Equivalent Electric Network Model for Ionic Polymer Metal Composite Dynamics

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Introduction

Ionic Polymer Metal Composites have been the focus of many researchers around the world for the past few years. Their inherent light weight, flexibility, repeatability and the tip force have been the major concerns to replace the electro-mechanical actuators in a vast variety of application areas ranging from bio medical engineering to unmanned flying devices. Many studies such as Colozza *et al.*, (2007) have been carried out to develop cost effective fabrication techniques, improve electro-chemo-mechanical characteristics, derive finite element and other modeling techniques, etc. However, very little attentions have been paid on the control of IPMCs. One of the main reasons for this is the absence of a globally acceptable model, whose parameters can directly be calculated from the dimensions and the physical properties of the IPMC.

This paper presents an unprecedented approach to dynamic modeling of IPMCs using standard electric network components to model the transient and steady state voltage and current characteristics. This leads to a global model for IPMCs with fine tunable parameters, which depend on the material properties, the manufacturing process and the physical dimensions of the actuator.

Equivalent electric network model

To apply precise control techniques for better performance, it is vital to obtain a dynamic model of the system. By observing the current waveform for an applied voltage on the IPMC, this section proposes a capacitor resistor based passive electric linear network to model the dynamics of IPMCs with no external load torque applied. Further, it is derived in the continuous time domain and a methodology is presented to evaluate the parameters using current and voltage measurements.

Background of the proposed model

When a square wave step voltage signal is applied on an IPMC, from a voltage source of finite output impedance, a voltage variation as shown in Figure. 1 (upper) can be observed. This leads to the conclusion that the voltage across an IPMC can not be changed instantaneously. Further, if the voltage source is disconnected, after being connected for some time, a potential difference retains across the top and bottom surface metallic electrodes of the IPMC. These two properties exactly match with the typical characteristics of a capacitor.

When the current through the IPMC corresponding to the above voltage step is observed, there is a spike caused by the voltage step change and it dies out over time. However, it does not decay to zero as in the case of a pure capacitor. Instead a non-zero current flows as long as the voltage is applied. This observation suggests that there should be a resistor parallel to the capacitor. The suggested model is shown in Figure 2(a). Since an uncharged capacitor behaves as short circuited at the instant of applying the input voltage, the initial current should rise to infinity. However, the current through the IPMC as shown in Figure 1 (lower) is finite at the instant of applying the voltage. Therefore there should be a resistor in series to the circuit suggested in Figure 2(a), through which the capacitor can be charged. Assuming the output resistance of the voltage source is R_{out}, the suggested passive electric network model consisting of a series resistor R_1, parallel resistor R_2 and a capacitor C, is shown in Figure 2(b).

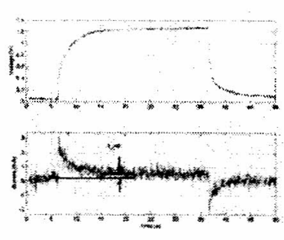

Figure 1. The voltage applied on the IPMC (upper) and the corresponding current (lower)

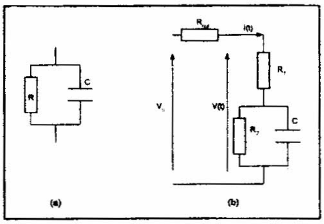

Figure 2. Initially suggested passive electric network model for the IPMC actuator. (b) Since the initial current is finite, a series resistor R1 is introduced. The output resistance Rout of the voltage source Vs is also included. The voltage measured across the IPMC is V(t)

Passive electric network model derivation

Referring to Figure 2(b), the transfer function from the input voltage V to the total network current I is:

$$\frac{I(s)}{V(s)}=\frac{\left(s+\frac{1}{R_2C}\right)}{R_1\left(s+\left(\frac{R_1+R_2}{R_1R_2C}\right)\right)} \quad (1)$$

where 's' is the *Laplace* operator. This can also be presented as

$$\frac{I(s)}{V(s)}=\frac{K(s+b)}{(s+a)}=\frac{B(s)}{A(s)} \quad (2)$$

where $K=\frac{1}{R_1}$, $b=\frac{1}{R_2C}$, $a=\frac{R_1+R_2}{R_1R_2C}$

For a step voltage input, it becomes (3)

$$\frac{I(s)}{V(s)}=\frac{K}{(s+a)}+\frac{Kb}{s(s+a)}$$

In the discrete time domain, with the z-transform operator and h being the sampling period, it becomes

$$\frac{I(z)}{V(z)}=\frac{K(z-1)}{\left(z-e^{-ah}\right)}+\frac{\left(1-e^{-ah}\right)Kb}{\left(z-e^{-ah}\right)} \quad (4)$$

which can be simplified as

$$\frac{I(z)}{V(z)}=\frac{K(z-c)}{(z-d)} \quad (5)$$

where $c=a(1-e^{-ah})-1$, $d=e^{-ah}$.

Introducing the pulse transfer operator q, it becomes

$$I(k)=dI(k-1)+KV(k)-cKV(k-1) \quad (6)$$

This parametric estimation method works well for noise free measurements, which is hard to achieve in practice. Therefore the measurement noise component has to be incorporated in the model. Different parametric system identification models such as Auto Regressive with Extra Input (ARX), Auto Regressive Moving Average with Extra Input (ARMAX) and Box and Jenkin (BJ), which can handle measurement noise are available as derived in Ljung *et al*., (1999) With the results of the preliminary identification experiments, the BJ model structure, whose block diagram is shown in Figure 3, is used here for the model verification as that has the capability of estimating independent dynamical models between input-output and noise-output.

The strategy used in this paper is to obtain a basic input output model for voltage vs. current dynamics using non-parametric identification methods and verify its validity using parametric identification experiments.

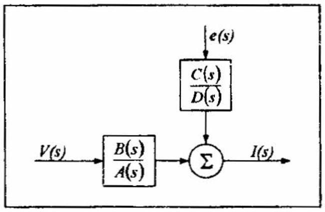

Figure 3. BJ model structure to incorporate measurement noise in the parameter estimation. More accurate noise models may be obtained by suitably selecting the orders of C(s) and D(s). A(s) and B(s) are same as in equation (2)

Results and discussion

The model verification is done using both parametric and non-parametric approaches.

Non-parametric identification

Referring to step response of IPMC shown in Figure 1, K, b and a of the transfer function model described in equation (2) were estimated using initial value, final value and the time constant of the step response of current. The values are given in Table 1. Figure 4 shows the applied step, measured current and simulated current using the above model.

Parametric identification

A BJ model was fitted to a recorded voltage and current data set. The input voltage was varied as a pulse sequence of random amplitude and duration. The strategy used in trying to fit the BJ model was to keep the voltage vs. current dynamics fixed according to equation (6) and fine tune noise model to achieve the best fit. The Figure 5 shows the step sequence applied and the corresponding current variation and simulated BJ model and non parametric model outputs for comparison.

As can be seen in Figure 4, most of the time, the non-parametric model output closely follows the basic shape of the experimental output. But the model does not take into account the measurement noise, which is why matching in Figure 4 (d) is poor.

The Figure 5 compares the models obtained by BJ method and non-parametric method with the experimental data, for the series of pulse input voltages. At A, C, and F, where the current rise is shape corresponding to high frequency excitations in the frequency domain, the non-parametric model output is more closer to the actual output. But when the changes are slower in a place like B, the BJ model is better as it incorporates a high order noise model.

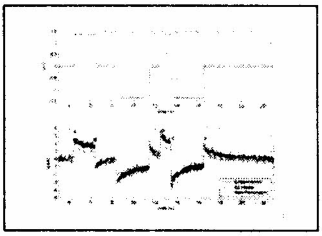

Figure 4. Verification of the identified non-parametric model

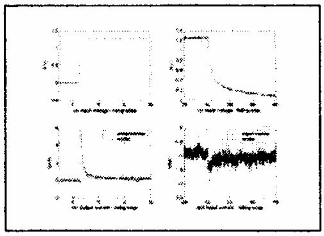

Figure 5. Comparison (lower) of BJ model and Non-Parametric model with the experimentally obtained output data corresponding to the input voltage pulse sequence (upper)

However, especially from D to E and some other places in the figure, none of the models can match the actual output. This is believed to be due to un-modeled non-linearities.

Table 1. Model parameters of the non-parametric identification

Estimated Parameter	Value
K	0.01168
b	0.0915
a	5.0813

Conclusions and future work

An equivalent electric network based dynamic model for IPMCs has been introduced derived and verified experimentally. It will be improved in the future to incorporate the un-modeled non-linearities.

References

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Ljung, L. (1999) *System Identification: Theory for User*. 2nd Ed., Prentice Hall.