Evaluation of dehydration loss and investigation of its effect on bending response of segmented IPMC actuators

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Efforts were made to estimate and analyze the effect of dehydration on the bending response of segmented ionic polymer–metal composite (IPMC) actuators. An experiment was conducted with an IPMC actuator to study the variation of bending characteristics with input voltage. Based on the experimental data, the Cobb–Douglas production method was used to obtain the dehydration factor in terms of input voltage and time. The motion of the patches was restricted to planar in two dimensions. A single-patch IPMC actuator was then modeled following the Euler–Bernoulli approach incorporating loss due to dehydration. A forward kinematics model for the segmented actuators was formulated after constituting the homogeneous coordinate transformation matrix, assuming it is a serial link multi-degree of freedom manipulator. An energy-based dynamic model of the patches was derived using the Lagrange principle. Simulations were performed for single and two segmented IPMC patches to demonstrate the bending response for various input voltages. The results demonstrate the gradual reduction of bending response of an actuator owing to moisture loss.

Keywords: ionic polymer–metal composite (IPMC); Lagrange principle; dehydration factor

1. Introduction

In the quest for active materials, ionic polymers, e.g. Nafion™, a type of electroactive polymer (EAP), were originally developed as fuel cell membranes. Polymers labeled as EAPs have a mechanical response to electrical stimulation and produce an electrical potential in response to mechanical stimulation. EAPs are divided into two categories: electronic, driven by electric field, and ionic, driven by diffusion of ions. A typical ionic polymer–metal composite (IPMC) is fabricated from a thin ionic polymer membrane chemically plated on both sides by dispersing noble nanoparticles such as gold or platinum as the electrode layer. Under the application of an electric potential of 1–3 V across the thickness of the IPMC, hydrated mobile cations in the ionic membrane are attracted towards the negatively charged electrode. As a result of mass transfer from one side to the other, an expansion occurs near the negative electrode and equivalent contraction near the positive electrode, resulting in bending deformation of the actuator [1–3]. Interesting properties, such as low operating voltage, light weight, both actuation and sensing capability in water as well as in air, softness and biocompatibility, make IPMCs promising candidates for...
applications in the areas of biomimetics, robotics, aerospace and medicine [4]. The bending motion of an IPMC depends on the moisture content in the working condition as well as the backbone materials. An IPMC can undergo fast and large bending motion when a low electric potential is applied to it. Thus, an IPMC can be used as an actuator since they can move and exert force [5].

Conventional water-based IPMCs require a wet environment to function properly. The water content of the base polymer of the IPMC serves as a medium for ion migration and thus influences the performance of the IPMC. Dehydration of moisture/water particles through the porous electrode surface causes degradation of IPMC performance under working conditions. Moreover, electrolysis sometimes results in a further decrease in the performance of an IPMC [6,7].

To predict the response of a Nafion-based IPMC, Nemat-Nasser and Li [1] developed a model that accounts for the coupled ion transport, electric field, and elastic deformation of the IPMC. Shahinpoor and Kim [8] showed that actuation of IPMCs is due to mass transfer and proposed a technique to minimize water leakage and to increase the force density of IPMCs. Considering viscoelastic properties, Newbury and Leo [9] proposed a linear electromechanical model for IPMC transducers. Extensive experimental studies have been carried out by Nemat-Nasser and Wu [10] to find out the role of backbone materials and the effect of various cations on the actuation behavior of IPMCs. To reduce the effect of dehydration, a freeze-dried IPMC sample was used by Kim et al. [11] since this increased the storage of free water, allowing more effective diffusion. An experimental study was carried out by Lee and Yoo [12] to find out the performance of the ionic liquid-based IPMCs and they have concluded that the performance depends on the size and ionic mobility of the anion in the ionic liquids. Weiland and Leo [13] developed a computational micromechanics model to assess the impact of uniform ion distribution on spherical clusters of IPMC ionomer. However, there is no experimental evidence on how the water acts as carrier agent inside the IPMC when an electric potential is applied to it [14].

When an IPMC patch is actuated by an applied voltage, it is observed that the bending motion of the IPMC is characterized by parasite vibration. As the IPMC vibrates and dehydrates continuously under working conditions, it is, therefore, important to study the effect of dehydration on bending response. The present analysis is thus important to assess the bending response of IPMCs for control applications.

In the present work, an IPMC actuator was studied experimentally to estimate the loss due to dehydration in working medium and subsequently to assess the effect of dehydration on bending response. Initially an experiment was conducted with an IPMC actuator with varying input voltages. Based on the experimentally obtained deflection data, a relationship was established using the Cobb–Douglas production method to obtain the dehydration factor in terms of input voltage and time. The main objective of the study was to estimate the dehydration loss and to investigate the effect of dehydration on the bending response of segmented IPMC actuators.

The micro-manipulated motion of segmented actuators is similar to the modeling of a serial link multi-degree of freedom (DOF) manipulator. Each segment of an IPMC is considered as a link of the manipulator, which can be actuated independently by applying a voltage. It is assumed that each link bends with a uniform curvature and with constant modulus of elasticity. To realize a multi-DOF motion of a manipulator one can connect several links in series in the same way as conventional serial link multi-DOF robot manipulators. The motion of the manipulator is restricted to two dimensions in which two DOFs are positions, although one can control all three DOFs separately by controlling three links of the IPMC separately. An energy-based dynamic model of the segmented patches was
derived using the Lagrange principle incorporating loss due to dehydration. Simulations were performed based on the experimental voltage–deflection data for various input voltages. The results demonstrate the change in response of the segmented actuators due to dehydration.

The paper is organized by first calculating the dehydration factor from the experimental deflection data in terms of voltage and time, then discussing the bending characteristics of IPMC taking into account the dehydration effect followed by modeling of single and segmented IPMC patches. Simulation results are discussed based on experimental data and finally conclusions are drawn.

2. Calculation of dehydration factor and bending characteristics of IPMC from experimental data

An IPMC actuator of size $40 \times 5 \times 1$ mm$^3$ was used in experiments with varying input voltages. Water was used as a polar solvent. The IPMC used in the experiment is based on a gold electrode with Nafion-117 as the base polymer. Experiments were conducted in the hydrated state and in a cantilever mode by applying a voltage at the fixed end to calibrate its bending characteristics. Figure 1 shows a schematic diagram of the experimental setup. Copper strips were used at one end and the voltage was applied quasi-statically from a dc power supply (0–60 V, 0–10 A) and subsequent bending of the IPMC was measured. The IPMC was subjected to input voltages from 0.5 V to 5 V with an increment of 0.5 V. For each input voltage, the tip deflection of the IPMC was measured after 30 s. The objective was to obtain dehydration factor, $\lambda$, from the loss in tip angle for each input voltage.

By taking the experimental tip deflection data [15], the tip angles of the IPMC in hydrated and dehydrated conditions were plotted, as shown in Figure 2. Initially, at the start of the experiment, the moisture content was considered to be 100% and then gradually the dehydration was estimated on account of the bending deflection loss of the actuator.

Figure 1. Schematic diagram of the experimental setup.
The model is based on the experimental data, which were obtained for varying input voltage and time. As the potential is applied through a dc power supply, in the model both dc input voltage and experimental time were taken into account, but the effect of frequency, if any, was neglected. The dehydration factor ($\lambda$) can be expressed as

$$\lambda = 1 - \frac{M}{M_0} = 1 - \frac{\theta}{\theta_0}, \quad (1)$$

where $\theta$, $\theta_0$ and $M$, $M_0$ are the tip angles and bending moments with dehydration and zero dehydration, respectively. However, it was observed that dehydration depends on the applied voltage and actuation time; therefore, the dehydration factor ($\lambda$) can also be expressed as a function of both input voltage ($V$) and actuation time ($t$), i.e.

$$\lambda = \alpha V^a t^b, \quad (2)$$

where $\alpha$, $a$ and $b$ are constants that depend on the material properties. A set of equations was developed using Equation (2) and are solved by the Cobb–Douglas production method to obtain the dehydration factor ($\lambda$) in terms of applied input voltage ($V$) and time ($t$). The resulting expression for the dehydration factor is thus obtained as

$$\lambda = 1.433 V^{0.142} t^{-0.594}. \quad (3)$$

Figure 3 shows the variation of the dehydration factor with applied voltage and actuation time. It is observed that the dehydration factor increases as the voltage increases, although, for a particular input voltage, it decreases as the time increases. This is because water/moisture content in the IPMC decreases with time in the working medium due to dehydration. The IPMC used in the experiment was quite thick and capable of withstanding a large potential of around 5 V. However, dehydration of moisture content through the porous metal electrode on the polymer surface affects the repeatability of the IPMC.
Figure 3. Change in dehydration factor with voltage and time.

Figure 4. Curve fitted along the experimentally obtained y-deflection data and input voltages.

The experimental tip deflection data were plotted using a cubic order polynomial curve fitting approximation \( y = aV^3 + bV^2 + cV + d \). Figure 4 shows the curve fitted along the experimentally obtained y-deflection data with input voltages. The relation between input voltage \( V \) and y-deflection can be approximated as

\[
p_y = -0.03497V^3 - 0.0979V^2 + 6.733V - 0.25.
\]  
(4)
Figure 5. Loss in bending moment of IPMC with various input voltages.

Figure 6. Change in bending deflection of an IPMC actuator due to dehydration with input voltage.

Figure 5 shows the change in bending moment at the fixed end with input voltage. It was observed that the bending moment decreases with dehydration compared to its hydrated state. Figure 6 shows the change in bending deflection pattern of a single-patch IPMC due to dehydration. Figure 7 shows the effect of dehydration on a two-segment IPMC actuator for various input voltages. Here the input voltage is applied in the same sequences. It was observed that the bending deflection of the IPMC decreases due to dehydration.

3. Modeling of IPMC actuator

The property of developing bending deflection towards the anode under a potential gradient makes an IPMC actuator suitable for micro-scale manipulation. It is anticipated that by
segmenting an IPMC strip into many parts (patches), and applying a different sequence of voltages to different strips, it would be possible to control the deflection of the end-tip in the manner shown in Figure 7. This concept allows one to fabricate and design IPMCs for manipulating micro-objects on a surface. Obviously, the work volume depends on the length of the strip and the number of parts of a strip for a desired position of the end point.

3.1. Modeling of single patch IPMC

The experimental results obtained in the previous section were used to model the bending characteristics of an IPMC following the Euler–Bernoulli approach. The maximum bending moment generated for each input voltage is given by $M = \frac{EI}{R}$, where $EI$ is the flexural rigidity of the IPMC. An analogical assumption has been made that the bending phenomenon is equivalent to the same amount of tip deflection caused by external bending moment $M$ acting at the tip of the IPMC. This concept is employed here to model the IPMC for each input voltage. Following the Euler–Bernoulli approach, the tip position of the actuator is obtained as [7]

$$p_x = Q \sin \theta$$
$$p_y = Q (1 - \cos \theta),$$

where $Q = \frac{EI}{M_0 (1 - \lambda)}$.

The velocity at any point at a distance $x$ on the strip can be expressed as

$$v^2 = \dot{p}_x^2 + \dot{p}_y^2 = Q^2 \left[ \cos^2 \theta + \sin^2 \theta \right] \dot{\theta}^2 = Q^2 \dot{\theta}^2.$$
The kinetic energy of the system is the sum of the kinetic energy of the IPMC actuator and kinetic energy of the payload, if any. The kinetic energy of the patch at any instant is given by

\[ T = T_{\text{link}} + T_{\text{payload}} = \int_{0}^{l} \frac{v^2}{2} \rho A ds + \frac{v_p^2}{2} m_p, \]  

(7)

where \( m_p \) is the payload, \( \rho \) is the mass density, \( A \) is the area of cross section. At the end-tip, \( v = v_p \). Simplifying Equation (7) one may write,

\[ T = \frac{1}{2} m Q^2 \dot{\theta}^2, \]  

(8)

where \( m = \rho A l + m_p \). The potential energy of the system is due to resistance to deformation of the link, payload and its own weight. Hence, the potential energy of the link can be expressed as \( U = U_g + U_s \), where \( U_g \) and \( U_s \) are potential energies due to gravity and torsional spring. Torsional spring of an IPMC signifies the bending resistance of the IPMC. The motion of the actuator is restricted to planar; therefore, the potential energy due to gravity can be neglected. Hence, the potential energy of the IPMC patch is expressed as

\[ U = U_s = \frac{1}{2} K \theta^2, \]  

(9)

where \( K \) is the torsional spring constant. The Lagrangian of the system is expressed as

\[ L = T - U = \frac{1}{2} m Q^2 \dot{\theta}^2 - \frac{1}{2} K \theta^2. \]  

(10)

Incorporating damping \((C)\) into the system and applying the Lagrange principle, the governing equation of the system is obtained in state-space form as

\[ \frac{d}{dt} \begin{bmatrix} \theta \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} - \frac{K}{m Q^2} & - \frac{1}{m Q^2} \\ - \frac{C}{m Q^2} & - \frac{1}{m Q^2} \end{bmatrix} \begin{bmatrix} \theta \\ \dot{\theta} \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{m Q^2} \end{bmatrix} M \theta (1 - \lambda). \]  

(11)

### 3.2. Modeling of the two segmented IPMC patches

The response of the segmented patches depends on the orientation and the applied input voltage sequence. Each segment of IPMC may be subjected to a different sequence of input voltage and, based on this the tip of each segment follows a path on a surface. A homogeneous coordinate transformation matrix is constituted based on the tip position with respect to the base coordinate. The generalized transformation matrix in two dimensions is given by

\[ A^i_{i+1} = \begin{bmatrix} \cos \varphi_i & -\sin \varphi_i & p_{xi} \\ \sin \varphi_i & \cos \varphi_i & p_{yi} \\ 0 & 0 & 1 \end{bmatrix}, \]  

(12)

where \((p_{xi}, p_{yi})\) are the position coordinates. For the first and second patch the transformation matrix is given by
\[ A_0^1 = \begin{bmatrix} \cos \varphi_1 & -\sin \varphi_1 & Q \sin \varphi_1 \\ \sin \varphi_1 & \cos \varphi_1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \tag{13} \]

\[ A_2^1 = \begin{bmatrix} \cos \varphi_2 & -\sin \varphi_2 & Q \sin \varphi_2 \\ \sin \varphi_2 & \cos \varphi_2 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \tag{14} \]

where \((\varphi_1, \varphi_2)\) are the orientations of patch 1 and 2, respectively. Therefore, with respect to base,

\[ A_2^2 = \begin{bmatrix} \cos (\varphi_2 + \varphi_1) & -\sin (\varphi_2 + \varphi_1) & Q \sin (\varphi_2 + \varphi_1) \\ \sin (\varphi_2 + \varphi_1) & \cos (\varphi_2 + \varphi_1) & 0 \\ 0 & 0 & 1 \end{bmatrix}. \tag{15} \]

Thus, the tip position is obtained as

\[ p_{x_2} = Q \sin (\varphi_2 + \varphi_1), \quad p_{y_2} = Q (1 - \cos (\varphi_2 + \varphi_1)), \tag{16} \]

Subsequently, the tip velocity of the link is obtained as

\[ v_2^2 = Q^2 \left[ \cos^2 (\varphi_2 + \varphi_1) + \sin^2 (\varphi_2 + \varphi_1) \right] (\dot{\varphi}_2 + \dot{\varphi}_1)^2 = Q^2 (\dot{\varphi}_2 + \dot{\varphi}_1)^2, \tag{17} \]

where \(Q = \frac{EI}{M(1-\lambda)}\), \(EI\) is the flexural rigidity of the IPMC and \(M\) is the bending moment generated. The total kinetic energy of the system is obtained by summing up the kinetic energy of two strips and the payload, i.e.

\[ T = \frac{1}{2} \rho A_1 Q^2 \dot{\varphi}_1^2 + \frac{1}{2} \rho A_2 Q^2 (\dot{\varphi}_2 + \dot{\varphi}_1)^2 + \frac{1}{2} m_p Q^2 (\dot{\varphi}_2 + \dot{\varphi}_1)^2. \tag{18} \]

Taking \(I_{11} = \rho A_1 Q^2\), \(I_{22} = (\rho A_2 + m_p)Q^2\), and then incorporating this into Equation (18),

\[ T = \frac{1}{2} I_{11} \dot{\varphi}_1^2 + \frac{1}{2} I_{22}(\dot{\varphi}_2 + \dot{\varphi}_1)^2, \tag{19} \]

where \(I_1, I_2\) are the lengths of the respective IPMC segments. The potential energy of the system is obtained similarly due to resistance to deformation of the patches with respect to input voltage, and can be expressed as

\[ P = P_s = \frac{1}{2} K_1 \varphi_1^2 + \frac{1}{2} K_2 \varphi_2^2, \tag{20} \]

where, \(K_1, K_2\) are the torsional springs constant for the first and second segment of IPMC patches respectively.
3.3. Governing equation of motion of the system

After obtaining the total kinetic and potential energy of the system, the Lagrangian of the system is expressed as

\[ L = T - P = \left[ \frac{1}{2} I_{11} \dot{\varphi}_1^2 + \frac{1}{2} I_{22} (\ddot{\varphi}_2 + \dot{\varphi}_1)^2 \right] - \left[ \frac{1}{2} K_1 \varphi_1^2 + \frac{1}{2} K_2 \varphi_2^2 \right]. \]  

(21)

Therefore, the governing equation of the system is given by

\[ \frac{d}{dt} \left( \frac{\partial L}{\partial \dot{\varphi}_i} \right) - \frac{\partial L}{\partial \varphi_i} = M_i. \]  

(22)

Substituting the value of Equation (21) into Equation (22), the governing equations of the system are obtained as

\[ (I_{11} + I_{22}) \ddot{\varphi}_1 + I_{22} \ddot{\varphi}_2 + K_1 \varphi_1 = M_1(1 - \lambda) \]

\[ I_{22} \ddot{\varphi}_1 + I_{22} \ddot{\varphi}_2 + K_2 \varphi_2 = M_2(1 - \lambda), \]  

(23)

where \( M_1 \) and \( M_2 \) are the bending moment of the first and second segment of the IPMC patches, respectively, at zero dehydration. Incorporating the damping into the system, Equation (23) is modified to

\[ (I_{11} + I_{22}) \ddot{\varphi}_1 + I_{22} \ddot{\varphi}_2 + C_1 \dot{\varphi}_1 + K_1 \varphi_1 = M_1(1 - \lambda) \]

\[ I_{22} \ddot{\varphi}_1 + I_{22} \ddot{\varphi}_2 + C_2 \dot{\varphi}_2 + K_2 \varphi_2 = M_2(1 - \lambda), \]  

(24)

where \( C_1 \), \( C_2 \) are the respective damping coefficients of the IPMC patches. The generalized governing equation of the system is expressed as

\[ I_m \ddot{\Theta} + C_d \dot{\Theta} + K_s \Theta = M_g, \]  

(25)

where \( I_m = \begin{bmatrix} I_{11} + I_{22} \\ I_{22} \end{bmatrix}, C_d = \begin{bmatrix} C_1 & 0 \\ 0 & C_2 \end{bmatrix}, K_s = \begin{bmatrix} K_1 & 0 \\ 0 & K_2 \end{bmatrix}, M_g = \begin{bmatrix} M_1(1 - \lambda) \\ M_2(1 - \lambda) \end{bmatrix}, \)

\( \Theta = \begin{bmatrix} \varphi_1 \\ \varphi_2 \end{bmatrix} \).

The state-space representation of the governing equation is given by

\[ \frac{d}{dt} \begin{bmatrix} \varphi_1 \\ \varphi_2 \\ \dot{\varphi}_1 \\ \dot{\varphi}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\frac{K_s}{I_m} & -\frac{C_d}{I_m} \\ \frac{1}{I_m} & \frac{1}{I_m} \end{bmatrix} \begin{bmatrix} \varphi_1 \\ \varphi_2 \\ \dot{\varphi}_1 \\ \dot{\varphi}_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{I_m} \end{bmatrix} M_g. \]  

(26)

4. Simulation results and discussions

In this section, results obtained from numerical simulation based on the IPMC properties (Table 1) and the experimental deflection data are discussed. The tip deflection data were taken after 30s for each input voltage. A program was developed in MATLAB to solve
Table 1. Physical properties of IPMC material.

| Property                        | IPMC value       |
|--------------------------------|------------------|
| Elastic modulus ($E$)           | 1.2 GPa          |
| Length ($l$)                    | 40 mm            |
| Width ($w$)                     | 5 mm             |
| Thickness ($h$)                 | 1 mm             |
| Area of c/s ($A = wh$)          | 5 mm$^2$         |
| Density ($\rho$)                | 3385 kg/m$^3$    |
| Torsional spring constant ($K$) | 18.95 N mm       |
| Mass ($m$)                      | 0.67 g           |
| Damping coefficient ($C$)       | 0.1962 N s/rad   |

the differential equations in state-space, i.e. Equations (11) and (26) to obtain the bending response for various input voltages. Initially, a single patch of IPMC was analyzed and the bending response studied. Both instantaneous tip position and rate of change of tip position from its static position have been evaluated to show the performance of the system. The damping coefficient is obtained as $C/m' = 2\xi\omega$, where $\xi = 0.05$ is the damping factor of the IPMC obtained experimentally and $m' = mQ^2$. The actuation frequencies were obtained from the expression [6]:

$$\omega_n = \sqrt{\left(\frac{EI(n^4\pi^4)}{l^4} + K\right) / \rho A}.$$  \hspace{1cm} (27)

Equation (27) was used to calculate the first fundamental mode of frequency of the actuator in order to obtain the damping coefficient. Figure 8 shows the change in tip angles and rate of change of tip angles with dehydration at peak deflection for various input voltages before reaching steady-state. It is observed that the maximum response occurs just immediately

![Graphs](image_url)

Figure 8. Change in tip angles and the rate of change of tip angles due to dehydration of the single patch actuator with input voltage.
after the input voltage and gradually diminishes before reaching the steady-state. Under steady-state conditions, no bending response of the IPMC is observed.

Figure 9 shows the change in angular position of segmented actuators with respect to the mean axis. It is observed that the response of the system remains similar for each input voltage. However, the response is more sensitive as the input voltage increases. Figure 10 shows the rate of change of tip angles of the segmented IPMC actuators. It is observed that in both cases (Figures 8 and 10) the amplitude of response decreases due to dehydration. Figure 11 shows the phase portrait of the single patch actuator; the results reflect the stability of the system for each input voltage.
Further, it is demonstrated that with increment of input voltage the response of the actuator (Figures 8 and 9) and hence the frequency of the bending response increases faster to reach the steady-state.

5. Conclusion

In this paper, a new model has been developed to estimate the dehydration loss of an IPMC actuator following the Cobb–Douglas production method. The proposed model is robust and suitable for any IPMC actuator in a working medium that experiences continuous dehydration. Segmented IPMC actuators have also been modeled and the results are obtained to ascertain the effect of dehydration. It is observed that with dehydration, the response of the actuator reaches the steady-state more rapidly, although the amplitude of the bending response decreases. The estimation helps to understand the amount of input voltage or the moisture quantity that has to be added with time to compensate the loss. The proposed idea can be employed for controlling the tip position by compensating the loss proportionate to input voltage.

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