

# Verification of Micromechanical Models of Actuation of Ionic Polymer-metal Composites (IPMCs)

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## ABSTRACT

Ionic Polymer-metal Composites (IPMCs) are soft actuators and sensors. They generally consist of a thin perfluorinated ionomer membrane, metal electrodes plated on both faces, and are neutralized with certain counter cations, balancing the charge of the anions covalently fixed to the membrane. Under a suddenly applied step function (1 to 3 V), the IPMC in alkali-metal cation forms exhibits a fast bending motion towards the anode, followed by a slow relaxation. For Nafion-based IPMCs, this slow relaxation is towards the cathode, whereas for Flemion-based IPMCs, the slow relaxation continues the initial fast motion towards the anode. IPMC samples in sulfonic forms having sodium as cations are prepared, their electromechanical properties are characterized, and their actuation responses to various electric stimuli are investigated. Results show that for Nafion-based IPMCs, initial motion towards the anode can be ultimately eliminated by applying a slowly increasing potential, due to very slow charge accumulation and extensive cation redistribution within a boundary layer near the cathode electrode.

**Keywords:** ionic polymer-metal composite, IPMC, electroactive polymer, Nafion, actuation, electromechanical response.

## 1. INTRODUCTION

A typical IPMC consists of a thin perfluorinated polymer with noble metal electrodes plated on both faces. Its coupled electrical-chemical-mechanical response depends on the structure of the polyelectrolyte membrane, the morphology and conductivity of the metal electrodes, the properties of cations, and the level of hydration.<sup>1</sup> The actuation characteristics of IPMCs under various alternating waveforms have been studied extensively by Asaka *et al.*<sup>2, 3</sup>, Bar-Cohen *et al.*<sup>4</sup>, and others. In our previous work, an experimental evaluation of the IPMC in response to suddenly imposed direct voltage (dc) is presented,<sup>5, 6</sup> and a micro-mechanical model of the actuation is established.<sup>7, 8</sup> In order to further disclose this mechanism, linearly increasing input dc potentials have been incorporated to actuate IPMC samples.

The Nafion-based IPMC used in our tests have sulfonic membrane (Nafion<sup>®</sup>-117, DuPont) plated with platinum and a layer of finishing gold. In a typical actuation test, a water-saturated 3.0 by 0.3-cm IPMC strip with Na<sup>+</sup> as counter cation is immersed in room temperature deionized water, with one end clamped between platinum electrodes. A linearly increasing dc potential (Fig. 1) is suddenly applied. The time-history of sample's tip displacement is obtained through video analysis and normalized by dividing its gauge length. Simultaneously, the current and potential across the thickness of the sample are recorded. The results and the analysis of the experiments are presented in the sequel.

## 2. EXPERIMENTAL METHOD AND RESULTS

Initially, a Nafion-based IPMC is actuated by a 1 V dc step function (function A in Fig. 1). As evident from the data in Fig. 2(a), the current across the thickness of the sample increases abruptly and then falls to a small value. The

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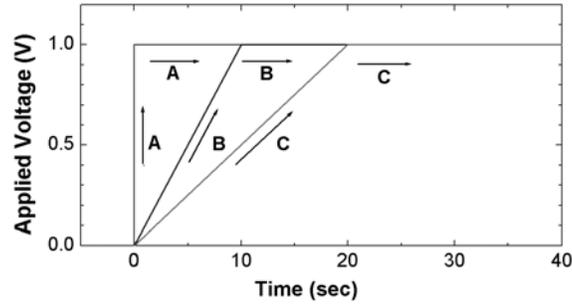


Fig. 1. Input functions of IPMC actuation tests. Applied voltage linearly increases to 1 V in 0 s (function A), 10 s (function B), and 20 s (function C) respectively, and then sustains at 1 V for the rest of time.

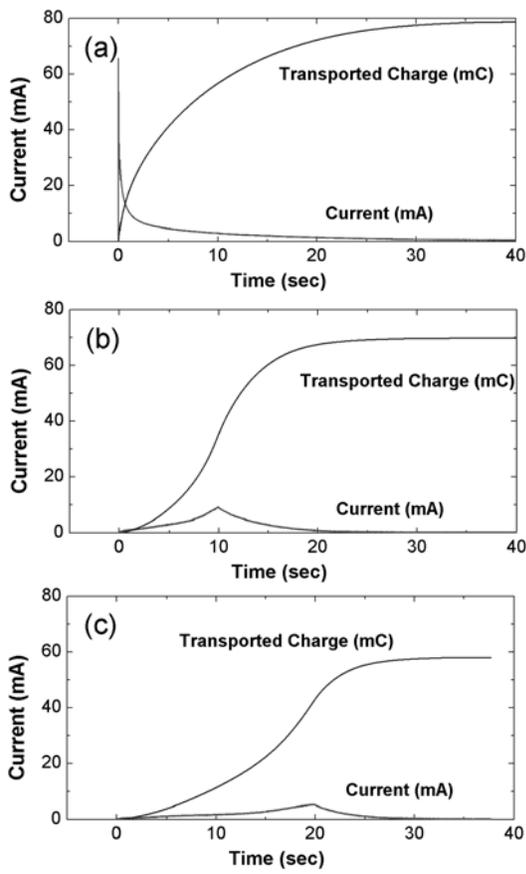


Fig. 2. Current across samples' thickness and transported charge when Nafion-based IPMC is actuated under function A, B, and C, respectively.

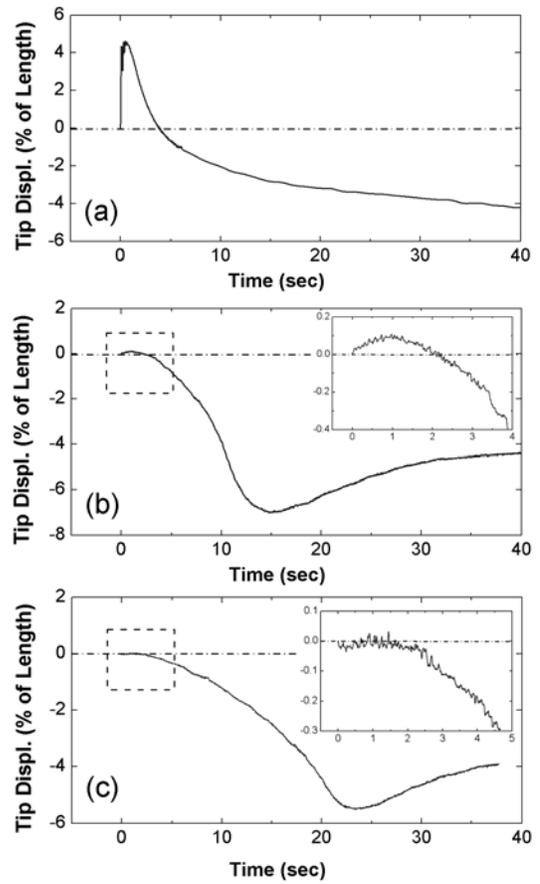


Fig. 3. Tip displacement of Nafion-based IPMC when actuated under function A, B, and C, respectively. Inserted graphs disclose the actuation direction in the first few seconds upon electronic stimuli. Positive displacement represents bending towards the anode.

accumulated charge, representing the total transported charge by cation during actuation, is obtained by the time-integration of the measured current, upon subtraction of the measured residual current due to sample's resistance (0.6 mA in this case).<sup>5,9</sup> The corresponding normalized tip displacement is illustrated in Fig. 3(a). The sample shows a fast motion towards the anode, followed by a slow relaxation towards the cathode.

Starting from the electrically neutral state, the same Nafion-based IPMC is actuated under function B (applied voltage linearly increases to 1 V in 10 s and then sustained at 1 V for the rest of the time). As depicted in Fig. 2(b), the sample's current gradually increases to 9.2 mA at 10.0 s and then decreases to 0.26 mA. The calculated transported charge (less the residual current since the 10th s when integration) shows the relatively slower speed of charge accumulation comparing with Fig. 2(a). Correspondingly, the sample shows very small amount of initial bending towards the anode [1/50 of that in the previous test, see the insertion in Fig. 3(b)], and then slowly relaxes back towards the cathode, followed by a second-phase relaxation towards the anode until equilibrium. The same sample is then neutralized and actuated under function C (applied voltage linearly increases to 1 V in 20 s). The results are shown in Fig. 2(c) and 3(c). This time, the sample's initial bending towards the anode is completely eliminated, due to very slow charge accumulation at the cathode. The same results are also obtained for other Nafion-based IPMC samples in various cation forms.

### 3. ANALYSIS

The experimental observations provide additional evidences to Nemat-Nasser's micro-mechanical model of IPMC actuation.<sup>8</sup> The application of electric potential causes the redistribution of  $\text{Na}^+$  cations within the membrane. As a result, the clusters near the anode are depleted of cations and a thin anode boundary layer is formed, whereas the clusters near the cathode are cation rich and a thin cathode boundary layer is formed. Within these two boundary layers, the changes in the electrostatic forces and the osmotic pressure that are produced by the cation migration and the resulting charge imbalance drive water into or out of the clusters. The actuation of IPMCs is thus caused by the volume change of these boundary-layer clusters. At equilibrium, the internal cluster pressure is balanced by the elastic resistance of the polymer matrix. Such mechanism requires a coupled electrical-chemical-mechanical formulation for calculating the charge and water density distribution as functions of time, taking into account all the competing factors.

By applying a linearly increasing dc potential, the charging process of the Nafion-based IPMC sample could be carried out very slowly. This has given time for the extensive cation redistribution. The interaction between cations and cation-anion pseudo-dipoles<sup>8</sup> at the cathode boundary layer is diminished to zero or even to negative. Thus, direct displacement towards the cathode is expected. This is in line with our experimental observations. The results in Fig. 2 and 3 show the cation transportation towards the cathode while the clusters at the cathode boundary layer are actually contracting. Especially for the actuation test under input function C, it has been very clear that the electrostatic forces are dominant over the osmotic and hydraulic pressure, suggesting that the cations rather than their solvation water molecules be of primary importance, and negating the so-called hydraulic model of the IPMC actuation. The actuation deformation can be modeled similarly, using the numerical approach. Besides, the experimental results can provide values of parameters for the actuation modeling.

### 4. CONCLUSIONS

It is concluded that the actuation tests under various linearly increasing dc potentials have profound meanings in understanding the actuation mechanism and verifying the proposed micro-mechanical model. In addition, it reveals that the electro-mechanical responses of Nafion-based IPMCs are electrically controllable, having potentials to mimic biological processes.

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## REFERENCES

1. S. Nemat-Nasser and C. Thomas, in *Electroactive Polymer (EAP) Actuators as Artificial Muscles - Reality, Potential and Challenges*, edited by Y. Bar-Cohen, SPIE, Bellingham, WA, Chap. 6, 2001.
2. K. Asaka, K. Oguro, Y. Nishimura, M. Mizuhata, and H. Takenaka, "Bending of Polyelectrolyte Membrane-Platinum Composites by Electric Stimuli I. Response Characteristics to Various Waveforms", *Polymer Journal*, **27**, 436, 1995.
3. K. Asaka, N. Fujiwara, K. Oguro, K. Onishi, and S. Sewa, "State of Water and Ionic Conductivity of Solid Polymer Electrolyte Membranes in Relation to Polymer Actuators", *J. Electroanal. Chem.*, **505**, 24, 2001.
4. Y. Bar-Cohen, S. Leary, M. Shahinpoor, J. O. Harrison, and J. Smith, "Electro-Active Polymer (EAP) Actuators for Planetary Applications", *Proc. SPIE*, **3669**, 57, 1999.
5. S. Nemat-Nasser and Y. Wu, "Comparative Experimental Study of Ionic Polymer-metal Composites with Different Backbone Ionomers and in Various Cation Forms", *J. Appl. Phys.*, **93**, 5255, 2003.
6. S. Nemat-Nasser and Y. Wu, "Tailoring Actuation of Ionic Polymer-metal Composites Through Cation Combination", *Proc. SPIE*, **5051**, 245, 2003.
7. S. Nemat-Nasser and J. Y. Li, "Electromechanical Response of Ionic Polymer-metal Composites", *J. Appl. Phys.*, **87**, 3321, 2000.
8. S. Nemat-Nasser, "Micro-mechanics of Ionic Polymer-metal Composites", *J. Appl. Phys.*, **92**, 2899, 2002.
9. K. M. Newbury and D. J. Leo, "Electrically Induced Permanent Strain in Ionic Polymer-metal Composite Actuators", *Proc. SPIE*, **4695**, 67, 2002.