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SELEMION CMV-BASED IPMC ACTUATORS' DSP-ASSISTED BENDING CURVATURE OSCILLATION BEHAVIOR IN HUMIDITY-CONTROLLED ENVIRONMENTS

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ABSTRACT
Fabrication of a practical electroactive polymer-based actuator is one of significantly important topics in the material science field. It is expected that the electroactive polymer-based actuator motion is quite similar to the real muscle motion due to its innate softness. Therefore a number of scientists acknowledge that the electroactive polymer-based actuator could exhibit unprecedentedly fascinating performance as an electroactive actuator. IPMC (Ionic Polymer Metal Composite) is one of polymer-based actuators. The research's main objective was to obtain, compute and analyze the actuator's dynamics and transfer functions for controlling purposes of the Selemion CMV-based IPMC actuators in humidity-controlled environments. This paper presents the DSP assisted Feedforward, Feedback and two-degree-of-freedom control applied to Selemion CMV – based IPMC actuator. Previously, the authors of this paper have noted that the dehydration treatment improves the electrical controllability of the bending curvature oscillations in Selemion CMV – based IPMC actuators. This was evident in the DSP assisted control systems. The bending curvature oscillations experiments were carried out during the winter season, where the relative humidity was 30% at a room temperature of 24°C. Prior to performing the experiments, actuator's dynamics and transfer functions were obtained through a series of experiments and simulations. From the computed and derived transfer functions, the controllers were implemented. The three controllers performed quite well, with just slight deviations during the repeat experiments due to changes in electrical properties the actuators underwent.

Keywords: IPMC, Selemion-CMV, Simulink-Matlab, DSP, DSpace

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INTRODUCTION

Fabrication of a practical electroactive polymer-based actuator is one of significantly important topics in the material science field. It is expected that the electroactive polymer-based actuator motion is quite similar to the real muscle motion due to its innate softness. Therefore a number of scientists acknowledge that the electroactive polymer-based actuator could exhibit unprecedentedly fascinating performance as an electroactive actuator. IPMC (Ionic Polymer Metal Composite) is one of polymer-based actuators. It has been investigated as a highly promising candidate of practical bending mode polymer-based actuator (Ngetha, *et al*, 2014; Ngetha, *et al*, 2015; Ikeda *et al*, 2015; Minoru, *et al*, 2014)

Soft actuators, also referred to as, the pulling actuators, are based on transducing materials configured in thin sheets or wires so that they only withstand traction forces. Hard actuators on the other hand have the capabilities in sustaining both traction and compressional forces, hence, referred to as the push-pull actuators. Thus hard actuators are two-directional actuators, while the soft actuators are inherently unidirectional. IPMC is electrically activated usually in aqueous solution or in the highly hydrated state in the air. This is one of IPMCs' featuring facets. However, the primary focus by the researchers in the IPMC research field lies in the fabrication of IPMC utilizable in the atmosphere. But the research progress has stagnated recently. Designing and fabricating a practically utilizable IPMC is an uphill task. The reasons for this stagnation in IPMC research lie in the strong requirements for achieving the practical IPMC since IPMC has to be able to generate higher force and exhibit more precisely controllable bending behavior.

The IPMC is a thin beam shape composite. Its structure is illustrated in Figure 1. IPMC is electrically activated in the highly hydrated state. It is due to the need of water for the activation of IPMC. It has been believed that the bending of IPMC is due to the shift of mobile hydrated ions inside the IPMC under applied voltage as illustrated in Figure 2 (Ngetha, *et al,* 2013).

It means that a large quantity of water is needed in inducing the bending of the IPMC. However, contrary to that; bending mechanism firmly believed and accepted, it was found that one of IPMCs consisting of a Selemion CMV coated with silver exhibited relatively large bending under applied voltage even in the highly dehydrated state (Tamagawa and Nogata, 2004; Tamagawa and Nogata, 2006; Tamagawa and Nogata, 2007; Tamagawa, *et al*, 2011). The Selemion CMV-based IPMC is an ion exchange membrane manufactured by Asahi Glass Co., Ltd., Tokyo, Japan.

It's worthy to note that; a completely dehydrated Selemion CMV-based IPMC cannot exhibit bending due to the loss of electrical conductivity, but even highly dehydrated Selemion CMV-based IPMC exhibited large bending. The highly dehydrated Selemion CMV-based IPMC was found to exhibit largely improved bending controllability compared to the highly hydrated one and its bending curvature was well-controllable electrically (Tamagawa and Nogata, 2004).

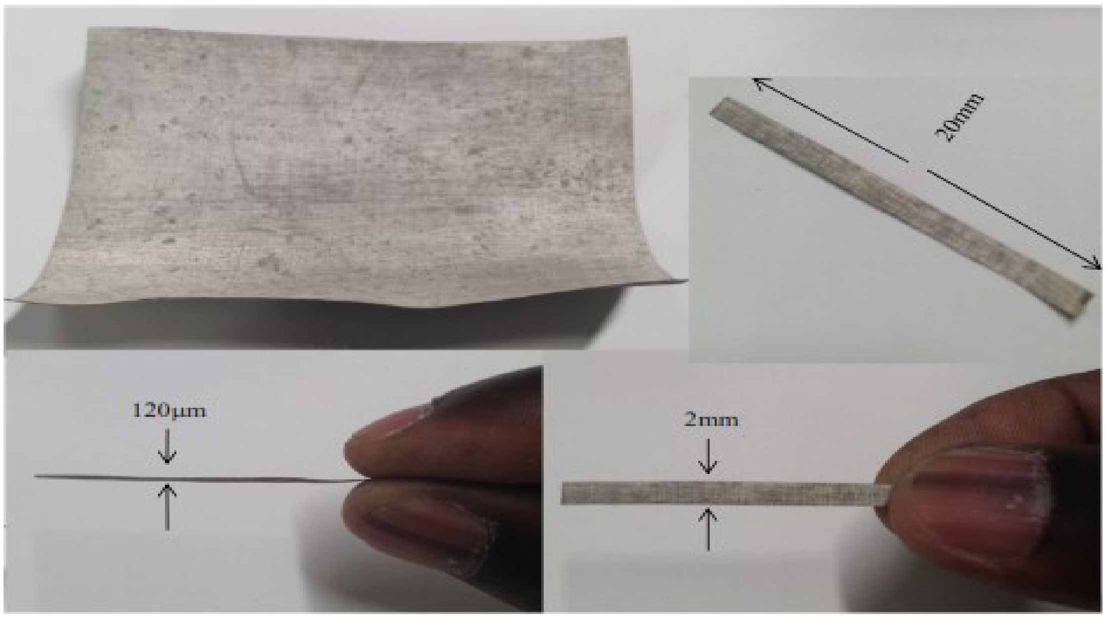


Figure 1 Structure of IPMC

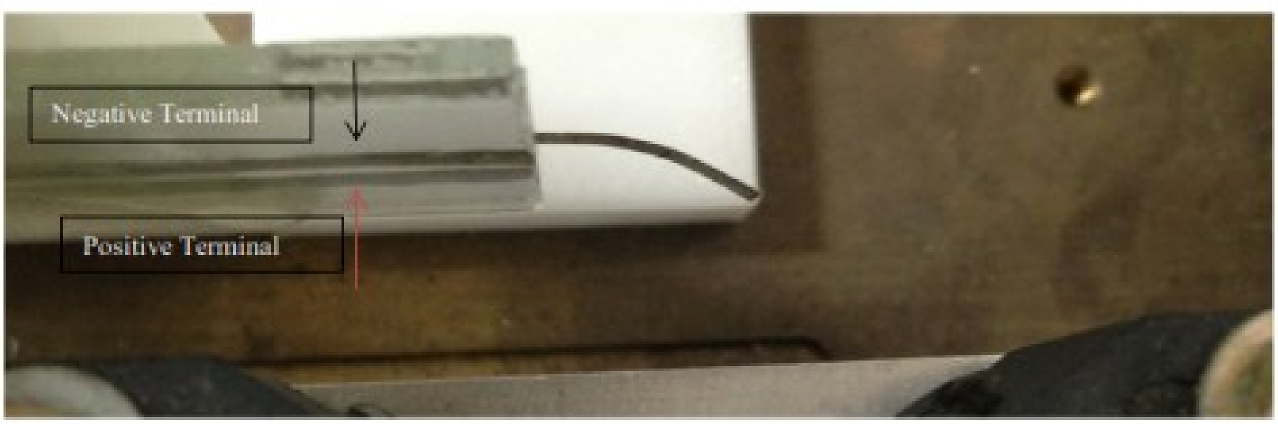


Figure 2 Shift of hydrated mobile cations contained in the IPMC

Another type of an IPMC with almost same properties and bending behavior as the Selemion

CMV-based IPMC is Nafion-based one (Nafion coated with silver). Nafion is an ion exchange membrane manufactured by DuPont (Delaware, USA), whose chemical structure is quite similar to Selemion CMV. Nafion is the first IPMC in the IPMC research field that has been studied as an IPMC component up until today. Through the research work carried out previously, it was found that Nafion-based IPMC exhibited bending under applied voltage, too, even in the highly dehydrated state, though its bending curvature was quite small (Sasaki, *et al*, 2010).

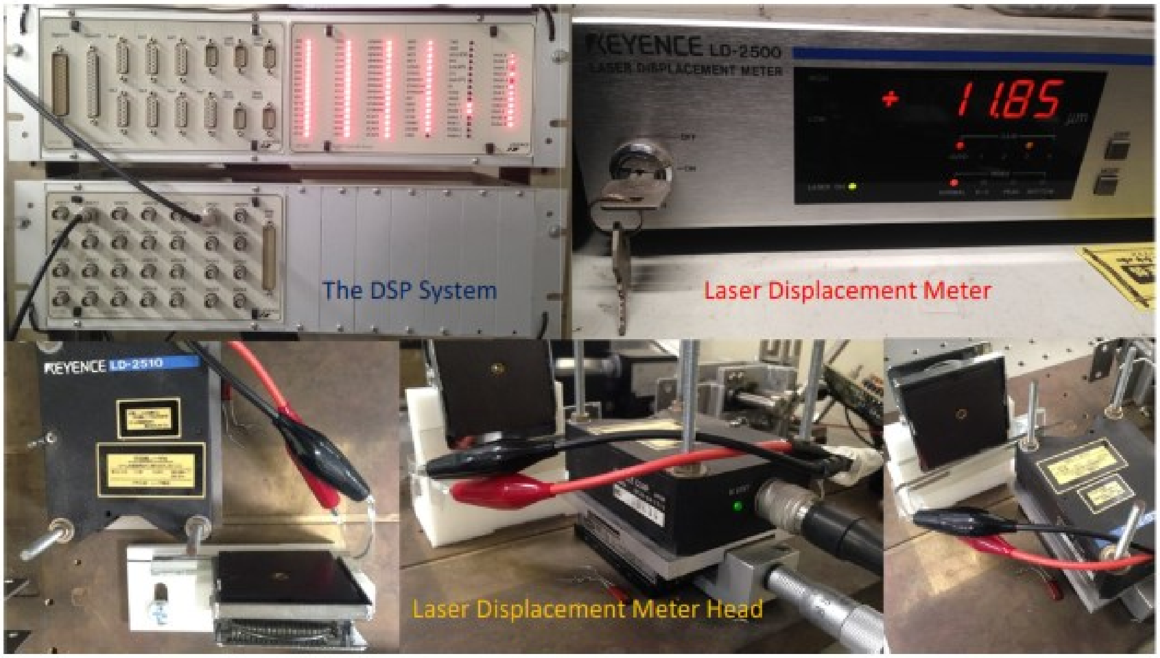
It had been discovered that, the Nafion-based IPMC bending controllability was largely improved in the highly dehydrated state compared with that in hydrated state. The dehydration treatment of the Selemion CMV-based IPMC and Nafion-based IPMC led to a considerable amount in bending controllability improvements.

The study of dehydrated IPMC makes it clear that there is a quantitative relationship between the IPMC bending curvature and the charge quantity imposed on the IPMC. It led previously to a successful theoretical treatment based on the circuit model for associating the IPMC bending curvature with the charge (current) quantity. The circuit model previously proposed, takes into consideration of influence difference between Faradaic and non-Faradaic currents on the IPMC bending induction, and it successfully reproduced the experimentally observed bending behavior of IPMC. However, for the precise bending control of IPMC, another facet of IPMC bending need be focused on too. This is the bending stability of IPMC. Stability analysis of IPMC bending has not been studied so intensively in IPMC research field. Therefore, the primary topic of this research work lies in the bending stability analysis of IPMC based on the circuit model.

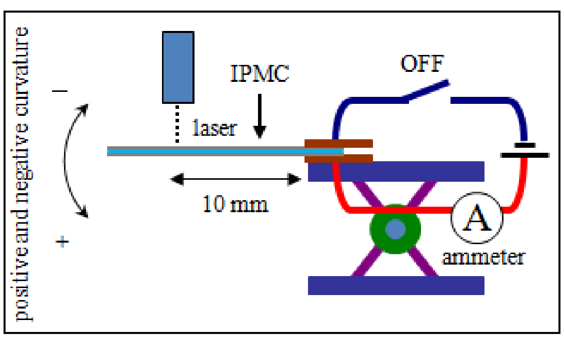
METHODOLOGY

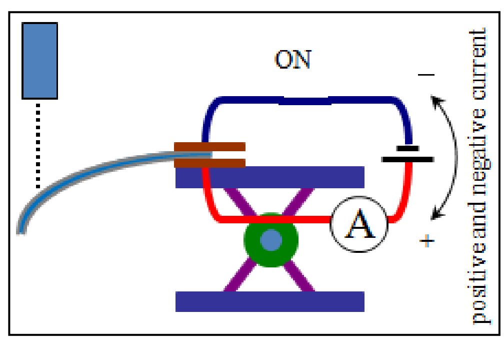
Circuit Model

Ikeda *et al* (2014) conducted experimental research studies on bending behaviors of Selemion CMV-based IPMC and proposed an RC circuit model. This involved rigorous tests, assumptions and the essential conditions for building a circuit model of the Selemion CMV-based IPMC. The outcome was an RC circuit model that mimicked the real Selemion CMV-based IPMC. The following procedures indicate the initial preparations of the Selemion CMV-based IPMC strips;



(a) The Equipments' set up





(b) (c)

Figure 3: Experimental setup for measuring the tip displacement of CMV IPMC

Using the experimental setup, the following bending tests on CMV IPMC were carried out: 1.5 V constant voltage was imposed on the CMV IPMC from time t = 0 s to 20 s, and subsequently its top and bottom surfaces were short-circuited with a resistor.

CMV IPMC Actuator Control System

Using the experimental data derived from Figure 3, we derived a transfer function Equation (2) for the Selemion IPMC which associates an output parameter (output current), Equation (1) to the input signal I (electrical signal imposed) via the equation L[O] = G(s) L[I] where L, represents the Laplace transform. The derivation was achieved through the SIMULINK-Matlab software. Procedure for solving the circuit equations is given by Ikeda *et al* (2014).

$$I(t) = V(t)\left[\frac{1}{r_s}e^{\left(\frac{-t}{r_s C_s}\right)} + \frac{R}{r_\xi(r_\xi+R)}e^{\left(\frac{-(r_\xi+R)t}{r_\xi R C_2}\right)} + \frac{1}{r_\xi + R}\right] \quad (1)$$

$$I(s) = [V(s)] * 10^{-3}\left[\frac{25.06S^2 + 37.83S + 1}{2.398S^2 + 7.464S + 1.714}\right] \quad (2)$$

In this study, we built a model using the Control Toolbox in MATLAB. The data set used for the input to the system was a rectangular voltage wave, as the input, shown in Figure 3 and the corresponding bending curvature and output current of the Selemion IPMC strip piece shown in Figure 3 as the output. The derived transfer function is shown in Equation (2).

We found that the transfer function of dehydrated Selemion IPMC is fairly stable at extremely low absolute humidity environment, but that change with increase in absolute humidity levels.

To validate the transfer function Equation (2) of the Selemion IPMC, we compared the simulated results to the experimental ones.

Control Strategy of the Actuator

We successfully attempted to control the bending of highly dehydrated Selemion IPMC using feedforward, feedback and two-degree-of-freedom techniques, Figure 6 - 12. Feedforward control requires an inverse control system using the transfer function of the Selemion IPMC. Thus, we performed a system identification to obtain it. All three control systems were tested in turn by implementing them in Simulink (within Matlab). All the bending control tests were carried out at the absolute environmental humidity of around 7 gm−3, Figure 6 - 12.

Feed forward Control

The diagram of the feedforward control that was implemented to control the bending of the Selemion IPMC specimen appears in Figure 4 (a). The input was the same rectangular wave as before (1.5V_P, 1/60Hz), [1]. The tests were carried out a number of times and on different CMV IPMC specimen strips.

Feedback Control

We implemented the feedback control system in Figure 4 b, where P and I were determined by trial and error. The input signals were the step and oscillating rectangular waveforms. The inverse system ($G^{-1}(s)$ = inv (I(s)) given by equation (3) was implemented in the control system.

$$I(s) = [V(s)]\left[\frac{2.398S^2 + 7.464S + 1.714}{0.025065S^2 + 0.0\ 3783S + 0.001}\right] \quad (3)$$

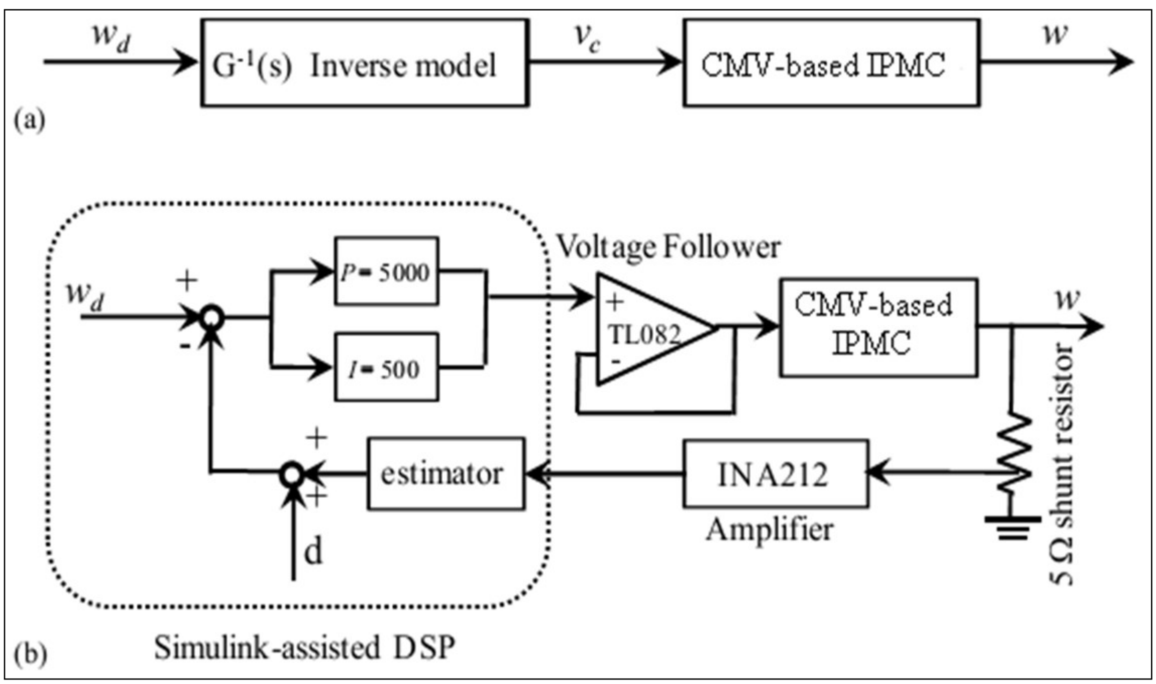


Figure 4 (a) Feedforward control system (b) Feedback control system.

Two-Degree-of-Freedom Control

Figure 5 shows the block diagram of a two-degree-of-freedom control system. The input signals used were same step and oscillating rectangular input waveforms as applied earlier.

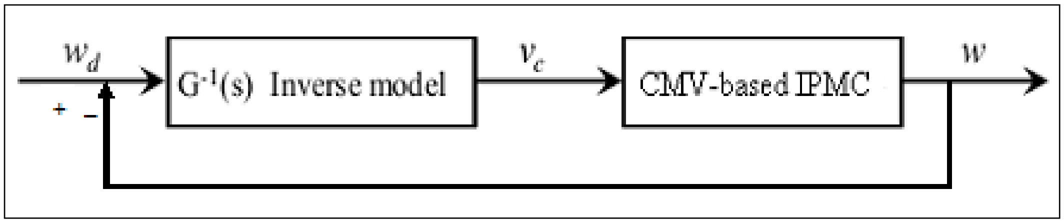


Figure 5 Two-degree-of-freedom control system.

Since the experimentally measured data quantitatively agrees well with the simulated data for both the step and square waveforms inputs, the resulting controllability was not much different from that of the feedback.

Study Area

This research work is paramount in that, it presents stability analysis and a Control System design, which when applied to the Selemion CMV-based IPMC actuators, have high probabilities in development of miniature robots, biomedical devices and artificial muscles.

This will provide the much needed breakthrough in designing the electroactive soft motion robots. The study would also help the researchers understand the various operating conditions in terms of absolute humidity environments and the corresponding bending curvatures.

Data

Since the experimentally measured data quantitatively agrees well with the simulated data for both the step and square waveforms inputs, the resulting controllability was not much different from that of the feedback. Exploiting the linear relationship exhibited by the Selemion IPMC, a feed-forward, feedback and two-degree-of-freedom controls for output currents were successfully implemented. Thus, under conditions of extremely low humidity, all three control techniques worked well.

This research work emphasizes the fact that the dehydration treatment gives rise to the simple linear relationship of “bending curvature vs. total charge” and such a simple relationship enables us to control the Selemion IPMC bending using the presented control techniques such as feedforward, feedback and two-degree-of-freedom controls. Also, at extremely low humidity environments, there exists a linear relationship between the output current and the charge responsible for the bending of the Selemion IPMC. Thus, controlling the response of the input voltage, step or square, effectively controls the bending curvature.

Furthermore, we would like to emphasize that the dehydration treatment enable us to achieve a longer duration time of Selemion IPMC bending control. The designed and derived system was then tested using the DSP System, Simulink Matlab, DSpace (Board ds1103) together with the Laser Displacement Meter.

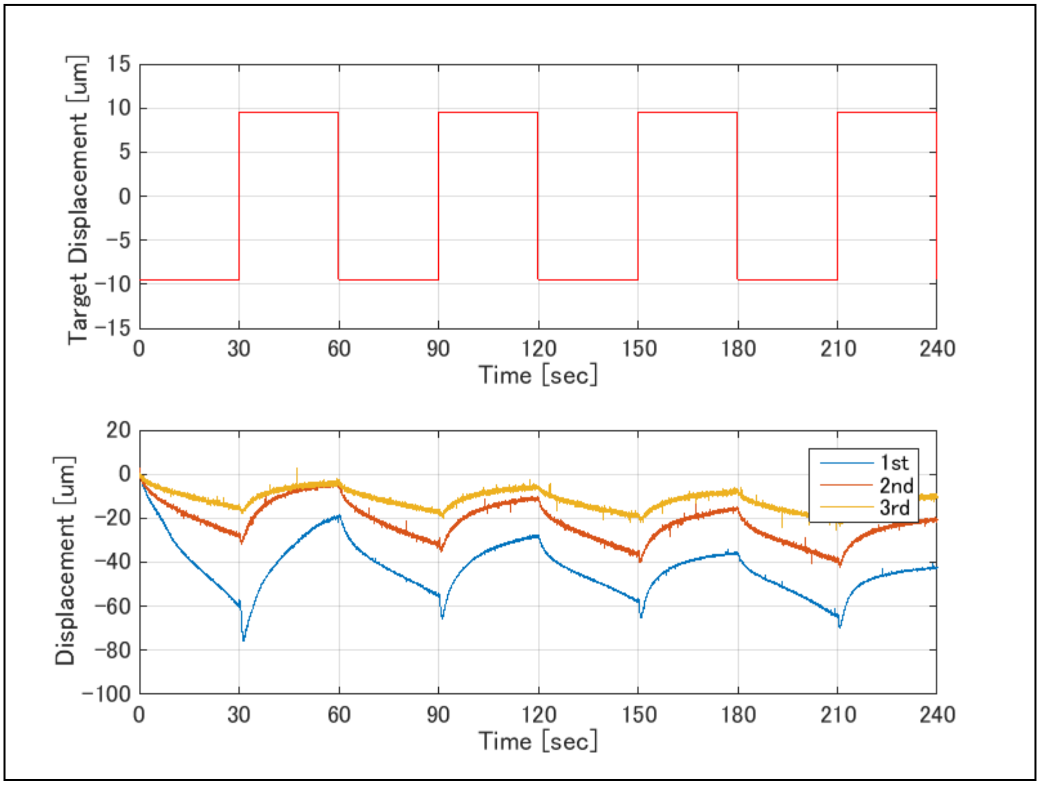


Figure 6 The Selemion IPMC responses vs. time under the DSP assisted 2DoF control (1.5V_P, 1/60Hz) input.

The Humidity level in the room was at 30% and the temperature at around 24 degrees Celsius. The length duration of the experiment: 300secs. The Generator Version: Control Desk CSV File Format Revision 1.0 with a Sampling Period of 0.005 seconds. The displacement is indicated in micrometers.

The following experiments were carried out in succession, one after another. The graphs indicate that the IPMC property already underwent a change and hence the slight difference in the graphs. The input signal is a rectangular wave (1.5Vpp, 1/60Hz). The experiments were conducted on the same CMV IPMC strip for a number of times and then the strip would be changed for the same or different experiment. The subsequent experiments had inclusion of error as well as the reduction in amplitude. The redox action causes the internal characteristics of the CMV IPMC to undergo changes. The heat generated within the strip causes a change in internal resistance and thus affects the bending curvature.

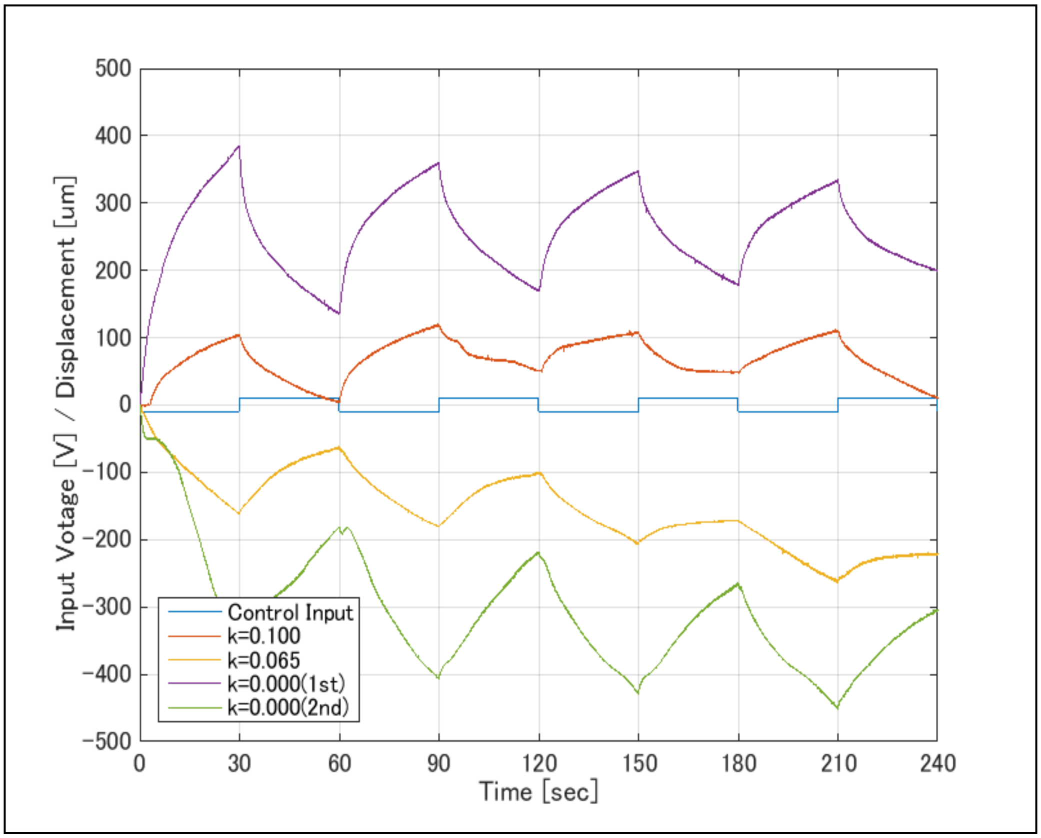


Figure 7 The Selemion IPMC responses vs. time under the DSP assisted 2DoF control (1.5V_P, 1/60Hz) input.

The Experimental set up as well as the room conditions were same as in Figure 6; however the IPMC strip used was a different one. The value of the Proportional gain (k) was varied and the resultant corresponding waveforms generated.

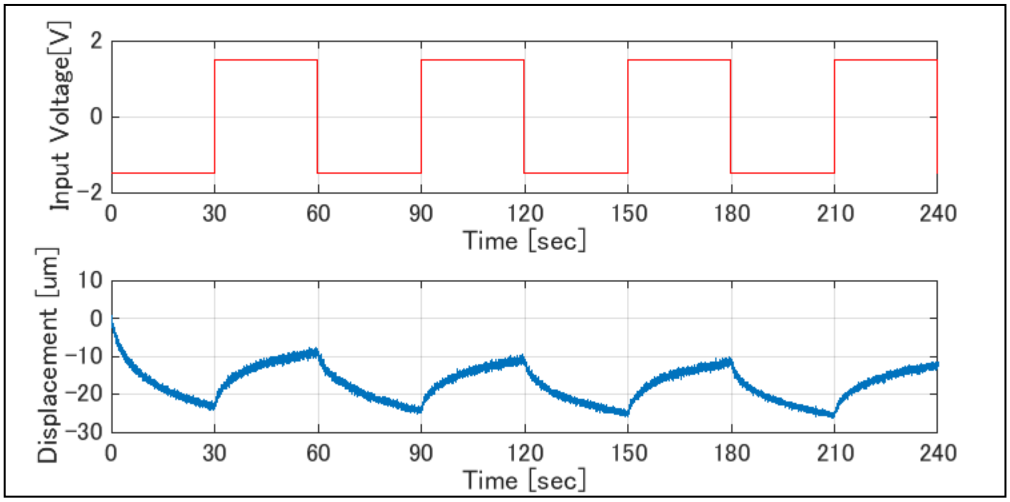


Figure 8 The Selemion IPMC responses vs. time under the DSP assisted Open Loop System control (1.5V_P, 1/60Hz) input.

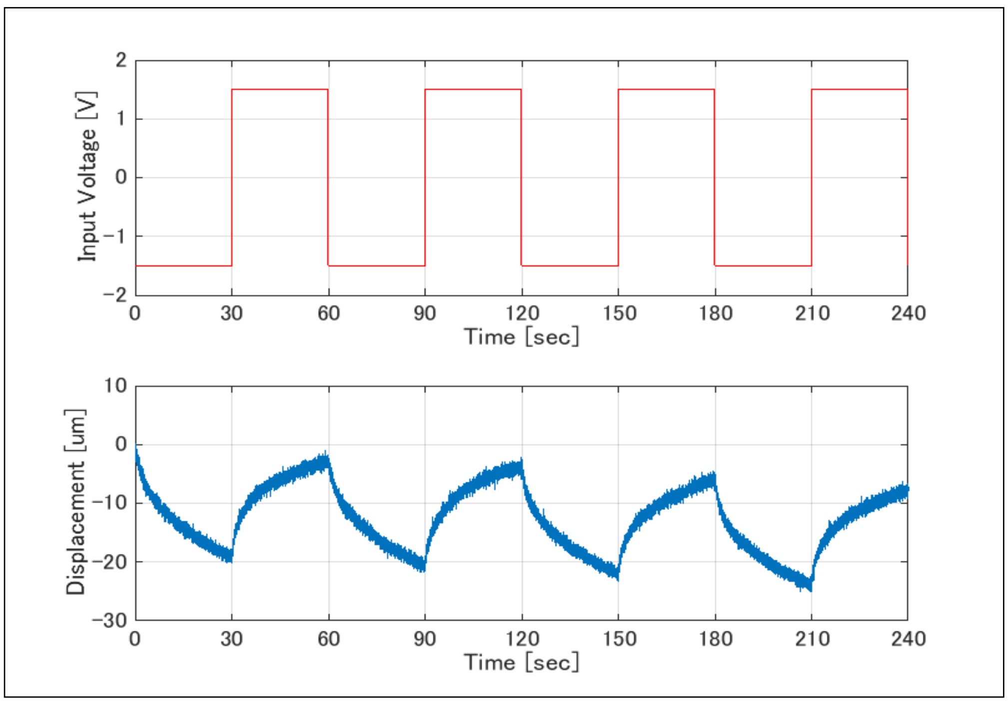


Figure 9 The Selemion IPMC responses vs. time under the DSP assisted Inverse System control (1.5V_P, 1/60Hz) input.

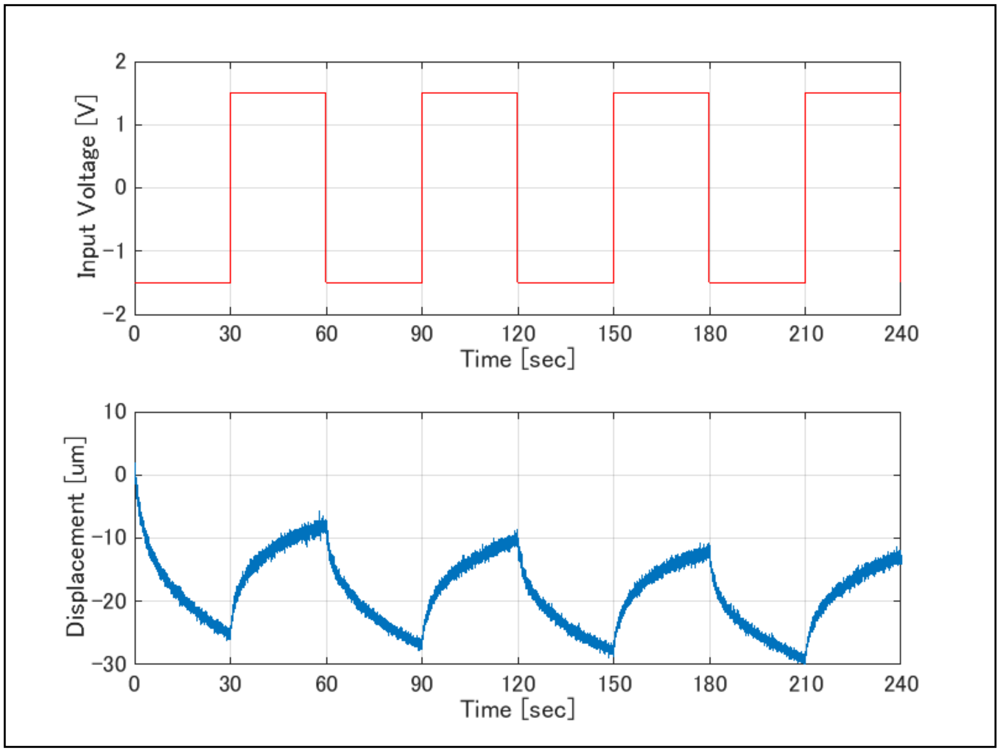
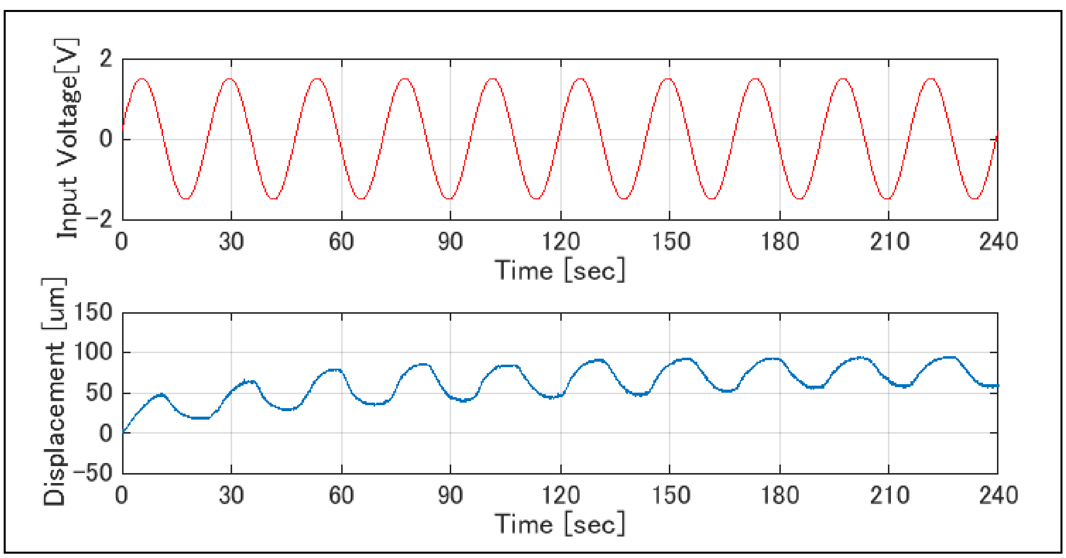
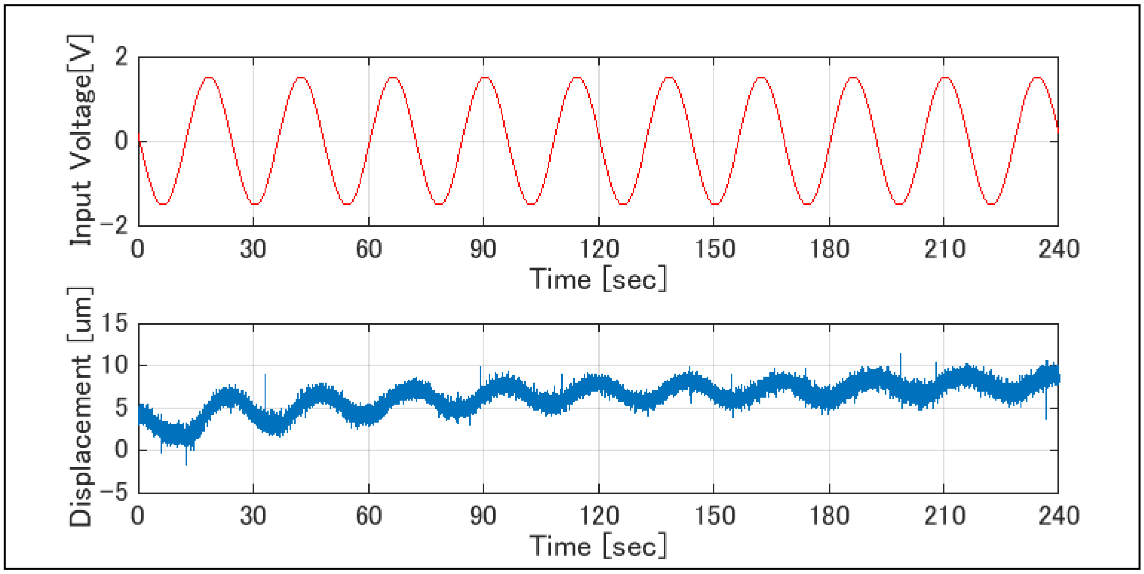


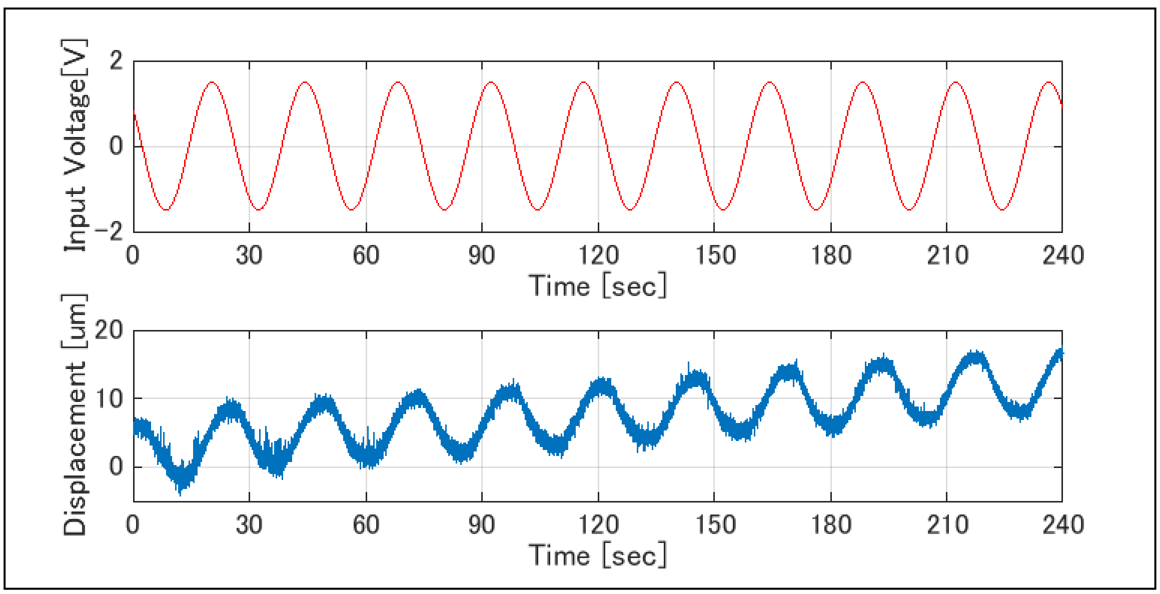
Figure 10 The Selemion IPMC responses vs. time under the DSP assisted Inverse System control (1.5V_P, 1/60Hz) input.



(a)



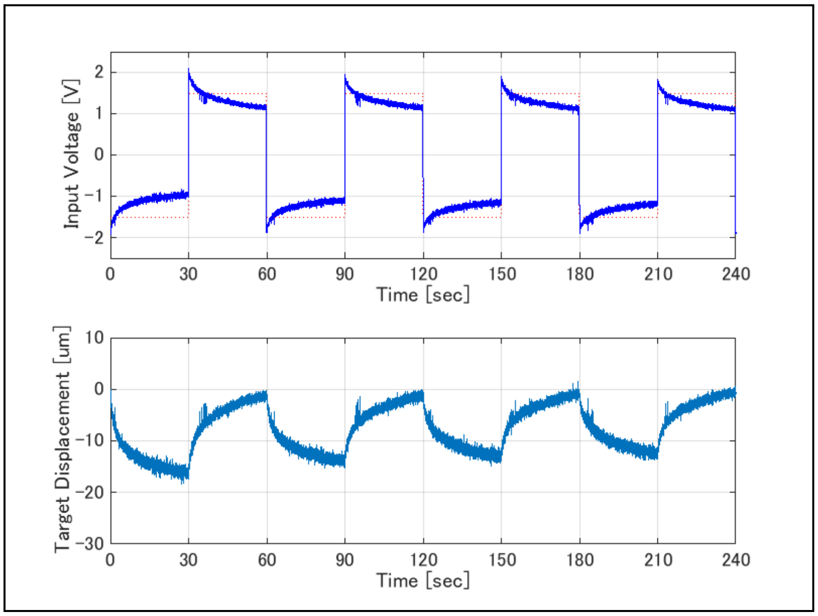
(b)



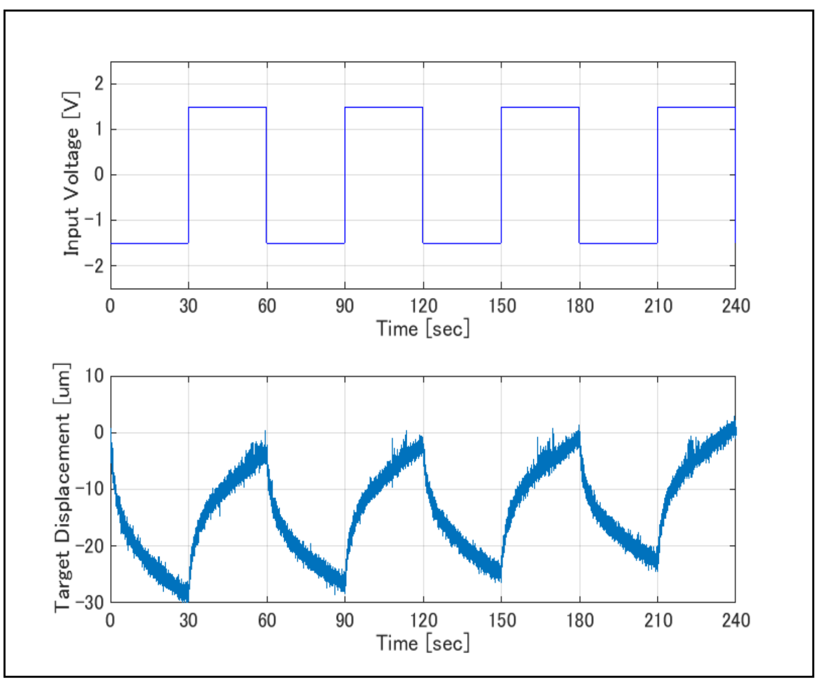
(c)

Figure 11 The Selemion IPMC responses vs. time under the DSP assisted Inverse System control (1.5V_P, 1/60Hz) input.

The Experimental set up as well as the room conditions were same as for Figure 6 - 10, however the input signal was a Sine wave (Amplitude: 100, Freq: 0.2618 rads/sec). High Humidity parameters were used. Graph (a) indicates the displacement test conducted on the IPMC strip first and the second test generated the second graph (b). For graph (c), the high humidity parameters were considered [1]. Two output displays were used for the input voltage, one to monitor and ensure that no changes occur.



(a)



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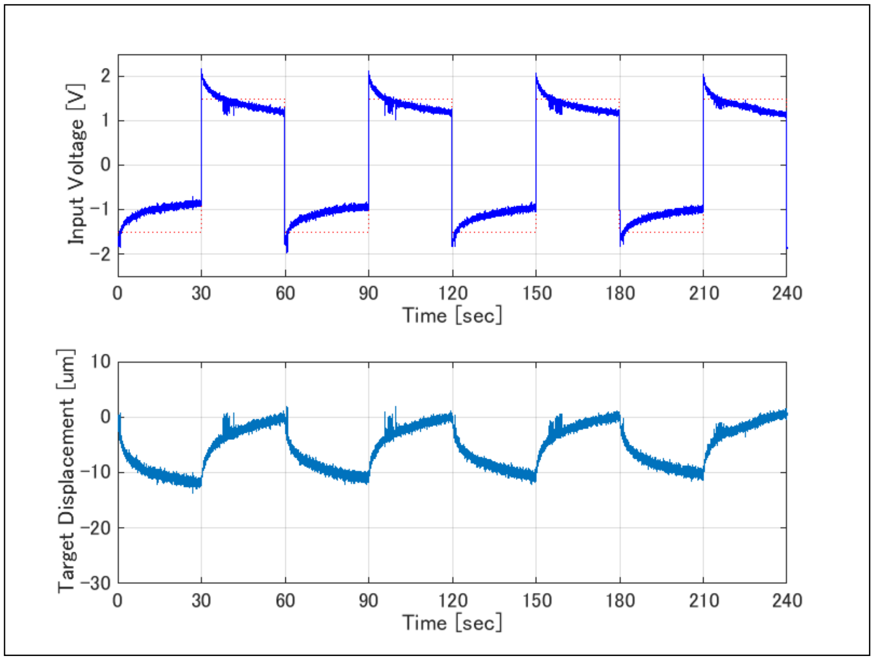
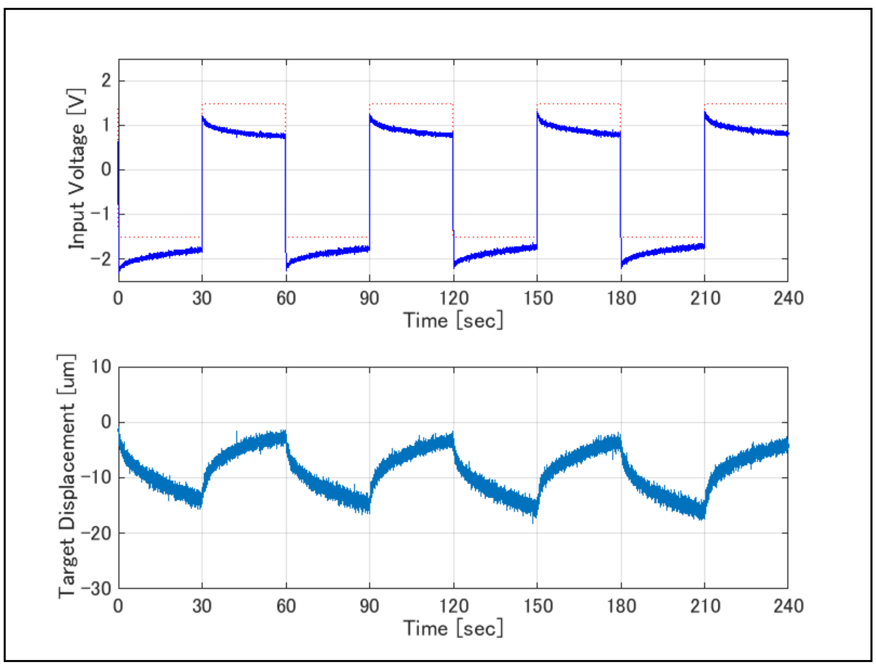
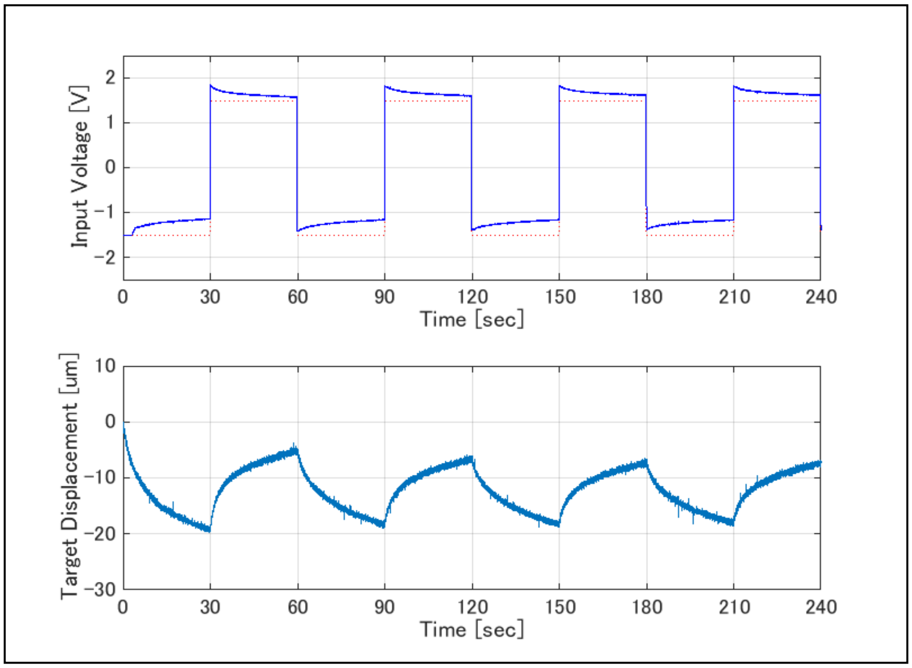

Input Voltage [V]
Time [sec]
Target Displacement [um]
Time [sec]

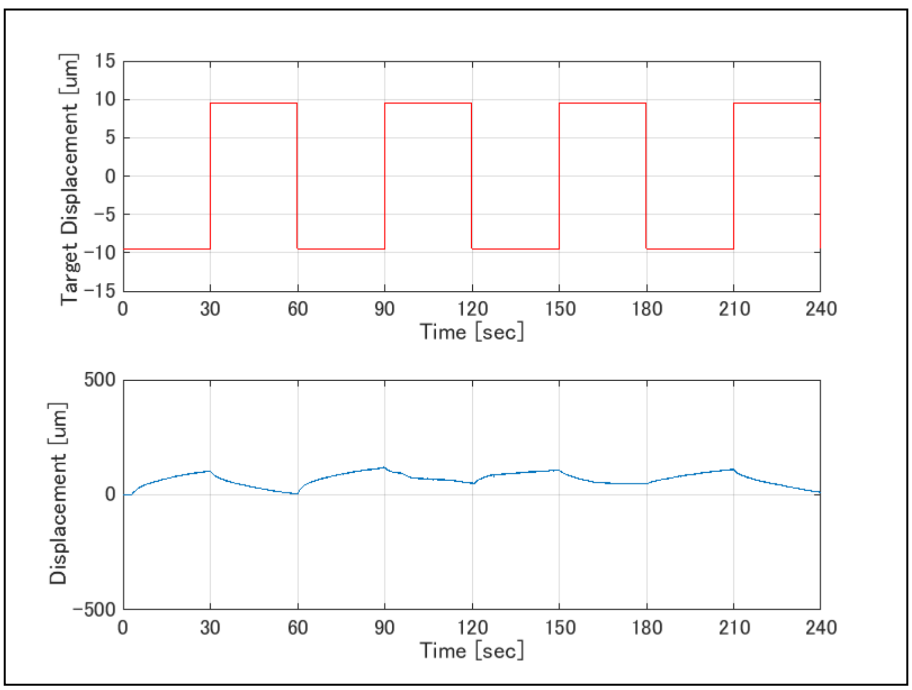
(c)


Input Voltage [V]
Time [sec]
Target Displacement [um]
Time [sec]

(d)



(e)



(f)

Figure 12 The Selemion IPMC responses vs. time under the DSP assisted Feedback System control (1.5V_P, 1/60Hz) input.

The Experimental set up as well as the room conditions were same as for Figure 6 – 10. Low Humidity parameters were used. The graphs indicate the displacement test conducted on the IPMC strip for the feedback gains (K), of 0, 0.02, 0.04, 0.06, 0.08, and 0.1.

RESULTS AND ANALYSIS

Based on the circuit model, the transfer functions were derived. Those transfer functions successfully reproduced the experimentally obtained bending and current behaviors of CMV IPMC. It was found that the dehydrated Selemion IPMC exhibits linear relationship of curvature vs. charge in the low absolute humidity environment. The simple linear relationship of curvature vs. charge enables us to control the Selemion IPMC bending actuator. We successfully achieved the bending control of the Selemion IPMC using feed-forward, feedback and two-degree-of-freedom controls. The experimentally measured output current quantitatively agrees well with the desired ideal bending curvature.
By analyzing the electrical properties of the IPMC actuator dynamics, a modified control circuit model of the polymer actuator was derived, designed and implemented.

Using the circuit model derived to determine the parameters, and by comparing the simulated results with the experimental results, the feasibility, usefulness of the circuit model was tested and verified. An attempt to control for the circuit model by varying parameters such as weight gain was made and the results indicated.

CONCLUSION

The results 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; and (iii) bending behavior is marginally stable under the input at any frequency.

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