Sensors and Actuators A 224 (2015) 43–49

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

# A model based predictive compensation for ionic polymer metal composite sensors for displacement measurement

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ARTICLE INFO

*Article history:*
Received 28 March 2014
Received in revised form 12 January 2015
Accepted 12 January 2015
Available online 20 January 2015

*Keywords:*
Ionic polymer metal composite
Sensor
Hysteresis
Model
Compensation
Prediction

ABSTRACT

It is known that IPMC sensors can be used for the measurement of displacement and vibration. However, the IPMC sensors are also involved with both hysteresis and dynamics which significantly affect the performance of the measurement. In this paper, a model based compensation scheme to degrade the effect of hysteresis and dynamics is proposed. Firstly, a modeling method to describe the characteristics of an ionic polymer metal composite (IPMC) sensor is proposed. As the hysteresis in IPMC is a non-smooth nonlinearity with multi-valued mapping, an expanded input space with hysteresis operator is introduced to transform the multi-valued mapping of hysteresis to a single-valued mapping. To describe the dynamic and hysteretic characteristics, a nonlinear auto-regressive and moving average model with exogenous input (NARMAX) is used to describe the behavior of the IPMC sensor. By considering the case that time-delay exists in IPMC sensor, a d-step-ahead nonlinear predictor based on the obtained model is developed. Subsequently, the corresponding model based predictive compensator is constructed to compensate for the effect of hysteresis, dynamics and time-delay inherent in IPMC sensor. In this scheme, the compensator is developed based on inverse model of the sensor on the expanded input space consisting of the output of sensor and the output of inverse hysteretic operator. Finally, the experimental results are demonstrated to validate the proposed model based compensation scheme for IPMC sensors.


## 1. Introduction

Ionic polymer metal composite (IPMC) is an electroactive polymer material and can be used as both actuators and sensors [1]. The advantages of using IPMC as sensors are lightness, softness, flexibility, and biocompatibility [2,3]. However, similar to the other smart material based sensors, they also have hysteresis. Moreover, the temperature and humidity have influences on the performance of IPMC [4–6]. Those complex characteristics will degenerate the performance of the sensor and decrease the accuracy of measurement. It is known that the expected relation between the input and output of a sensor should be linear. However, the above-mentioned complex characteristics of IPMC sensor are nonlinear. They should be compensated in order to derive a linear input and output relation. Usually, the model based compensation scheme for an IPMC sensor is one of the very important alternatives. To construct a model-based compensator, a nonlinear model to describe the complex features of an IPMC sensor, i.e. hysteresis, creep and uncertain phenomenon should be built.

Up till now, there have been some methods to build models of IPMC sensors or actuators [5–14,27]. Ref. [5] analyzed the characteristic of an IPMC actuator affected by temperature and humidity and used a gray-box approach to establish the model of IPMC actuator, while Ref. [6] built a phenomenal model to describe the influence of temperature and humidity on IPMC sensor. Ref. [7] proposed a dynamic model of IPMC based on equivalent passive electric network components. On the other hand, the physics-based models of IPMC transducers have been proposed [8–10]. Ref. [27] proposed an inverse modeling and compensation method to compensate the dynamics in IPMC sensor. Ref. [11] developed a model to describe the electromechanical charge sensing of IPMC transducers. For description of the characteristic of IPMC actuators, Ref. [12] proposed a modeling scheme based on ANFIS–NARX method. However, the modeling methods shown in [5–12] were lack of the consideration of the influence of hysteresis on the performance of IPMC transducers. In fact, some researchers have already paid attention to the influence of hysteresis on the behavior of IPMC transducers. For example, Ref. [13] proposed a Preisach type fuzzy NARX model for modeling of IPMC actuators. Also, Refs. [14,25] constructed a discrete-time Preisach model for IPMC actuators. On the other hand, Ref. [24] employed a discrete-time Prandtl–Ishlinskii (PI) model to describe the hysteresis in IPMC actuators. However,

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http://dx.doi.org/10.1016/j.sna.2015.01.015

those methods are just available to the case of rate-independent hysteresis moreover the architectures of Preisach model and PI model are not so simple since large number of hysteretic operators and backlash operators, e.g. one or two hundreds should be employed in order to obtain good approximation of hysteresis.

Although there have existed different modeling methods for hysteresis [15–21], most of them are not used to model the hysteresis properties in IPMC sensors except some models for hysteresis of IPMC transducers [13,14,24,25]. It is known that the characteristic of IPMC is very complicated due to the existence of hysteresis and complex dynamics etc. Hence, it is necessary to build a proper model to describe the performance of IPMC sensor including both hysteresis and complex dynamics.

In this paper, a phenomenal model taking account of the effect of hysteresis and dynamics for an IPMC sensor is proposed. In this modeling method, the first thing we will do is to introduce an expanded input space with hysteretic operator to transform the multi-valued mapping between the input and output of hysteresis in IPMC sensor into a single-valued mapping. In order to describe the nonlinear dynamic characteristic of the IPMC sensor, a nonlinear auto-regressive and moving average model with exogenous input (NARMAX) is applied due to its inherently dynamic characteristic. By considering the existence of time-delay in IPMC sensor may affect its performance of response, a d-step-ahead nonlinear predictive scheme to compensate the effect of time delay based on the obtained model is developed. Then, a model based predictive compensator to suppress the effect of hysteresis, dynamics and time-delay of the sensor is proposed.

This paper is organized as follows: In Section 2, the experimental setup of IPMC sensor test is illustrated. Then, the data of the sensor are analyzed. In Section 3, the NARMAX model based on the constructed expanded input space is presented to model the behavior of the IPMC sensor. Moreover, the corresponding nonlinear d-step-ahead predictor based on the obtained NARMAX model to overcome the effect of time-delay is built. After that, in Section 4, the model based predictive compensator is constructed. In Section 5, the experimental results of modeling as well as nonlinear dynamic compensation are illustrated. Finally, the conclusions are presented.

## 2. Experimental setup for IPMC sensor test

The IPMC has a sandwich structure consisting of three layers, with an ion-exchange polymer membrane sandwiched by metal electrodes. The corresponding principles of IPMC actuators and sensors have been described by Refs. [9,10], respectively. Inside the polymer (negatively charged) anions covalently fixed to polymer chains are balanced by mobile (positively charged) cations. Deformation under externally mechanical perturbation redistributes the cations, producing a detectable electric signal (e.g. open-circuit voltage) that is related to the corresponding mechanical deformation [1,10].

The experimental setup used to test the performance of IPMC sensor operating in dry air is shown in Fig. 1. In Fig. 1, the IPMC sensor is deformed by a stepping motor through a driveshaft. Then, the deformation of the IPMC senor is measured by a laser displacement sensor (LK-G5000, Keyence Co.), while the electric signal produced by the IPMC sensor is amplified by a signal conditioning circuit. As the time constant of the amplifier is very small comparing with the sensor. Thus, it can be regarded as a gain. In the experiment, the data measured by both laser displacement sensor and signal conditioning circuit are sent to a real-time signal processing system implemented by a data acquisition (DAQ) board (PXI-6225) of the National Instruments in Labview environment.

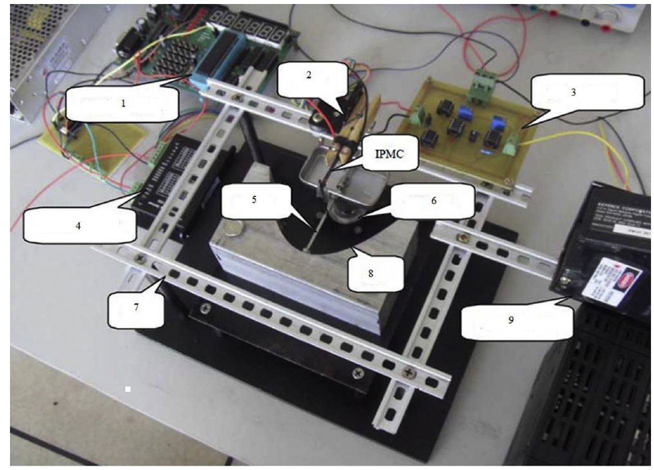


**Fig. 1.** The experimental setup for IPMC sensor (1 – single chip control circuit, 2 – electrode clamp, 3 – signal conditioning circuit, 4 – Stepping motor driver, 5 – driveshaft, 6 – stepping motor, 7 – guide rail, 8 – parabola slideway, 9 – laser sensor).

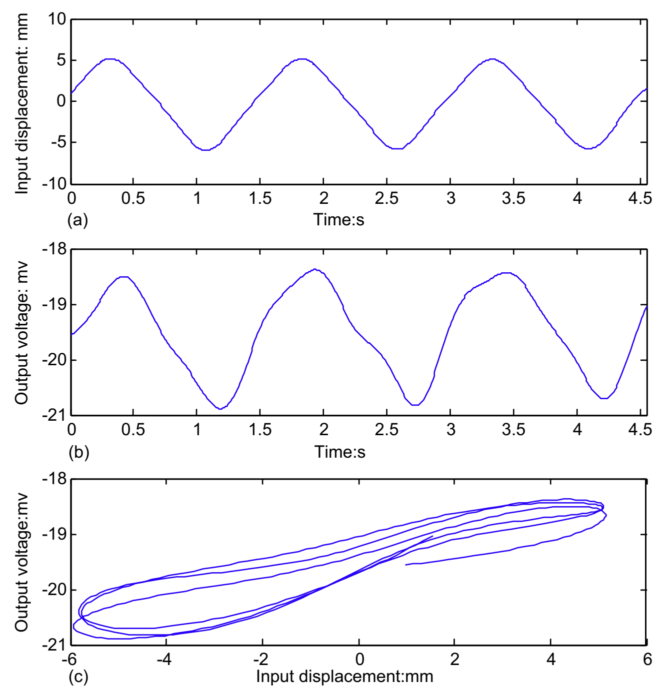


**Fig. 2.** Characteristics of the IPMC sensor's output voltage stimulated by displacement with triangle variation.

In the experiment, the geometric size of IPMC strip (produced by Nanjing University of Aeronautics & Astronautics) is 30 mm × 5 mm × 0.5 mm, and IPMC strip was deformed by a periodic force under 25 °C and 60% relative humidity, moreover, the force being added at the tip of the IPMC membrane and measuring point also being at the tip of the IPMC slice. The input of the sensor is the deformation displacement of the IPMC membrane and its output is the voltage of the signal conditioning circuit. The sampling frequency is chosen as 1 kHz.

When the excitation signal is a triangular wave series with period of 1.5 s, the corresponding input and output curves of the IPMC sensor are shown in Fig. 2. From Fig. 2(c), it is known that characteristic of hysteresis is inherent in the IPMC sensor. Moreover, from Fig. 2, we can see that the sensor involves not only hysteresis but also dynamic drift. When the sensor measures the displacement with time-varying amplitude, the corresponding response of