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Research Article

Identification of IPMC nonlinear model via single and multi-objective optimization algorithms

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ABSTRACT

Ionic Polymer–Metal Composites (IPMCs) are electro-active polymers transforming mechanical forces into electric signals and vice versa. This paper proposes an improved electro-mechanical grey-box model for IPMC membrane working as actuator. In particular the IPMC nonlinearity has been characterized through experimentation and included within the electric model. Moreover identification of the model parameters has been performed via optimization algorithms using both single- and multi-objective formulation. Minimization was attained via the Nelder–Mead simplex and the Genetic Algorithms considering as cost functions the error between the experimental and modeled absorbed current and the error between experimental and modeled displacement. The obtained results for the different formulations have been then compared.

1. Introduction

In the last decade a new breed of polymers, known as electro-active polymers or more commonly EAPs, has emerged thanks to their electro-active capabilities [1]. Ionic Polymer–Metal Composites (IPMCs) [2] belong to this materials class; they bend when solicited by an external electric field and act as motion sensor when an external deformation is applied. They are characterized by several interesting properties such as high compliance, lightness and softness. IPMCs exploit ionic polymers for electrochemical transduction and noble metals as electrodes and they represent a promising alternative to classic actuators and/or sensors in a number of application fields. They can be cut in any shape and size, they are characterized by large deformations applying very low level of voltage and they can work in humid or wet environment. These properties make them particularly attractive for possible applications in very different fields such as robotics, aerospace and biomedicine [3,4].

1.1. IPMC modeling

Intense research is currently carried out in order to improve the smart material performances in terms of power consumption, developed force, and deformation [5,6]. Moreover research efforts have been spent in finding improved models that are able to predict the EAPs behavior both as actuators and sensors [7,8]. Such advanced modeling methods are necessary in the definition of guidelines to the designers for fabrication strategies and performance optimization of this class of transducers [9–11].

Several models that describe the IPMC as actuator can be found in the literature. In detail, they can be sorted into three categories: white box, black box and grey box models.

The first category, called white box, or physical models, is based on the underlying physical mechanisms of the IPMC to develop a system of equations that fully describe the device response [12–14]. Numerical implementation via methods such as Finite Element Analysis can be found in the literature [15,16]. Some difficulties are presented with physical modeling of IPMC transducers, such as a complete knowledge of the chemical and/or physical mechanisms involved in the electromechanical transduction and the direct measurement of some material parameters; moreover the numerical implementation is computationally onerous due to the distributed nature of the problem solution.

The second approach for modeling IPMC actuators is called black-box and uses a linear [17] or differential [18] equation to simulate the actuating behavior. In [19] the authors have exploited black box identification, based on Hammerstein models, identifying the nonlinear and the linear model of a similar device, an IP^2C, by using a single set of input/output data in order to compare the identification performances.

These models, also called empirical and phenomenological, are based on identification of some coefficients obtained through a

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series of curve fits based on experimental data and the internal physics is only a minor consideration.

An alternative to the complicated physical models and the simplistic empirical models, which are not scalable, is grey box models. They comprise the fundamental physical laws into time-domain equation or frequency representation and empirically identified parameters to describe IPMC electromechanical behavior [20–24,28].

1.2. Grey-box model identification

The grey-box model identification is often a multi-objective optimization problem in a multi-dimensional space since multiple cost functions can be used for parameters estimation. A very popular method in the field of parameter identification is the Nelder–Mead unconstrained simplex algorithm [29]. The method works on the exploration of the design space and does not require any derivative information, being therefore suitable for problems with non-smooth functions. It is widely used in optimization software tools (i.e MATLAB®) to solve parameter estimation and similar statistical problems, when the function values come from experimentation and are thus uncertain or subject to noise [30]. On the other hand, the simplex method is prone to local minima issues and the lack of convergence theory is often reflected in practice as a numerical breakdown of the algorithm, even for smooth and well-behaved functions.

These disadvantages can be overcome by evolutionary optimization that explores a poorly understood solution space in parallel by intelligent trials. More specifically Genetic Algorithms (GAs) are global optimization techniques and, therefore, when applied on a single objective problem, they converge to the global solution rather than to a local solution. Modified Genetic Algorithms can be applied on multi-objective problems [31]. In this paper GAs are used as global optimization algorithm to determine the parameters of the considered IPMC membrane.

The paper is structured as follows. A view on IPMC physics and working principles is presented in Section 2 to give an introduction on such a composite material. Moreover the description of the experimental setup is given as the basis for understanding the experimental data used for model identification and parameter estimation.

In Section 3 a grey-box electromechanical model of the IPMC actuator is presented and a novel method based on experimental data is proposed for IPMC nonlinearity identification.

In Sections 4 and 5 the authors investigate on both single-objective and multi-objective optimization methods for optimal parameter estimation; in particular the Nelder–Mead simplex and the Genetic Algorithms have been applied.

In Section 6 final conclusions are given.

2. IPMC: physics and experimental configuration

2.1. Working principles and manufacturing

IPMCs consist of a fluorocarbon membrane containing sulfonate groups covered on both sides with a thin noble metal coating layer, the core of device is based on Nafion®, distributed by DuPont™. The IPMC actuator sample considered in this paper is manufactured with three primary coatings and one secondary coating of platinum. To increase platinum deposition the dispersing agent polyvinylpyrrolidone (PVP) has been used with a concentration of 0.001 M [2,6]. The characteristics of such an ionic polymer working in a humid environment allow the IPMC to work as actuator.

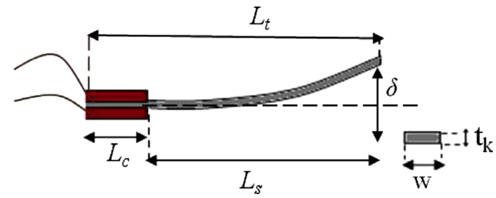

Fig. 1. Example of measurement to extract the experimental nonlinearity trend.

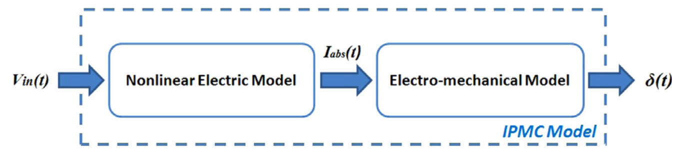

Fig. 2. IPMC grey-box model: nonlinear electric and electro-mechanical cascade models.

2.2. Experimental setup

The IPMC model was developed considering the configuration of a beam clamped at one end, as schematized in Fig. 1. The pinned end is also used to apply the electrical stimulus to the polymeric actuator via the electrodes and to perform the experimental measurement on the absorbed current (I_{abs}) through a suitable conditioning circuit. The geometric parameters of IPMC, as reported in Fig. 1, are L_S=20 mm, L_C=10 mm, t_k = 200 μm, ω = 5 mm.

The input signals (V_{in}) are applied to the IPMC electrodes, the absorbed current I_{abs} is acquired by using an acquisition board (*National Instrument, DAQ NI6052*) at a sampling frequency of f_S=3 kHz. Moreover the free displacement (δ) in the vertical direction has been acquired by a laser distance sensor (*Baumer Electric OADM 12*).

3. IPMC actuator grey-box model

This paper reports the identification of a grey box nonlinear model of an IPMC motion actuator working in air.

The model is in the Hammerstein form and is divided into two parts as depicted in Fig. 2.

It is known from IPMC literature that the nonlinear part can be modeled, see [23,25], and simplified as in (1). Different approaches are used to identify this nonlinearity. In [25] and [26] a variable amplitude set of sinusoidal signals is applied as input for both nonlinear (Volterra series) and linear parts identification. In [27] a variable amplitude step signal is used to identify both the linear and nonlinear part (NARMAX model with nonlinear basis function).

In our approach, which differs from the previous ones, the identification of the nonlinear and linear parts is sequential.

As a first step, the dependence of the IPMC absorbed current ($I_{abs}(t)$) on the voltage ($V_{in}(t)$) applied across its thickness is taken into account; a nonlinear circuit model is proposed to describe this relationship [23].

In a second step the transduction of the absorbed current into the IPMC mechanical displacement ($\delta(t)$) is modeled. The model resulting from the cascade of both the electrical and the electromechanical stage allows to predict the electromechanical behavior of the IPMC actuator.

3.1. Nonlinear electric model

The electric stage is modeled by using a circuit where the nonlinear block *NL* is included [23]. In detail, the circuit is reported in Fig. 3.