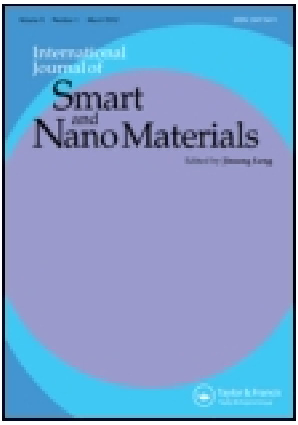

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Nonlinear dynamics of curved IPMC actuators undergoing electrically driven large deformations

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The nonlinear dynamics of curved ionic polymer–metal composite (IPMC) actuators having large tip displacement and periodical jumping locomotion was investigated experimentally. Through snap-through phenomena, the actuator generates much larger tip displacement and shows abrupt jumps in the transitions of upswings and downswings with low input energy. Two curved IPMC cantilever actuators having two different constant curvatures of 0.01 mm^{-1} and 0.02 mm^{-1} were fabricated through thermal treatment from flat IPMCs, simultaneously with no residual stress. As-fabricated IPMC actuators were tested to evaluate the effect of initial curvature under static and dynamic electrical excitations. Unlike the case of the flat IPMC actuator, asymmetric characteristics in step and harmonic responses were investigated in the curved IPMC actuators. Also, at relatively higher input voltage, snap-through phenomena were observed with much larger transverse displacements and periodical abrupt jumps of the instant speed. This revealed jumping movements between the multiple equilibrium points. The results show that optimum curvatures for better bending performance of curved cantilever IPMCs exist and that this snap-through mechanism could be applied to IPMC actuators by considering their soft and flexible properties and the geometric structures.

Keywords: ionic polymer–metal composite; snap-through dynamics; thermal treatment; actuator

1. Introduction

In newly emerging biomimetic engineering [1], actuators as artificial muscles have been studied to realise the biomimetic mechanism. Biomimetic actuators have lightweight, efficient and distributed characteristics compared to electro-mechanical motors which exhibit disadvantages such as complex structures, unnaturalness, reduction of efficiency, vibration and noise, etc. Especially, electro-active polymer (EAP) actuators, including electronic EAPs (dielectric elastomers [2], ferroelectric polymers [3], electrostrictive graft elastomers [4], and electrostrictive papers [5]), ionic EAPs (ionic polymer gels [6], carbon nano-tubes [7], conducting polymers [8], and ionic polymer-metal composite) and shape-memory polymers [9] have been extensively studied to mimic biological locomotion. Among the electro-active polymers, the ionic polymer–metal composite (IPMC) actuator has received considerable attention for the realisation of flexible biomimetic bending actuation [10]. The

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IPMC actuators have several merits, such as miniaturisation, ease of manufacture, biocompatibility, biomimetic activation and low energy consumption. Especially, the IPMC actuator exhibits large bending deformations under low external electrical excitation, owing to the ion migration of cations and water molecules in the ionic-exchange polymer membranes. Therefore, the IPMC actuators are promising candidates for the next generation of smart materials with significant potential for practical applications to biomimetic robots [11], biomedical devices [12] and manipulators [13–15]. This also includes fundamental approaches to improve the basic bending performance and to overcome several drawbacks through the synthesis of novel ionic-exchange membranes [16–19] and the development of nanocomposites [20–22].

For practical applications of IPMC actuators, some drawbacks and nonlinear behaviours of IPMC actuators, including the distortion and chattering in harmonic responses at low frequency, the straightening-back phenomenon under static excitations and low repeatability of performance, should be investigated and improved in-depth. Some experimental studies for IPMC actuators under relatively high harmonic excitations have indirectly revealed severe harmonic distortion partially resulting from the snapping mechanism. However, the nonlinear dynamics of curved cantilever IPMC actuators has not been investigated. Using piezoelectric actuators and shape memory alloys (SMAs), some experimental observations for snap-through behaviours of asymmetrically laminated composite cantilever beams have been reported [23,24].

The snap-through mechanism can be applied to make multi-stable structures [25], bi-stable morphing structures [26], large-stroke micropumps and microvalves [27,28], and MEMS devices [29–31] by using smart materials and geometric structures. Even though smart materials such as a piezoelectric ceramic and a SMA were studied to generate [32] and suppress [33,34] the snap-through dynamics of smart structures, those materials have practical limitations for large deformation because of their brittleness. Thus, soft and flexible polymer actuators such as IPMCs and dielectric elastomers have attracted attention owing to the availability of durable and repeatable snapping mechanisms with large strokes by considering geometric structures, boundary configurations and their flexible properties [35,36].

Until now, the snap-through dynamics of curved cantilever IPMC actuators has not been studied. Therefore, in the present study, the dynamic snap-through and periodical rapid locomotion of curved cantilever IPMC beam actuators were investigated experimentally. Also, the proper curvature and bending direction of the actuators were studied for better bending performance and snap-through motion. Especially, this snap-through mechanism of curved cantilever IPMC actuator can be applied to micro-scale and biomedical active devices in conjunction with the distinguished advantages of large stroke, geometric stability, material flexibility and energy efficiency.

2. Experiment

In order to study the snap-through dynamics of cantilever IPMC actuators, two curved beam-type actuators were fabricated and compared with a flat actuator under both static and dynamic electrical excitations. First, the flat IPMC actuator was fabricated via the electroless plating of Pt onto a Nafion^{TM} 117 membrane [10]. The actuator samples were cut into 10×40 mm strips by a sharp blade. Then, thermal treatment of the flat IPMC was conducted to obtain the curved shape of the IPMC actuators, where a curved fixture was used under hot water at 90°C for 1 h to lower the residual stresses. From these processes, curved IPMC shapes with constant curvatures (κ) of 0, 0.01 and 0.02 mm^{-1} were formed,

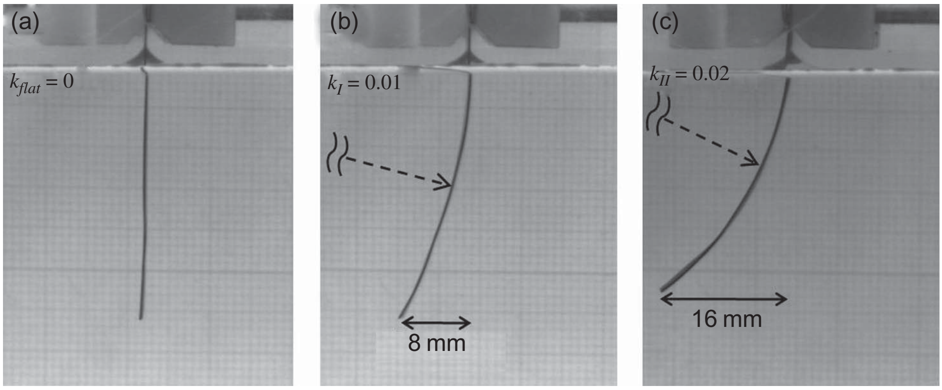

Figure 1. IPMC actuators: (a) flat actuator; (b) curved-I actuator with initial curvature of 0.01 mm^{-1}; (c) curved-II actuator with initial curvature of 0.02 mm^{-1}.

as shown in Figure 1. The initial tip displacements of the three curvatures were measured as 0, 8 and 16 mm, respectively.

To measure the static and dynamic electro-mechanical responses of the flat and curved IPMC actuators, a laser displacement sensor (KEYENCE LK-031) and a NI-PXI 6252 data acquisition system were used. In the case of lower or little higher input excitation (below 2.5 V) responses, this instrument can sufficiently measure tip displacement of these types of actuators, and simultaneously can adjust the measuring points from the cantilever tip. However, for higher excitation (above 3.0 V) responses, it was difficult to measure the larger tip displacement using the laser displacement sensor because of the limitation of measuring distance of the laser sensor. Also, significant errors may occur between measured values and actual values. So, a vision sensing system was implemented to capture the large tip displacements with a NI-PXI 1409 image acquisition board, a digital CCD (Sony XC-HR50) camera with high resolution of 640×480 pixels and LabVIEW programming. The overall integrated measurement system is shown in Figure 2.

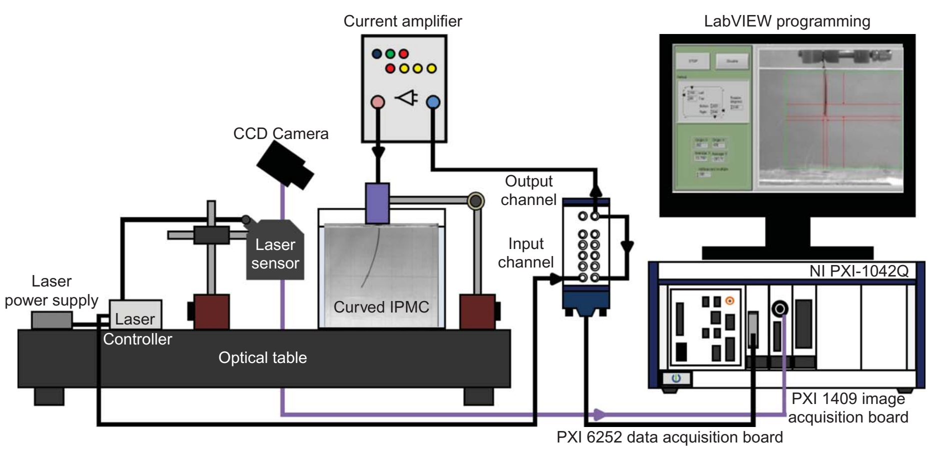

Figure 2. Schematic illustration of integrated experimental setup for measurement of tip displacement and total movement shape of curved IPMC actuators.

3. Results and discussion

3.1. Snap-through mechanism of the curved cantilever beam

The nonlinear responses of the curved cantilever beam exhibit a similar trend to those of an asymmetric composite to an applied in-plane strain [24]. They demonstrate the snap-through actuation of piezoelectric and SMA materials that have bi-stable cantilever structure with an initial deformation [24]. Figure 3a shows a schematic diagram of the curved cantilever IPMC beam actuator under the bending moment (M_{IPMC}) due to external electrical excitation. Figure 3b depicts the relationship between the transverse tip displacement and bending moment. It also shows the post-buckling and buckling response of the curved cantilever beam with two post-buckled and buckled equilibrium states under the bending moment. The curved beam initially reaches the position A, which is the same to the position when as-fabricated curved cantilever IPMC actuators are under the post-buckled equilibrium state (Figure 3b). As higher input voltages, i.e. larger bending moment, applied to the curved IPMC vary statically or dynamically, a snap-through phenomenon from initially curved state A to B is observed through path I, resulting in very large stroke in the direction of transverse displacement, as shown in Figure 3b. Moreover, the state change from buckled equilibrium state B to state A follows path II due to the unstable equilibrium of the curved beam shape.

3.2. Frequency response function of curved cantilever IPMC

Before investigating the snap-through nonlinear dynamics of the curved IPMC actuators, the frequency response functions based on small-oscillation theory were measured through a swept-sine method in order to investigate the effect of the curvature on the variation in the global stiffness. Since the maximum input voltage is 0.1 V, the responses are very small and do not reflect large deformations. As shown in Figure 4, the natural frequencies of the flat, curved-I, and curved-II IPMC actuators are obtained as 13.5 Hz, 13.5 Hz, and 14 Hz, respectively. This means that the curved shape does not strongly affect the change in the global stiffness within a small range of vibration although the highly curved shape becomes a little bit stiffer.

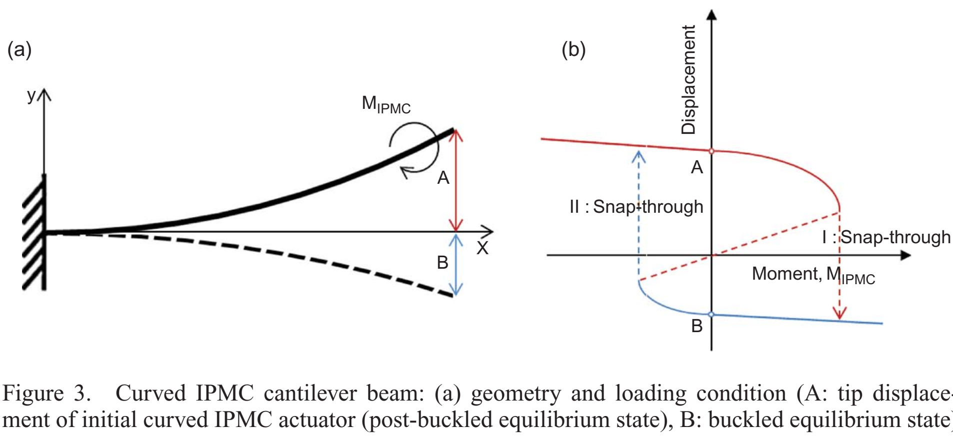

Figure 3. Curved IPMC cantilever beam: (a) geometry and loading condition (A: tip displacement of initial curved IPMC actuator (post-buckled equilibrium state), B: buckled equilibrium state) and (b) snap-through mechanism of the curved IPMC actuators under transverse load due to IPMC actuation.

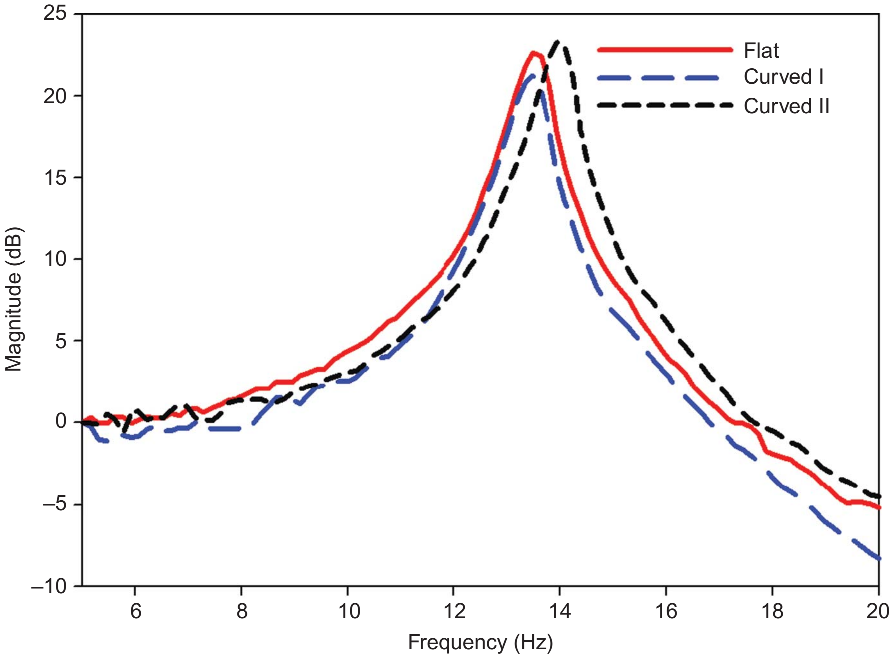

Figure 4. Frequency response functions of flat and curved IPMC actuators.

3.3. *Step response of curved cantilever IPMC*

The time-histories of the tip displacements of the as-fabricated IPMC actuators were obtained using relatively low (±0.5 V) and high (±1.5 V) input voltages. The negative direction was designated as that which makes the curved IPMC fold. Under lower input voltages, as shown in Figure 5a, all actuators show almost symmetric responses for both positive and negative step inputs with ±0.5 V. Therefore, it can be said that the geometrical shape does not lead to a significant effect at small deformation barring excessive initial deflection in the case of the curved-II actuator. Also, the straightening-back phenomena resulted from the diffusion of the water molecules of the flat and curved-I actuators have a similar tendency. On the other hand, under the positive, higher voltage of the step input, as shown in Figure 5b, the curved-I IPMC actuator shows much larger displacement than the flat and curved-II IPMC actuators. Also, the flat IPMC actuators show symmetric characteristics for both positive and negative step inputs, while the curved IPMC actuators show asymmetric characteristics because of the initial curvatures. This means that there exists a proper curvature and bending direction for better bending performance of the curved cantilever IPMC actuators.

3.4. *Harmonic response of curved cantilever IPMC*

The harmonic responses of the three IPMC actuators under sinusoidal electrical inputs, 0.5 V and 2.0 V voltage amplitudes and an excitation frequency of 0.5 Hz are shown in Figure 6. As indicated in the curves made at 0.5 V, it is proved that low input voltage, 0.5 V is not sufficient to generate the snap-through phenomenon underlying rapid jumping in time history. Thus, the corresponding responses show small and smooth harmonic oscillation without highly nonlinear behaviours such as distortion and chattering,

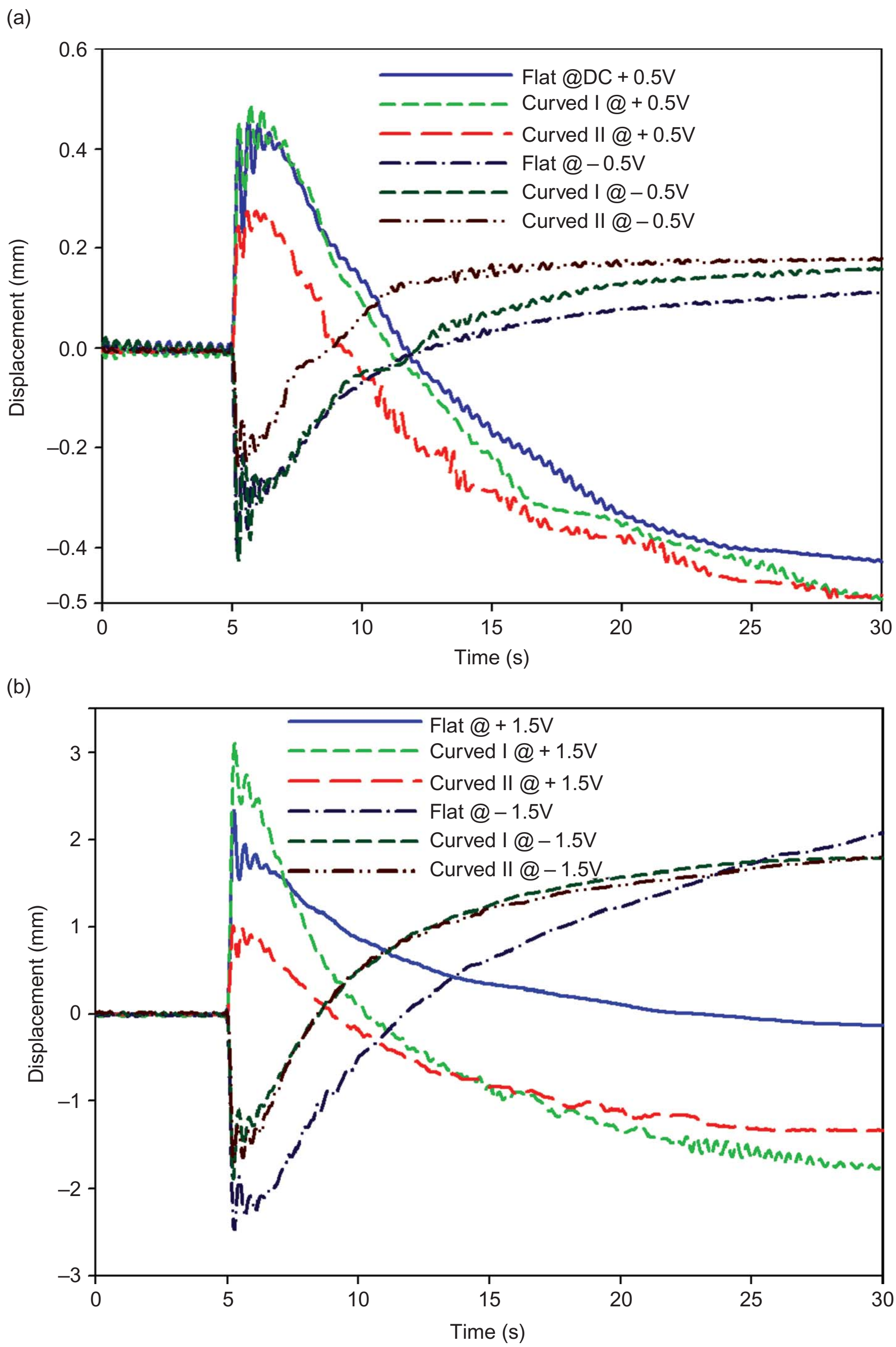

Figure 5. Step responses of flat and curved IPMC actuators (a) with low input voltage, 0.5 V, and (b) higher input voltages, 1.5 V.

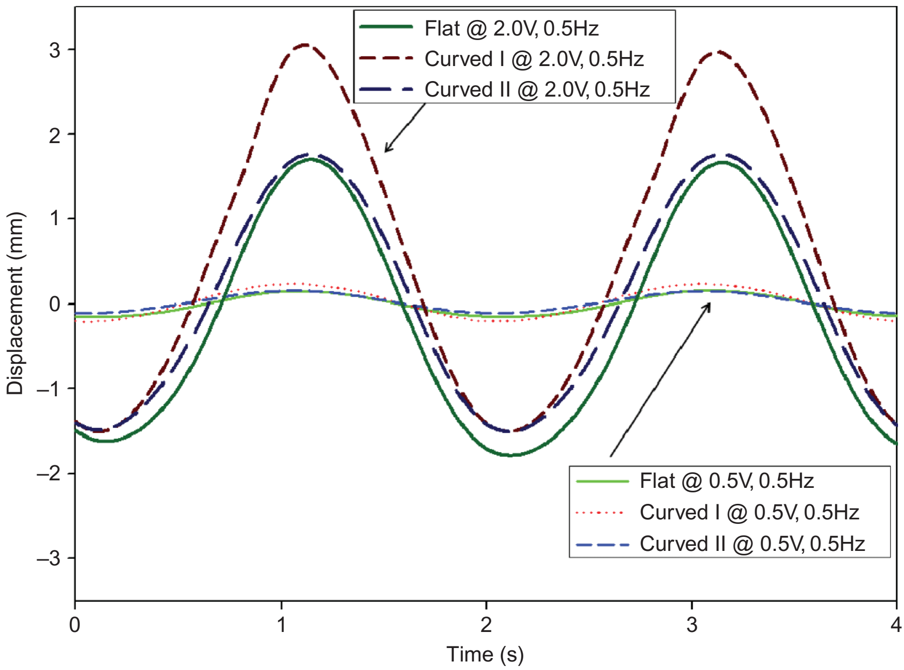

Figure 6. Harmonic responses of flat and curved IPMC actuators under the frequency of 0.5 Hz and amplitude of 0.5 V and 2.0 V.

etc. At very low driving voltage, only a small oscillation at one static equilibrium point of an initial curvature state is shown, which is similar to the small dynamic stable locomotion of the post-buckling state of the buckled IPMC at one static equilibrium point [35]. All actuators exhibit symmetric harmonic responses without DC offset at a sinusoidal input of 0.5 V. However, under the higher input voltage of 2.0 V, the flat actuator shows a symmetric harmonic response with almost zero mean values, while the two curved IPMC actuators show a positive mean value with harmonic responses. The positive peak value of the curved-I IPMC actuator is double the negative peak value. Also, the curved-I IPMC actuator with the constant curvature of 0.01 mm^{-1} and an initial tip deformation of 8 mm shows 50% larger tip displacement than those of the other two actuators because the highly curved IPMC has a slightly higher stiffness and the flat IPMC is not seriously affected by nonlinear characteristics under lower and a little higher excitations. The presented results show that a properly curved shape of the IPMC actuator can increase the amplitude of the bending deformation through the nonlinear phenomenon under the same higher harmonic inputs.

3.5. Snap-through dynamics of curved cantilever IPMC under high input voltage

In contrast to the flat actuator, a snap-through response was observed in the curved-I IPMC actuator at a considerably higher input voltage of 2.5 V. Figure 7a shows the time history of the transverse tip displacement, which was measured by a laser displacement sensor by adjusting the measuring point from the tip. In spite of the measuring point being 25 mm away from the tip, two-shape slopes of the transverse tip displacement occurred for one time-period. The harmonic response has two periodical and abrupt jumps in the transition

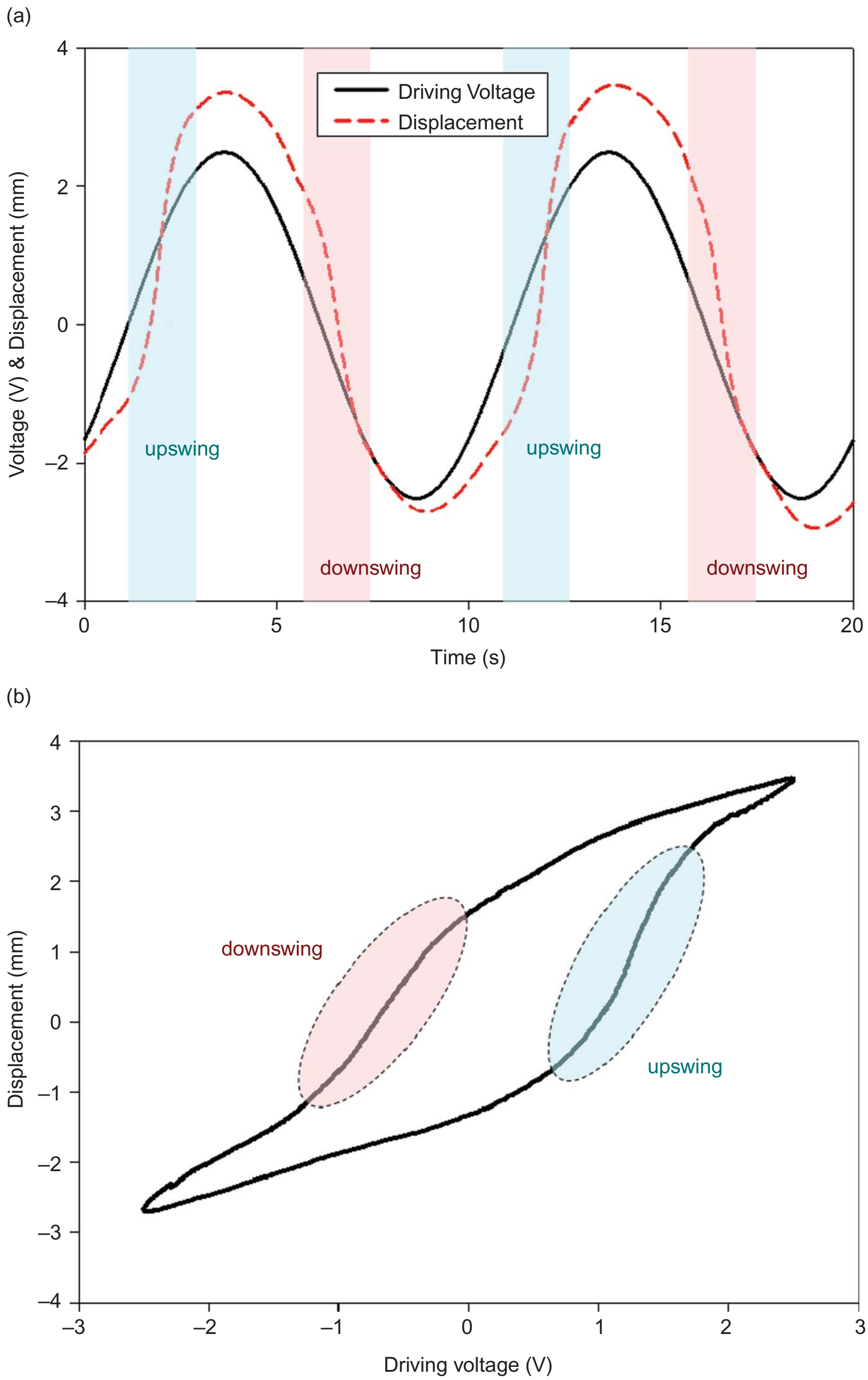

Figure 7. Snap-through responses of curved-I actuator under harmonic excitation of $2.5\sin(2\pi 0.1t)$: (a) transverse displacement history and (b) actuation hysteresis curve.

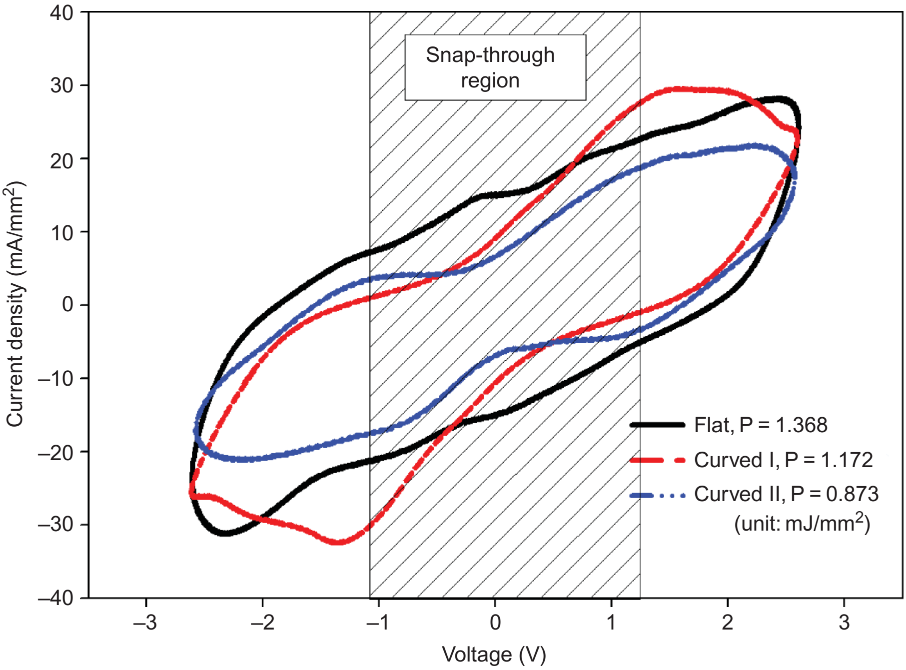

Figure 8. Hysteresis diagrams of the voltage–current relationship of three IPMC actuators under harmonic excitation of $2.5\sin(2\pi 0.1t)$.

region of upswings and downswings and also exhibits asymmetric behaviour because of the initial curvature of the curved-I IPMC actuator. Figure 7b shows the hysteresis response between the tip displacement and driving voltage. As shown in the figure, two periodical and abrupt jumps are observed in the transition region. The curved cantilever IPMC actuator shows snap-through motion under a sinusoidal input voltage of 2.5 V, as mentioned in section on harmonic excitation.

Figure 8 shows the hysteresis diagrams of the voltage–current relationship of the three IPMC actuators. The flat IPMC actuator only exhibits a simple harmonic response, while the two curved IPMC actuators exhibit snap-through motion under relatively high driving voltage. In the snap-through region, the current densities are decreased. It means that the electric input energy will be reduced in the snap-through region since the geometrical instability can induce a jump in the kinetic energy without additional electric input energy. Owing to the snap-through dynamics, the total input energy in the curved-I IPMC actuator (1.172 mJ/mm^2) was a little smaller than that of the flat IPMC actuator (1.368 mJ/mm^2). This means that much larger transverse stroke in the curved IPMC actuator can be generated with lower input energy through snap-through phenomena.

To capture the snap-through motion, a vision sensing system was used because the laser displacement sensor cannot measure the large bending deformation. Also, the speed of the tip point of IPMC actuators was accurately calculated through LabVIEW programming. Figure 9 shows the instant speed of the tip point of the three IPMC actuators under the water for two time-periods under an excitation frequency of 0.1 Hz. Two jumps that occur in the transitions of upswings and downswings are observed in the curved IPMC actuators for a period. So, it was observed that the snap-through dynamics of the curved cantilever IPMC

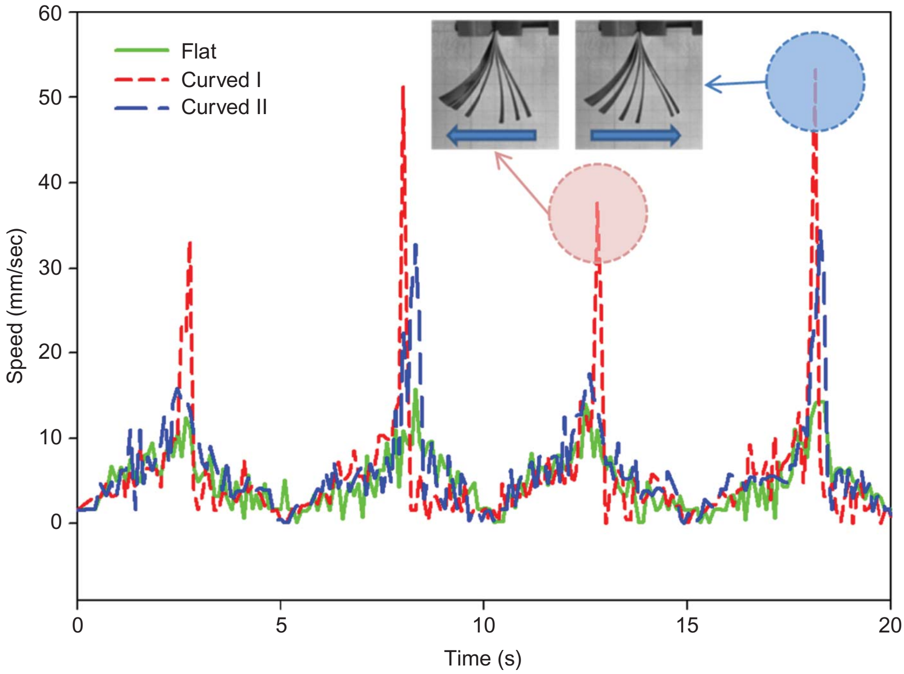

Figure 9. Instant speed of tip point of three IPMC actuators under driving voltage of $3.0\sin(2\pi 0.1t)$.

beam actuators has similar characteristics to the response of an asymmetric composite to an applied in-plane strain. Also, from this phenomenon, it could be evaluated that much larger displacement and periodical stable locomotion based on jumping phenomena could be generated using a curved cantilever IPMC beam under relative low input power. The curved IPMC actuators had the maximum speed when the IPMC goes up along the positive direction. These results demonstrate that the curved IPMC actuators can have much larger strokes under smaller electric input energy. Moreover, the jump speed due to the snap-through dynamics can be applied for active devices such as micro-pumps and switches. A demonstration of the snap-through dynamics of curved IPMC actuators is presented at the following URL: http://sdss.kaist.ac.kr/main/snap-through_dynamics.avi.

4. Conclusion

The nonlinear dynamic responses of curved IPMC actuators undergoing electrically driven large deformations were investigated experimentally. The curved IPMC actuators were fabricated by thermal treatment with different curvatures of 0, 0.01 mm^{-1} and 0.02 mm^{-1}, and initial tip deflections of 0, 8 and 16 mm, respectively. From the present results, some conclusions can be drawn, as indicated below.

A properly curved shape of the IPMC actuator can exhibit much larger bending deformations through snap-through dynamics, which can be asymmetric depending on the direction of the applied input signal under the same step and harmonic inputs. The curved IPMC actuators exhibit snap-through motion, while the flat IPMC actuator exhibits just a simple harmonic response. The harmonic response has two periodical and abrupt jumps, which are generally observed in the process of snap-through dynamics. This occurs in the transition of upswings and downswings with lower input energy because the curved-I IPMC actuator has an initial curvature. The curved IPMC actuators have a maximum instant speed when the IPMC goes up along the positive direction. Owing to the snap-through dynamics, total input energy of the curved-I IPMC actuator is much smaller than that of the flat IPMC actuator, resulting in jumps between multiple equilibrium points. The present results show that there may exist a proper curvature and bending direction for efficient snap-through motion. Thus, it is expected that curved IPMC actuators can be applied for active devices by employing the snap-through phenomena that have crucial advantages such as large stroke, geometric stability, material flexibility and energy efficiency.

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