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The Study of Dynamic Characteristics of Selenium CMV-based IPMC Actuators in Humidity-Controlled Environments

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IPMC (Ionic Polymer Metal Composite) actuators have numerous promising applications in designing electroactive soft motion structures. It was reported that the bending behavior of Selenium CMV-based IPMC in response to the electrical stimulation was quite susceptible to the environmental absolute humidity, and the environmental absolute humidity increase appeared to cause the unstable bending of Selenium CMV-based IPMC. Previously a circuit model for the analysis of Selenium CMV-based IPMC bending behavior was proposed and it actually resulted in quite successful prediction of bending behavior. However, it does not provide us with any information of bending stability. In this study, using Simulink – Matlab, an open loop model was built, based on the circuit model, the stability analysis of Selenium CMV-based IPMC bending was carried out.

Keywords: IPMC, Selenium-CMV, Open loop systems, electric circuit model, compensator, MATLAB.

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1. Introduction

Ionic Polymer-Metal Composite (IPMC) is an electroactive actuator consisting primarily of polymer [1-4]. It exhibits quite fast bending under applied voltage. The voltage required for the bending induction is as low as a few volts, quite low energy consumption. Owing to the soft property intrinsic of the polymer, fast bending motion, quite low energy consumption and etc, IPMC has been a quite promising candidate to be used as an artificial muscle [5-7]. Indeed, there are striking similarities between the IPMC nature and the real muscle properties, for example, both of them primarily consist of polymers, contain solutions and are activated electrically, and so on [1-4]. Nowadays a number of researchers are involved in the research aiming at fabrication a practical bending mode IPMC actuator.

Usually, IPMC is electrically activated in highly hydrated state. So, the IPMC can be activated even in an aqueous solution unlike other type of actuators, and it is one of IPMCs’ featuring facets. Despite intensive efforts made by a number of researchers toward the ultimate research goal of fabricating a practical bending mode actuator of IPMC, the research progress is stagnant these days. For the practical use of IPMC, the IPMC have to be able to generate higher force and have to exhibit precisely controllable bending behavior.

Selenium CMV-based IPMC (hereafter called CMV IPMC) is a type of IPMC, where Selenium CMV is an ion exchange membrane manufactured by Asahi glass Co., Ltd. (Tokyo). As described already, IPMCs are usually activated in the highly hydrated state and often in an aqueous solution. However, its bending controllability is poor. Previous research has shown that the bending controllability could be improved greatly by dehydration treatment [8-10]. Furthermore, the bending curvature of the dehydrated Selenium CMV IPMC is basically proportional to the total charge imposed on it. Owing to such a proportionality relationship between the curvature and charge, bending control of CMV IPMC by the control of charge imposed on it has been undertaken successfully [11]. But further investigation of the CMV IPMC indicated that its bending behavior becomes less controllable only by the slight raise of environmental absolute humidity. Recently, three of the authors of this paper (M. S., H. T. and K. I.) proposed a circuit model for predicting the CMV IPMC bending behavior and successfully predicted the CMV IPMC bending in the broad range of absolute humidity [12]. However, the circuit model does not provide the cause of the occurrence of less controllable bending of CMV IPMC only by the slight raise of environmental absolute humidity.

In this study, the stability analysis of CMV IPMC bending was carried out by the use of circuit model. The analysis provided us with some explanation how the environmental absolute humidity influences on the CMV IPMC characteristics and bending behavior.

2. Preparation of CMV IPMC and measurements

A CMV IPMC was fabricated simply by coating a Selenium CMV surface with silver through the silver mirror reaction process (see Fig. 1). Its fabrication requires several steps [12]. The results described below

Fig. 1 Fabrication process of Selenium CMV IPMC.
were obtained using CMV IPMCs that were slightly hydrated. Hereafter we refer to "slightly hydrated CMV IPMC" simply as "dehydrated CMV IPMC".

3. Bending testing

The dehydrated CMV IPMC was horizontally clamped with a pair of electrodes as illustrated in Fig. 2 (a). Once the voltage is induced the CMV IPMC exhibits bending. Bending direction depends on the voltage polarity, and the CMV IPMC usually exhibits bending in the anode direction as illustrated in Fig. 2 (b).

In order to make observations of what happens to the CMV IPMC bending under applied voltage, bending tests in response to rectangular oscillating voltage was carried out using the setup illustrated in Fig. 2 in the controlled absolute humidity environment [12], where the bending testing was carried out low (4.5 gm⁻³) and moderate (6.8 gm⁻³) absolute humidity environment.

Figure 3 shows the time dependence of CMV IPMC (a) curvature and (b) current under the rectangular oscillating voltage (1.5V amplitude, 1/60 Hz frequency) at the low absolute humidity 4.5 gm⁻³. Curvature and current exhibited quite well-ordered regular oscillation in accordance with the rectangular oscillating voltage imposed. Such well-ordered regular oscillation of curvature and current were observed at the moderate absolute humidity.

4. Circuit model

Ikeda et al. proposed a circuit model illustrated in Fig. 4 for associating the charge flowing through the IPMC with the IPMC bending curvature, where they used the same IPMC as CMV IPMC [12]. They succeeded in theoretically reproducing the experimental observation of CMV IPMC bending behavior by the use of the circuit model. Usefulness of the circuit model for predicting the bending curvature behavior of CMV IPMC was already confirmed by Ikeda et al. [12]. We speculated that such a highly useful circuit model is even more useful for further theoretical analysis of CMV IPMC characteristics. We have for long while looked for a method of analyzing the bending stability of CMV IPMC. The circuit model could be utlizable for the stability analysis of CMV IPMC bending behavior.

Prior to proceeding with the explanation of our study, the circuit model is detailed more. CMV IPMC exhibits bending under V. Pervious works suggests that current flowing through the CMV IPMC plays a fundamental role of its bending induction [5-9, 11, 12]. The bending induction is basically accompanied by the induction of redox reaction of silver on the CMV IPMC surfaces. The silver...
5. Derivation of transfer function

In order to carry out the stability analysis of CMV IPMC bending under the rectangular oscillating voltage, we derived the transfer function associating the input voltage and CMV output (bending output). The following procedure was undertaken to derive the transfer function: Formula of current represented by I (= I(t)) in Fig. 4, which flows through the entire body of CMV IPMC, is derived by solving the circuit equation. Procedure of solving the circuit equation is given in the ref. [12]. The current I(t) and bending curvature B(t), associated with voltage input V (= V(t)) is given by Eq. (1a) and (1b) respectively. Then, assuming V(t), which is given by Eq. (2), is the input signal (see Fig. 5), and I(t), which is given by Eq. (1), is the output signal, the transfer function G(s) is obtained by the use of MATLAB, where G(s) satisfies \( I(s) = V(s)G(s) \).

\[
I(t) = V(t) \left[ \frac{1}{\tau_e} e^{-\frac{t}{\tau_e}} + \frac{R}{R + \tau_{ef} + \tau_e} e^{-\frac{t}{R + \tau_{ef} + \tau_e}} + \frac{1}{\tau_{ef} + \tau_e} \right] \tag{1a}
\]

\[
B(t) = \frac{V(t)}{\tau_e + \tau_{ef}} \left[ k_F \tau_0 - k_F R C_0 - k_{nF} R C_0 e^{-\frac{t}{\tau_0}} + [k_F + k_{nF}] R C_0 - k_F \tau_0 + k_F t \right] \tag{1b}
\]

Where: \( k_F \) – Faraday current constant, \( k_{nF} \) – Non Faraday current constant, and the values of parameters are given in Table 1.

\[
V(t) = 1.5 \left[ \text{sgn} \left( \sin \left( \frac{2\pi t}{60} + \frac{\pi}{2} \right) \right) \right] \tag{2}
\]

Transfer functions of low and moderate humidity cases are given by Eqs. (3) and (4), respectively.

\[
G_L(s) = 10^{-6} \frac{5.4675 + \frac{4.4}{s+0.25}}{s^2+2.8625} \tag{3}
\]

\[
G_M(s) = 10^{-6} \frac{5.935 + \frac{3.133}{s+0.623}}{s^2+7.15} \tag{4}
\]

Prior to carrying out the stability analysis of CMV IPMC bending as this research aim, we proceeded with the assessment of the validity of these transfer functions by seeing if the CMV IPMC bending curvature behaviour such as Fig. 3 (a) was reproducible by the use of those transfer functions. Although Ikeda et al. already revealed that the bending curvature of CMV IPMC is not perfectly proportional to the total charge imposed on the CMV IPMC [12], it is not extreme to say that the CMV bending curvature is approximately proportional to the total charge imposed on the CMV IPMC [6-9]. Hence, we hypothesized that the CMV bending curvature is proportional to the total charge imposed on the CMV IPMC throughout the study described in this paper.

\( I(t) \) represents the current in the low humidity environment, and it was computationally evaluated using the transfer function Eq. (3). Then the total charge CMV IPMC was computed. Taking into the consideration the proportionality between the CMV IPMC curvature and the charge imposed on it, the computational prediction of

![Fig. 5 The rectangular oscillating voltage (1.5V amplitude, 1/60 Hz frequency) applied to the CMV IPMC.](image_url)
CMV bending curvature was obtained as shown in Fig. 6 (a). Fig. 6 (a) also suggests that the computational curvature well reproduce the experimental data of curvature. Fig. 6 (b) shows that the computational and experimental data of current. The computational data perfectly reproduces the experimental data of current. Concerning the moderate humidity case, good experimental data reproducibility was achieved, too. So the transfer functions of Eqs. (3) and (4) are reliable enough for further analysis of CMV IPMC bending stability.

Before closing this section, the authors have to make a comment on the above described analysis. This paper deals with the characteristics of CMV IPMC in distinct humidity environments by employing the circuit model. As described earlier, the authors hypothesized that bending curvature of CMV IPMC is approximately proportional to the total charge imposed on the CMV IPMC [6-9]. The authors already notice that such an approximation is not universally valid, but it is valid only in the environment with the absolute humidity less than 10 gm⁻³. Analysis for the bending behaviour of CMV IPMC at above 10 gm⁻³ absolute humidity needs another way of analysis. We also notices that bending the basic characteristics of CMV IPMC in Moderate absolute humidity environment is not so significantly different from those in Low humidity environment and sometimes they are almost the same each other, while those at above 10gm⁻³ absolute humidity environment were significantly different from those in Low and Moderate absolute humidity environment. Analysis of bending behaviour of CMV IPMC at above 10 gm⁻³ absolute humidity is to be reported in other occasion.

![Image](image1.png)
(a) Time course of bending curvature.

![Image](image2.png)
(b) Time course of current.

Fig. 6 Time course of CMV at low humidity, 4.5 gm⁻³
Fine line: Experimental  Thick line: Computational.

6. Bending stability analysis

By the use of transfer function derived, bending stability of CMV IPMC is carried out in this section. The transfer functions, $G_L(s)$ and $G_M(s)$ respectively given by Eqs. (3) and (4) were transformed from partial fraction to polynomial expressions, Eqs. (5) and (6), respectively, and of course, they suffice the relationship given by Eq. (7).

$$I_L(s) = [V(s)] * 10^{-3}$$ \[\begin{bmatrix} 25.06s^2+37.83s+1 \\ 2.398s^2+7.464s+1.714 \end{bmatrix} \] (5)

$$I_M(s) = [V(s)] * 10^{-2}$$ \[\begin{bmatrix} 1.242s^2+4.675s+1 \\ 1.122s^2+8.725s+5 \end{bmatrix} \] (6)

$$I(s) = V(s)G(s)$$ (7)

In this study, an open loop system model was built using the MATLAB. Using the open loop transfer functions – the polynomial expressions given in Eqs. (5) and (6) – the following results were obtained:

Figure 7 shows the root locus diagram, and poles and zeros are summarized in Table 2. For a zero steady-state error, $\lim_{s \to 0} I(s) = \infty$, and for limit to be finite, at least one pole must be at the origin $s = 0$. The results suggest that the system is marginally stable. Since we assumed that the CMV IPMC curvature is proportional to the total charge imposed on the CMV IPMC, and the charge is given merely by the time integration of current. Hence, the CMV IPMC bending behavior is also marginally stable.

Figure 8 shows the experimental and computational response of current to the input of Heaviside step function voltage. Experimental results shown in Fig. 8 (a) indicates the existence of a large time delay and the system was highly damped for both humidity conditions. Fig. 8 (b) shows the computationally obtained current. The computational results do not well reproduce the experimental results. However, qualitative characteristics - a large time delay and highly damped system - were relatively well reproduced.

For both humidity conditions, there is a pole almost at the origin which is a dominant pole (see Table 2). This makes the whole system behave like an integrator, which is clearly shown by Figure 9 of Bode plot. We carried out further analysis of system stability. Figure 10 is a Nyquist plot and it indicates that the system is basically marginally stable at any frequency.

<table>
<thead>
<tr>
<th>Table 2 Poles and Zeros of the open loop system models.</th>
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<tbody>
<tr>
<td><strong>Low humidity</strong></td>
</tr>
<tr>
<td>-0.2496</td>
</tr>
<tr>
<td>-2.8734</td>
</tr>
<tr>
<td><strong>Moderate humidity</strong></td>
</tr>
<tr>
<td>-0.6230</td>
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<tr>
<td>-7.1533</td>
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</table>
7. Conclusions

Based on the circuit model, the transfer functions were derived. Those transfer functions successfully reproduced the experimentally obtained bending and current behaviours of CMV IPMC. Hence, the transfer functions derived are quite reliable. Analysing the transfer functions we obtained and validated, it was found that the bending behaviour of Selenium CMV-based IPMC in response to the electrical stimulation was quite susceptible to the environmental absolute humidity, and the environmental absolute humidity increase appeared to cause the unstable bending of Selenium. The results also indicated that CMV-based IPMC CMV IPMC has the following characteristics.

(i) There exists a large time delay in the current in response to the voltage input.

(ii) Current is highly dumped.

(iii) Bending behaviour is marginally stable under the input at any frequency.

References


