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# Analysis and Study of the Nonlinear Electrodynamics Behaviour of a Micro-beam Made of Ionic Polymer Metal Composite (IPMC)

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**Abstract:** Ionic Polymer Metal Composites (IPMCs) are a group of electroactive polymer materials that exhibit a large deformation due to the application of low voltages resulting from the movement of cations inside the polymer. These materials have many applications in various fields such as Micro-robotics, biomedical engineering equipment and artificial muscles. Due to the possibility of producing these materials in micro dimensions they can also be used in micro-electromechanical systems. On the other hand, due to their sensitivity to very low voltages, they can be a good substitute for silicon in micro-electromechanical systems. In the present study, the dynamical analysis of a micro-beam fixed at two ends made of these materials is investigated using electrical-chemical-mechanical relations. COMSOL Multiphysics software is used to solve the relations. The results showed that for harmonic stimulation (sinusoidal voltage) the system experiences only the same form of the first mode. It was also observed that increasing the frequency would decrease the amplitude of the micro-beam oscillation.

**Keywords:** Ionic Polymer Metal Composites, Micro-beam, Physical Model, COMSOL Multiphysics, Micro-electromechanical Systems

## 1. Introduction

There are many type of composites which have been used in different aspects [1], like Nanocomposites [2], Ionic polymer composites and so forth. Ionic Polymer Metal Composites (IPMCs) are a new group of polymer electroactive materials, which represent large deformations when exposed to a small electric field (zero to five volts). Recently, polymer electroactive materials have been extensively studied for their wide application in various industries such as robotics, biomedical engineering and artificial muscles [3-6]. This material was first discovered by Shahinpoor in 1992 and then formally introduced in 1998 [7]. IPMCs are consisted of a polymer membrane surrounded by two metal electrodes, that can be produced in various sizes and dimensions depending on the intended use. Polymer membranes are usually made of Nafion or Flemion and the electrodes are made of high conductivity metals such as platinum and gold. IPMCs are intelligent materials and their deformation results from the application of voltage to two electrodes, which leads to an electric field inside the polymer membrane causing the movement of ions [8-9]. These materials are also used as sensors, which by forcing mechanical deformation into the fragment, the ions are imposed to move, thereby generating the potential difference between the two electrodes [10].

Although the above materials have found increased use in various industries and their scope of application is rising dramatically, researchers are still investigating the identification and prediction of their behavior against different input voltages with different frequencies. Hence, different models have been developed to identify the behavior and performance of these materials, which can be divided into three general categories: 1- Black Box Model, 2- Gray Box

Model and 3- White Box Model (Physical Model). In the black box model, the model is based solely on the relations between inputs and system response. In this case, the model is strongly dependent on the sample being studied and the test conditions. Therefore, the more experiments in this model, the more reliable results will be. And in the gray box model, the material parameters are obtained based on the experimental results. These parameters represent physical concepts with a process. But in the physical model, which is the most developed and sophisticated method yet for detecting the behavior of an IPMC actuator, the laws governing the transfer of ions as well as the electrical-mechanical and electrical-chemical effects are examined. To model these materials in this way, differential equations with partial derivatives must be analyzed [11].

Annabestani et al. (2013) used a black box model to identify the behavior of actuator made of IPMCs [12]. Their model also included 2 main sections. One part consisted of a fuzzy-neural adaptive system and the other consisted of a retrograde automatic system with nonlinear external input. Caponetto et al (2014) proposed a gray box model to identify the behavior of the target actuators [13]. They modeled the nonlinear properties of this type of operator with an electric circuit. They also used single and multi-objective optimization functions to estimate the parameters of their model. They used the Genetic Algorithm (GA) to compare the displacement of their proposed model and of the actual operator and tried to minimize the error with GA. Micro-beams are used as resonators, optical switches, micro-pumps and so on in micro-electromechanical systems. In most of these systems, the micro-beam is made of silicon, which requires high voltages to stimulate. When the voltage reaches a certain value, the micro-beam's internal forces are out of equilibrium with the Coulomb pressure, causing the micro-beam to be drawn toward the fixed electrode (called Pull-in phenomenon) and be in contact with it and become disrupted [14-15]. Due to the excitation mechanism of the IPMC, it can be concluded that the use of these materials in micro-electromechanical systems can eliminate the Pull-in instability.

Black and gray box models are valid only for the sample tested and are not scalable. For example, if the sample length changes in black or gray box model, it cannot predict the operator's behavior against different voltages [16]. According to this point, a physical model based on electrochemical equations has been used in this study to analyze and predict the dynamic behavior of IPMC actuator. The governing equations are solved using the Finite Element Method (FEM) by COMSOL Multiphysics software. Studies show that this method has not been used so far for an IPMC micro-beam analysis. Many research have been conducted in this field as Esmaeili et al in 2016 has worked on Wave function properties of a single and a system of magnetic flux tube [17]. There are different methods to solve this issue, Mohammadzadeh et al. suggest particle swarm optimization method [18-19] or Afshar implements Population Balance Modeling (PBM) and Initial Development Method (IDM) [20-21] on the other hand Azarang et al. describe about Laplacian-based and Nonfragile fuzzy method [22-24]. Ramtin et al. have studied Self-stabilizing algorithms [25-27]. In which different materials have been derived, such as coatings by non-isocyanate polyurethanes [28-31].

Khiabani et al. have conducted research on design and implementation of an optimal switching controller based on State-Dependent Riccati equation [32-34]. Razzaghi has worked on nonlinear dynamics and control of an inertially actuated jumper robot [35-36], and on the following Hayati et al. have studied different methods like Low-power and CMOS burst-mode [37-38], dynamic addressing by Ghayouraneh et al. who have worked on Holistic optimization technique for solving low thermal conductivity [39-43]. Many other researches have been conducted in this field by Gharib [44] in quantitative-fuzzy Controller Design for Multivariable Systems with Uncertainty, and Kondori [45] in identifying catalytic active sites of trimolybdenum phosphide (Mo3p) for electrochemical hydrogen evolution and Ranjbar [46-48] in laser-induced studies. Hemmati et al. [49-51] have used metaheuristic optimization techniques for solving problems in this field. Evaluating the stability of specific adhesion of particles to membranes in simple shear flow is what have been studied by Sarvestani et al. [52-54]. The damage of beams is studied by Moghaddam et al. [55-56] by signal processing based approach for damage. Evaluating the risk of accident and damages has been studied by Movahedi et al. [57-58]. One of the main aspects of this study is nonlinear behavior and optimization, many ways are considered to be done like digital comparative holography which have been studied by Ahmadzadegan et al. [59-62].

# 2. Modeling and Governing Equations

The figure 1 shows a schematic diagram of an IPMC micro-beam (fixed at both ends). We assume that the micro-beam is homogeneous and isotropic with linear elasticity, L length, A the area of rectangular cross section, b width and thickness of d.

According to Figure 1, by applying a voltage to two electrodes and generating an electric field within the polymer membrane, free cations begin to move toward the cathode, which causes swelling in the cathode and shrinkage at the anode side, resulting in a bending motion in the actuator. It should be noted that anions are stable and constitute the polymer membrane. The transfer of cations is described by the Nernst-Planck equation [63].

$$\frac{\partial C}{\partial t} + \nabla.(-D\nabla C - z\mu FC\nabla\varphi) = 0 \quad (1)$$

In the above relation C is the cation concentration, μ cations transferability, D diffusivity constant, F Faraday constant, z charge number and φ electric potential within the polymer layer. The electrical potential inside the polymer membrane (φ) differs from the electrical potential inside the electrode (V). φ is described using Poisson's equation [63].

$$\nabla.\breve{E} = -\nabla^2\varphi = \frac{\rho}{\varepsilon} \quad (2)$$

Where ε is the permeability coefficient and ρ is the charge density inside the polymer membrane and is defined as follows [63].

$$\rho = F(C - C_0) \quad (3)$$

Where $C_0$ is the initial concentration of the cation, and the Ohm's Law is used to define the electrical potential inside the electrodes (V) [63].

$$\sigma\nabla V = -\breve{j} \quad (4)$$

Where σ is the electrical conductivity of the electrodes and j the current density inside the electrodes. Now one can establish a relation between the electrical potential at the electrodes and the electrical potential at the polymer membrane. Such a relation can be obtained by using Gauss's law [64].

$$j_I = -b\varepsilon\frac{\partial\varphi}{\partial t}.n^r \quad (5)$$

In the above relation n is the normal vector of the interface between the polymer membrane and the electrodes. By coupling and simultaneously solving the above equations in COMSOL, the charge density inside the polymer membrane ρ is obtained. Nemat-Nasser (2) showed that the deformation of an IPMC can be attributed to a charge-proportional force.

$$f_z = \alpha\rho \quad (6)$$

The α coefficient can be calculated by experiment. Now with the force f and using the elasticity equation one can calculate the displacement field.

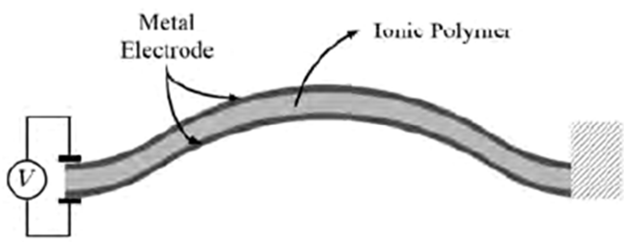


***Figure 1.*** *Schematic model of a micro-beam of IPMC in a micro-electromechanical system.*

## 3. Results

To ensure the accuracy of FEM modeling, the tip displacement of an IPMC strip of 51,07×9,94×0.582 mm³ is considered to be applied by a sinusoidal voltage and acting at 4V and 1Hz. The simulation constants are given in Table 1. As can be seen in Figure 2, a good agreement is observed between the present modeling and the research of Mr. Shen et al. [65].

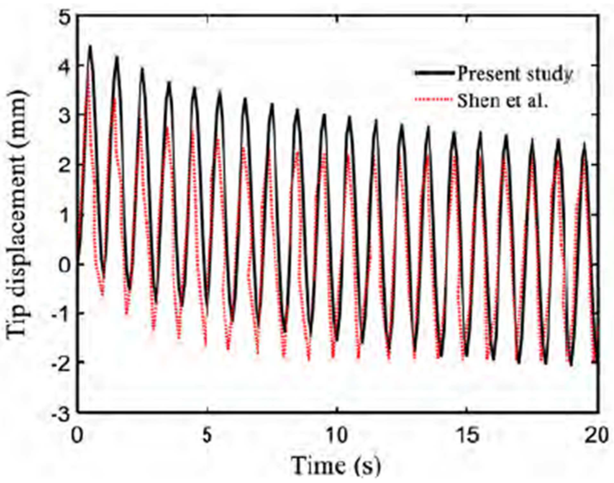


***Figure 2.*** *Time history graph of a single-end fixed IPMC strip.*

***Table 1.*** *Constants used for the simulation.*

| Row | Quantity | Unit | Value |
|---|---|---|---|
| 1 | D diffusivity constant | $m/s^2$ | $7\times10^{12}$ |
| 2 | $C_0$ initial concentration | mol/m³ | 1200 |
| 3 | F Faraday constant | C/mol | 96485 |
| 4 | μ cations transferability | s.mol/kg | $2.9\times10^{-15}$ |
| 5 | Z Charge value | - | 1 |
| 6 | ε permeability coefficient | F/m | 0.0002 |
| 7 | σ electrical conductivity | S/m | $4.65\times10^{12}$ |
| 8 | E Young Modulus | MPa | 90.92 |
| 9 | $\rho_m$ Composite density | kg/m³ | 784 |
| 10 | υ Poisson's ratio | - | 0.49 |
| 11 | α Proportionality constant | J/C | $7.5\times10^{-8}$ |

It should be noted that by using micromachining technologies it is possible to fabricate micro-beam out of IPMC [65]. Figure 3 shows the time history diagram for a fixed two-end micro-beam of 1000×50×30 $\mu$m³ 3 dimensions [65]. The applied voltage is sinusoidal with an amplitude of 2 V and a frequency of 1 Hz.

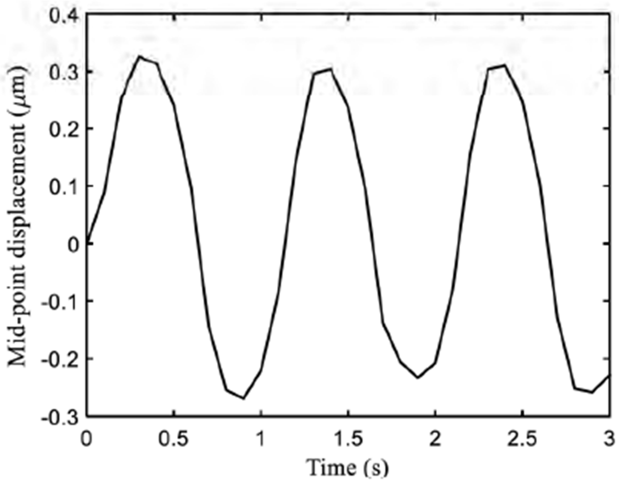


***Figure 3.*** *Time history diagram of a fixed two-end IPMC micro-beam.*

Figure 4 shows the micro-beam deformation for a cycle of oscillation, and as can be seen the system experiences only the first mode shape.

Figure 5 shows the micro-beam frequency response for a sinusoidal voltage of 1 and 2 V amplitudes.

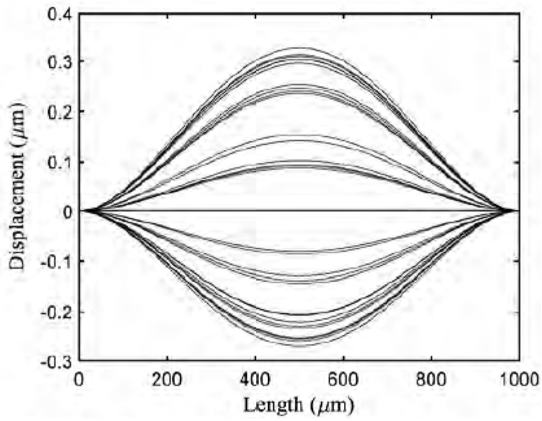


*Figure 4. Micro-beam deformation for a cycle of oscillation, sinusoidal voltage with amplitude of 2 V and a frequency of 1 Hz.*

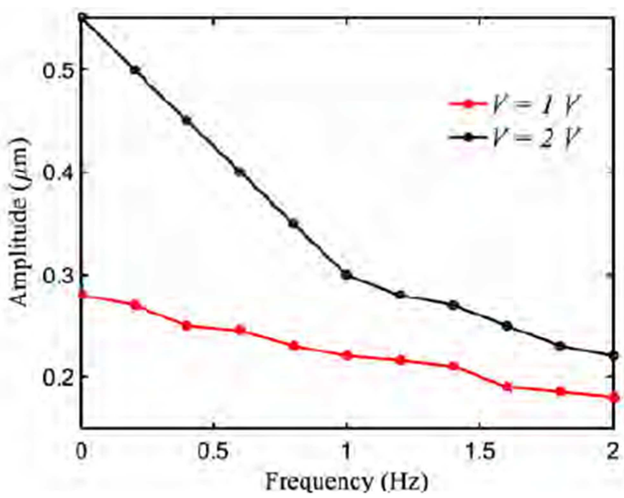


***Figure 5.*** *Frequency response of the micro-beam.*

As it can be seen in Figure 5, for a 1 V amplitude, the frequency change does not have much effect on the oscillation domain. On the other hand, it is observed that with increasing frequency the oscillation amplitude decreases.

## 4. Conclusion

In this study, the electro-dynamic behavior of a micro-beam of these materials is investigated using electrical chemical mechanical relationships governing the behavior of IPMCs. Governing equations are solved using four software modules (1-electric currents, 2-particle transport, 3-Partial differential equations, 4-structural mechanics), and the results show that for the harmonic excitation (sinusoidal voltage) the system only experiences the first mode shape, it was also observed that increasing the excitation frequency leads to a decrease in excitation amplitude. Comparing the results of the present study with some research in the field of silicon micro-beams (10, 11) leads to a conclusion that IPMCs can replace silicon in micro-electromechanical systems. With the advantage that the voltage and frequency needed to excite them are much lower than for silicon. On the other hand, this replacement can lead to the removal of pull-in instability from micro-electromechanical systems.

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