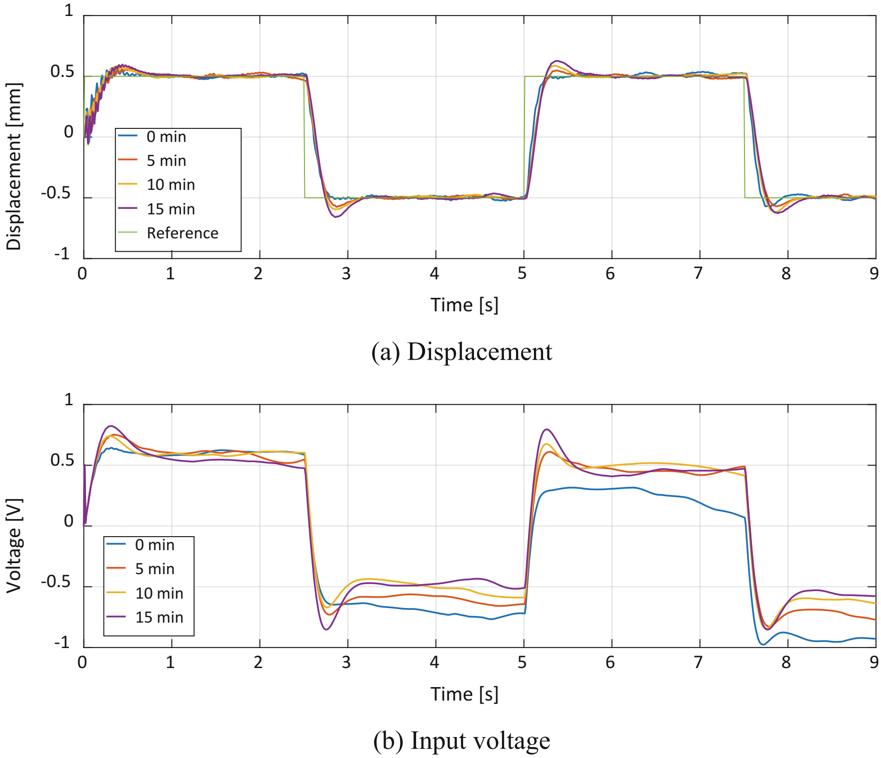


Fig. 25.3 Experimental results of self-tuning control (in air). (**a**) Displacement, (**b**) input voltage. (Adapted with permission from Ref. [13]. Copyright 2017 The author)

25.4 Cellular Actuator Control

The cellular actuator is an actuator system which consists of many actuator units. The structure and control mechanism are inspired by skeletal muscles [11]. The cellular actuator is formed by connecting many actuator units in series and/or in parallel, which are called "cells." The controllers of the cellular actuator consist of a central controller and distributed controllers. The central controller broadcasts a control signal such as an error signal to distributed controllers uniformly. The distributed controllers switch *on/off* states based on the broadcasted signal stochastically. The central controller does not measure the states of each cell, and the control signals are calculated by using the output signal of the overall integrated actuator and reference signal. In applying the stochastic *on/off* control, the integrated IPMC actuator can be controlled without considering the individual differences and characteristics changes. In addition, it is possible to construct the actuation system by a simple driving circuit since the state of the actuator elements switches the *on/off* states only.

25.4.1 Control Law [14]

A block diagram for the stochastic *on/off* control of the IPMC integrated actuator is shown in Fig. 25.4. The broadcast signal generated by the central controller $u(t)$ is set as

$$u(t) = e(t) = r(t) - y(t), \tag{25.18}$$

where $r(t)$ is the reference signal and $y(t)$ is the output signal which is the summation of each unit output. Transition probabilities of the distributed controllers are given by

$$\text{ON} \quad \rightarrow \quad \text{OFF} : p(u) = \begin{cases} g_p u/N & (u \geq 0) \\ 0 & (u < 0) \end{cases} \tag{25.19}$$

$$\text{OFF} \quad \rightarrow \quad \text{ON} : q(u) = \begin{cases} 0 & (u \geq 0) \\ -g_q u/N & (u < 0) \end{cases} \tag{25.20}$$

where g_p and g_q are transition probability gains and N is the number of IPMC actuators. The stochastic *on/off* control is realized by comparing this transition probability with a sequentially generated random number.

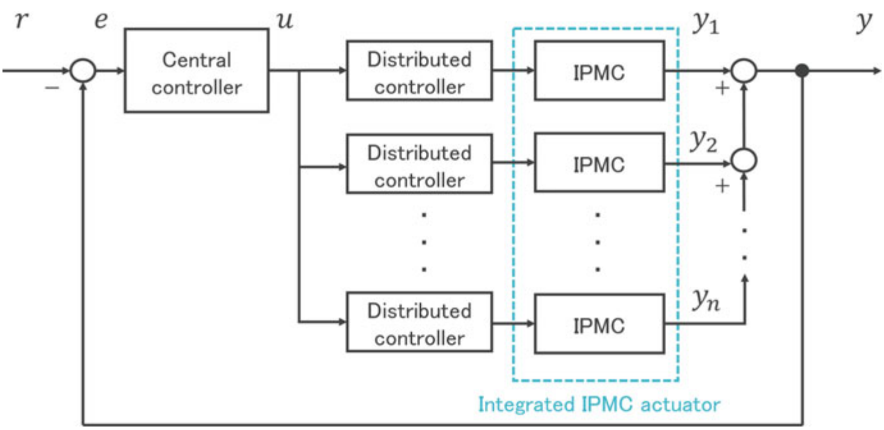


Fig. 25.4 Block diagram of stochastic *on/off* control. (Adapted with permission from Ref. [13] Copyright 2017 The author)

25.4.2 Results

The validity of the stochastic *on/off* control for the IPMC integrated actuator is demonstrated though the force control experiment. In the experiments, 24 pieces of IPMC strips were stacked in parallel, and all tip sections were fixed by a flat plastic plate. The output force at the central part of the plastic plate was measured by a strain gauge force sensor. In these experiments, the output force was fed into a computer, and the *on/off* switching on the distributed controllers was calculated in the computer.

Experimental results are shown in Fig. 25.5. In the results, the output force and the number of the ON state pieces are plotted. The output force tracks to the reference signal. The number of ON state elements changes as time proceeds. It is observed that feedback control of the integrated actuator is realized by adequate switching of each element.

In addition, results of three types of actuators are plotted in Fig. 25.5, where the ion species of cation and their combining ratio in the IPMC are different. A is the

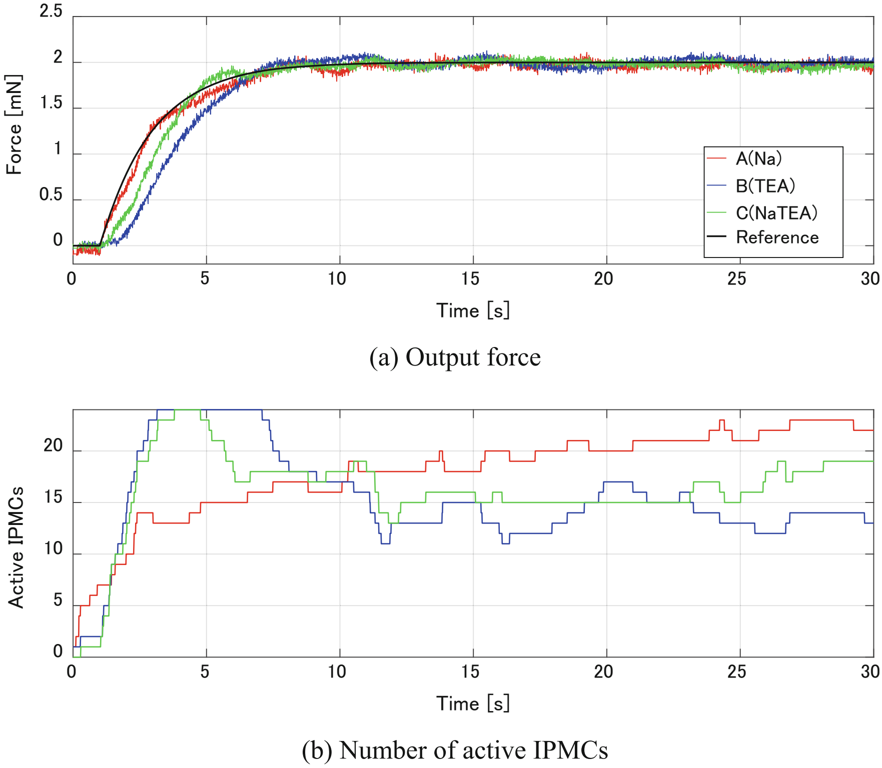


Fig. 25.5 Experimental results of stochastic *on/off* control. (**a**) Output force, (**b**) number of active IPMCs. (Adapted with permission from [13]. Copyright 2017 The author)

case of all sodium (Na) ions. B is the case of all tetraethylammonium (TEA) ions. C is the case of combining the Na and TEA ions half and half. The transient response of the IPMC with Na ion is fast compared to that with TEA ion; however, it is difficult to keep the output force for a long time due to characteristics of the stress relaxation. The response of the IPMC with TEA ions is relatively slow; however, it is possible to keep constant output force in a long time. Furthermore, in case of combining the cation, fast response and keeping of output force are realized. It is confirmed that the response characteristics can be adjusted by combining the types of actuator.

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