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A SCALABLE FRACTIONAL MODEL FOR IPMC ACTUATOR

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Abstract
In this work a scalable non integer model of IPMC actuator is presented. The goal is to obtain a model able to predict the behavior of IPMC, with a generic shape and any boundary condition. An experimental setup has been realized to study the IPMCs behavior and an algorithm has been developed in $Matlab^{®} Environment$ to identify a fractional order model of IPMC actuators.

Key words
IPMC, Fractional order systems, Marquardt algorithm.

1 Introduction

Ionic Polymer Metal Composites (IPMCs) are innovative materials made of an ionic polymer membrane with electrodes plated on both sides. The ionic polymers, that constitute the core of the IPMCs, are macromolecules with a part fixed in the polymeric net and a part weakly linked to the rest. The latter one could be an ionic group, an anion or a cation, depending on the specific polymer. The bond between the two parts can be easily broken by giving a small amount of energy. At room temperature almost all bounds are broken so there are small size ionic groups free to move inside the net, and big size fixed groups with opposite charges with respect to the free ions. Another interesting property of ionic polymers is the capability to absorb a big amount of solvent, e.g. water, whose molecules can link with the movable ions. Eventually, the water content plays an important role in the deformation of IPMCs.

The $Nafion^{®}$ is an ionic polymer usually used to realize IPMC. It has fixed groups have negative charges while cations can move freely. When a voltage signal is applied across the thickness of the IPMC, mobile cations will move toward the cathode. Moreover, if a hydrated sample is considered, the cations will carry water molecules with them. The cathode area will expand while the anode area will shrink; consequently the polymer will bend toward the anode. Also, by mechanically bending the material it is possible to change the distribution of the charges with respect to the membrane neutral axis: the applied stress will contract one side of the membrane while the other will spread, the mobile ions will consequently move toward the region characterized by a lower charge density parasitically carrying the solvent molecules (i.e. deionized water). It would be possible to measure to the IPMC electrodes an electrical signal.

IPMC can hence work either as low-voltage-activated motion actuators or as motion sensors [Shahinpoor and Kim, 2001; Shahinpoor, Bar-Cohen, Simpson and Smith, 1998]. In Fig. 1 a picture of a IPMC sample is shown.

Different models of IPMCs both as sensor and as actuator have been proposed [Kanno, Tadokoro, Takamori and Hattori, 1996; DeGennes, Okumura, Shahinpoor and Kim, 2000; Bonomo, Fortuna, Giannone, Graziani and Strazzeri, 2007; Bonomo, Fortuna, Giannone, Graziani and Strazzeri, 2006]. More specifically, for the case of IPMC actuators, when a voltage is applied and the corresponding deflection is considered, a non integer order behavior was noticed. For this reason the authors proposed a new model for IPMC actuators, based on non-integer order system modeling [Caponetto, Dongola, Fortuna, Graziani and Strazzeri, 2008].

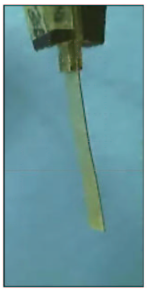

Figure 1. An IPMC sample.

Recently a renewed interest has been devoted to non integer, or fractional, order systems. This is due to the fact that they well model a lot of physical systems. Transmission lines [Wang, 1987], electrical noises [Mandelbrot, 1967; Keshner, 1982], power-law [Korabel, Zaslavsky, and Tarasov, 2007], dielectric polarization [Onaral and Schwan, 1982], heat transfer phenomena [Le Mehaute, 1991] and systems with long-range interaction [Tarasov and Zaslavsky, 2006; Tarasov and Zaslavsky, 2007] are some of the fields having "Non Integer Order" physical laws. In this paper the authors investigated the variation of the parameters of the proposed non-integer model with the length of the IPMC strip.

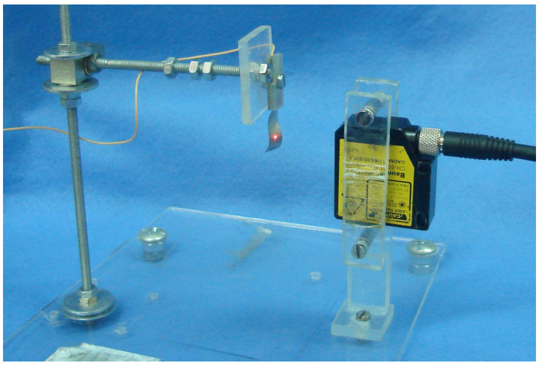

Figure 3. The photo of the measuring apparatus used to characterize the tip deflection of an IPMC strip.

2 The Experimental Set-up

Considering the beam parameters, the length L_{free} and the cross-sectional dimensions (thickness t and width w), it was assumed that the beam vibrates in the vertical plane. The experimental setup is composed of a circuit to impose the voltage input signal to the membrane and a distance laser sensor to measure the tip deflection. The schematic and the photo of the experimental setup are shown in Fig. 2 and 3, respectively.

The deflection of the cantilever tip was measured by a commercially available distance laser sensor (Baumer Electrics OADM12U6430). Light from the laser diode was focused onto the end of the cantilever. The signals acquired by DAQ 6052E, that is, the voltage input imposed to the membrane and the deflection of the cantilever tip, measured with the laser sensor, for IPMC with different length are shown in Fig. 4.

The voltage input signal applied to the IPMC electrodes is a composite signal consisting of a linear sweep signal from $500mHz$ to $50Hz$ for $30s$, and a white noise signal for $2.5s$. Using a sample frequency equal to $1000samples/s$, $32500samples$ are obtained for a data acquisition campaign during $32.5s$. The output signal acquired, i.e. the deflection of the cantilever tip, shows clearly that the IPMC reaches the maximum deflection in the resonance condition. It is clear that the system presents a resonance frequency that decreases with the increasing of the length while the amplitude increases with the length. Processing these data in $Matlab^{®} Environment$, the transfer function of the system has been obtained, supposing that the system is linear, and using the "tfestimate" $Matlab^{®} function$. Thus, the Bode diagrams of the system, shown in Fig. 5, has been estimated for three different lengths of IPMCs and for 20 measurements to verify the system repeatability. By inspection of the Bode diagrams it is clear that IPMCs present a non integer order behavior [Arena, Caponetto, Fortuna and Porto, 2000]: the module Bode diagrams present a slope equal to $\pm m * 20db/decade$, and the phase Bode diagrams present a phase lag equal to $\pm n * 90°$, where m and n are real numbers. These Bode diagrams can be also identified by integer order models, but non integer order models allow to obtain comparable modeling performance by using a smaller set of parameters [Caponetto, Dongola, Fortuna, Graziani and Strazzeri, 2008]. It was, therefore, decided to identify the models of the three systems with non-integer order models. Since in this case the values of fractional exponents need to be estimated along with the corresponding transfer function zeros and poles values, the identification problem is nonlinear and an adequate optimization procedure needs to be used. In this paper the Marquardt algorithm for the least-squares estimation is used [Marquardt, 1963].

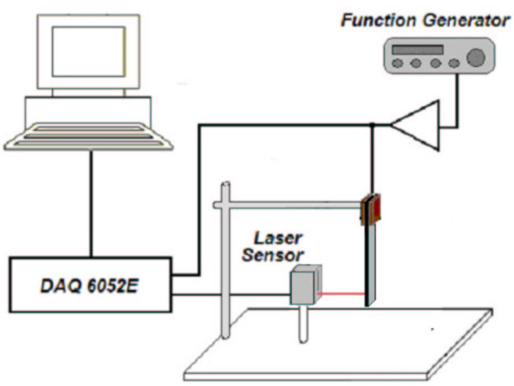

Figure 2. The block scheme of the measuring apparatus used to characterize the tip deflection of an IPMC strip.

2.1 Experimental Results

Applying the Marquardt algorithm to the acquired data, the obtained model is:

$$F(s) = \frac{k_0}{s^n\left(\frac{s}{p_1}+1\right)^m\left(\frac{s}{p_2}+1\right)^m} = \frac{k}{s^n\left(s^2+2\alpha s+\alpha^2+\beta^2\right)^m} \tag{1}$$

with $p_1 = \alpha + i\beta$ and $p_2 = \alpha - i\beta$, where the values of the parameters for the different IPMC lengths are shown in Table 1.

Table 1. Parameters values of the Fractional Order Model for different lengths of IPMCs.

$IPMCLength$	k_0	n	M	p_1	p_2
$25mm$	$3.89 * 10^{-4}$	0.62	1.15	$3 + i72$	$3 - i72$
$30mm$	$5.986 * 10^{-4}$	0.62	1.15	$1.72 + i50.7$	$1.72 - i50.7$
$35mm$	$7.516 * 10^{-4}$	0.62	1.15	$1.36 + i33$	$1.36 - i33$

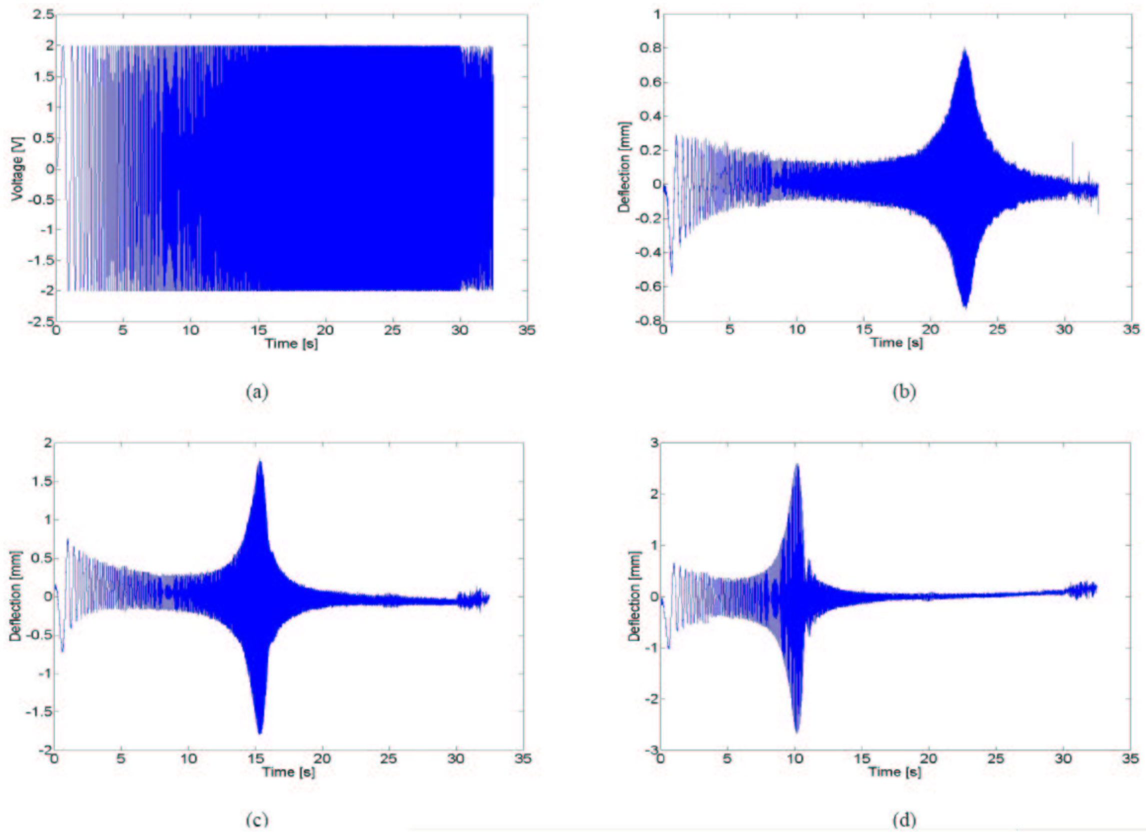

Figure 4. Measured signal: (a) Voltage input applied to the IPMC electrodes, (b) (c) (d) Tip deflection of the IPMC strip with length 25 mm, 30 mm and 35 mm.

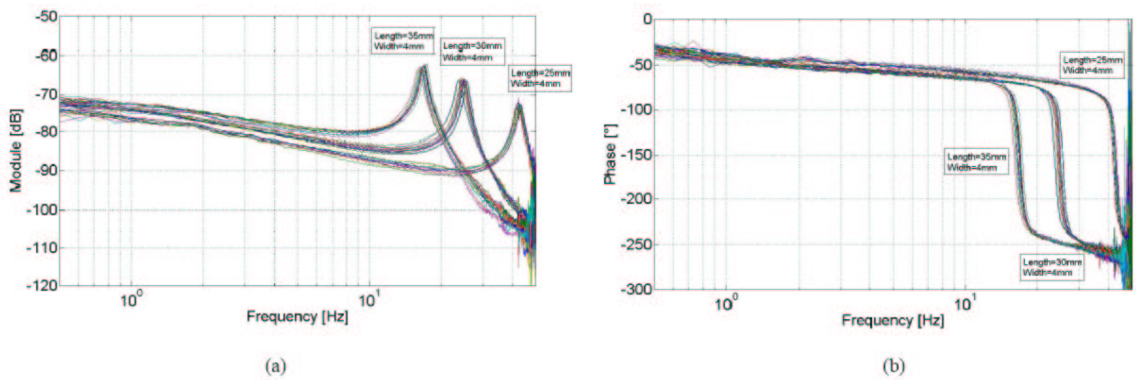

Figure 5. Measured signal: module (a) and phase (b) of the Voltage-Deflection transfer function for the 3 IPMC samples.

A comparison between the tip deflections of the cantilever IPMC as predicted by model and corresponding acquired data is shown in Fig. 6 for the three different lengths of IPMCs. More specifically, the module and phase Bode diagrams are shown, respectively. The graphs shown in the reported figures are referred to a 117 $Nafion^{®}$ IPMC with 25, 30 and $35mm$ long, $4mm$ wide, and $200m$ tick. Results show a good prediction of the frequency response. Examining the parameter values of the IPMCs Fractional Order Model:

1. The gain k increases with the increasing of the

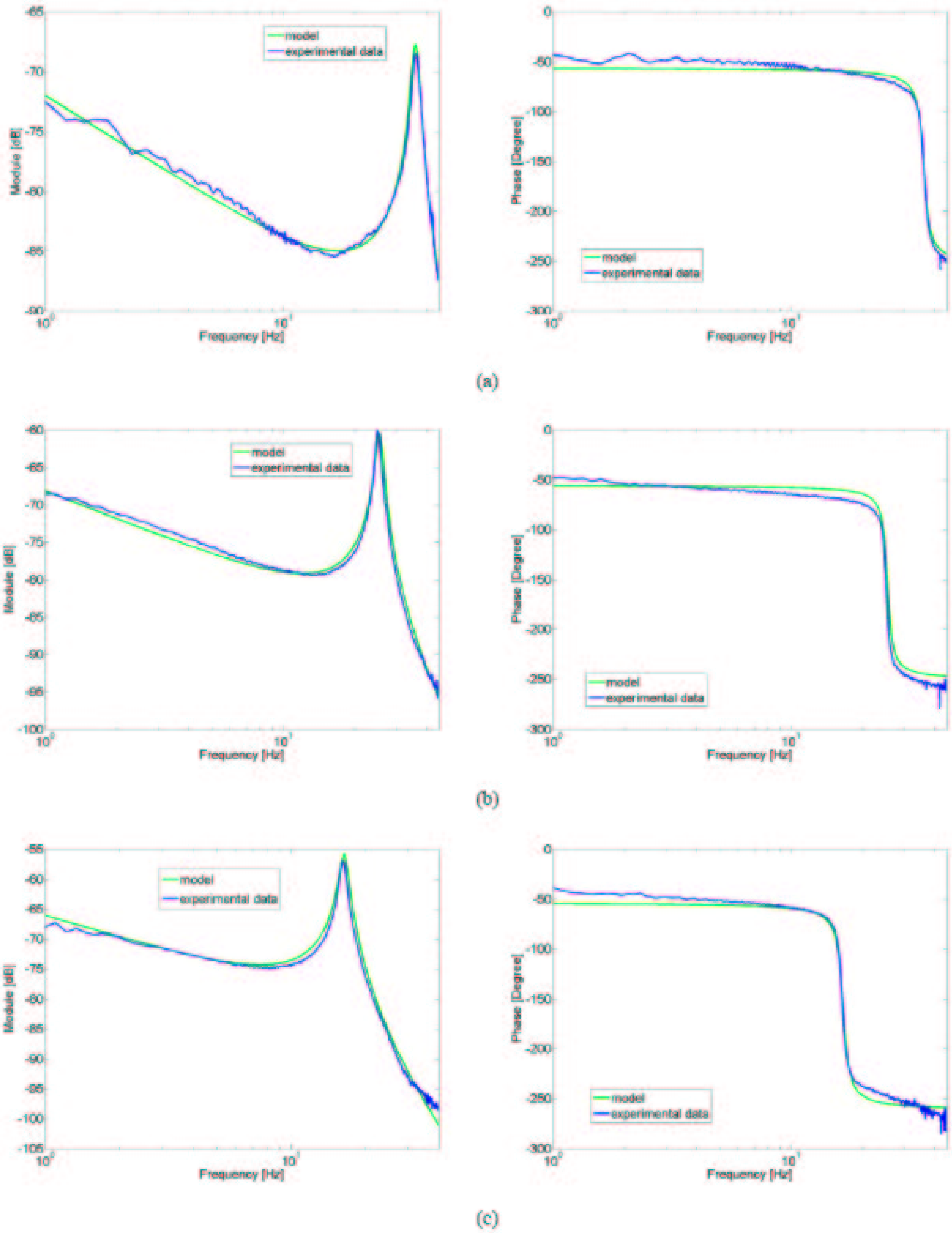

Figure 6. Experimental and simulated module and phase of the Voltage-Deflection transfer function for the 3 IPMC samples: (a) $L_{free} = 25mm$ (b) $L_{free} = 30mm$ (c) $L_{free} = 35mm$.

IPMC length.

2. The exponents n and m are practically independent respect to the IPMC length.
3. The real and imaginary part of the poles p_1 and p_2 decrease with the increasing of the IPMC length.

The parameters trend of the IPMCs Fractional Order Model is also observable in the Bode diagrams in the Figs. 5 and 5, because:

1. The exponent n determines the behavior of the IPMC strip at lower frequencies.
2. The real and the imaginary part of the poles p_1 and p_2 determine the resonance frequency and the amplitude at the resonance frequency.
3. The exponents m determines the lag-phase at the resonance frequency, that is equal to $m * 180°$.

3 Conclusion

In this paper a novel model for IPMC actuators has been presented. In particular a fractional order model has been developed after an experimental setup has been realized and the Marquardt algorithm has been developed in $Matlab^{®} Environment$.

The developed fractional order model is able to predict accurately the behaviour of the IPMC actuator according to the variations of the length of the IPMC strip.

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