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Modelling and Design of All-Organic Electromechanic Transducers

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Abstract. The recent development of innovative organic materials with intriguing features such as their flexibility, lightness, low cost and easy manufacturability, has driven researchers to develop innovative smart applications based on such kind of materials. In this work, all - organic electromechanical transducers, with both sensing and acting capabilities are proposed. The actuator and sensor models have been identified by using a grey box approach, as a function of membrane geometric parameters. The obtained models have been validated through comparison among estimated and experimental data.

PACS. 07.05.Tp Computer modeling and simulation – 43.60.Qv Signal processing instrumentation, integrated systems, smart transducers, devices and architectures, displays and interfaces for acoustic systems – 73.61.Ph Polymers; organic compounds

1 Introduction

In recent years a wide interest has been devoted to the research of innovative materials for the development of flexible electromechanical transducers. In particular, ElectroActive Polymers (EAPs) have been extensively investigated because of their flexibility and lightness. Such kind of materials bends when solicited by an external electric field or an external voltage and act as motion sensor when an external deformation is applied. Among these materials Ionic Polymer Metal Composites (IPMCs) exhibit large bending when solicited with an external low voltage and produce an output current when an external deformation is applied. Such composites are constituted by an ion exchange perfluorinated membrane (usually Nafion[®]115 or Nafion[®] 117), coated on both sides with a metallic electrode, generally a noble metal such as platinum is used [1]. In this work, all-organic electromechanical transducers are proposed. The device metallic electrodes are substituted with an organic conductor coating layer, such as PEDOT/PSS or Polyaniline (PANI). The obtained Ionic Polymer Polymer Composites (IP²Cs) have already demonstrated both sensing and acting features [2]. In order to fully exploit these all-organic electromechanic transducers features, their behaviour must be characterized thus enabling the development of novel smart applications. Is therefore fundamental the development of a model describing the IP²C behaviour considering the presence of nonlinearities. Starting from previous model developed for EAP actuators and sensors [3]-[6], considering a beam in cantilever configuration, the

actuator and sensor model parameters have been identified using a grey box approach, as a function of membrane geometric parameters. The models have been validated trough comparison among estimated and experimental data. It is demonstrated how the design of flexible all-organic electromechanical transducers is enabled by adopting the identified models and suitable material technologies.

2 Devices Manufacturing

The Nafion[®] membrane, which is the core element of the IP²C devices, is first subjected to a sandblasting process in order to ensure the electrode mechanical adhesion and then cleaned by both ultrasonic and chemical bath (by boiling HCl (2.5 M) and by boiling water). Then the IP²C devices have been realized by covering Nafion[®] 117 membranes with an organic conductor in order to realize the device electrodes. The conductor of choice has been, according to previous results[2], the PEDOT/PSS. In particular OrgaconTM 3040 conductor furnished by AGFA has been used. Among the possible manufacturing techniques the drop casting one gave the best results and has therefore been chosen. Nafion[®] strips of 3.0 cm x 4.0 cm size fixed on a petri dish have been covered with the organic conductor solution and then left in ambient air for about three days until solvent evaporation from the substrate took place, then the procedure has been repeated over the other side. Strips of different size have been cut with length L_{tot} ranging from 1 up to 3 cm and $w = 5$ mm.

The membrane geometrical parameters are summarized in the following Fig. 1

Fig. 1. Parameters characterizing the actuator and sensor devices

The value t_h takes into account the Nafion[®] 117 thickness (178 m) plus the organic electrodes thickness; w is the membrane width, L_{TOT} is the membrane length, L_t is the length of the free membrane, L_c is the clamped part length. L_S is the point in which the force is applied, δ is the obtained displacement and f the blocking/applied force.

3 IP²C actuator linear model

In this chapter a linear model to describe the all-organic actuator electrical behavior is presented. The model is based on a grey box approach, in particular a lumped parameters equivalent circuit is presented to describe the electrical behavior of an IP²C actuator in cantilever configuration. The model is parameterized according the actuator geometrical dimensions shown in Fig. 1. The electric equivalent circuit model performs the conversion between applied voltage $V_{IN}(t)$ and actuator absorbed current $I_{absorbed}(t)$ as schematically shown in Fig. 2

Fig. 2. IP²C actuator equivalent electric linear circuit

The circuit comprises two RC branches, introduced to model the capacitive nature intrinsic of the device structure, two resistances R_e modelling the organic conductors effect, and a resistance R_1 which is the equivalent bulk resistance of Nafion[®] in DC conditions. In order to parameterize the model as a function of membrane dimensions the resistance R_1 is expressed in terms of the Nafion[®] DC resistivity ρ_1 and actuator dimensions:

$$R_1 = (\rho_1 \cdot t_h) / (L_{TOT} \cdot w) \quad (1)$$

the value of ρ_1 according Dupont datasheets is $\rho_1 = 1205 \Omega m$.

To the same purpose the resistances R_2 and R_3 and capacitors C_2 and C_3 have been expressed in terms of the resistivities (ρ_2 and ρ_3) and permittivities (ϵ_2 and ϵ_3) respectively and actuator geometric quantities according to the following relations:

$$R_e = R_s \cdot L_T / w \quad (2)$$

$$R_2 = (\rho_2 \cdot t_h) / (L_{TOT} \cdot w) \quad (3)$$

$$R_3 = (\rho_3 \cdot t_h) / (L_{TOT} \cdot w) \quad (4)$$

$$C_2 = (\epsilon_2 \cdot L_{TOT} \cdot w) / t_h \quad (5)$$

$$C_3 = (\epsilon_3 \cdot L_{TOT} \cdot w) / t_h \quad (6)$$

R_e is also expressed as a function of actuator dimensions and an opportune parameter R_s which must be identified. The system transfer function

$$G(s) = \frac{I_{abs}}{V_{in}} \quad (7)$$

is the system equivalent admittance that can be obtained by evaluating the inverse of equivalent impedance Z_e :

$$Z_e = \frac{V_{in}}{I_{abs}} = 2 \cdot R_e + \left(R_1 // \left(R_2 + \frac{1}{sC_2} \right) // \left(R_3 + \frac{1}{sC_3} \right) \right) \quad (8)$$

3.1 Parameters Identification

Model identification has been performed on samples having the following dimension: $L_t=15\text{mm}$; $L_c=5\text{mm}$; $w = 5\text{mm}$; $t_h = 200\Omega m$; The actuator model is characterized by five parameters R_s , ρ_2 , ρ_3 , ϵ_2 and ϵ_3 which must be identified. Parameters identification has been performed in Matlab[®] by minimizing a cost function J_i which evaluates the error between measured and estimated absorbed current:

$$J_i = \frac{\sqrt{\sum (I_{absorbed} - I_{estimated})^2}}{\sqrt{\sum (I_{absorbed})^2}} \quad (9)$$

In order to identify the equivalent electric circuit parameters the membrane has been solicited with a frequency sweep voltage from 1 mHz up to 200Hz and 6Vpp amplitude. Data conditioning and acquisition has been performed through an ad hoc realized experimental setup shown in Fig. 3.

Both the input voltage and the absorbed current have been acquired by using the acquisition card DAQ 6052 by National InstrumentsTM. In the following figure an example of the acquired and estimated currents is plotted with different levels of detail.

Fig. 3. Experimental setup used for the IP²C actuator electric model identification.

Fig. 4. Example of experimental and estimated absorbed current.

Table 1. IP²C Actuator Model Parameters

$R_s[\Omega m/m]$	$\rho_2[\Omega m]$	$\epsilon_2[F/m]$	$\rho_3[\Omega m]$	$\epsilon_3[F/m]$
52.5806	25.6888	0.0059	0.0021	0.0003

The obtained parameter values are reported in Table 1.

The identified electric model has been validated by using a white noise input signal with uniform distribution. Experimental and predicted currents are shown in Fig. 5.

Fig. 5. Model validation.

4 IP²C sensor model

The IP²C membranes demonstrated sensor capabilities to detect mechanical deformation. An IP²C sensor device structure is shown in Fig. 1, where $f(t)$ is the applied

force, $\delta(t)$ is the deflection of the beam and $I_S(t)$ obtained in short-circuit condition.

Assuming the reciprocity of piezoelectric effect, the relation (10) between the input displacement $\delta(t)$ and the sensing current $i_s(t)$ in the frequency domain can be found [6].

$$\frac{i_S(s)}{\delta(s)} = \frac{3t_h w}{4L_S} s Y(s) d(s) \quad (10)$$

This relation models the electromechanical transduction properties of the polymeric membrane. The frequency dependent quantities $Y(s)$ and $d(s)$ represent respectively the Young's modulus and the piezoelectric coupling of the IP²C sensor. The hydration conditions of the IP²C membrane determine the value of the complex Young's modulus, mainly at very low frequencies. Moreover, when the membrane is wet in equilibrium with the environment in air, the Young's modulus becomes constant in the considered range of frequencies (less than 500Hz). The piezoelectric term $d(s)$, which derives from the theory of piezoelectricity, has been introduced to model the electromechanical coupling of the IP²C sensor. Different structures have been considered for the relation that describe the complex function $d(s)$. However, the experimental results show a single pole behavior in the considered frequency range (from 50mHz to 500Hz), thus (12) has been adopted to describe the piezoelectric coupling term.

$$d(s) = \frac{k}{(s + \alpha)} \quad (11)$$

The expressions of $d(s)$ and Y can be obtained through experimental measurements by means of a minimization algorithm which uses both the electromechanical model expressed in (10) and the Euler-Bernoulli pinned beam theory (12).

$$Y(s) = \frac{4L_S^3}{wt_h^3} \cdot \frac{f(s)}{\delta(s)} \quad (12)$$

In order to obtain the IP²C sensor model parameters, the experimental setup has been designed to measure at the same time both the imposed force, the displacement and the sensing current generated by the membrane. The forcing signal has been chosen to stimulate the transducer in the frequency range of interest. It is composed by a sequence of bipolar impulses, a bilateral chirp signal (from DC to 10 Hz) and a random noise of increasing amplitude as shown in Fig. 6. Young's modulus has been identified through minimization of an index J_Y which is function of the time series of measured displacement $\delta^{real}(t)$ and the predicted displacement $\delta^{predicted}(t)$ obtained from Euler-Bernoulli model.

The obtained value of Young's modulus Y has been substituted in (10) in order to identify the piezoelectric coupling parameters k and α whose values have been estimated through the minimization of a second index J_d which is function of the time series of both measured sense current $I_S^{real}(t)$ and predicted sense current $I_S^{predicted}(t)$.

Fig. 6. Experimental data: displacement, force and sensing current.

Table 2. IP^2C sensor model parameters.

$Y[GPa]$	$k[CsN^{-1}]$	$\alpha[Hz]$
4.60	$2.14 \cdot 10^{-8}$	13.08

The values obtained by the minimization of index J_d are shown in table 2.

The IP^2C sensor model has been validated both in time and frequency domain by comparing measured and predicted values of sensing current time series and electromechanical transfer function bode diagrams. An electric equivalent circuit has been obtained starting from the electromechanical model of IP^2C sensor, as shown in Fig. 7.

Fig. 7. Electric equivalent circuit of IP^2C sensor model

As for the IP^2C actuator model, the resistance R_e models the organic conductor resistance while R_1 is the equivalent bulk resistance of Nafion[®] in DC conditions. The electromechanical transduction has been modeled by means of the voltage source generator V_d controlled by the displacement $\delta(t)$ and the capacitance C , where

$$C = \frac{(\epsilon \cdot L_{TOT} \cdot w)}{t_h} \quad (13)$$

The term β is a proportionality coefficient which realizes a coupling between displacement and voltage. The relations which associate the electric circuit parameters ϵ and β to the electromechanical model parameters are expressed by (14) and (15) where R_p is the equivalent parallel resistance between R_1 and $(2 \cdot R_e)$.

$$\epsilon = \frac{t_h}{L_{TOT} w \alpha R_p} \quad (14)$$

$$\beta = \frac{3}{2} t_h Y k R_s \quad (15)$$

The obtained normalized circuit parameter values are reported in the following table:

Table 3. IP^2C Sensor equivalent circuit parameters.

$R_s[\Omega m/m]$	$\beta[V/m]$	$\epsilon[F/m]$
52.5806	1.5514	$6.226 \cdot 10^{-4}$

5 Conclusions

All organic electromechanical transducers with acting and sensing features have been modelled by means of a grey box approach. In both cases a lumped parameters equivalent circuit has been adopted to model the devices dynamics. The proposed models have been validated through comparison among estimated and experimental data. It is demonstrated how the design of flexible all-organic electromechanical transducers is enabled by adopting the identified models and suitable material technologies.

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