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A comparison between robust and parameterized controllers for fractional order modeled Ionic Polymeric Metal Composite actuator

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Abstract:
In this paper a fractional order transfer function, identified from experimental data, is used to model IPMC actuators. The IPMC model is parameterized as a function of the actuator length. Two different control approaches are proposed and compared; the first one is a parameterized controller designed with a classical frequency domain strategy, while the second is designed by using a robust control approach.

1. INTRODUCTION

IPMC (Ionic Polymeric Metal Composite) are innovative materials made of a ionic polymeric membrane covered on both sides with a noble metal. It is known that IPMC can exhibit deformations if the metallic electrodes are forced by a voltage signal. Conversely, dynamic deformation of the IPMC membranes produces a voltage across their electrodes. So IPMC membrane can work either as low-voltage motion actuators or as motion sensor.

The evolution of IPMC technology from its infancy towards its full exploitation for the production of polymeric transducers, requires the development of applications in fields such as robotics, aerospace, and medicine, just to mention a few, with significant advantages with respect to competing technologies Shahi [2005]. Notwithstanding the large number of proposed applications, most of them are actually lab scale prototypes and further efforts are needed before IPMC based applications can influence real life quality.

The design of a control system for IPMC actuators requires adequate models, see classical modeling approaches in Nemat-Nasser [2009(] and Chen [2008]. Moreover such models can be scaled as a function of the parameters that the designer can fix in order to obtain the desired system performance, see Bonomo [2007].

IPMC are difficult to control because they are nonlinear and time-variant and can exhibit variable mechanical properties even when produced in the same batch. A number of control approaches are based on black-box models and therefore they are often dependent on the experiments performed for data acquisition. Even if some classical approaches have been proposed, like PID or LQG controller, intelligent, adaptive or robust controller design methodologies are usually applied to cope with model uncertainties, nonlinearity, time-variability and non-repeatability of the IPMC behavior.

One of the first papers in the area of IPMC control, see Mallavarapu et al. [2001], proposes a classical LQR controller to regulate the deformation of an IPMC actuator in order to improve the dynamic behavior. A more advanced approach is given in Lavu et al. [2005]. It proposes a model reference adaptive control (MRAC) structure for tracking control, along with a pole-placement approach, using a genetic optimization strategy to tune the parameters in order to deal with environmental variations, like humidity. A robust control designed to overcome uncertainties and non-repeatability by using the H^{∞} approach and $\mu -$ *syntesis* is proposed in Kang et al. [2007]. Shan et al. [2009] propose a model based frequency-weighted feed-forward controller designed to enable fast positioning while avoiding large voltages. A feedback controller is also used to take into account unmodelled effects. Ahn et al. [2010] shows a solution for IPMC high precision control based on the Quantitative Feedback Theory, in order to cope with the large parameter uncertainties, satisfying both robust tracking performance and the noise attenuation requirement. In Fang et al. [2011] the controller is designed both for IPMC actuators working in air and underwater on the basis of a black-box linear model. More recently in Kang et al. [2012] a time variant black-box model, identified with a real-time approach, is used to design an adaptive feed-forward controller. A noise cancelation technique is also used to alleviate the effects of plant disturbances.

In order to apply an effective control strategy is necessary to use a model. In their pioneering work, Bao [2002], Bao et all. proved that IPMC posses a fractal electrode structure. Starting from this work the authors in Caponetto [2008]

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have derived a fractional order transfer functions able to describe the dynamic of a IPMC actuator.

This model represents a realistic starting point to design effective controller. With these in view in the paper two controllers will be proposed: the first one is a parameterized controller designed with a classical frequency domain strategy, while the second is designed by using a robust control approach.

The paper is organized as it follows: a short introduction of IPMC features and its modeling phase is reported in section II, the two control approaches are proposed and described in sections III and IV respectively and some conclusive remarks are given in section V.

2. DATA ACQUISITION AND MEMBRANE MODELLING

2.1 Experimental setup for data acquisition

In this section few notes on IPMC manufacturing procedure are followed by the description of the experimental setup used to acquire the data that will be utilized in the successive IPMC membrane modeling phase.

IPMCs consist of a layer of ionic polymer, whose thickness is generally of the order of $100\mu m$, interposed between two conductive layers, to realize the electrodes. Noble metals, such as platinum and gold, are used to this purpose. Electrodes are used both to impose the electrical stimulus when an IPMC is used as an electromechanical transducer, and to collect electrical signals, when the IPMC is used as a sensor.

The most used polymer is Nafion, a perfluorinated alkene produced by Dupont. Since Nafion shares with Teflon its antiadherent property, electrodes cannot be simply applied to the polymer and a chemical plantation procedure needs to be used. More specifically, the standard impregnation reduction process, proposed by Dr. Oguro at $http : //ndeaa.jpl.nasa.gov/nasa - nde/lommas/eap/IPMC_PrepProcedure.htm$ was used.

Following this procedure, a sheet of Nafion 117, whose thickness is about $180\mu m$ is first allowed to soak in a platimun salt solution, typically $PtNH3Cl2$.

As the second step the membrane is soaked in a reducing agent, allowing metallic dendritic structures to build into the ion exchange membrane and to realize the electrodes at the membrane surface. It is generally accepted that such dentritic structure plays a main role in the electromechanical coupling behavior of the IPMC transducer since it contributes to a large increase in the effective area of the electrodes.

As a result of the production steps, a sample, soaked in water and whose thickness is abot $200\mu m$, is obtained. This has been further cut to obtain the transducers with the desired shape, i.e. rectangular strips with different length and width.

Different theories have been proposed to explain the electromechanical transduction properties of IPMCs. More specifically, Tadokoro et al. proposed that the actuation mechanism is due to the migration of mobile ions under the effect of the external electric field, see Takadoro [2000].

When a voltage signal is applied across the thickness of the IPMC, mobile cations will move toward the cathode. Moreover the cations will carry solvent molecules with them with a resulting bending of the membrane, see figure 1(a).

Considering the beam parameters, the length L_{free} and the cross-sectional dimensions, thickness t and width w, it will be assumed that the beam vibrates in the vertical plane, see figure 1(b).

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 photo of the experimental setup is shown in figure 1(c).

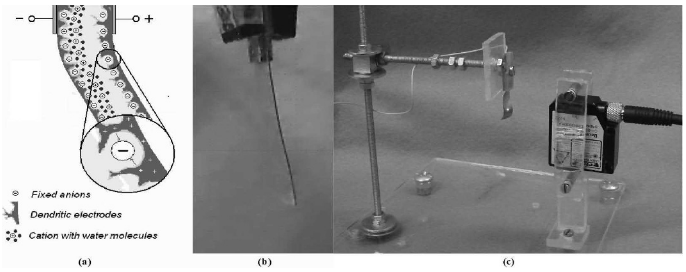

Fig. 1. (a) Chemical process of IPMC, (b) IPMC beam, (c) photo of experimental setup.

The deflection of the cantilever tip was measured by using the laser sensor Baumer Electrics OADM12U6430. Light from the laser diode was focused onto the end of the cantilever. The absorbed current is transduced by using a shunt resistor.

As an example the voltage input imposed to the membrane andthe deflection of the cantilever tip are shown in figure 2(a) and 2(b), respectively.

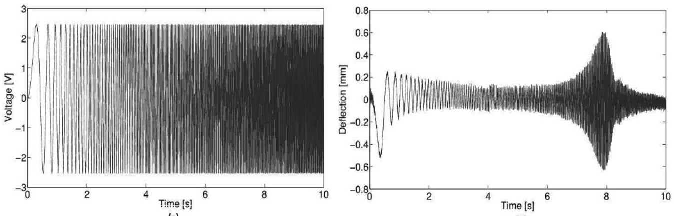

Fig. 2. Voltage input applied to the membrane (a), Deflection of the cantilever tip measured with the laser sensor (b).

The voltage input signal is a chirp signal spanning from $500mHz$ to $100Hz$. Using a sampling frequency equal to $1000samples/s$, 10000 samples are obtained for a data acquisition campaign lasting 10 s. 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.

By the inspection of Bode diagrams, see figure , it can be obseerved that the systems present a non integer order behavior, Caponetto [2010]: the module of the Bode diagrams presents a slope equal to $m * 20db/decade$, and

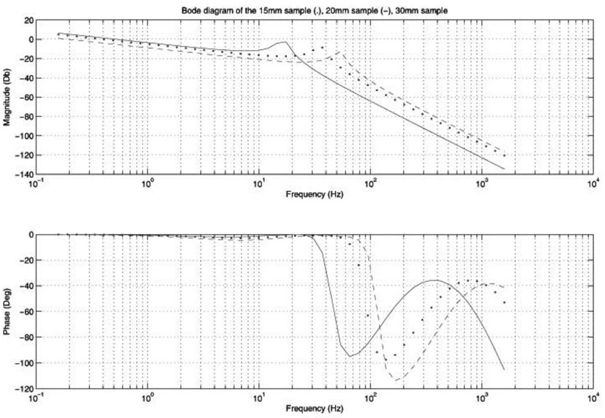

Fig. 3. Module and phase of three IPMC samples with different length. Continuous $15mm$, dotted $25mm$ and dashed $30mm$.

the phase Bode diagrams present a phase lag equal to $m*90^o$, where m is a suitable real number. The system can therefore identified by fractional order model which allows to obtain good modeling performance by using a small set of parameters, see Bonomo [2007] and Caponetto [2008].

2.2 Fractional Order System

The subject of fractional order calculus or non integer order systems, i.e., the calculus of integrals and derivatives of any arbitrary real or complex order, has gained considerable popularity and importance during the last three decades with applications in numerous seemingly diverse and widespread fields of science and engineering Oldham [2006], Podlubny [1999] and Caponetto [2010].

Transmission lines, electrical noises, power-law, dielectric polarization, heat transfer phenomena, systems with long-range interaction, Ionic Polymer Metal Composites modeling and biomedical engineering, are some examples of systems described by using non integer order physical laws.

Fractional derivatives provide an excellent tool for the description of memory and hereditary properties of various materials and processes. This is the main advantage of fractional derivatives in comparison with classical integer-order models, in which such effects are in fact neglected. The advantages of fractional derivatives become apparent in modeling mechanical and electrical properties of real materials.

The most frequently used definition for the general fractional differintegral is the Caputo one, see Caponetto [2010]:

$$ {}_aD_t^r f(t) = \frac{1}{\Gamma(r-n)} \int_a^t \frac{f^{(n)}(\tau)}{(t-\tau)^{r-n+1}} d\tau, \quad (1) $$

for $(n-1 < r < n)$. The initial conditions for the fractional order differential equations with the Caputo derivatives are in the same form as for the integer-order differential equations.

In the above definition, $\Gamma(m)$ is the factorial function, defined for positive real m, by the following expression:

$[mm]$	Hz	α	β
15	53.86	26	330
18	41.5	25	262
20	35.36	20	223
25	24.31	10	153
27	21	10	133
30	16.36	7	103

Table 1. Model parameters according to the sample length.

$$ \Gamma(m) = \int_0^\infty e^{-u} u^{m-1} du \quad (2) $$

Also for fractional order systems it is possible to apply the Laplace transformation. It assumes the form:

$$ L\left\{\frac{d^q f(t)}{dt^q}\right\} = s^q L\{f(t)\} - \sum_{k=0}^{n-1} s^k \left[\frac{d^{q-1-k} f(t)}{dt^{q-k-1}}\right]_{t=0} \quad (3) $$

and allow to easily manage fractional differential equation as non integer order transfer function.

In the following non integer order model of IPMCs will be considered. 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.

2.3 Membrane modeling

The fractional order models has been determined by using the Marquardt algorithm, see Marquardt [1963], with the available experimental data. The Levenberg-Marquardt method is commonly used to solve nonlinear least squares problems. The Levenberg-Marquardt curve-fitting method is actually a combination of two minimization methods: the gradient descent method and the Gauss-Newton method. It is similar to a gradient-descent method when the parameters are far from their optimal value, and acts more like the Gauss-Newton method when the parameters are close to their optimal value. The models obtained for the voltage-deflection transfer function, have be determined according to the following relation:

$$ G(s) = \frac{k}{s^n(s^2 + 2s\alpha + \alpha^2 + \beta^2)^m} \quad (4) $$

with $n = 0.62$ and $m = 1.15$. Parameter α and β depends of the IPMC membranes length as reported in table 1. In order to perform the IPMC control system design the resonance frequency as been parameterized as a function of the membrane length, so that the parametric controller can be designed.

$$ f_r = 0.09L^2 - 6.4L + 130 \quad (5) $$

Starting from the fractional order IPMC model (4), in the following two different type of controllers are proposed The first one is a parametric controller designed using a a classical frequency domain procedure while the second one is designed using robust control theory.

3. PARAMETERIZED CONTROL OF THE MEMBRANE

The goal of this approach is to determine a parameterized controller that depends on the values of α and β in equation (4). System performance aims to enlarge the bandwidth and to ensure a good tracking error of the IPMC membrane actuator.

In the parameterized control approach the open loop system is characterized by the presence of a three blocks controller: $C(s) = C_a(s)C_b(s)C_c(s)$. The roles of each block is defined as it follows. $C_a(s)$ has been added in order to guarantee a finite error to the step input. In fact it consists in a zero with slope 0.62 and in a gain that has been fixed with a trail and error procedure. The $C_b(s)$ is the parameterized block and has been added to obtain a good phase margin at the desired crossover frequency. $C_s(s)$ has been designed to guarantee a good tracking error inside the desired band width. The controller is therefore defined as it follows.

$$C_a(s) = 33s^{0.62} \tag{6}$$

$$C_b(s) = \frac{(1+s\tau)^3}{(1+s\frac{\tau}{m})^3} \tag{7}$$

where

$$\tau = \frac{0.5}{(2\pi f_r * 3.5)} \tag{8}$$

$m = 10$ and

$$C_c(s) = \frac{(1+\frac{s}{16\pi})}{(1+\frac{s}{2\pi})}; \tag{9}$$

The obtained open loop and closed loop transfer functions are reported in figures 4 and 5 respectively.

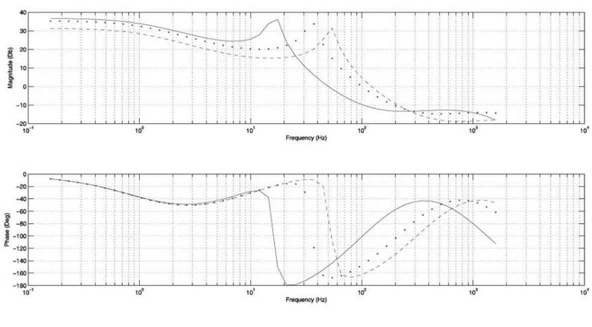

Fig. 4. Module and phase of the open loop transfer function with $C(s) = C_a(s)C_b(s)C_c(s)$.

As it can be observed from the Bode diagram of the controlled systems a crossover frequency greater than $50Hz$ has been obtained for any membrane length, corresponding to a bandwidth greater than $80Hz$. Regarding the phase margin the worst case, $M\phi = 20°$ and the best $M\phi = 80°$, have been obtained for the $15mm$ and $30mm$ length respectively, see Caponetto [2012] .

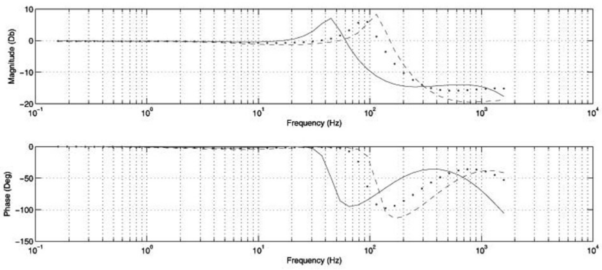

Fig. 5. Module and phase of the closed loop transfer function with $C(s) = C_a(s)C_b(s)C_c(s)$.

4. SINGULAR VALUE LOOP SHAPING FOR MEMBRANE CONTROL

The second control approach proposed in the paper is based on the singular value loop shaping, see Doyle [1979] and Safonoc [1980]. Let take into account the closed loop control system depicted in figure 6.

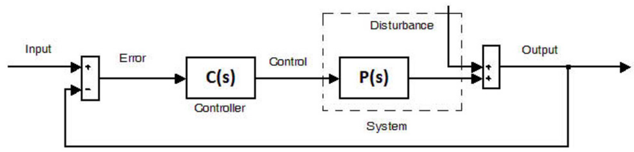

Fig. 6. Closed loop scheme for the singular value loop shaping approach.

In order to quantify the stability margins and performance of the systems, it is possible to use the singular values of the closed loop transfer function matrices from the input to each of the three outputs; error, control and system output given by:

$$\begin{aligned} S(s) &= (I + L(s))^{-1} \\ R(s) &= C(s) * (I + L(s))^{-1} \\ T(s) &= L(s) * (I + L(s))^{-1} \end{aligned} \tag{10}$$

The two matrices $S(s)$ and $T(s)$ are the sensitivity and complementary sensitivity, respectively. The singular values of $S(s)$ determine the disturbance attenuation since $S(s)$ is the closed loop transfer function from disturbance d to plant output y. Thus a disturbance attenuation performance specification cab be written as:

$$\bar{\sigma}(S(jw)) \leq |W_1^{-1}(jw)| \tag{11}$$

The singular value Bode plots of $R(s)$ and of $T(s)$ are used to measure the stability margins the system in face of additive plant perturbations and multiplicative plant perturbations respectively.

Therefore it is common to specify the stability margins of control systems via singular value inequalities such as:

$$\bar{\sigma}(R(jw)) \leq |W_2^{-1}(jw)| \tag{12}$$

and

$$\bar{\sigma}(T(jw)) \leq |W_3^{-1}(jw)| \quad (13)$$

where $|W_2^{-1}(jw)|$ and $|W_3^{-1}(jw)|$ are the respective sizes of the largest anticipated additive and multiplicative plant perturbations.

In the proposed approach the different length of the IPMC membrane are treated as multiplicative plant perturbation and the singular values shaping has been applied to determine a controller robust versus different IPMC lengths.

In order to determine the controller the $Matlab$ Robust control toolbox has been used with the following shaping functions:

$$W_1(s) = \frac{(s + 10000)}{(0.01 + s)} \quad (14)$$

$$W_2(s) = 0 \quad (15)$$

and

$$W_3 = \frac{0.56(1 + 0.22s)(1 + 0.0006s)^2}{(1 + 0.002s)^3} \quad (16)$$

The obtained controller has the following transfer function, (17), and the Bode diagram of the closed loop responses for the three membranes are shown in figure 7.

As it can be noted, system performances are guaranteed both for the magnitude and phase in useful frequency range and the resonance picks for all the membrane are almost all canceled.

$$C(s) = \frac{1.651e011s^6 + 2.51e014s^5 + 1.327e017s^4 +}{s^7 + 3.938e004s^6 + 6.899e008s^5 + 6.992e012s^4 +}$$

$$\frac{2.894e019s^3 + 3.324e021s^2 + 4.852e023s + 2.018e016}{5.72e015s^3 + 1.201e018s^2 + 9.712e020s + 5.964e018} \quad (17)$$

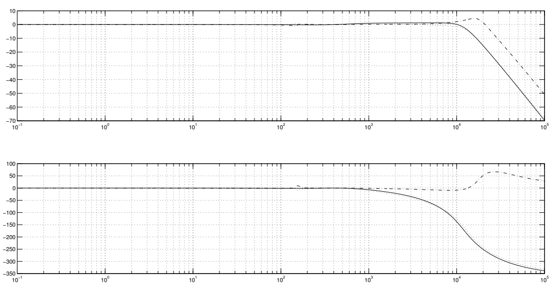

Fig. 7. Bode diagram of the closed loop robust controller for the three membranes. Continuous $15mm$, dotted $25mm$ and dashed $30mm$.

5. CONCLUDING REMARKS

In the paper a non integer order model and two control strategies for IPMC actuators have been presented. The first controller, designed using a trial and error approach is scaled as a function of the device length. The design procedure is simple and the results, showed in figure 6, are encouraging. The resonance peaks are out from the desired band, $80HZ$ but still remain present. On the other end the robust control approach is more effective, see figure 7 even the controller realization could more difficult due to the order of the controller and to the values of its coefficients.

Studies under development are planned in order to first reduce the robust controller order using model order reduction techniques and successively to implement and compare both controllers on an hardware in the loop system.

The obtained controllers, at present Matalb routines, will be implemented comparing three digital approaches; the Grunwald-Letnikov one, the direct method based on mixed operator, and the continued-fractions delta-domain approach.

Furthermore a new set of measurements, with variable sampling period, are going to be performed in order to model IPMC membranes produced with different fabrication parameters.

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