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An Electrical Model with Equivalent Elements in a Time-variant Environment for an Ionic-polymer-metal-composite System

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Abstract: Ionic polymer metal composite (IPMC) is a kind of ionic electroactive polymer (EAP) smart material that can exhibit conspicuous deflection with low external voltages ($\sim$ 5 V). It can be cut in various sizes and shapes, and used and applied in robots and artificial muscles with the capability in aquatic operation. An IPMC strip can be modeled as a cantilever beam with a loading distribution on the surface. Nevertheless, the loading distribution is non-uniform due to the imperfect surface conductivity that causes four different imaginary loading distributions employed in our structural model. The difference can be up to 5 times (3.8 mm to 19 mm). In this paper, a novel linear time-variant (LTV) model is introduced and applied to model an IPMC system. This modeling method is different from previous linear time-invariant (LTI) models because the internal environment of IPMC may be unsteady due to mobile cations with water molecules. In addition, the influence of surface conductivity is simulated and proven based on this model. Finally, by applying this novel modeling method, hysteresis that exists in IPMC and affects the relationship between the output deflection and the corresponding input voltage, such as 0.1-, 0.2-, and 0.3-rad/s sinusoidal waves, has been shown and simulated.

Keywords: EAP, hysteresis, IPMC, LTI, LTV method, modeling, smart materials.

1. INTRODUCTION

A smart material exhibits conspicuous physical outputs in response to various input signals, such as voltage, heat, pH, and light [1]. Both electronic and ionic EAPs are categorized as smart materials. The former needs high electric fields to deform the internal lattices by breaking powerful bonding. The latter operates by the movement of internal ions without destroying the structure. Therefore, ionic EAPs do not need high electric fields ($\sim$ 100 V/μm for electronic EAPs) [1]. IPMC, which belongs to ionic EAPs, can be excited by low external voltages ($\sim$ 5 V).

IPMC has been modeled in many ways for its internal uncertainty and instability [2–9]. Lee *et al*. modeled IPMC strips based on an equivalent cantilever beam [10, 11]. Bufalo *et al*. tried to model IPMC system based on its mixture theory framework for mechanical actuation [12]. Chen *et al*. derived a dynamic model for IPMC sensors with both mechanical and electrical methods [13]. Bonomo *et al*. built a nonlinear electrical model for an IPMC and made a comparison with a physical system [14]. Kim *et al*. had their own electrical model by analyzing two layers of surface metallic electrodes [15]. Among these models, only a few of them can be applied in most cases. In other words, the models that fit in one case might exhibit a large error in other cases. This might result from the negligence of the influence of the surface conductivity or the distribution of internal water molecules, which is not only non-uniform but also time-variant due to their movement. In addition, non-uniform metallic surface electrodes influence the external loading in structural modeling. Therefore, traditional models may not fit well without revision in both internal water distribution and imaginary external loading distribution. Imaginary loading distribution comes from the local deflection and is used to depict the magnitude of the local internal cations with water molecules.

The objective of this article is to introduce a novel modeling method by applying time-variant equivalent electrical elements in an IPMC system. An IPMC strip can be modeled as a cantilever beam with a loading distribution on the top surface although there is no physical external loading. In the above model, however, an error might still exist because the distribution of internal cations with water molecules is time-variant. In consideration of the electrical characteristics, such as internal or surface resistances, an IPMC strip can be modeled as an electrical system. Nevertheless, in practice, the entire system varies

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with time, so this model must be revised to enhance the accuracy. Finally, the deflection can be found and simulated with this electrical model. This electrical model has shown accurate output and hysteresis phenomenon.

The rest of this paper is organized as follows: Section 2 introduces the applications of the structural model and presents simulation results by modeling an IPMC strip as a cantilever beam. Section 3 describes not only time-invariant but also time-variant methods as an electrical system. In addition, the effect of surface conductivity is explained and simulated based on the model. Then the advantages of the time-variant model are verified experimentally.

2. MODELING OF AN IPMC STRIP AS A CANTILEVER BEAM WITH A LINEAR LOADING DISTRIBUTION

Fig. 1 gives the dimension of our IPMC strip used in this research. By considering an IPMC strip a cantilever beam, deflection of each point can be predicted. In this structural model, an IPMC strip as a cantilever beam is under various cases of loading distributions. With one end fixed, the other end exhibits a conspicuous bending motion as a cantilever beam. Four representative cases as shown in Fig. 2, which cause four curvatures of the bending at each point in practice, are taken into consideration because of the non-uniform surface conductivity on the IPMC surface. These four cases indicate a series of events occurring to an IPMC strip in operation.

Fig. 2(a) depicts that the strip exhibits a large bending by a uniform loading distribution for the perfectly uniform conductivity of surface electrodes, which is similar to the model in [10, 11]. Fig. 2(b) shows that the strip has a linearly decreasing loading but still has good conductivity at the free end. Fig. 2(c) illustrates that the strip has a linearly decreasing loading down to zero at the free end. Fig. 2(d) indicates that the strip has higher resistance of surface electrodes so the loading decreases down to zero at one point (at the middle point in this case). Surface conductivity, which originates from thickness of surface metallic electrodes and is related to the loading distribution, might be degraded in operation due to physical or chemical damages as shown in Fig. 3. In practice, it is very challenging to prepare a well-fabricated IPMC as shown in Fig. 2(a). Mostly, IPMC strips have non-perfect surfaces as shown in Fig. 3, so Fig. 2(b) is closer to practice. As time goes by, in around 10000 s, however, Figs. 2(c) and 2(d) will represent a more realistic loading distribution.

Fig. 3 shows some samples of IPMC strips without perfect surface electrodes. In Fig. 3(a), whereas the left strip is in a better condition, there are some conspicuous defects on the right one. The darker area has less platinum attached due to insufficient platinum reduction in fabrication. In addition, in Fig. 3(b), cracks by a tweezer

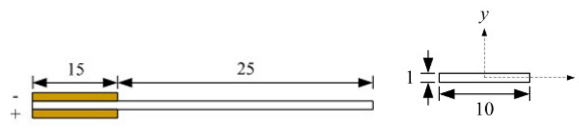


Fig. 1. Dimension of our IPMC strip (units: mm).

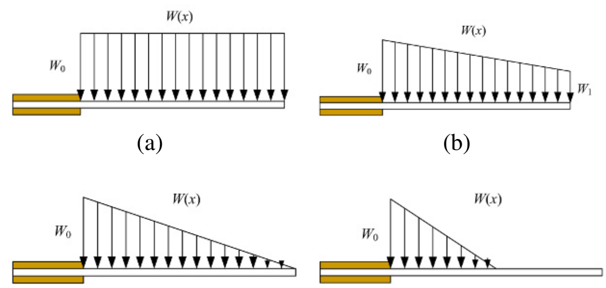


Fig. 2. IPMC strips as cantilever beams under various loading distributions on the top surface.

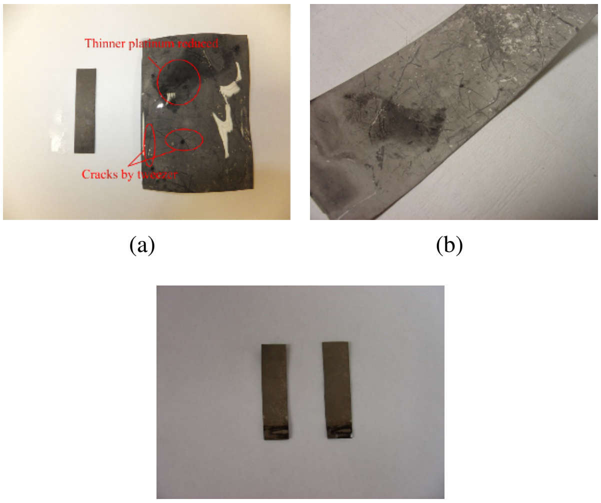
and insufficient reduction areas are shown. These areas may cause less attraction to the internal cations with water molecules due to insufficient surface voltage distribution. The IPMC strips in Fig. 3(c) have burned areas at the bottom, and they may also decrease the surface voltage distribution due to the chipping-away electrode. Deflection will be degraded as the voltage distribution decreases. Therefore, this phenomenon can explain the cases in Fig. 2 physically because the imagined loading distribution comes from the deflection in each strip. In practice, the loading may not be linear as shown in Fig. 2.

Fig. 4 depicts the simulated deflections of the IPMC strip corresponding to Fig. 2. In Case 1, the strip exhibited a large deflection by the large and uniform distribution of water molecules on the cathode side, and the maximum deflection was around 19 mm.

In Case 2, the loading still exists at the free end as shown in Fig. 2(b) and causes the deflection variation on the entire IPMC strip. In other words, the linearly decreasing distribution of the internal water molecules drives the deflection. In this case, the loading force at the free end is set to be half of the original force at the fixed end with a linear decrease.

In Case 3, the loading force decreases with the distance from the fixed end linearly down to zero because the distribution of internal water molecules becomes sparse as the distance from the fixed end increases. The maximum deflection is around 5 mm at the free end. In this case, the imaginary loading force is half of that in Case 1, but the difference of maximum deflection is around 15 mm.

Case 4 takes place if the surface conductivity is too



(a) (b)

(c)

Fig. 3. Physical samples of non-uniform surface electrodes due to (a) insufficient reduction, (b) cracking by a tweezer, and (c) burned by current.

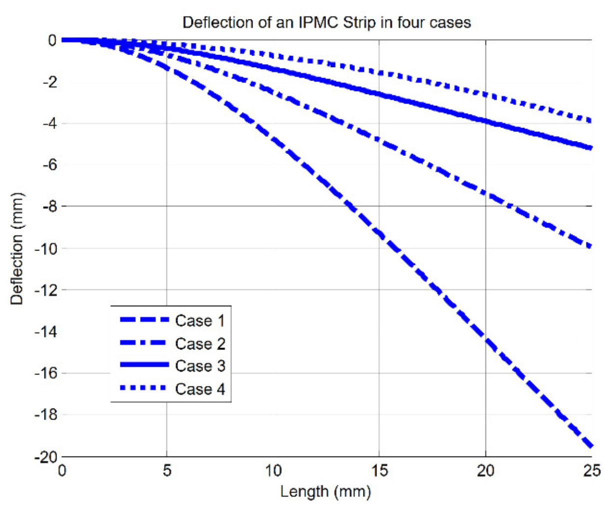


Fig. 4. Deflections of IPMC strips in the cases corresponding to Fig. 2.

low to attract sufficient cations with water molecules to the cathode side from the middle of an IPMC strip. As the thick dotted line drawn in Fig. 4, the IPMC strip can be considered a cantilever beam with decreasing loading force cut off at the middle point. The maximum deflection in this case would be the smallest due to insufficient distribution of internal water molecules. In Fig. 4, the maximum deflection is around 3.8 mm. In this case, not only the deflection but the variation rate of the deflection is much smaller than that the previous three cases.

Theoretically, IPMC should have highly conductive metallic electrodes on both surfaces to exhibit the maximum deflection as Case 1 in Fig. 2(a). However, the thickness of metallic electrodes might be insufficient for high surface conductivity in practice. In addition, metallic electrodes can be easily damaged in operation. Thus, Case 1 does not usually exist in practice. Cases 2, 3, and 4 occur to imperfectly conductive surfaces, causing the loss of power and deflection depending upon surface conductivity. In practice, for a piece of a brand-new IPMC strip, the surface conductivity will become worse due to the external surroundings such as electrode fall-off or surface cracks, which means that it was in Case 2 or 3, migrating to Case 4 eventually after repeated operations or with external physical damages. It might be better to derive a model by using physically measured outputs as to be presented in Section 3.

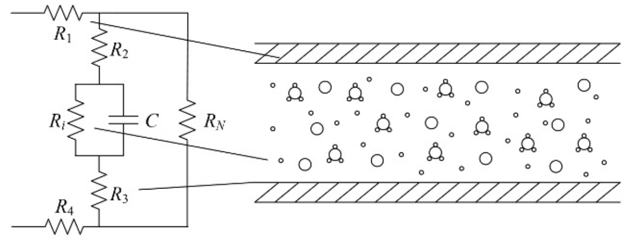


Fig. 5. IPMC structure and the corresponding RC system.

3. ELECTRICAL MODELS AS TIME-INVARIANT AND TIME-VARIANT SYSTEMS

An IPMC system exhibits output deflection in response to the stimulation of external voltages. A model of an IPMC system consists of various linear and passive elements such as resistors, capacitors, and inductors according to the characteristics [14–16]. For example, the conductive surface metallic electrodes make the surface to be full of the distribution of positive and negative charges, so it has similar characteristics to a capacitor. The basis of IPMC, Nafion® membrane, works as a resistor in this system, so Nafion® will be modeled as a group of impedances in an electrical model. Fig. 5 illustrates the electrical model with the corresponding elements.

There is a directly proportional relationship between the output deflection and the given current in an IPMC system [17]. That is, the current line appears to follow the deflection line. Therefore, the relationship between the deflection and the external voltage can be obtained via the relationship between the external voltages and the internal impedances as shown in Fig. 5.

In Fig. 5, R_1 and R_4 are the equivalent resistors on the top and bottom surfaces, respectively, and originate from the imperfectly conductive metallic surface electrodes. R_2 and R_3 indicate the equivalent resistors resulting from the gap between the electrode and the Nafion® on the top and bottom surfaces, respectively, and defective reduction of platinum on the surfaces because it might introduce non-conductive impurities. R_i is the internal resistance, representing the water molecules and impurities. The Nafion® used to fabricate IPMC is impure due to internal air bubbles or dusts, which might reduce the internal electrical conductivity. R_i is variant and would increase with a large number of internal water molecules. The symbol, C, indicates the capacitor-like characteristic of IPMC because of the electrodes on the anode and cathode surfaces with the full distribution of charges. The capacitance is closely depending upon the thickness of the IPMC. However, the capacitance is used to model the IPMC strip in various groups of thickness, so the parameter, C, is related to the capacitor-like characteristic in deflection instead of the internal characteristic. R_N is the resistance of the internal Nafion® membrane. It would be a constant if the size and shape did not change. According to Fig. 5, the equivalent impedance can be derived as (1), which can be seen as a relationship between the external voltage (V) and current (I) by Ohm's law. In addition, based on the proportional relationship between the current and the output deflection (D) with same external voltage, the equivalent impedance can be expressed with the input voltage and the output deflection as shown in (2). Therefore, the relation between voltage and deflection, the transfer function of this model, is derived in (3) and the constants, k_1 and k_2, can be determined by experiments.

$$R_{equi} = R_1 + \{[R_2 + (R_i \parallel C) + R_3] \parallel R_N\} + R_4, \tag{1}$$

$$R = \frac{V}{I} = \frac{V}{k_1 D}, \tag{2}$$

$$\begin{aligned} T.F. &= \frac{D}{V} = \frac{1}{k_1 \times R_{equi}} = k_2 \frac{1}{R_{equi}} \\ &= k_2 \{R_i(R_2+R_3+R_N)Cs + (R_2+R_i+R_3+R_N)\} \\ &\quad / [\{(R_1+R_4)(R_2+R_3+R_N)R_i + R_iR_N(R_2+R_3)\}Cs \\ &\quad + \{(R_1+R_4)(R_2+R_i+R_3+R_N) \\ &\quad + R_N(R_2+R_i+R_3)\}]. \end{aligned} \tag{3}$$

Table 1 lists the nominal values of each element in this electrical model. By measured manually, all values can be determined to predict and simulate the output deflection of the IPMC strip in this experiment.

Fig. 6 shows the simulation of the internal current in our 1-mm-thick IPMC strip as shown in Fig. 1 with an 8-V step input. This 1-mm-thick strip is thick enough to support the body of a robot and provide sufficient force in aquatic robotic applications [5]. In an LTI method, the deflection depicted in a solid line shows a slow downward curve toward the steady-state value. The simulated current line, however, does not seem to be well-matched due to the structural limitations such as the stiffness. For example, it is difficult for a thick IPMC strip to exhibit an instant bending, so the actual deflection may show a slow increase to the steady-state value.

Table 1. Values of all electrical elements in the electrical model.

Element	Value	Unit	Note
R_1	5	Ω	Originates from surface resistance
R_2	2	Ω	Due to the gap between Nafion® and surface
R_3	2	Ω	Due to the gap between Nafion® and surface
R_4	5	Ω	Originates from surface resistance
R_i	0.5	Ω	Results from internal cations and water
R_N	1	Ω	Only changes with Nafion® deformation
C	1	μF	No significant change

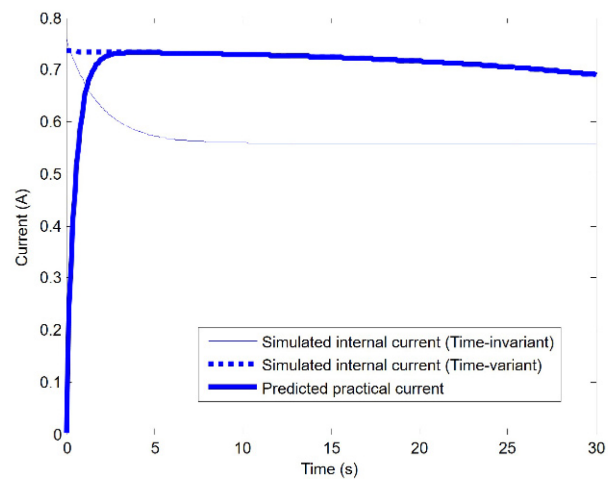


Fig. 6. Simulation of internal current of a thick IPMC strip.

A practical IPMC system is highly time-variant due to the internal mobile cations and external physical deflection. The internal characteristics, such as resistance, will not be constant. Moreover, the surface resistance changes with the expansion or contraction on the top and bottom surfaces while the IPMC strip bends. Therefore, some parameters such as surface and internal resistances would be time-variant in operation. In the following simulation, the result will be based on a time-variant method. With the consideration and employment of time-variant elements, the simulated results could be closer to the practical systems.

In order to apply an LTV method, the same electrical model was used, but all equivalent elements presented exponential variation due to the internal cations with water molecules and structures. Each element varies due to the specific reason, including exponentially changing physical and chemical characteristics. For example, in

Table 2. Constants in the revised equation.

Element	$A(\Omega)$	$B(s)$	C(Unitless)
R_1, R_4	1	1	1
R_2, R_3	0.1	1	1/6
R_i	0.1	2	1
R_N	0.1	1	1

Fig. 8, while the IPMC strip bends upward, R_1 and R_4 decrease and increase, respectively because the top and bottom surfaces expand and contract, respectively. This phenomenon is related to the surface voltage distribution. R_2 and R_3 originate from the gap between the metallic electrode and Nafion®, so they both increase when the strip bends. R_i results from the internal condition, such as the water-molecule distributions, so this internal resistance also increases when the strip exhibits a bending due to non-uniform water-molecule distributions. Overcrowded water molecules might hinder cations' movement, so the internal conductivity will be destroyed with the rising of water-molecule concentration. R_N is related to the properties of Nafion®, so it does not change as notable as the other elements due to the stability of Nafion® in operation. The last element, C, does not vary much with time because bending motion might not cause apparent influence on the overall thickness of IPMC strips. However, C will be different in the strips with various thicknesses and it will be smaller in a thicker IPMC strip. The general variation for the elements with respect to time is shown in (4). The dashed line in Fig. 6 depicts the simulated internal current in a thick IPMC strips by using an LTV method. The current shows a gradual and small decrease down to the steady-state value following the rapid rising. The thick solid line indicates the predicted current with an initial rising due to the structural limitation.

$$R(t) = R(0) + A(e^{t/B})^C, \tag{4}$$

where $R(t)$ and $R(0)$ indicate the present and the initial resistances, respectively. The constants A, B, and C, depending on the characteristics of each equivalent resistor and accumulation of internal water molecules, influence the variation speed of each element. After many iterations, the values of these constants were decided as presented in Table 2 for the best fit with the experimental results.

One of the internal resistors, R_i, varies with the accumulation of cations with water molecules, so this revised equation originates from the equation of capacitor charging [18] with a minority of revision in variation constants. The equivalent resistor of the Nafion®, R_N, also varies with the deflection of the Nafion®. The other elements in Fig. 5 such as the surface resistors and the gap resistors also exhibit similar variation in resistance due to bending.

By applying this equation, as t goes to infinity, this system becomes open-circuited like a charging capacitor. Without the given current from an external voltage source, the deflection of this thick IPMC strip may be degraded although a small equivalent capacitor still exists. This is a typical back-relaxation phenomenon prevalent in an IPMC system. Thus, in addition to modeling, this revised equation can be used to explain this phenomenon.

In Fig. 6, this LTV model can predict the deflection more precisely than a time-invariant method. This time-variant method can also predict the output deflection in various surface or internal conditions. The metallic surface electrodes have electrons distributed on the surface in order to exhibit large bending by the surface voltage distribution. Surface resistance acts as an important role because it causes great influences on bending by attracting and repelling internal cations. However, the metallic electrodes are not so perfectly conductive that the surface voltage is weakened as the distance from the fixed end grows. The imperfect surface electrodes degrade the deflection, which influences other equivalent resistors indirectly such as internal resistance. To enhance the surface conductivity, IPMC has been fabricated with repetitive coating to increase the thickness of electrodes, and only the metals with higher conductivity, such as gold and platinum, have been listed for the options of surface electrodes [17, 19]. In addition, treating the surface area by roughening it with sandpaper can enhance the metallic layer on the surface [20].

Fig. 7 shows the predicted internal current with various surface resistances for a thick IPMC strip. Six groups of initial surface resistances were decided and compared. In this figure, the instant rising can reach the maximum current of around 0.73 A and then goes down to 0.68 A gradually when the equivalent surface resistance is 5 Ω. The initial surface resistance increased by only 2 Ω in each case but exhibits the same rising. However, a large discrepancy exists between the two lines, so the surface resistances influence significantly on the current and deflection of IPMC strips. The surface resistance reduces the maximum steady-state currents, so the deflection would be degraded as well.

According to Fig. 7, there is no doubt that the surface resistance is one of the decisive factors to change current and exhibit the output deflection for an IPMC strip. The output deflection will be improved significantly if the IPMC has thicker metallic electrodes to enhance surface conductivity. In addition, the maximum deflection was degraded greatly although the surface resistance increased slightly. The surface with thick metallic electrodes not only influences the surface resistance, but the internal resistance. For example, if a strip exhibits a large deflection, R_2, R_3, and R_i will also increase significantly as well due to the boundary between the electrodes and Nafion® membrane, and non-uniform distribution of internal water molecules.

The LTV method exhibits a significant discrepancy in

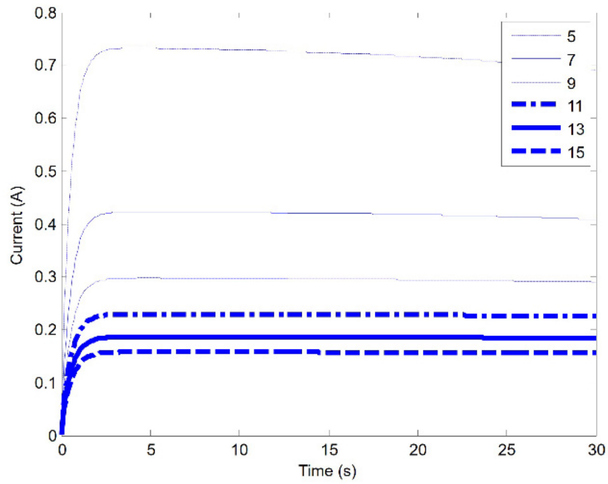


Fig. 7. Simulation of current with various surface conductivities of a thick IPMC strip.

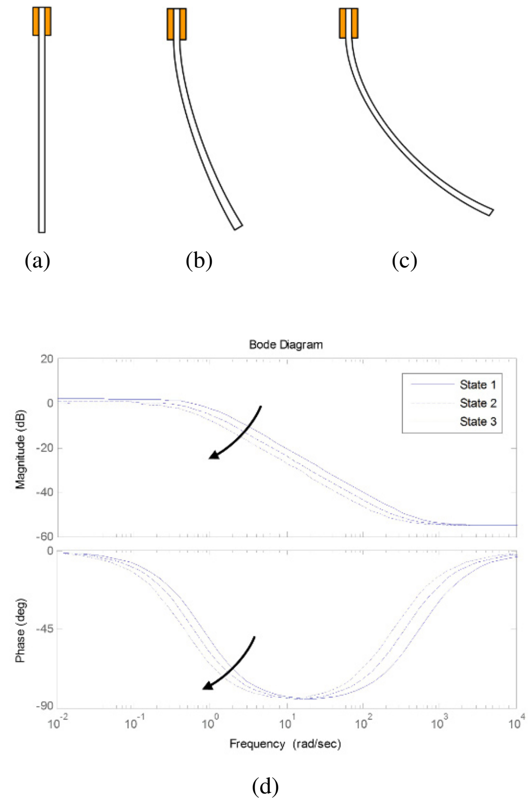


Fig. 8. A progress of IPMC deflection denoted as States 1, 2, and 3, which are illustrated in (a), (b), and (c), respectively. (d) The frequency responses of the IPMC system in the above three states are represented in the Bode plots.

simulation although only 2-Ω increase is accumulated each time in the surface resistance. As the equivalent elements of an IPMC system, R_1, R_2, R_3, R_4, R_i, R_N, and C can vary with the deflection and the movement of internal water molecules instead of keeping constant, so the results with the LTV method should be more precise than those with the time-invariant one. Therefore, this LTV method is more appropriate than the conventional model with constant equivalent impedances.

Other than the surface condition, this electrical model has been used to simulate a specific phenomenon, hysteresis. This is a delay between input voltage and output deflection. After taking this time-variant approach by applying the above equations and parameters, the system model of an IPMC strip will not be constant in operation. In addition, this time-varying system model affects other characteristics such as the relationship between the deflection and the corresponding input voltage. Fig. 8(a) shows the initial state (State 1), and this IPMC strip goes to (c) (State 3) through (b) (State 2) when the external voltage is given. It is clear that the phase-lag of this IPMC strip increases with the bending process due to the varying internal equivalent parameters. In other words, a largest phase-lag occurs when an IPMC strip bends up to the limit. Finally, the gain also decreases according to Fig. 8(d).

A comparison of the hysteresis in the time-invariant and time-variant models under the same conditions is shown in Fig. 9. Both of these two models have the same initial parameters. The parameters in the time-invariant one, however, were kept constant instead of changing with deflection as in the time-variant one. It is very clear that a larger hysteresis occurs when applying a time-variant model because it is much closer to the practical environment as the measured hysteresis. Therefore, this time-variant method was used to find an accurate model and simulate an output

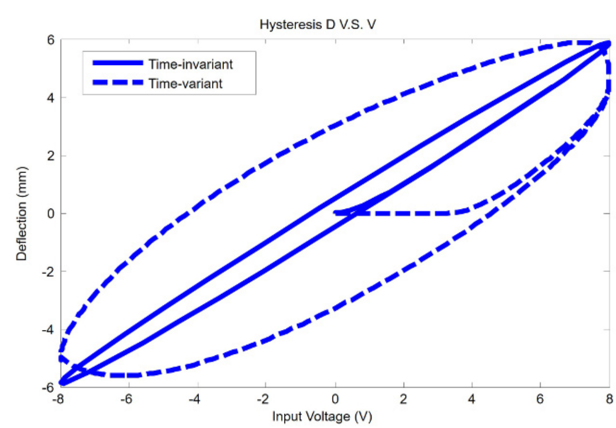


Fig. 9. Hysteresis simulation of a 1-mm-thick IPMC strip in response to a 0.2-rad/s sinusoidal waves between time-invariant and time-variant methods.

that is closer to a measured deflection in order to pursue a more accurate model and generate a more precise output response.

Figs. 10 (a), (b), and (c) show the comparison between simulated and measured output deflections in response to 0.1-rad/s, 0.2-rad/s, and 0.3-rad/s sinusoidal waves. In all of these three plots, the simulated hysteresis matches well with that from measurements, especially in Figs. 10(b) and (c). The measured hysteresis shows a large phase-lag and slow response due to this 1-mm-thick IPMC strip that affects the parameters as shown in Bode plots. In addition, the frequency of the input voltage also affects the deflection as shown in Fig. 8. Both the gain and phase are changed significantly when they are provided with 0.1-rad/s, 0.2-rad/s, and 0.3-rad/s input waves. According Fig. 10, the simulated and measured hystereses exhibit a good fit in all input voltages. Therefore, the time-variant method can predict more accurate hysteresis than the time-invariant one as shown in Fig. 9 because this model comes from the motion of real-time internal water molecules.

Besides the external voltage, the structures of IPMC strips also affect the entire system because an IPMC strip does not only act as an electrical system but also a structural beam as a strip. Therefore, this time-variant method takes the internal environment and output deflection of an IPMC strip into account by applying the real conditions.

The predicted deflection might be inconsistent with the corresponding internal current in a thick IPMC strip due to structural limitation. Higher stiffness, overcrowded water molecules, and non-mobile impurities reduce the bending speed so that there should be a model revision derived from the dimension of the thick IPMC strip to decrease the errors caused by the structural limitation. Fig. 11 shows the detailed comparison between the revised and measured deflection when the strips are given with step, sawtooth-wave, and square-wave signals in an LTV electrical model. In this figure, the response speed of the simulated deflection in the dotted line is greatly degraded but fits the actual deflection in a solid line much better than those in traditional mothods such as system identification method. In this figure, it has been shown that this LTV model has taken some real-time and realistic situations of an IPMC strip such as stiffness.

4. CONCLUSION

IPMC is a smart material and used as artificial muscles in robotic applications. However, it is challenging to develop a well-matched model for IPMC due to its unique working principle—swelling by non-uniform internal water-molecule distribution. In our structural model, an IPMC strip was seen as a physical cantilever beam with a force distribution on the top surface although the bending came from the movement of internal water molecules instead of physical external loading force. Moreover, the force distribution might be non-uniform due to the non-homogeneous surface conductivity. Uneven coating would break the uniformity of internal water-molecule distribution and influence the virtual force distribution in-

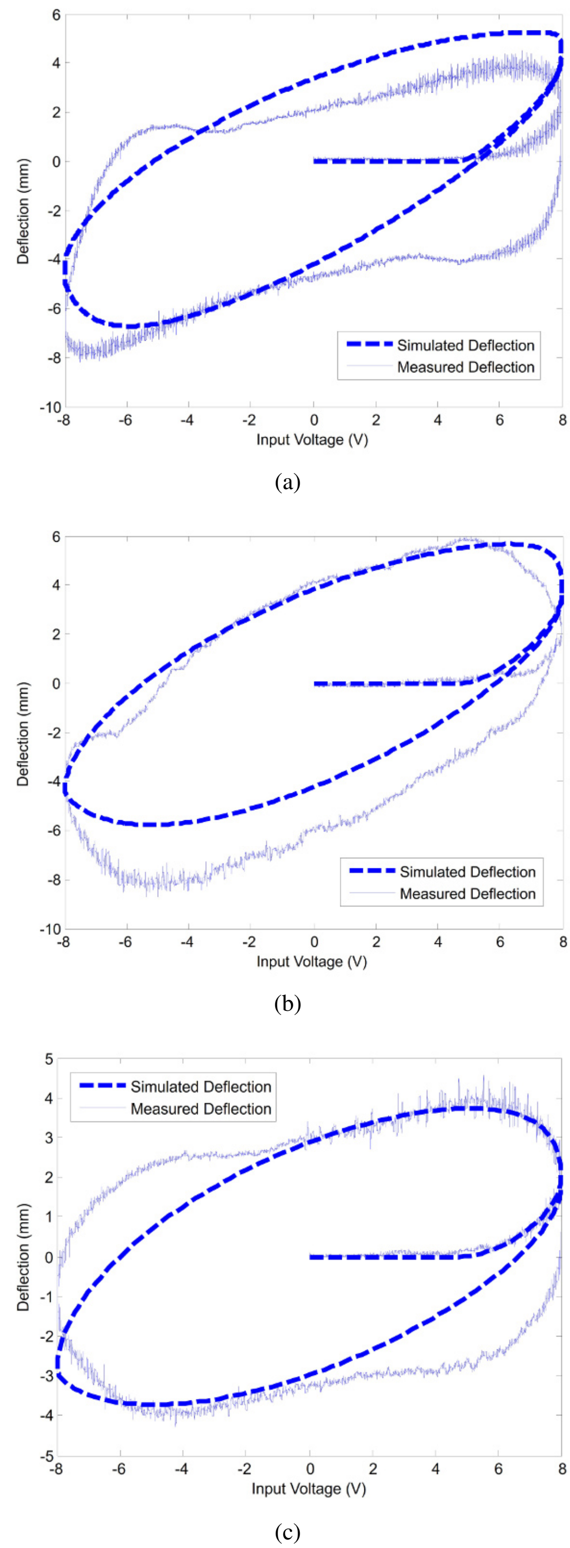
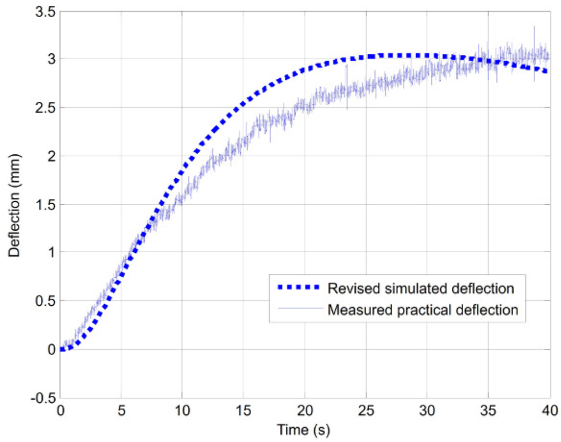
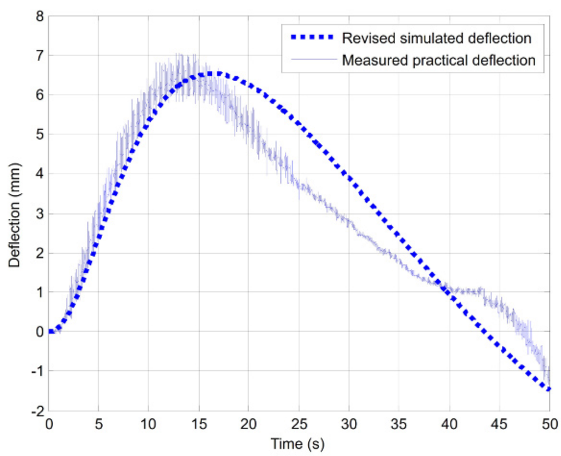


Fig. 10. Hysteresis phenomenon of an 1-mm-thick IPMC strip in response to (a) 0.1-rad/s, (b) 0.2-rad/s, and (c) 0.3-rad/s sinusoidal waves.

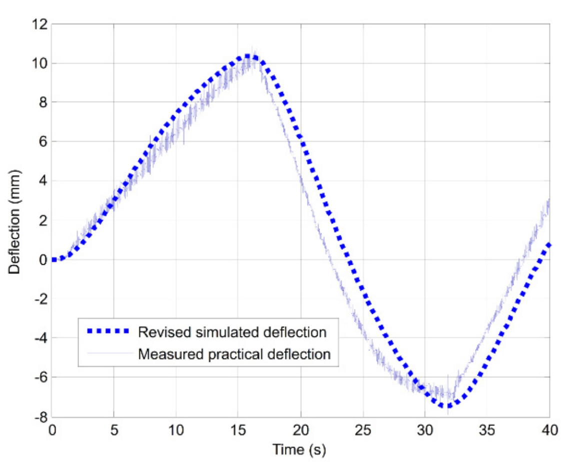
directly. In addition, the deflection of IPMC did not originate from external force but internal expansion and con-



(a)



(b)



(c)

Fig. 11. Revised simulated deflection and measured deflection in response to (a) step, (b) sawtooth-wave, and (c) square-wave signals.

traction. Therefore, there might be some discrepancies between the measured and simulated deflections.

In order to fit a physical system, surface conductivity has been taken into consideration and this model was applied to revise and obtain more precise models. According to our simulation, deflection may be up to 5 times (3.8 mm to 19 mm) in different surface conductivities. In addition, even small difference in surface resistance may cause large one in predicted internal current as shown in Fig. 7. In Fig. 7, when surface resistance increased to 3 times (from 15 Ω to 5 Ω), predicted internal current became about 5 times (0.15 A to 0.73 A). Therefore, the change of surface condition in operation much affects the IPMC system models and performance.

The complicated internal electrochemical environment in an IPMC strip caused non-uniformity to the electrical model. Unlike the previous cantilever-beam-based model, this model can be more precise and time-saving because it originates from the practical characteristics. In addition, this model is based on the physical external and internal characteristics, so it can be applied in various working environments. In the first modeling method, the simulated results might not be precise due to the nonlinear loading distribution. In the second model, nevertheless, the transfer function can be used with the various input signals. In other words, an IPMC transfer function can predict the deflection precisely when providing with a step, sawtooth-wave, and square-wave signals. Moreover, the internal equivalent elements might be highly time-variant due to the varying surface area and internal mobile water molecules in operation. An IPMC performance may change up to 44% when bending. Also, the model was revised due to the structural limitation of the measured IPMC strip. By treating the IPMC actuator as an LTV system, the revised model produced the results much closer to the measured outputs. In addition, a specific phenomenon of IPMC, hysteresis, has been shown in this LTV model successfully. The delay between input voltage and output deflection has been thoroughly simulated. In this paper, this hysteresis phenomenon was simulated when giving 0.1-, 0.2-, and 0.3-rad/s sinusoidal waves.

An IPMC strip is highly time-variant because both the external and internal characteristics, such as the surface conductivity, mobile cations, and the internal water-molecule concentration, are varying with respect to time. By introducing this time-variant approach, the model of IPMC could predict the deflection more precisely.

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