Modeling and Control of Ionic Polymer-Metal Composite Structures

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Abstract
Robotic devices are traditionally actuated by hydraulic systems or electric motors. However, in compact robotic systems, new actuator technologies are required. Ionic Polymer-Metal Composites (IPMCs) are attractive electroactive polymer actuators because of their characteristics of large electrically induced bending, mechanical flexibility, low excitation voltage, low density, and ease of fabrication. A dynamic analytical model of IPMC is developed in this study. An RC model is employed based on time response results of a typical silver deposited IPMC. Results show that the electrical model is a suitable presentation of IPMC actuators. The model is tested with two experimental data of IPMC actuators. Results show an excellent agreement between the theoretical and experimental data. The control of ionic polymer metal composite actuators is investigated from a practical perspective. A proportional, integrator and derivative (PID) control system is then employed for position control of the integrated composite structure. Results demonstrate the simplicity and effectiveness of the proposed model in active vibration control of smart structures using IPMC actuators.

Keywords: IPMC - Actuator - Equivalent circuit.

Introduction

Ionic Polymer-Metal Composites are widely used as artificial muscles especially because of their mechanical flexibility and low excitation voltage.

Electroactive Polymer (EAP) includes two main categories: Electronic and Ionic. The emphasis of this paper is modeling of IPMC.

The actuation of an IPMC actuator is mainly caused by the unbalance of water density in IPMC due to the molecular transportation from the movement of the counter ion and water molecules coupled to counter ions in IPMC under the electric field.[2] Redistribution of charges in IPMC due to imposed electric field is shown in Fig. 1.

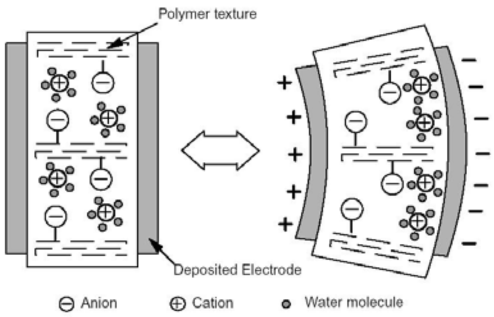

Fig. 1 - General redistribution of charges in an ionic polymer due to imposed electric field.

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The unique characterizations of the IPMC introduce new challenges in material performance evaluation. An experimental setup was developed at NDEAA Lab, JPL3 for IPMC modeling.

This article focuses on macro models of electric inputs and electromechanical actuation of IPMC. The macro models that relate the electric input and mechanical output are required for material characterization i.e. to define and extract the material parameters in order to support potential applications of actuator design [1].

Experimental data are employed to derive an equivalent electrical circuit of IPMC actuators. Based on this model, the effect of waveforms and frequencies of driving inputs on the characteristics of the IPMC actuators is investigated.

In addition, a desirable way of driving the IPMC actuator is suggested in terms of minimizing consumption of power with experimental verifications [2].

Another equivalent circuit model is developed to translate the input voltage into the relative current inside the membrane.

It's also concluded that with high frequency voltage signals, ionic motion strongly decreases [3].

Not only IPMC actuators play a vital role in many fields, such as medical and industrial applications, but also actuators are the core of artificial muscle design and application. Thus, improvement of IPMC actuators modeling is greatly important.

Using an equivalent model, some researchers have tried to reduce the surface-resistance. For example this can be done by depositing silver and copper instead of pure platinum on the polymer membrane. Onishi made an analysis on the relation between the number of the gold deposition and the deformation of IPMC [4].

In robotic applications various modeling approaches have been investigated. Tadokoro developed a new actuating mechanism, called elliptic friction drive element employing the actuating mechanism of ultrasonic motors [5]. Several models have been developed based on the effect of the surface resistance of electrodes. For instance, Kim and Shahinpoor have addressed the effect of the surface resistance of the electrode [6].

Another method of addressing this issue is to overlay a thin layer of a highly conducting metal (such as silver or copper) on top of the platinum surface electrode [7]. The low temperature behavior of an IPMC has also investigated in the recent research [8].

In this paper, a new equivalent electrical circuit as a model of IPMC is developed. Each circuit element presents a specific characteristic of IPMC. This model introduces major advantages over previous models.

2. Equivalent electrical circuit

As RC model of IPMC actuators is introduced with based on time response results. This result reported in [1].

The physical model includes a Li^+/ Nafion IPMC made by ERI with dimension of 30 $\times 3 \times 1$mm.

This model is shown in Fig. 2, in which resistance r_1 denotes electrode resistance.

The capacitance corresponding to the ionic polymer and surface-electrode-electrolyte presented as C in the equivalent model (Fig. 2). Another two resistances (r_2 and r_3) show polymer resistance and surface resistance respectively.

Under step voltage V, the response of the IPMC is given by:

$$I(t) = \frac{V}{r_0 + r_3 + r_2}[1 + \left(\frac{r_1 + r_2}{R} - 1\right)e^{-\alpha . t}] \quad (1)$$

Where,

$$R = r_1 + \frac{(r_0 + r_3)r_2}{r_0 + r_3 + r_2} \quad (2)$$

$$\alpha = \frac{1}{R.C} \quad (3)$$

r_0 is the internal resistance of voltage source.

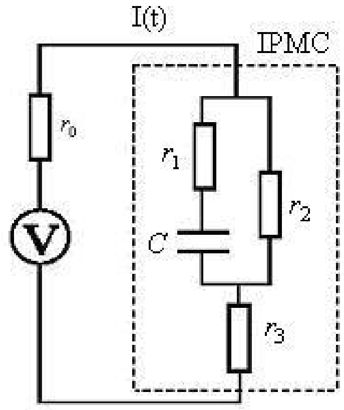

Fig. 2 - Equivalent electrical model of IPMC

The circuit parameters are $r_1= 50\Omega$, $r_2= 46.6\Omega$, $r_3= 0.2\Omega$ and $C= 47000\mu f$. Calculating the value of circuit parameters, a curve is fitted to time domain response data presented in Fig 3.

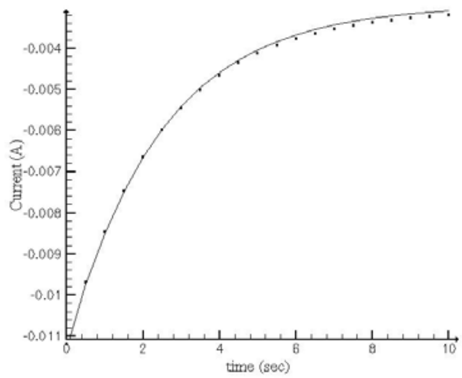

Fig. 3 - Time response of IPMC:
. : Experimental data
- : Proposed model

The frequency domain response of the IPMC model, developed in this research, is compared with experimental data reported in [2]. This IPMC is made by depositing five layer of platinum on Nafion-117. The dimension of this sample is $10\times10\times0.2$ mm. The transfer function of the equivalent model is given as:

$$G(s)=\frac{R_0[(R_1+R_2)Cs+1]}{((R_1+R_2).(R_3+R_0)+R_1R_2)Cs+R_0+R_2+R_3} \quad (4)$$

Where R_0 is internal resistance of voltage source.

Comparison between theoretical result and experimental data is presented in Fig 4.

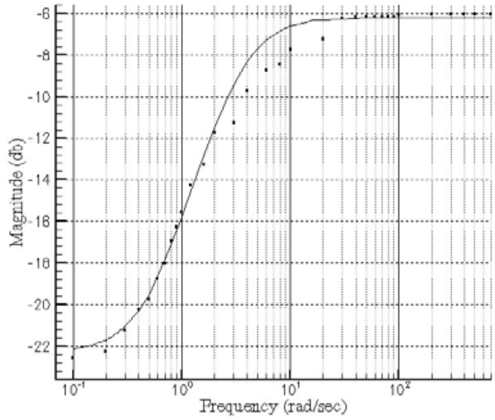

Fig. 4 - Bode diagram of experiment data and equivalent model
. : Experimental data
- : Proposed model

In this case, the values of circuit parameters are $r_1= 0.4\Omega$, $r_2= 46.6\Omega$, $r_3=3.98\Omega$ and $C=42917\mu f$.

Now, comparison between bode diagram of new model and previous model is presented in Fig. 5.

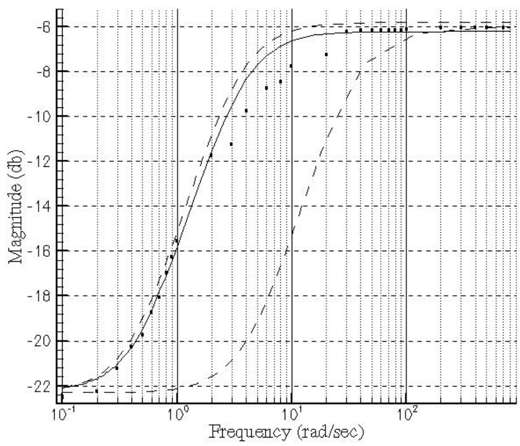

Fig. 5 - Bode diagram of IPMC:
. : Experimental data
- : Proposed model
-- : Previous model

It's obvious that new curve is more appropriate to experimental data.

Previous models didn't cover all characteristics of IPMC, such as electrode

resistance (r_1) or surface resistance (r_3). Thus, it has been tried to cover all of them together in presented model.
For specifying the preferences of new model, some points should be noticed:
Theoretically the value of polymer resistance corresponding to kind of polymer and dimension of model; thus other parameters such as deposited layers have no affect over resistance of polymer.
By calculating the circuit parameter in this model, the value of polymer resistance doesn't change based on time response results and frequency response result.
It's obvious that the capacity of C is related to the area of electrodes. The area of electrodes in first sample is 90 mm^2 and in second sample is 100 mm^2. Thus, equal values of capacitances are expected, which is true.
Based on previous documents, it's proved that by depositing more layers on IPMC, the total resistance reduced.
In second sample, five layers of platinum deposited on polymer surface; thus, reduction in total resistance is expected. Calculation showed that total resistance in second sample is almost 5 time less than first sample.

3. Control

In this section, control of the actuator is investigated through closed-Loop position control using PID controller.
Comparison the stability of models will be investigated through this circuit. PID controller used because it is an industry standard control technique due to its performance and the ease at which it can be implemented.
Therefore, by using simulink toolbox, a circuit which can control the IPMC is designed. Step function is used as input signal of position control circuit. This circuit is presented in Fig. 6.

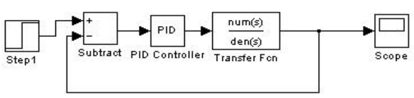

Fig. 6 - closed-Loop position control of IPMC

A PID controller with the parameter of P=10, I=10, D=1 is used as a controller. Comparison between the step response of previous model and new model is plotted in Fig. 7.

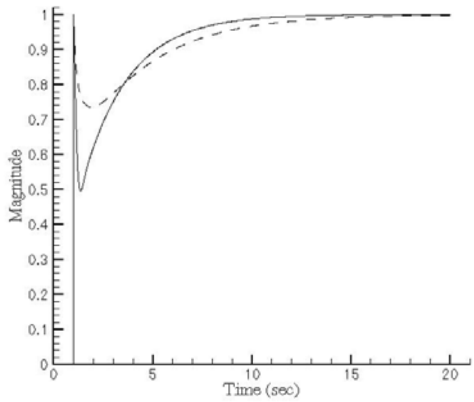

Fig. 7- Step response of closed-loop position control
- : Proposed model
-- : Previous model

As it's obvious, the value of overshoot decreases by 47% in new model. It means that new model is more stable, which will be very important when the value of proportional parameter increased.

4. Conclusion

In this paper, a new circuit model is developed, which fully describes the characteristics of IPMC actuators. The model is tested with two experimental data of IPMC actuators.
Comparison between the value of polymer resistances and polymer capacitance is fully studied. Effect of platinum deposited on electrodes is also investigated corresponding to reduction in value of total resistances. , which is critical in practical design of systems using IPMC actuators.
Finally, a proportional, integrator and derivative (PID) control system is then employed for position control of the integrated composite structure.

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