Finite Element Modeling of Blocking Force of Ionic Polymer Metal Composites (IPMC) in Micro gripper

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***Abstract*-Ionic polymer metal composites (IPMCs) are emerging class of electro active polymers (EAP) that are used as sensors and actuators. As an actuator, it can be used for supporting micro tools in different biomedical applications. Finite element analysis (FEA) of IPMC's actuators is an ideal candidate for researchers. This paper represents a comsol multi-physics model to simulate blocking force of micro gripper fingers. In comsol Multi-Physics Model, the Structural Mechanics module, Electric Current module, Transport of Diluted Species module and General Form PDE module are used to simulate the IPMC micro gripper finger. Electric current module used to apply potential difference across electrodes. Transports of Diluted Species module explain the deflection due to transport of ions on applied voltage. Multi-Physics Finite Element tool is used to get reaction force (blocking force) for different potential differences and different parameters of gripper finger. The experimental and simulated results show that our model is more effective in simulation and analyses of micro gripper.**

***Index Terms*—EAP, Ionic polymer–metal composite IPMC, blocking force, FEM**

I. INTRODUCTION

Ionic polymer–metal composite (IPMC) is an emerging class of smart materials that are used as sensors, micro grippers and actuators [1]. Its significant deflection on very small voltage makes IPMCs suitable for microsystems and biomimetic state [6]. The black box FEM model was developed by Lee and Metz to show the mechanical deformation of IPMC using thermal correspondence. In previous models precisely predict the electro-thermal mechanism of IPMCs but require experimental validation both physically and chemically. On the study thermal analogy (thermo-structural coupled field approach) for computational analysis is used to find deflection and reaction force in which voltage is applications as micro grippers. The importance of IPMC is that, it is a replacement of traditional actuators and sensors materials. Its properties are minor electrical energy intake, bio compatibility, less weight, yielding properties, ability to function in air and aquatic environment. It is unaffected to magnetic field and its fabrication procedure is simple. The material that give good mechanical response on applying electrical properties is EAP; they have better size and shape. EAPs categorized into two main classes depending on mechanism of actuation, activated by field and ionic EAPs [2]. IPMC gives large displacement on small input voltage, frequently less than 2.5 V. Its behavior encouraged the use of these smart materials in microsystems, such as micro grippers [3]. and become popular for the micro manipulation applications which include the assembly of the micro systems and bio-micromanipulation [1]. Due to its biocompatibility and resiliency, the smart IPMC material has marvelous applications in biomedical devices, biomimetic robotics, sensors and actuators [4]. The prediction of deflection and reaction forces is considerably helpful in many biomedical and industrial applications. Computational models are of three types black box, white box and gray box models. Shahinpoor [5], Nemat-Nasser and Johnson developed physical models or white box models based on physics and chemistry of IPMC deflection. These physical

other hand, black box or empirical models although require only system recognition yet restricted of particular shape, verifiable nature and functioning mimicked by temperature [7]. Also, there were limitations of particular shape and experimental verification of results which is very time consuming and expensive. Different experiments were performed to explain the science behind actuation properties. The dehydration was detected by Kanno, the IPMC stopped actuating after while [6].

These water molecules bond to the positively charged cations and migrate towards the cathode. This migration is responsible for some of the actuation in the material, but many believed it did not account for the fast response. It was soon discovered that Columbic forces between the charges in the electrodes were responsible for this fast reaction. These forces caused the migration of hydrated cations towards the cathode, causing the IPMC to swell towards the cathode side and shrink on the anode side [8]. Bonomo presented a prototype of tactile and touch sensor for applications of biomedical field that utilized an IPMC as both an actuator and sensor. Their sensor was enough to check both contact force and relative hardness of the tissue compared to a control sample. The IPMC actuator in their prototype was used to bend the sensor membrane around an object [9]. Covering of IPMC in a case stops loss of water molecules, which is a critical issue currently [10].

A 2D Multi-Physics, IPMC strip by defining in to the plane thickness is modeled and assigned electrical, chemical and mechanical properties to find the exact deflection and blocking force with all the necessary boundary conditions by applying potential difference as driving force across the anode and cathode [11] .This study provide researchers a gateway to find the deformation of wholesome IPMC material of different shapes and thickness in limited time for using it as sensors and actuators in number of industrial and biomedical applications

We developed a Multi-Physics Model, in which the Structural Mechanics module, Electric Current, Transport of the Diluted Species, and General Form PDE module are used to simulate the IPMC micro gripper finger. Electric current module used to apply potential difference across electrodes. Transports of Diluted Species module explains the deflection due the transport of ions on applied voltage. Multi-Physics Finite Element tool is used to get reaction force (blocking force) for different potential differences and different parameters of gripper finger.

II. THEORETICAL BACKGROUND

Charge Redistribution

As stated in introduction, the main cause of IPMC bending under applied voltage is ion redistribution.

The time variation of the charge distribution is governed by the following "equation 1".

$$\frac{\partial C}{\partial t} + \nabla.(-D\nabla C - Z\mu FC\nabla\emptyset - \mu C\Delta V\nabla P) = 0 \qquad (1)$$

The cation concentration is C, mobility of cations is m, diffusion constant is D , Faraday constant is F, charge number is z , the molar volume is ΔV that quantifies the cation hydrophilicity, solvent pressure is P, and electric potential is ∅ in the polymer. Mobility can be clearly expressed as "equation 2".

$$\mu = D/RT \qquad (2)$$

Gas constant R, absolute temperature is T and local displacement vector is u.

The solvent pressure is caused by local strain in the polymer matrix, forcing the solvent from the concave side to the convex side of IPMC. Effective cation transport due to this term is governed by the pressure gradient ∇P and molar volume constant ∇V. According to the momentum conservation, the solvent pressure and the pressure of the polymer p are related as follows "equation 3".

$$\nabla(P + p) = 0 \qquad (3)$$

It has been shown that "equation 4".

$$p(dV) = \left[\frac{E(1-v)}{(1+v)(1-2v)}\right] dV \qquad (4)$$

Where Young's modulus of material is 'E' and the Poisson's ratio is n.

By knowing those constants, Navier's equation can be constructed for displacements "equation 5".

$$-\nabla.\sigma = F. \qquad (5)$$

Here, F being the force per unit volume. Time-dependent deformation is described by Newton's Second Law "equation 6".

$$\rho * \frac{\partial^2 u}{\partial t^2} - \nabla.c\nabla u = F \qquad (6)$$

Where ρ the density of the material and the second term is 'static Navier's equation', where the Navier constant is 'c' the first term in equation presents dynamic part. In cases of electromechanical transduction, the body force F is defined as a function of charge density ρ "equation 7".

$$F = f(\rho) \qquad (7)$$

Depending on the level of hydration and type of solvent being used, the cations may migrate easily. A fully hydrated sample will allow more migration than a dehydrated sample. This becomes quite evident on the macroscopic level when testing different samples, as only hydrated samples are capable of movement. Nemat-Nasser and Li proposed a model that demonstrated the increase in concentration of cations at the cathode, resulting in a fast expansion [6].

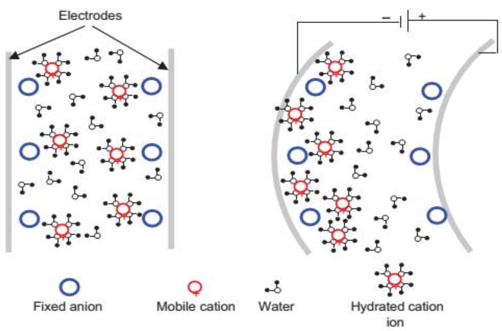

Figure 1: IPMC working Principal [4]

Hydration level, type of solvents and cations being used have a great effect on IPMC actuation [5]. When a voltage is applied to an IPMC, an electric field is set up through the thickness of the Nafion, which produces an electrostatic force on the cations. These cations are then driven through the channel, as seen above. Solvent molecules attached to cations also migrate towards the cathode. The combined migration of solvent and cations results in a fast actuation response towards the cathode that may last several minutes. This migration of cations towards the anode leaves a depleted region of cations in the anode. These clusters slowly redistribute, causing a decrease in actuation, known as back relaxation. The anions that migrate towards the anode during this process repel one another, also causing relaxation. This relaxation causes a bending back towards the anode.

III. FINITE ELEMENT MODELING OF IPMC

IPMC material consists of an ionic polymer with covalently attached 'anionic groups' which are balanced by cations moving in water solution (or in other solvent).On applied voltage the electrodes of an IPMC, cation flux or the ionic current is induced by the forced electric field. In cases of water-based IPMCs migrating cations drag the water molecules beside, cause osmotic pressure to change and therefore swelling of polymer close to the cathode and shrinkage near the anode occur. This cause bending of the material towards the anode. For modeling material like IPMC with complex physical, chemical and mechanical properties Multi-Physics model is developed.

Following modules are used to construct Multi-Physics model of IPMC.

The 'AC/DC' interfaces used to calculate the electric field and magnetic field in the static and low-frequency systems. In such systems the wavelength is substantially larger than the studied device. Under AC/DC module the Electric Currents interface used to calculate current, electric field and potential distributions in directing media below conditions. The inductive effects are small when the skin deepness is larger than studied device. The Chemical Species Transport interfaces used to calculate concentration fields of the chemical species in the solutions. It describes chemical reactions and transport through diffusion, convection, and migration in dilute and concentrated solutions under Chemical Species Transport of Diluted Species interface used to calculate concentration field of the dilute solute in solvent. The driving forces during transport are expressed by Fick's law, convection, when coupled to fluid flow, migration, an electric field. Modeling multiple species during transport is possible. Also convection, diffusion, adsorption dispersion and volatilization in saturated or partly saturated porous media are available.

The Mathematics module used for solving PDEs and ODEs, it performs sensitivity analysis and modeling meshes and distorted geometries. Under mathematics 'PDE' Interfaces branch contains Partial Differential Equation (PDE) interfaces for 'PDEs in coefficient form and general form and for weak form 'PDEs' on dissimilar geometry level

The following properties are defined to generate the Multi-Physics model of IPMC.

Table 1 Global properties

Name	Expression
Width of IPMC (in to the plane width)	9.94 [mm]
Diffusion coefficient D_{cation}	7e-11 [m^2/s]
Gas constant'R'	8.31 [J/(mol*K)]
Temperature'T'	293 [K]
Charge no (Z cation)	1
Concentration of cation (mol)	1200 [mol/m^3]
Epsilon	2 [mF/m]
Faraday	96485.3415 [s*A/mol]
Young modulus IPMC	41 [MPa]
Poisson ratio IPMC	0.49
Density_IPMC	2000 [kg/m^3]
Alpha	0.0001 [N/C]
Mobility my_cat	D_cat/(R/T)
Voltage positive	3V
Voltage negitive	0V

Under Structural Mechanics, Solid Mechanics module has physics interfaces for analyzing deformation, stresses and strains of solid structures. The available analysis type includes Stationary, the 'Eigen-frequency', Frequency response, Transient and Linear Buckling. Time Dependent Study 1 containing Electric Current, Transport of Dilute Species and

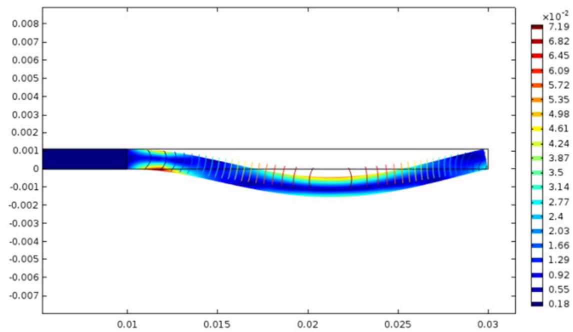

Figure 2: Gripper finger simulation

General Form PDE. Time Dependent Study 2 containing Solid Mechanics are combined to propose exact FE model of IPMC rectangular strip. Figure 2 shows graphic window of an IPMC micro gripper finger analyses in comsol multi-physics to get blocking force. Free end of the finger is fixed to get reaction force at that end.

IV.RESULTS AND CONCLUSIONS

For incorporating all the properties of IPMC material and to get blocking force at the tip of micro gripper finger, a multi-physics model is developed in Finite element software. The experimental tip force responses of IPMC with DC voltage of micro gripper having dimensions (40mm*10mm*0.2mm) and (40mm*10mm*2mm) are used [12].

Table 2 IPMC strip (40mm*10mm*0.2mm)

Applied voltage (V)	Blocking force experimental (g)	Theoretical blocking force (g)	Blocking force Comsol simulation (g)
0.5	0.01	0.02	0.012
1	0.025	0.26	0.021
1.5	0.06	0.05	0.055
2	0.08	0.06	0.068
2.5	0.09	0.08	0.0972
3	0.1	0.1	0.103

Results of the simulations of different parametric fingers are plotted against different voltages.

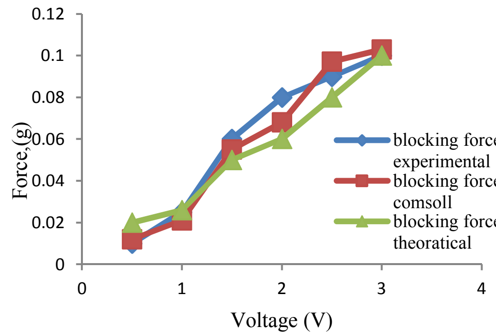

Figure 3 graph between Force and voltage

Table 3 IPMC strip (40mm*10mm*2mm)

Applied voltage (V)	Blocking force experimental (g)	Blocking force Comsol simulation (g)
1	0.045	0.0432
2	10	9.36
3	18	18.036
3.5	20	19.54

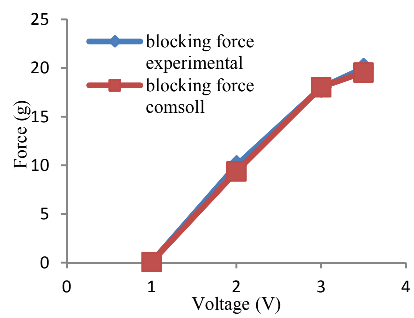

Figure 4 graph between Force and voltage

Table 2 and figure 3 show tabular and graphical result including experimental and Comsol simulation.

Thin IPMC strips have similar trend of experimental, theoretical and simulated blocking force results.

Table 3 and figure 4 show tabular and graphical result including experimental and Comsol simulation in case of thick ionic polymeric metal composites strip, it shows low performance in experimental. Results as compared to theoretical, simulated results due to migration of the hydrated cations in the strip. Small difference between simulated and experimental result is due to different error like systematic and personal errors during experimentation. We can use this comsol model to simulate IPMC for different applications.

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