

## Self-oscillating electroactive polymer actuator

Doyeon Kim and Kwang J. Kim<sup>a)</sup>

*Active Materials and Processing Laboratory, Mechanical Engineering Department, University of Nevada, Reno, Nevada 89557*

Yongsuk Tak

*School of Chemical Engineering, Inha University, Incheon, Kyungki Do 402-751, South Korea*

Deivid Pugal

*Active Materials and Processing Laboratory, Mechanical Engineering Department, University of Nevada, Reno, Nevada 89557 and IMS Laboratory, Institute of Technology, Tartu University 50410, Estonia*

Il-Seok Park

*Active Materials and Processing Laboratory, Mechanical Engineering Department, University of Nevada, Reno, Nevada 89557*

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To drive the electroactive polymer (EAP) materials and subsequently control their strain generation, the need for power electronics and driving circuits has been eminent. In this letter the authors demonstrate a spontaneous actuation of an electroactive polymer that requires only dc power to produce its ac responses. Such a dc-to-ac response of the EAP was achieved by the deposition of an effective electrocatalyst, i.e., platinum, on an ionomer, Nafion™. The coated ionomer was immersed into an acidic formaldehyde solution. An applied dc voltage will produce current oscillations in the system, and therefore oscillating bending of the actuator. © 2007 American Institute of Physics. [DOI: 10.1063/1.2735931]

A number of representative electroactive polymeric materials of interest include ferroelectric polymers,<sup>1</sup> conducting polymers,<sup>2</sup> ionomeric polymer-metal composites<sup>3</sup> (the subject of this study), carbon nanotubes,<sup>4</sup> dielectric elastomers,<sup>5</sup> and ionic polymeric gels.<sup>6</sup> These materials exhibit an active deformation capability under applied voltages, producing useful force density. Ionomers (such as a perfluorinated sulfonic acid polymer, i.e., Nafion™) in a composite form with a conductive metallic medium such as platinum (Pt) are called ionic polymer-metal composites (IPMC). In a cantilever configuration, these materials can exhibit large dynamic deformation if placed in a time-varying low electric field of less than a few volts.

Spontaneous oscillations are a widespread phenomenon in nature. They have been studied for large number of experiments, including electrochemical systems, such as the oxidation of metals and organic materials.<sup>7</sup> Electrochemical systems exhibiting instabilities often behave like activator-inhibitor systems. In these systems the electrode potential is an essential variable and takes on the role either of the activator or of the inhibitor. If certain conditions are met, an activator-inhibitor system can generate oscillations.<sup>8</sup>

Platinum-electroded IPMCs were prepared using the electroless deposition<sup>9</sup> onto Nafion 1110. The standard IPMC sample size was 0.27 mm thick by 10 mm wide by 50 mm long. By using an INSTRON™ 5565, we measured Young's modulus of the standard IPMC samples—48.8 MPa.

Actuation of the platinum-electroded ionomer was carried out in a conventional electrochemical cell with three electrodes. The reference electrode used was a saturated calomel electrode (SCE) and the two platinum electrodes functioned as the working and counterelectrode, respectively. Voltammograms were obtained using a potentiostat/

galvanostat (Radiometer Analytical, Voltalab80 model PGZ402). Deformation data of IPMC in a cantilever configuration were obtained using a laser optical displacement sensor (Micro-Epsilon Model 1400-100). Prior to all experiments, dozens of cyclic voltammetric curves between −0.25 and +1.2 V (versus SCE) were performed in 0.5M H<sub>2</sub>SO<sub>4</sub> to confirm the absence of any residuals of impurities on the platinum surface. All experiments were performed at room temperature.

We conducted a series of tests with IPMCs in formaldehyde (HCHO) solutions. Measurements under constant electric field showed that current oscillations occur from onset potential of approximation 0.75 V. The initial burst of current at this voltage is due to the reaction  $\text{CO}_{\text{ads}} + \text{OH}_{\text{ads}} \rightarrow \text{CO}_2 + \text{H}^+ + e^- + 2^*$ , where subscript ads denote species adsorbed on the surface of platinum and <sup>\*</sup> denotes an active platinum site. This reaction frees up two platinum sites, which cause CO again to adsorb on the surface. Due to CO poisoning, anodic current abruptly decreases until the burst again. Between current decrease and second burst, the current slightly increased due to OH adsorption. These electrochemical reactions lead to self-rhythmic motion of an IPMC, as shown in Fig. 1.

During the oxidation of formaldehyde, the intermediate (CO) of the reaction strongly binds to the platinum surface of the IPMC and blocks active sites. Since platinum is particularly vulnerable to a poisoning effect, both cathode and anode can be poisoned by CO in acidic media. In this process the resistance of platinum is increased, which leads to weaker field strength between electrodes of an IPMC. Platinum also adsorbs OH which then oxidizes the CO on adjacent platinum sites to CO<sub>2</sub>. Due to this reaction, conductivity of platinum improves and results in a stronger field strength between the electrodes. The simultaneous adsorption and de-

<sup>a)</sup>Electronic mail: kwangkim@unr.edu

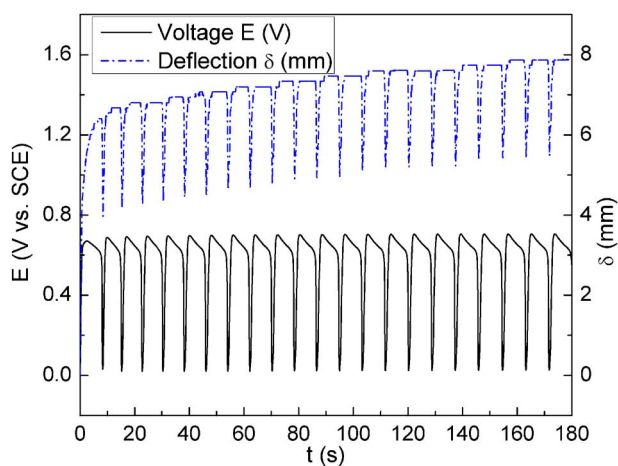


FIG. 1. (Color online) Chronopotentiogram and corresponding deflection data of a platinum IPMC in 2M HCHO+3M H<sub>2</sub>SO<sub>4</sub> under constant current of 10 mA/cm<sup>2</sup> (scan rate of 1 mA/s).

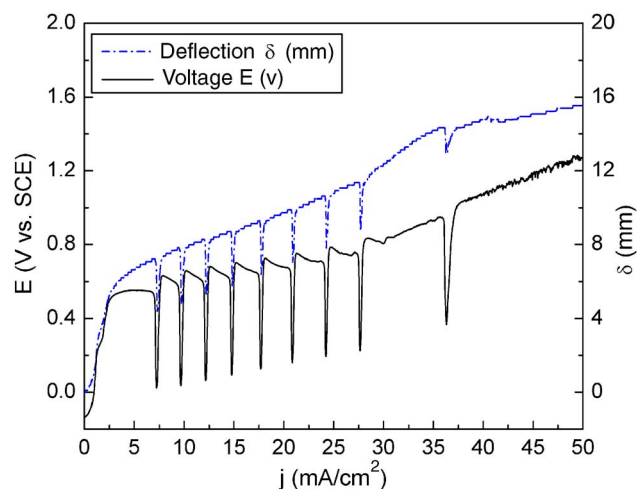


FIG. 2. (Color online) Galvanostatic linear sweep voltammograms of a platinum IPMC in 1M HCHO+3M H<sub>2</sub>SO<sub>4</sub> at the scan rate of 1 mA/s.

sorption processes result in the oscillatory potentials which can be used as a driving source of IPMCs.

Chronopotentiometry scans for three different concentrations of HCHO help us to characterize behavior of IPMC in HCHO solution. For all cases, oscillations start at approximately 7 mA/cm<sup>2</sup> (further noted as threshold current) with a constant value of 0.11–0.13 Hz up to the current density of 14 mA/cm<sup>2</sup>. After further increasing current, in 1M HCHO, the frequency decreases as shown in Fig. 2. In 2M HCHO, the frequency maintains a constant value regardless of higher current density, and in 3M HCHO, the frequency increases. Tests also show that maximum potential difference increases until threshold current and stays constant after that. However, maximum deflection tends to decrease after increasing current over threshold current. We achieved the largest deflection of 2.86 mm at 10 mA/cm<sup>2</sup> in 1M HCHO. It is interesting to note that relationship between corresponding deflection and potential on the electrode is nearly linear. So, by varying concentration of HCHO and changing driving current, it is possible to create self-oscillating IPMC systems with different characteristics, as shown in Fig. 3, appropriate for specific tasks.

Electrochemical oscillations during electro-oxidation of small organic molecules under specific conditions are usually observed. It was reported that HCHOOH shows electrochemical oscillation phenomena during oxidation.<sup>10</sup> As we have seen, oscillations obtained from a HCHO system can be useful for self-oscillatory IPMC systems. However, cyclic voltammetry tests were conducted for HCHOOH and in addition, for alcohols, such as CH<sub>3</sub>OH, C<sub>2</sub>H<sub>5</sub>OH, and C<sub>3</sub>H<sub>7</sub>OH to find out a possibility of using them in IPMC systems. We found that there are no peaks in alcohol solutions from 0 to 1.4 V. It is determined that adsorbed CO coming from those organic molecules converts into CO<sub>2</sub> without oscillation phenomena. There are oscillations in HCOOH solution. However, peaks are shown in a narrower range of applied current and the number of oscillations is also much smaller than in the HCHO system. This means that HCOOH is not proper for a self-oscillatory IPMC with high frequency. It could be used for low-frequency oscillations. However, alcohol solutions do not work at all.

Biological systems usually exhibit rhythmic phenomena. Their typical time scale is in the range from less than a second to years. How can this effect be really important for

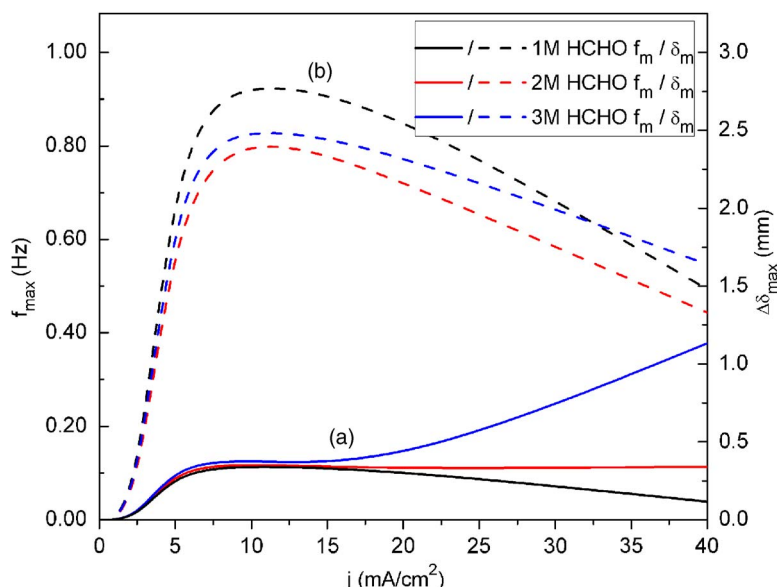


FIG. 3. (Color online) Current dependence (a) of oscillation frequency of the platinum IPMC and maximum deflection difference (b) of the oscillations with three different concentrations of HCHO (scan rate of 1 mA/s).

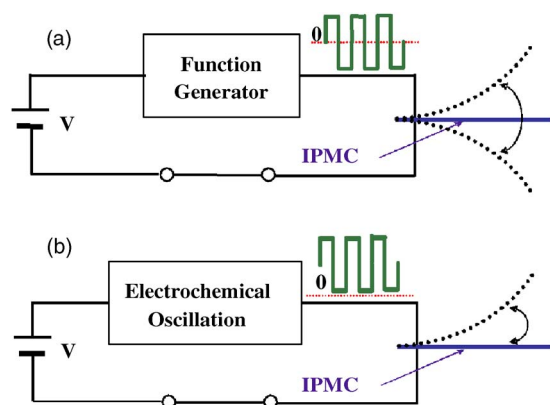


FIG. 4. (Color online) Illustration of conventional (a) and self-oscillatory (b) operations of IPMC-based artificial muscles.

developing IPMC based applications? The self-oscillatory operation allows simplifying the driving electronics of IPMC systems and can lead to significant increase of the payload. It can also be useful as a means of minimizing the use of complex electronics in many engineering applications (see Fig. 4). We have been able to achieve frequencies in the range of 0–1 Hz and deflections up to almost 3 mm. If further developed, the self-oscillatory feature of IPMC allows one to obtain desired properties for numerous future engineering ap-

plications. Potential applications include self-oscillating propulsor blades for small underwater vehicles, self regulating drug delivery systems, artificial organs such as heart, biosensors, etc.

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<sup>1</sup>Q. M. Zhang, V. Bharti, and X. Zhao, *Science* **280**, 2101 (1998).

<sup>2</sup>E. Smela, *Adv. Mater. (Weinheim, Ger.)* **15**, 481 (2003).

<sup>3</sup>M. Shahinpoor and K. J. Kim, *Smart Mater. Struct.* **10**, 819 (2001).

<sup>4</sup>R. H. Baughman, C. Cui, A. A. Zakhidov, Z. Iqbal, J. N. Barisci, G. M. Spinks, G. G. Wallace, A. Mazzoldi, D. De Rossi, A. G. Rinzler, O. Jaschinski, S. Roth, and M. Kertesz, *Science* **284**, 1340 (1999).

<sup>5</sup>R. Pelrine, R. Kornbluh, Q. Pei, and J. Joseph, *Science* **287**, 836 (2000).

<sup>6</sup>S. Kim, G. Spinks, S. Prosser, P. Whitten, G. Wallace, and S. Kim, *Nat. Mater.* **5**, 48 (2006).

<sup>7</sup>B. Miller and A. Chen, *J. Electroanal. Chem.* **588**, 314 (2006).

<sup>8</sup>K. Krischer, *J. Electroanal. Chem.* **501**, 1 (2001).

<sup>9</sup>K. J. Kim and M. Shahinpoor, *Smart Mater. Struct.* **12**, 65 (2003).

<sup>10</sup>T. J. Schmidt, B. N. Grgur, N. M. Markovic, and P. N. J. Ross, *J. Electroanal. Chem.* **500**, 36 (2001).