Characterization of The Electromechanical Properties of IPMC

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ABSTRACT

Ionic Polymer-Metal Composite (IPMC) as electroactive polymers (EAP) was the subject of research and development since 1992. Its low required activation voltage and the large bending led to the considerations of various potential applications. However, before the benefits of IPMC can be effectively exploited for practical use, the electromechanical behavior must be properly quantified. An experimental setup was developed for data acquisition from IPMC strips subjected to various tip mass levels and in parallel an analytical model was developed to predict the material response. Using the analytical model and an inversion algorithm the modulus, and relaxation time were determined. The programmable setup was used to acquire the displacement and curvature of IPMC as a function of the electrical signal characteristics. Sample strips were immersed in water to minimize the effect of moisture content and were tested with and without tip mass. In order to avoid hydrolysis the samples were subjected to 1-V square wave with either positive or negative polarity. Mathematical models were developed that showed satisfactory results for tetra-n-butylammonium$^+$ cations/Flamion IPMC, which responds slowly and monotonically without relaxation and Li^+ cations/Nafion IPMC, that response quickly with a following back relaxation. These models are macroscopic ordinary differential equations whose solution fits the observed behavior well.

INTRODUCTION

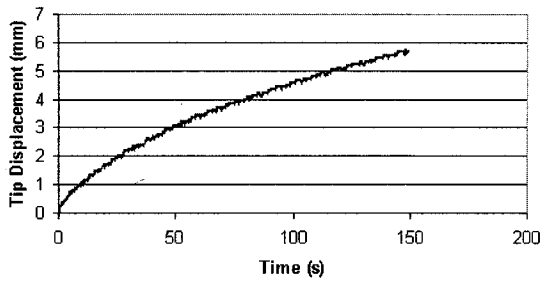
Electroactive polymers (EAP), which are an emerging class of actuation materials, have many attractive characteristics [Bar-Cohen, 2001]. Implementing these materials as actuators requires the availability of properties database and scaling laws to allow actuator or transducer designers to determine the response at various operation conditions. A metric for the comparison of these material properties with other electroactive materials and devices is needed to allow impartial comparison of the performance of the various materials [Sherrit and Bar-Cohen, 2001]. In selecting characterization techniques it is instructive to look at the various Electroactive Polymers and the source of their strain-field response. Two main classes can be identified: Electronic and Ionic. The emphasis of this paper is on IPMC that is a part of the category ionic EAP. These materials usually contain an electrolyte and they involve transport of ions/molecules in response to an external electric field. Examples of such materials include conductive polymers/polyaniline actuators, IPMC, and ionic gels. The field controlled migration or diffusion of the various ions/molecules results is an internal stress distribution. These internal stress distributions can induce a wide variety of strains from volume expansion or contraction to bending. In some conductive polymers the materials exhibit both ionic and electronic conductivities. These materials are relatively new as actuator materials and have received much less attention in the literature than the piezoelectric and electrostrictive materials. At present, due to a wide variety of possible materials and conducting species, no generally accepted phenomenological model exists and much effort is underway to determine the commonalties of

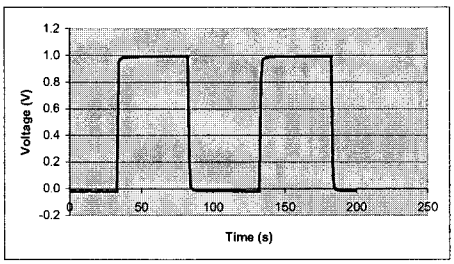
the various materials systems. A clearer understanding of the characterization techniques would help immensely in determining underlying theories and scaling laws for these actuator materials.

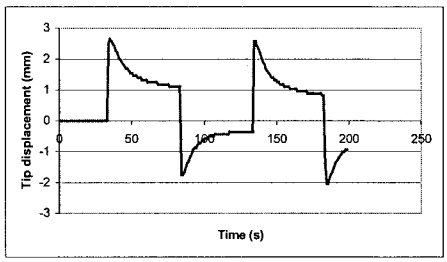
ELECTROMECHANICAL RESPONSE AND RELAXATION

Studies indicate that the response of IPMC strongly depends on its ionic content [Asaka, et al, 2001; & Nemat-Nasser and Thomas, 2001]. Basically, they can be divided to two categories based on their cations size, (a) Small cations such as Li+, Na+ and K+; and (b) large cations such as alkyl ammonium ions. The typical actuation responses of these two types of IPMC are presented in Figure 1 and 2. The IPMC with small cation of Li+ has a quick response to the applied voltage and a slow back relaxation. The IPMC with large cation of tetra-n-butylammonium responds slowly to applied voltage but with no back relaxation. It is believed that the small cations move easier over the polymer backbone. The fast movement of the cations toward the cathode together with associated water molecular results in an initial quick bending toward to the anode. This response is followed with a relaxation that may be caused by water leakage resulting from a high-pressure layer near the cathode toward to the anode through channels in the polymer backbone. The process stops when a water equilibrium is reestablished. On the contrary, large cations are significantly slower and present slow reaction to the electric field. Thus no relaxation is observed and it may be the result of the fact that the ions block the channels or the water equilibrium with concentrated cations require more water.

Figure 1. Response of tetra-n-butylammonium/Framion







(a) Applied voltage (b) Tip displacement

Figure 2. Response of a Li+/Nafion strip sample to 0V/1V square wave

ANYLYTICAL MODEL FOR ELECTROMECHANICAL ACTUATION

Model for IPMC without back relaxation

To characterize the IPMC with large cations like tetra-n-butylammonium$^+$ cations/Flamion, a phenomenological model was developed [Bhattacharya, et al, 2001]. The IPMC sample is a narrow strip that bends when a voltage is applied. The experimental data shows that the curvature is uniform when there is no applied force. We call this curvature the load-free curvature or eigen-curvature κ.

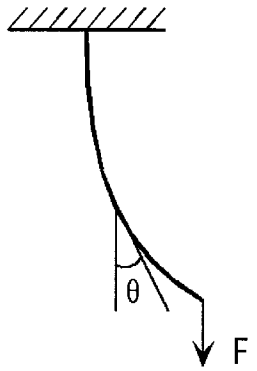


Figure 3: An IPMC strip.

If we apply a step voltage on the strip, the eigen-curvature changes according to the formula

$$\kappa(t) = \kappa_v V - (cV - \kappa_0)\exp(-\tfrac{t}{\tau}), \tag{1}$$

where κ_v and τ are material constants, and κ_0 is the initial curvature. For a more general time-dependant applied voltage the response can be described by the first order ODE

$$\frac{d\kappa}{dt} = \frac{1}{\tau}(cV - \kappa). \tag{2}$$

When there is an applied force on the tip of strip (as show in Figure 3), assuming that it is inextensible, we can describe the deformation of the strip using a function $\theta(s)$, where θ is the angle and s is the arc-length along the strip. The equilibrium equations and boundary conditions are written as

$$EI\theta'' - F\sin\theta = 0, \quad \theta(0) = 0, \quad \theta'(l) = \kappa. \tag{3}$$

This is a simple second order semi-linear ODE, which we can solve semi-analytically for any given κ.

With this simple model there are three material constants E, c and τ (respectively the elastic modulus, the saturation curvature at unit applied voltage and the time-constant). Providing the experimental data of free bending and bending with tip mass under the step voltage, these material constants can be characterized by fitting the model to the data. The results for a tetra-n-butylammonium$^+$ cations/Flamion sample from the ONRI, Japan are

$$\kappa_v = 0.0193\ (\text{mmV})^{-1}, \quad \tau = 76.81\text{sec}, \quad E = 72\ \text{Mpa}.$$

Figure 4, 5 show the curve fitting curves and results the experimental data.

The power density of the material can be estimated according to this model. We calculate the maximum mechanical power output under harmonic voltage driving. From $V(t) = Ve^{j\omega t}$ and Eq.(2), we have

$$k = \frac{K_v V}{1 + j\omega\tau}. \tag{4}$$

The voltage induced a momentum of

$$M_v = k\text{EI} = \text{EI}\frac{K_v V}{1 + j\omega\tau} \tag{5}$$

to the strip. If there is a mechanical momentum resistance $M_L = j\alpha\,\text{EI}k$ on the strip, the equation becomes

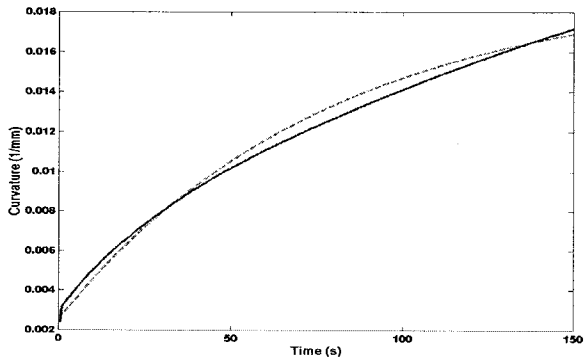


Figure 4: Comparison of the theoretical results with experiment of ONRI sample.

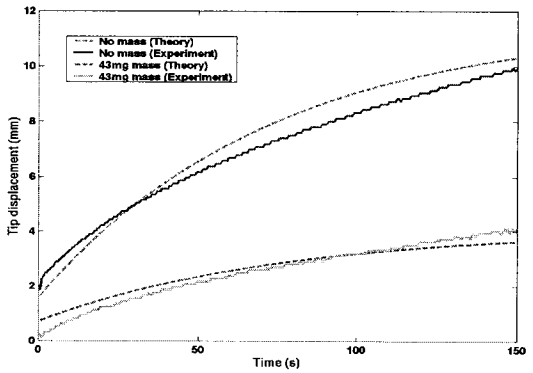


Figure 5: Comparison of the theoretical results with the experimental with and without tip mass load.

$$\mathrm{EI}k = M_v - M_L = \mathrm{EI}\frac{K_v V}{1 + j\omega\tau} - j\alpha\mathrm{EI}k\,. \tag{6}$$

The curvature can be solve and the power to momentum resistance is as

$$P = \frac{(K_v V)^2 \mathrm{EI}l}{2}\frac{\omega}{1+\omega^2\tau^2}\frac{\alpha}{1+\alpha^2}. \tag{7}$$

The power reaches maximum at $\omega = 1/\tau$ and $a = 1$ with the value of

$$P_{\max} = \frac{(K_v V)^2 \mathrm{EI}l}{8\tau}, \quad \text{(8)where } l \text{ is the length of the strip. The power density is evaluated as } P_{\max}$$

over volume as

$$P_d = \frac{(K_v V)^2 \mathrm{E}h^2}{96\tau}, \tag{9}$$

where h is the thickness of the strip.

The power density of the sample mentioned above (h=0.18 mm) is calculated as P_d = 0.48W/m3 for 2 V peak voltage at frequency of 0.0021 Hz.

Model for IPMC with back relaxation

Samples having small cations like Li+/Nafeon exhibit a very different behavior than the one with large cations. Under a step voltage, after a very quick bending towards anode, it shows a large relaxation towards cathode, indicating existence of two time constants. We constructed the model using the understanding of the possible underlying mechanism of the phenomena. We assume the positive ions bring more water to the cathode than the water they should be associated in equilibrium. There is a diffusion of the water back to the anode after initial moving to the cathode.

$$\frac{dk}{dt} = K_1\frac{dq}{dt} - \frac{1}{\tau_2}(k - K_2 q), \tag{10}$$

where k is the curvature of the strip, q the electric charge, K_1 is the coefficient for bending effect of the charge freshly moving to the electrode, K_2 is the coefficient for bending effect of the charge in equilibrium state, and τ_2 is the relaxation time constant.

We use the simple RC circuit to calculate the electric charge on the electrode,

$$R\frac{dq}{dt} = V - \frac{q}{C}. \tag{11}$$

The solution for the step voltage is

$$q = VC(1 - e^{-t/RC}) = VC(1 - e^{-t/\tau_1}). \tag{12}$$

where τ_1 is time constant of the RC circuit which is equal to 1/RC. Substituting Eq. (12) to Eq. (10) and assuming the initial condition $k(0) = 0$, we have

$$k = VC(K_2 - \frac{K_1\tau_2 - K_2\tau_1}{\tau_2 - \tau_1}e^{-t/\tau_1} + \frac{\tau_2(K_1 - K_2)}{\tau_2 - \tau_1}e^{-t/\tau_2}). \tag{13}$$

The material parameters in this model can be found by curve fitting with the experiment data. Figure 6 shows the fitting results for the Li+/Nafion strip. The theoretical curve conforms the experimental data very well. The parameters extracted are $\tau_1 = 0.3$ s, $\tau_1 = 10.7$ s, $K_{V1}^t = 2.87$ mm/V, $K_{V2}^t = 1.07$ mm/V, where K_{V1}^t and K_{V2}^t are the coefficients of tip displacement over voltage corresponding to the K_1 and K_2 in Eq. (10).

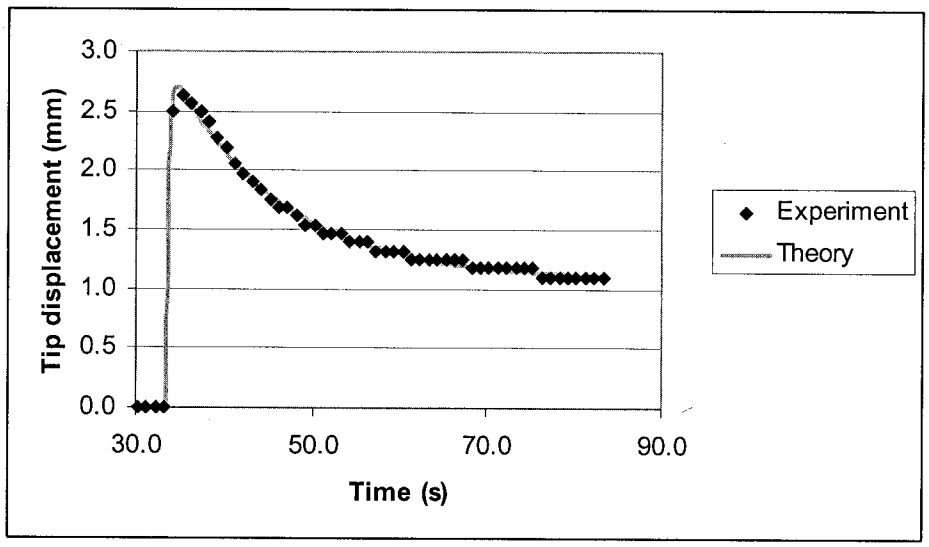


Figure 6. Comparison of the theoretic model with the experimental data for Li+/Nafion strip

SUMMARY

Accurate information about the properties of EAP materials is critical to designers who are considering the construction of mechanisms or devices using these materials. In order to assess the competitiveness of EAP for specific applications there is a need for a properties matrix. This matrix needs to provide performance data that is presented in such a way that designers can scale the properties for incorporation into their models of the device under design. In addition, such a matrix needs to show the EAP material properties in such a form that allows the users to assess the usefulness of the material for specific application. This data needs to include properties and information that can be compare with the properties of other classes of actuators, including piezoelectric ceramic, shape memory alloys, hydraulic actuators, and conventional motors. The range of actuation and stress generation of the various types of EAP is quite large and the excitation field that is required for these materials can vary by 5 orders of magnitude.

While some of the properties (particularly those that are driven by polarization mechanisms) have relatively well-established methods of characterization, the ionic materials and particularly IPMC still require new techniques. These materials pose the greatest challenge to characterization methods developers due to their complex behavior. This complex response is associated with the mobility of the cations on the microscopic level, the strong dependence on the moisture content, as well as the nonlinear and the hysteresis behavior of the material.

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