Quasi-static Positioning of Ionic Polymer-Metal Composite (IPMC) Actuators

Zheng Chen, Xiaobo Tan*, and Mohsen Shahinpoor

***Abstract*— Ionic polymer-metal composites (IPMCs) generate large bending motions under a low driving voltage (about 1 V). In this paper quasi-static actuation of IPMC is investigated with the goal of precise positioning. It is found that IPMC exhibits hysteresis between its bending curvature and the applied quasi-static voltage. The Preisach operator is proposed to model the hysteresis, and its density function identified experimentally. An open-loop positioning strategy is presented based on efficient inversion of the Preisach operator, and its efficacy is demonstrated by experimental results. Finally a cascaded model structure is proposed to capture both the hysteresis and the dynamics of IPMC actuators.**

I. INTRODUCTION

Ionic polymer-metal composites (IPMCs) form an important category of electroactive polymers [1]. An IPMC sample consists of a thin polyelectrolyte film, chemically plated on both surfaces with a noble metal (typically platinum or gold). The sample bends when subject to an applied voltage of 1-2 V (see Fig. 1 for illustration); conversely, a voltage (in millivolts) is generated across the surfaces when the sample is subject to mechanical loading [2]. Thus an IPMC has both built-in actuation and sensing capabilities.

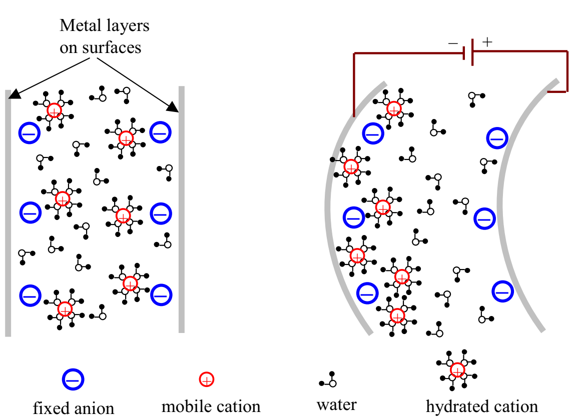

Fig. 1. Illustration of the actuation principle of IPMC [2]. (a) before a voltage is applied; (b) after a voltage is applied. Hydrated cations move quickly toward the cathode creating pressure imbalance leading to bending; at a slower time scale, back-relaxation takes place possibly due to back-diffusion of loose water molecules (not shown in the figure).

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IPMCs have won the nickname *artificial muscles* due to their large bending displacement, low driving voltage, resilience, and biocompatibility, and have been explored for potential applications in biomimetic robotics [3], [4], medical devices [5], and micromanipulators [6], [7], [8]. In most of these applications, IPMC actuators were driven dynamically. Indeed the back-relaxation phenomenon in IPMCs [9] leads to the doubt whether IPMCs are suitable for DC actuation. To address this issue, linear feedback laws were attempted for positioning control where IPMCs were modeled as linear systems [10], [11].

In this paper the behavior of IPMCs under a quasi-static input is investigated. The motivation is two-fold: a) to understand and model the characteristics of IPMCs under DC actuation, and b) to develop an (open-loop) control scheme for positioning based on the quasi-static model. The (counterintuitive) advantage of open-loop control over feedback is that external sensing device and circuitry are not needed, which can be very important in microsystems.

There are a number of dynamic processes (e.g., ion migration, water diffusion) taking place in IPMC actuation despite that the exact mechanisms are still a subject of active research [12], [13], [9]. Under a quasi-static input, the dynamic effects die out. A hysteretic relationship between the steady-state curvature and the applied voltage is observed. To the authors' knowledge, this is the first formal, careful study on hysteresis in IPMCs, although the *electrically induced permanent strain* [14] could be an indication of hysteresis. A Preisach operator [15] is used to model the hysteresis in IPMC. Note that the Preisach operator models hysteresis as a weighted superposition of elementary delayed-relay operators (called Preisach *hysterons*). An open-loop positioning strategy is obtained through inversion of the Preisach operator. Experimental results on comparison with a non-hysteretic model-based positioning show that the proposed modeling and control approach is effective.

A model structure is further proposed for IPMC actuators, which is aimed at accounting for both the hysteresis nonlinearity and the dynamics. In this structure a linear dynamical system is preceded by a hysteresis operator (represented by the Preisach operator). The underlying rationale is that the overall model should degenerate to the Preisach operator alone under quasi-static conditions, while the choice of a linear system (versus a nonlinear system) offers convenience in controller design. Experimental evidences are presented to support the proposed model structure.

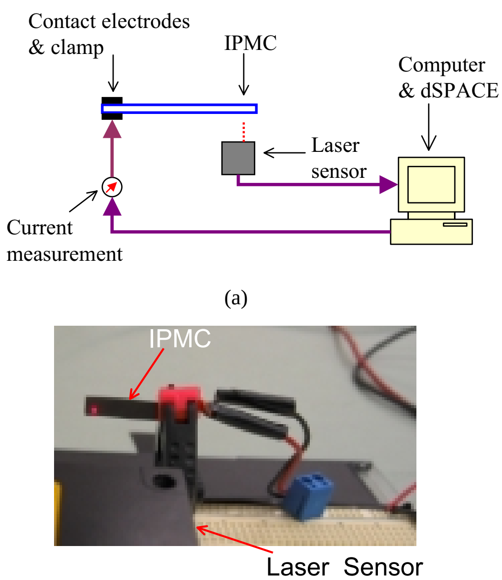
The remainder of the paper is organized as follows. In Section II the experimental setup is introduced. Experiments to verify and identify hysteresis are described in Section III. A brief introduction to the Preisach operator is also provided in this section. In Section IV inversion-based open-loop positioning of IPMC is discussed. A cascaded model structure for IPMCs is proposed in Section V. Finally concluding remarks are provided in Section VI.

II. EXPERIMENTAL SETUP

Fig. 2 shows the experimental setup. An IPMC sample (Environmental Robots Inc., Albuquerque,NM) of dimensions 20 mm $\times 5$ mm $\times 0.1$ mm is clamped at one end, and is subject to voltage excitation generated from the computer (through dSPACE DS1104 and ControlDesk). A laser displacement sensor is used to measure the bending displacement d. As the laser incident point varies as the IPMC bends, a more meaningful quantity is the bending curvature $1/\rho_c$, where ρ_c is the radius of curvature. Assuming a constant curvature throughout the sample, one can compute $1/\rho_c$ based on the displacement measurement d using the geometry (refer to Fig. 3):

$$\frac{1}{\rho_c} = \frac{(d-d_0)^2 + h_0}{2(d_0 - d)},$$

where d_0 is the horizontal distance from the laser sensor to the fixed end of IPMC, and h_0 is the vertical distance. Note that a negative curvature (corresponding to $d_0 < d$) denotes the opposite bending direction.



(b)

Fig. 2. Experimental setup. (a) Setup schematic (not to scale); (b) Picture of an IPMC sample and the laser sensor (the red dot on IPMC is the laser beam spot).

III. HYSTERESIS MEASUREMENT AND IDENTIFICATION

A. Hysteresis in IPMC

The bending response of IPMC was measured under a quasi-static input. A sequence of voltage values was applied,

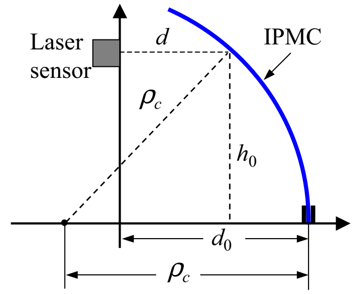


Fig. 3. Calculation of the bending curvature $1/\rho_c$ based on the displacement d.

monotonically from -1.2 V to 1.2 V and then back to -1.2 V. Each voltage value v was held for 200 seconds to allow the IPMC to reach the steady-state (Fig. 4(a)). This makes sure that the effects of other dynamics are eliminated or minimized, and any measured output-input loop would then indeed come from hysteresis.

Fig. 4(b) plots the measured steady-state curvature *vs.* the voltage input. It is evident from the figure that the output-input relationship shows hysteresis as there is a significant gap between the ascending branch and the descending one.

B. The Preisach Operator

The Preisach operator has been used for modeling hysteresis in various smart materials [16], e.g., piezoelectrics [17], [18], shape memory alloys [19], and magnetostrictives [20], [21]. Its basic building block, a Preisach *hysteron*, is a delayed relay $\hat{\gamma}_{\beta,\alpha}$ (Fig. 5) characterized by a pair of thresholds (β, α) with $\beta \leq \alpha$. Let $C([0,T])$ denote the space of continuous functions on $[0,T]$. For $u \in C([0,T])$ (the space of continuous functions on $[0,T]$) and an initial configuration $\zeta \in \{-1, 1\}$, $\omega = \hat{\gamma}_{\beta,\alpha}[u,\zeta]$ is defined as, for $t \in [0,T]$,

$$\omega(t) \triangleq \begin{cases} -1 & \text{if } u(t) < \beta \\ 1 & \text{if } u(t) > \alpha \\ \omega(t^-) & \text{if } \beta \leq u(t) \leq \alpha \end{cases},$$

where $\omega(0^-) = \zeta$ and $t^- \triangleq \lim_{\epsilon > 0, \epsilon \to 0} t - \epsilon$.

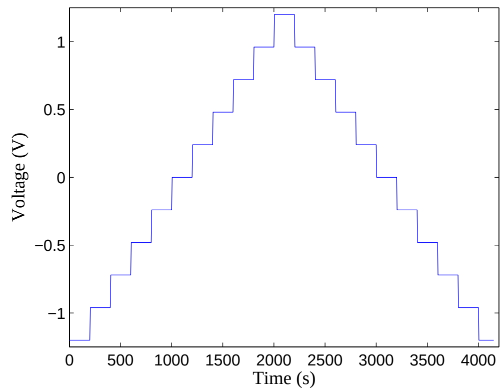
Define

$$\mathcal{P}_0 \triangleq \{(\beta,\alpha) \in \mathbb{R}^2 : \beta \leq \alpha\}.$$

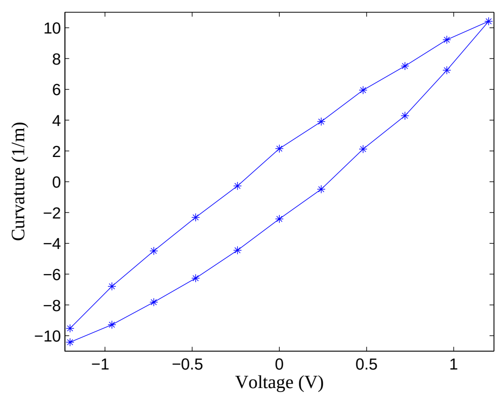
$\mathcal{P}_0$ is called the *Preisach plane*, and each $(\beta,\alpha) \in \mathcal{P}_0$ is identified with the hysteron $\hat{\gamma}_{\beta,\alpha}$. For $u \in C([0,T])$ and a Borel measurable initial configuration ζ_0 of all hysterons, $\zeta_0 : \mathcal{P}_0 \to \{-1, 1\}$, the output of the Preisach operator Γ is defined as:

$$y(t) = \Gamma[u,\zeta_0](t) = \int_{\mathcal{P}_0} \mu(\beta,\alpha)\hat{\gamma}_{\beta,\alpha}[u,\zeta_0(\beta,\alpha)](t)d\beta d\alpha, \quad (1)$$

where the weighting function μ is often referred to as the *Preisach density function*. Throughout the paper it is assumed that $\mu \geq 0$.



(a)



(b)

Fig. 4. (a) The sequence of quasi-static inputs applied to the IPMC sample; (b) Steady-state curvature *vs.* voltage input.

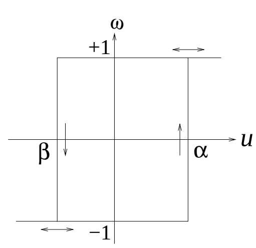


Fig. 5. An elementary Preisach hysteron $\hat{\gamma}_{\beta,\alpha}[\cdot,\cdot]$.

C. Identification of the Preisach Operator

The Preisach operator is proposed to model the quasi-static curvature *vs* voltage hysteresis in this paper. In order to identify the "parameter" - the Preisach density function, we discretize the Preisach plane into a grid of L levels (see Fig. 6 for illustration), and assume that the density function is piecewise uniform, in particular, $\mu(\beta,\alpha) = \mu_k$, $\forall(\beta,\alpha) \in$ cell k. Due to practical constraints on the input magnitude, one often discretizes a finite triangular area

$$\{(\beta,\alpha) : \beta \le \alpha, \beta \ge -r_0, \alpha \le r_0\},\ r_0 > 0,$$

instead of the whole Preisach plane. Under this discretization scheme, the output of the Preisach operator can be expressed as

$$y = \sum_{k=1}^{K} \mu_k W_k + y_0, \tag{2}$$

where K is the total number of cells on the grid, y_0 is the contribution from hysterons outside the discretized triangle, and W_k represents the *signed area* of the cell k:

$$W_k = \text{area of } C_k^+ - \text{area of } C_k^-, \text{ and}$$
$$C_k^\pm \triangleq \{(\beta,\alpha) \in \text{ cell } k : \hat{\gamma}_{\beta,\alpha} = \pm 1\}.$$

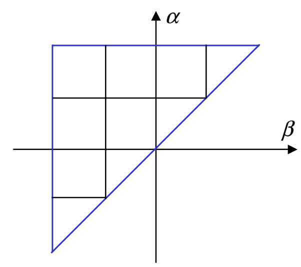


Fig. 6. Illustration of the discretization of Preisach plane for the discretization level $L = 4$.

In the identification of $\{\mu_k\}_{k=1}^K$, one applies a sequence of input $u[n]$, and evaluates $W_k[n]$ (such evaluation can be efficiently performed by tracking the *memory curve* [22]). Let the measured output be $\hat{y}[n]$. A constrained least squares method [23] can then be used to obtain the density values $\{\mu_k\}$ and y_0, i.e., the parameters are determined such that $\sum_n \| \sum_{k=1}^K \mu_k W_k[n] + y_0 - \hat{y}[n] \|^2$ is minimized.

The choice of input sequence $u[n]$ deserves further discussion. For effective identification of the density values, $u[n]$ should be picked in such a way that the influence of every μ_k can be isolated for each k. This condition has close connection to the *persistent excitation* condition in the context of recursive identification [24]. Examples of "Good" input sequences include first-order reversal sequences and oscillating sequences with decreasing (or increasing) amplitudes [24]. In the identification of hysteresis in IPMC actuators, an oscillating sequence with decaying amplitude is used since it requires fewer number of measurements in comparison with a first-order reversal sequence and each quasi-static measurement can take as long as 4-5 minutes.

Fig. 7 shows the voltage input used for identification of the Preisach operator. The steady-state curvature under each voltage is obtained and plotted (Fig. 8), and the trend of minor loops is evident. The discretization level $L = 10$ was picked to achieve a good tradeoff between the approximation accuracy and the experiment time. Fig 9 shows the identified Preisach density function.

IV. INVERSION-BASED POSITIONING CONTROL

A fundamental approach to dealing with hysteresis is inverse compensation (Fig. 10). By constructing an approximate (right) inverse $\hat{\Gamma}^{-1}$ to the Preisach operator Γ, one (almost) cancels out the hysteresis effect and the actual output y is approximately the desired one y_{des}. For a Preisach

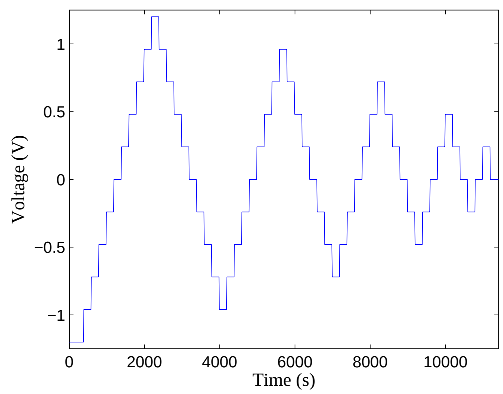


Fig. 7. Voltage input for identification of the Preisach operator.

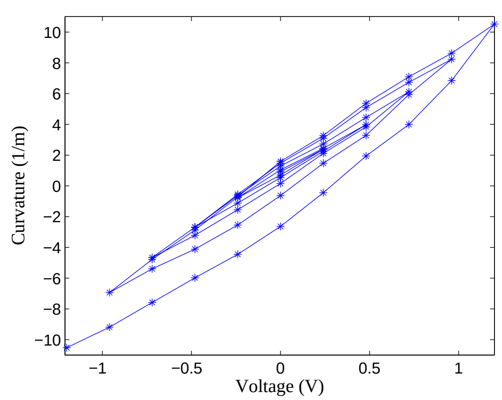


Fig. 8. Steady-state curvature *vs* voltage input.

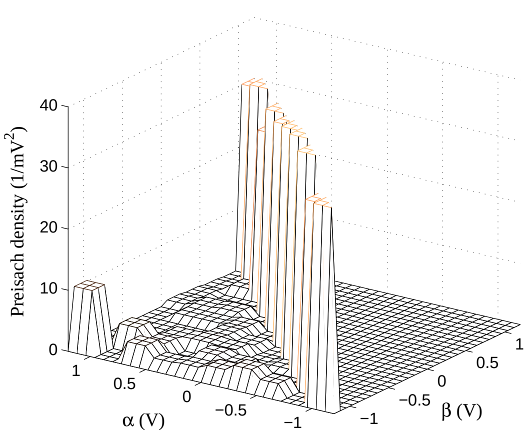


Fig. 9. Identified Preisach density function.

operator with piecewise uniform density function (as is considered in this paper), an efficient inversion algorithm is available [20], which was used here.

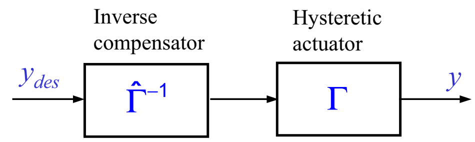


Fig. 10. Inverse compensation of hysteresis.

Quasi-static positioning experiments were performed to verify the hysteresis model and the inverse control strategy. For comparison purposes, a non-hysteretic model was also identified through the least squares method using the experimental data in Fig. 8. The single-valued map was determined to be:

$$y = -0.35u^2 + 8.2u + 0.34,$$

and it is plotted in Fig. 11 together with the experimental data.

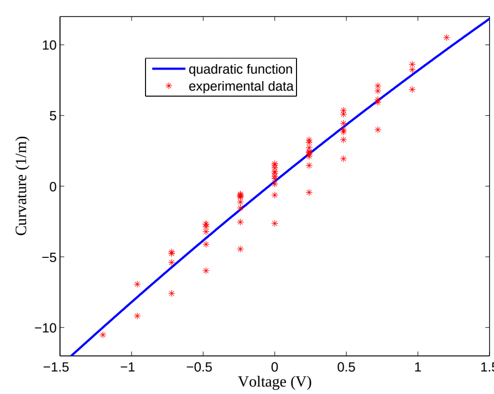


Fig. 11. A non-hysteretic model identified using the experimental data.

A sequence of 14 target values of curvature was specified, and two voltage sequences were obtained through inversion of the Preisach operator and inversion of the non-hysteretic model, respectively (see Fig. 12). A voltage value was held for 200 seconds to make sure that the steady state was reached before application of a different voltage. The actual curvature trajectory under the Preisach-based inversion is shown in Fig. 13. Fig 14(a) shows the achieved (steady-state) curvature sequences under the two inputs, and Fig. 14(b) shows their positioning errors. From the figure, the positioning approach based on the inversion of Preisach operator achieves much smaller error and hence is effective.

V. A MODEL STRUCTURE

As discussed in the previous sections, the quasi-static behavior of an IPMC actuator is captured by the Preisach operator. To account for the dynamics in IPMCs under general conditions, a model structure is proposed by cascading the Preisach operator with a dynamical system. To facilitate

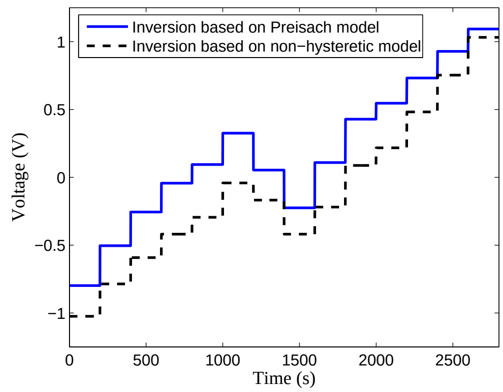


Fig. 12. The voltage inputs obtained based on the Preisach operator and the non-hysteretic model, respectively.

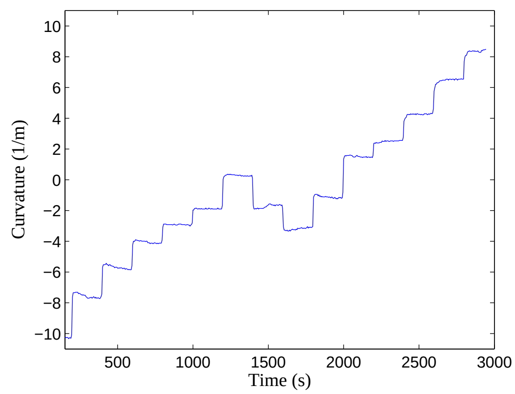
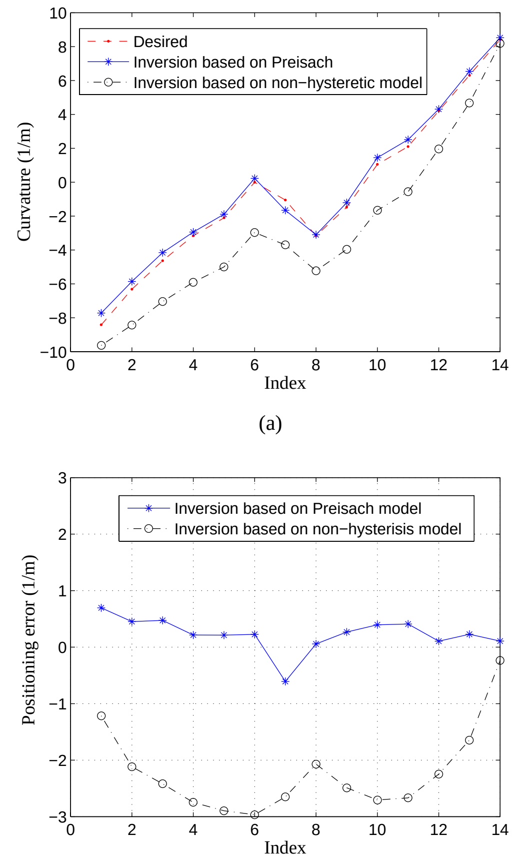


Fig. 13. The curvature trajectory obtained through Preisach operator-based inversion.

the controller design, the dynamical system is assumed to be linear, represented by some transfer function $G(s)$ (Fig. 15).

Experiments were conducted to validate the model structure in Fig. 15. The frequency response (Bode plots) of the IPMC actuator was measured for two different input amplitudes, 0.7 V and 1 V. The discrepancy between the gain plots (from voltage input to curvature output), shown in Fig. 16(a), reveals that the behavior of IPMC is highly nonlinear (otherwise the gain plots under different voltages should match). In plotting the responses FFT was performed to find the fundamental frequency components of the output y since y contains high-order harmonics. Next, the input u was fed to the Preisach operator Γ (with the Preisach density identified in Section III-C), yielding the signal w. The frequency response from w to y was then calculated (both based on the fundamental frequency components) and plotted in Fig. 16(b). The phase responses under the different input amplitudes matched well for both $u \to y$ and $w \to y$ and thus are not shown here. Note that in Fig. 16(b) the match between the responses for the different amplitudes is improved significantly over that in Fig. 16(a). This demonstrates that indeed one can approximate the dynamic part of the model by a linear system.



(a)

(b)

Fig. 14. (a) Steady-state curvature values achieved under the two control schemes; (b) Positioning errors under the two schemes.

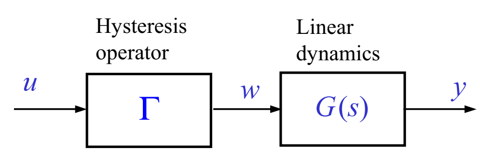


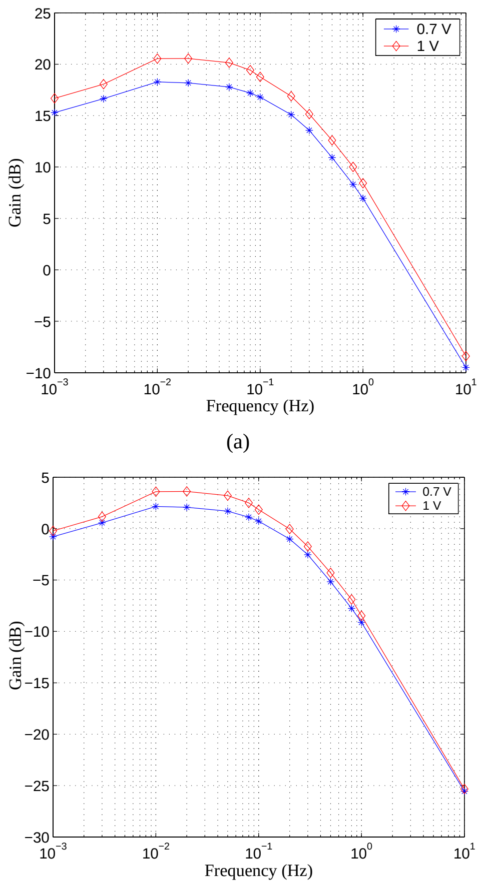
Fig. 15. Proposed model structure for an IPMC actuator.

VI. CONCLUSIONS

In this paper the hysteresis during quasi-static IPMC actuation was reported. The origin of hysteresis could arise from the hysteretic stress-strain relationship in IPMCs, as is typical for porous materials [25]. The porous polymer matrix could also lead to multiple metastable equilibria of ion migration, which constitutes another potential source of hysteresis.

The Preisach operator was used to model the hysteresis. An open-loop positioning scheme was presented based on the inversion of the Preisach operator. It was shown that using IPMC for quasi-static applications is feasible. It was noticed that the quasi-static behavior of IPMC slightly varies over time. The methods on recursive identification and adaptive control of hysteresis [24] could be useful for IPMC actuators.

A cascaded structure was also proposed for IPMC actu-



(a)

(b)

Fig. 16. (a) Gain responses from the voltage input to the curvature output ($u \longrightarrow y$); (b) Gain responses from the output of the Preisach operator to the curvature output ($w \longrightarrow y$).

ators. It separates the hysteresis nonlinearity from the linear dynamics. Experimental results on frequency responses supported the conjecture. On the other hand, the remaining discrepancy in Fig. 16(b) indicates that the proposed model structure does not fully address the nonlinearities in IPMCs. Future work will involve further development of the dynamic model and the controller design based on the full model.

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