Study of flapping actuator modules using IPMC

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Hong-Il Kim, Dae-Kwan Kim, and Jae-Hung Han

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ABSTRACT

The Ionic Polymer Metal Composite (IPMC), an electro-active polymer, has many advantages including bending actuation, low weight, low power consumption, and flexibility. These advantages coincide with the requirements of flapping-wing motion. Thus, IPMC can be an adequate smart material for the generation of the flapping-wing motions. In this research, a flapping actuator module operated at the resonant frequency is developed using an IPMC actuator. First, IPMC actuators are fabricated to investigate the mechanical characteristics of IPMC as an actuator. The performances of the IPMC actuators, including the deformation, blocking force and natural frequency, are then obtained according to the input voltage and IPMC dimensions. Second, the empirical performance model and the equivalent stiffness model of the IPMC actuator are established. Third, flapping actuator modules using the first resonance frequency are developed, and their flapping frequency and stroke characteristics are investigated. Fourth, adequate flapping models for a flapping actuator module are selected, and dimensional data such as wing area and wing mass are obtained. Finally, the flapping actuator module is designed and manufactured to adjust the flapping models and its performance is tested. Experimental results demonstrate the potential IPMC has for use as a flapping actuator.

Keywords: Ionic Polymer Metal Composite, IPMC, natural frequency, flapping wing

1. INTRODUCTION

EAPs (Electro Active Polymers) are promising materials for actuator and sensor applications because they have special properties, such as their flexibility, low density, low power consumption, and large strain. These properties are not found in other systems such as mechanical linkages, SMAs (Shape Memory Alloys) or EACs (Electro Active Ceramics). Among all EAPs, the newly developed IPMC (ionic polymer metal composite) materials are highly feasible for use in bio-related applications mainly due to their biocompatibility.

Typically, IPMC is comprised of a pair of electrodes attached to opposite surfaces of an ion exchange membrane [1]. IPMC is actuated by an electrical stimulus in a wet condition [2]. Due to this, IPMC is a somewhat complicated material, as mechanical, electrical and chemical properties interact with each other in the ionic polymer. Many studies concerning the mechanical, electrical and chemical characteristics of IPMC and IPMC modeling have been performed recently. From a microscopic perspective, the principle of IPMC actuation was explained by the immigration of hydrated cations using the electrical parameters of water and the cation [3]. From a macroscopic point of a view, on the other hand, equivalent models of IPMC are established using empirical results for practical use. From static test results such as those from the displacement and blocking force tests, an IPMC actuator can be equivalent to a composite beam; FEM(Finite Element Method) model of IPMC actuator has also been established using obtained equivalent mechanical properties such as the Young’s modulus of IPMC [4]. There are many applications based on this basic research [5, 6].

Flight speeds, weights and wing loadings of all the flying creatures, even the man-made airplanes, have correlations with each other [7]. This suggests that the study of natural flyers can help to improve the performances of air vehicles. In particular, imitation of flapping motion is a very good shortcut to realizing a micro air vehicle; such a vehicle should operate with a low Reynolds number and thus a large viscosity [8]. Therefore, most research on flapping is performed based on geometrical and physical imitations of actual flying creatures such as birds and insects in order to reproduce

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their native ability to fly economically. In order to understand the flapping motions, the unsteady aerodynamics of natural flapping flyers which are essentially different from the aerodynamics of a fixed wing airplane, was studied using visualizations and numerical analysis [9]. In order to realize the flapping motions, bio-mimetic materials such as LIPCA, MFC and IPMC have been used as actuators [5, 10, 11].

In the present study, a casting method is used to fabricate general IPMC actuators with various dimensions. IPMC properties such as the blocking force and frequency response are tested to establish empirical IPMC models. Based on these results, a flapping actuator module is designed to realize flapping motions, and experimental tests are performed to investigate the potential of IPMC for use as a flapping actuator.

2. NAFION CASTING AND THE FABRICATION OF IPMC

To make IPMC, Nafion® is used as an ionic polymer from among various ionic polymers such as Flemion® or Aciplex®. The performance of IPMC can vary with its thickness; the bending stiffness and electric field of the Nafion membrane can be affected by the thickness of IPMC. Nafion samples cast with different thicknesses, rather than a commercial Nafion membrane, are used to determine how the performance changes as the thickness changes for practical uses.

2.1. Nafion casting

According to the technical information concerning Nafion [12], the volume of Nafion dispersion (DE 1021) is approximately ten times the volume of cast Nafion. Hence, the Nafion thickness can be controlled by the adjustment of the volume of the Nafion dispersion. For this reason, a casting method was chosen for making the Nafion thickness to a desired value. The overall casting procedure consists of three steps as outlined in Fig. 1.

2.2. Fabrication of IPMC

Essentially, the purpose of the IPMC fabrication procedure is to create a surface electrode on the surface of the Nafion. There are several means to this end, including sputtering, taping with conductive film, or chemical reduction among others. Generally, however, IPMC is fabricated using the chemical reduction method due to the low cost and good surface toughness gained using this method. Chemical reduction is mainly based on an oxidation-reduction reaction. Fig. 2 shows the fabrication procedure. Li⁺ is selected as the cation, as IPMC is of the highest quality when Li⁺ is used.

![Figure 1: Nafion casting procedure](image1)

![Figure 2: Fabrication procedure of IPMC](image2)
3. PERFORMANCE TESTS OF IPMC

IPMC is a type of EAP actuator that transmits its own deformation to other materials when electro-stimulation is applied. Thus, the deformation, blocking force and frequency response of the IPMC actuator are important properties. These properties are influenced by parameters such as the fabrication method, cation type, and IPMC dimensions. In this research, as mentioned above, the fabrication method and cation type are fixed to test the effects of the dimension on the performance of IPMC.

3.1. Deformation test

A deformation test was performed in order to measure change in the shape according to the applied voltage. The deformation of IPMC was photographed using a digital camera, and point data was extracted from the resulting picture when maximum deformation had taken place after the electric power was applied. The test results are plotted in Fig. 3 according to the applied voltages of 1V, 2V and 3V. The actual deformation shapes of IPMC are plotted in Fig. 3 (a) and only the transverse displacements of each point are plotted in Fig. 3 (b). As shown in Fig. 3 (b), it is clear that the deformation of IPMC is not linearly proportional to the applied voltage.

3.2. Blocking force test

The blocking force was measured at the IPMC tip, as depicted in Fig. 4, by constraint the tip using a load cell that measures the reaction force. The blocking force is mainly dependent on the thickness, width and length of IPMC. Therefore, IPMC samples with various dimensions were used to measure the blocking force. Initially, the correlation between the blocking force and the IPMC thickness was investigated. As seen in the results in Fig. 6, the solid line, is fitting line of the dotted data, expresses that the blocking force of IPMC is proportional to the square of the thickness. Similar to Fig. 6, the solid lines in Fig. 7 and 8 denote the fitting line of the test results. Fig. 8 shows that the blocking force is linearly proportional to the width of the IPMC. However, on the other side, the blocking force is inversely proportional to the IPMC length. This is shown in Fig. 8. From Figs. 6, 7 and 8, it is expected that IPMC can generate a blocking force of over 10gf by a change in its dimensions. The blocking force of IPMC can be expressed as follows.

$$F = C_1 \times \frac{w t^2}{L} \text{ [gf]}, \quad C_1 : 29.18 \text{ [gf/mm}^2\text{]}$$  \hspace{1cm} (1)

where, \(F\), \(w\), \(t\) and \(L\) are the blocking force in gf, the width, the thickness and the length of IPMC in mm. From the data, the mean value of \(C_1\) was found to be 29.18 gf/mm\(^2\) and its standard deviation was 5.06 gf/mm\(^2\). The dashed lines plotted in Figs. 6, 7, 8 represent the results of Eq. (1) calculated with the specified dimensions used in each figure. These lines are very similar to the test results. These results clearly demonstrate that Eq. (1) can adequately predict the blocking force of IPMC.

3.3. Frequency response test

While the deformation and blocking force characteristics of IPMC might be changed due to the microcracks of the surface electrode that can increase the surface resistance, the natural frequencies are little affected by the surface electrode condition. Therefore, the results of a frequency response test are used to establish the equivalent Young’s modulus of IPMC. As mentioned above, IPMC is an actuator that changes the electric signal to shape deformation. This suggests that the frequency response of IPMC contains not only the structural characteristics of IPMC but also electrical characteristics as shown in the block diagram of Fig. 10. Therefore, the poles or zeros of an electrical system may affect the frequency response of IPMC. To verify this, the structural responses of IPMC excited using a shaker as shown in Fig. 5, and the electrical responses of IPMC actuated by random electric signals were compared. Fig. 9 shows that the electrical characteristics change the IPMC system, while the 1\(^{st}\) and 2\(^{nd}\) natural frequencies, the most important characteristics for an actuator, are quite similar. In other words, the electrical characteristics do not have an effect on the 1\(^{st}\) and 2\(^{nd}\) natural frequencies. Thus, a random electric signal was used as a source.
3.4. Measurements of 1st natural frequency

The 1st natural frequency of IPMC is the most important property, as many applications using IPMC utilize its 1st natural frequency. Therefore, the frequency response tests were performed mainly focusing on the 1st natural frequency while changing the dimensions of IPMC. From Figs. 11 and 12, which show the results with varying IPMC thicknesses and lengths, it is clear that the 1st natural frequency of IPMC is proportional to the IPMC thickness and inversely proportional to the square of the IPMC length, as in Eq. (2). From this data, the mean value of $C_3$ is $6.360 \times 10^3 \text{ Hz:mm}$ and its standard deviation is $3.651 \times 10^3 \text{ Hz:mm}$. These results coincide with correlations between the 1st natural frequency of the cantilever beam and its dimensions, as the natural frequencies of a cantilever beam, the Bernoulli-Euler beam, can normally be obtained from the Eq. (2). For the following blocking force test, the results of Eq. (2) are plotted by the dashed line, Eq. (2) also can predict the 1st natural frequency adequately.

$$f = \frac{C_2}{L^2} \times \sqrt{\frac{E \rho A}{\rho A}} = C_3 \times \frac{I}{L^2} \text{ [Hz]}, \quad C_3 : 6.360 \times 10^3 \text{ [Hz:mm]} \quad (2)$$

where, $f$, $E$, $\rho$, $A$ are the 1st natural frequency in Hz, Young’s modulus in Pa, density in kg/m$^3$, and area of cross section in m$^2$, respectively. As $\rho$, $A$, $L$ and $I$ are already known, $E$ can be obtained from the Eq. (2). In this paper, $E$ is 328MPa, and this result is used in the numerical model of IPMC.
Figure 6: Blocking force with varying IPMC thickness

Figure 7: Blocking force with varying IPMC width

Figure 8: Blocking force with varying IPMC length

Figure 9: Comparison of shaker test & electric excitation

Figure 10: Block diagram for IPMC operation

Figure 11: 1st natural frequency vs. IPMC thickness

Figure 12: 1st natural frequency vs. IPMC length
4. CHARACTERISTICS OF FLAPPING ACTUATOR MODULE USING IPMC

4.1. Flapping actuator module using IPMC
The objective of this research is to realize a flapping actuator module using IPMC. Thus, a flapping actuator module was designed to transmit the bending deformation of IPMC to the wing. The wings are attached to the tips of the IPMC actuator directly as shown in Fig. 13, and the flapping actuator module is actuated at the 1st natural frequency to increase the actuating frequency and the flapping angle.

![Schematic diagram of flapping actuator module using IPMC](image)

4.2. Characteristics of the flapping actuator module
Among the various performance parameters, the most important parameters for the flapping actuator module are the flapping actuating frequency and the flapping angle. These two parameters can vary according to the dimensions of the IPMC and wing, as in the IPMC performances. Henceforth, these properties of the flapping actuator module are investigated while changing the two dimensions by analyses and experiments.

4.2.1. Flapping frequency
As expressed earlier, the flapping frequency of the designed flapping actuator module is its 1st natural frequency. The dimensions of the IPMC and wing change the 1st natural frequency. Therefore, parameter studies were executed using Nastran to understand the effects of each dimension. Fig. 14 shows the variation of the 1st natural frequency as the IPMC dimensions change. From the results, the larger the IPMC dimensions (except the IPMC length) are, the higher the 1st natural frequency is. IPMC length shows the opposite effect to those of other dimensions. In particular, the 1st natural frequency is saturated as the thickness of IPMC increases. Fig. 15 shows the effect of the wing dimensions. In a strict sense, the wing dimensions are the wing frame dimensions that are mainly concerned with flapping actuator structures. From Fig. 15, the effects of the wing thickness and length are similar to those of IPMC, but the effect of the wing width is opposite to that of the IPMC width. As the wing width increases, the 1st natural frequency decreases, and the 1st natural frequency decreases when the wing thickness is larger than a given value. These are mass effects of a wing in that the wing can be considered an attached mass of IPMC. As whole wing dimensions can have a larger effect on the 1st natural frequency, a light small wing frame is more practical to increase the 1st natural frequency. Adequate wing frame thickness is required to make the 1st natural frequency high. A thicker wing is not always helpful in terms of the performance of the 1st natural frequency.

4.2.2. Flapping angle (Stroke angle)
Flapping angles were measured using a high-speed camera for cases when actuating at the 1st natural frequency. Figs. 16 and 17 show the experimental results according to the IPMC length and thickness, and Figs. 18 and 19 illustrate the results according to the wing length and width, respectively. From the results, wing width has no effect on the flapping angle, but the 1st natural frequency decreases as the wing width increases, and both the lengths of the IPMC and wing increase the flapping angle. The flapping angle is mostly dependent on the length of the wing. Even the effects of the wing length are dominant on the flapping angle, but the wing length also shows contrary effects on the 1st natural frequency. From Fig. 17, it is clear that a thicker IPMC decreases the flapping angle.

4.2.3. Added mass effect
The wing frame model was used to simulate the wing effects. However, an added mass effect also exists due to the air friction acting on the wing surface. Therefore, this effect should be considered. Fig. 22 shows the deformation results of the wing without a surface (a) and the wing with a surface (b). Figs. 22 (a) and (b) have the same wing frame, but (b) has a wing surface with not only the mass of the surface but also the added mass due to the air friction added to the wing frame. Thus, the 1st frequency and flapping angle decrease as confirmed in Fig. 22 (b).
Figure 14: 1st natural frequency vs. IPMC dimensions

Figure 15: 1st natural frequency vs. wing dimensions

Figure 16: Flapping angle vs. IPMC length

Figure 17: Flapping angle vs. IPMC thickness

Figure 18: Flapping angle vs. wing frame length

Figure 19: Flapping angle vs. wing frame width

Figure 20 Schematic diagram of flapping actuator modules

Figure 21 Available region for flapping actuator module
5. SELECTION OF FLAPPING MODEL

From the results of Chapter 3, it is known that IPMC can generate a blocking force of approximately 10gf. The range of available wing loading is obtained using the maximum blocking force and momentum equilibrium of the flapping actuator, as depicted in Fig. 20. From Fig. 20, Eq. (3), which satisfies the moment equilibrium at the root, is obtained. In Eq. (3), \( W, b, AR \) and \( L' \) are the weight, wing span, aspect ratio and distance from the pressure center of the wing to root, respectively. Weight and wing loading \( W/S \) are related, as shown in Eq. (4). Generally, weight is proportional to the cube of the wing span as expressed in Eq. (5), and wing loading is proportional to wing span. Thus, weight and wing loading are related as shown in Eq. (6).

\[
F \times L = \frac{W}{2} \times L' \leq \frac{W}{2} \times \frac{b}{2} = \frac{Wb}{4}, \quad W \geq F \times \frac{4L}{b}
\]

\[
\frac{W}{S} [N/m^2] = \frac{W \cdot AR}{b^2}
\]

\[
W = C_4 \times b^3, \quad C_4 : 1-10 \text{ N/m}^3
\]

\[
\therefore W = C_5 \times (W/S)^3, \quad C_5 : 10^{-6} - 10^{-3} \text{ N}^2/\text{m}^6
\]

After arranging these equations, Eq. (7) regarding the blocking force and wing loading is obtained. Assuming that \( AR \) is approximately 3 and \( L \) is approximately 20mm, Eq. (7) can be reduced to Eq. (8). Eq. (8) and 10gf line are plotted in log scale in Fig. 21. From the figure, it is clear that IPMC can realize any model whose wing loading is under 4N/m^2.

\[
F = \frac{W}{S} \times b^3 = \frac{W}{S} \times W \times \frac{1}{4L \cdot AR} \times C_4 = \frac{W}{S} \times W \times \frac{1}{4L \cdot AR} \times C_4 = 10^{-4} \sim 10^{-7} \times (W/S)^4 \text{ [N]}
\]

\[
F_{\text{min}} = \left(4.167 \times 10^{-2} \sim 4.167 \times 10^{-5}\right) \times (W/S)^4 \text{ [gf]}
\]

From the ‘The Great Flight Diagram [7]’, this wing loading range is that of insects. Therefore, Eq. (10) was formulated to calculate the flapping frequency according to wing loading using Eq. (9), which expresses the insects’ flapping frequencies [13]. The results of Eq. (10) indicate that the flapping frequencies range from approximately 10Hz to 100Hz when the wing loading is close to 1N/m^2. Therefore, insects that have a flapping frequency and wing loading of about 10Hz and 1N/m^2 can be realized using a flapping actuator module.

\[
f \text{ (small insects)} = 28.7 \times m^{\frac{1}{3}} \text{ [Hz]} \quad (m : \text{mass [g]}) \quad [13]
\]

\[
\frac{13.32}{W/S} \leq f \text{(small insects)} \leq \frac{133.2}{W/S} \text{ [Hz]}
\]

Among the numerous insects, butterflies are very suitable models as they have very low flapping frequencies. Thus, butterflies were selected for use in this study. The butterfly’s data are presented in Table 1.

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<th>Table 1 Butterfly Data [14]</th>
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<td>total mass</td>
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6. REALIZATION OF A FLAPPING ACTUATOR MODULES USING IPMC

6.1. Design of the flapping actuator module
A flapping actuator module consists of IPMC and the wing. The dimensions of the IPMC and wing as well as the materials for the wing were designed to realize the flapping motion. In this flapping actuator module, as the dimensions of the wing are fixed to as in the butterfly data, only the dimensions of IPMC are adjustable. First, the wing is designed to have dimensions similar to those presented in Table 1. Therefore, the wing area is about 7cm$^2$ and its length is 40mm, as shown in Fig. 24 (a). Materials for the wing frame and wing surface were selected to make the wing as light as possible. Therefore, the wing frame was created using PET film with a thickness of approximately 0.1mm and the wing surface is composed of PVA film. Consequently, the wing frame mass is 0.024g and the total wing mass is 0.040g.

Second, the dimensions of IPMC are selected to increase the 1st natural frequency and flapping angle. From the results in Chapter 4, to increase the 1st natural frequency, the thickness of IPMC should be increased. However, the flapping angle decreases in this case and the length of IPMC has the opposite effect on the performances of the flapping actuator modules. Therefore, the thinnest possible IPMC was used to increase the flapping angle, and the length of IPMC is controlled to increase the 1st natural frequency based on the results from Chapter 4. The dimensions of IPMC are presented in Table 2. Finally, IPMC and wing are manufactured separately and attached directly, as shown in Fig. 24 (b).

6.2. Performance test of the flapping actuator module
The performance test consisted of a frequency response test that determined the 1st natural frequency and a flapping test that measured the generated lift and flapping angle. After measuring the 1st natural frequency, a load cell measured the generated lift when actuated by a 2.5V sinusoidal input with the frequency of the 1st natural frequency while a high-speed camera captured pictures that measured the flapping angle, as depicted in Fig. 23. Test results show that the 1st natural frequency of the flapping actuator module is 4.75Hz, and 2.5V and a 4.75Hz sinusoidal signal were then used as the input. The measured lift and flapping angle are plotted in Fig. 25. Due to the down stroke and upstroke of the wing, the lift can be both positive and negative. Thus, the mean, maximum and minimum lifts were measured. The mean lift of the flapping actuator module is 0.00258gf, the maximum lift is 0.0361gf and the minimum lift is -0.0313gf. These lift results are much smaller than the total mass as only one wing was used to measure the lift and because the 1st natural frequency and flapping angle were not large enough. From the data shown in Table 1, the flapping frequency is must be 10.5Hz, but the 1st natural frequency of this flapping actuator module is 4.75Hz, and the measured flapping angle is 35°, which is much smaller than the flapping angle of a butterfly. Generally, the phase angle between the flapping angle and the lift is approximately 90° as the maximum lift is generated when the flapping angle is 0° during the down stroke. However, the phase angle of the test is nearly 39.6°. This indicates that the measured lift contains not only the aerodynamic force but also the inertia force of the wing. Therefore, an additional test was performed to measure the inertia force of the wing at the same frequency. To exclude the aerodynamic force, only the wing frame was used, and the effects of mass difference and flapping angle difference were corrected. The inertia test result is plotted with the lift results in Fig. 26. Fig. 26 shows that the inertia force has a magnitude that is nearly identical to the measure lift. This implies that the generated lift is nearly the inertia force of the wing, and that most of the IPMC energy is used to move the wing. There are many reasons why the performances are not sufficient. Among these reasons, the most important reasons are the wing mass and added mass effect. The wing mass is large compared with the butterfly wing mass. As listed in Table 1, the total mass of the model butterfly is 0.128g, and general wing mass of butterfly is under 20% of the total mass. But mass of the wing used in this experiment is 0.040g; two wing masses are 0.080g which is 63% of the total mass. Thus, it is clear that heavy wing reduces the 1st natural frequency and flapping angle. The added mass effect, the reaction induced by the acceleration of the air, also influences in the actuation of flapping actuator module. In this case, however, added mass acts like air damping on wing surface and decrease the 1st natural frequency and flapping angle as described in Chapter 4. Finally, to improve the performance of the flapping actuator module, the wing mass should be shrunk. But added mass effect is related to the wing area that is already fixed. For this reason, only the wing mass is controllable using other materials and structure, and the advanced IPMC or mechanism are needed to overcome the added mass effect. Novel mechanisms composed of bar linkages and gear trains should be considered to increase the performances.
Table 2 Data of the flapping actuator module

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<td>5mm</td>
<td>0.205mm</td>
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<tr>
<td>Wing</td>
<td>length</td>
<td>area</td>
<td>mass</td>
</tr>
<tr>
<td></td>
<td>40mm</td>
<td>7cm²</td>
<td>0.040g</td>
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Figure 22: Comparison of flapping test between wing frame and wing; (a) without wing surface, 0.0148g, 1st freq: 8.25Hz, stroke: 65°, (b) with wing surface, 0.0357g, 1st freq: 6.25Hz, stroke: 30°

Figure 23: Flapping test setup

Figure 24: Manufacture of flapping actuator module; (a) Wing frame structure, (b) Picture of flapping actuator module
7. CONCLUDING REMARKS

In this study, Nafion® polymers are cast with various thicknesses, and IPMCs are fabricated using these polymers. Consequently, IPMCs with various dimensions were obtained. These IPMCs were used to carry out experiments on the deformations, blocking forces and frequency responses. From the results, empirical equations concerning the blocking force and frequency response were achieved. In addition, from frequency response tests, the equivalent stiffness of IPMC could be derived as well. As an application of IPMC, a flapping actuator module was devised to transmit the bending deformation of IPMC to the wing directly for better efficiency. The characteristics of the flapping actuator module were investigated through numerical analyses and experiments. Additionally, adequate flapping models which were applicable in this study were selected. Finally, the flapping actuator modules were fabricated using the refined IPMC and a wing. Performance results of the flapping frequency and lift were examined. From the results, performances of flapping actuator module are not sufficient due to the heavy wing and added mass effect. Therefore, further investigations on lighter wing structure and advanced mechanisms with improved IPMC are needed. Provided these problems are overcome successfully, better flapping actuator module can be realized based on this study.

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Study of flapping actuator modules using IPMC

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Ionic Polymer Metal Composite (IPMC), an electro-active polymer, has many advantages such as bending actuation, low weight, low power consumption, flexibility and so on. These advantages coincide with the requirements of flapping-wing motion which is the main wing motion of small flying insects. Thus, IPMC is an adequate smart material for generating the flapping-wing motion. In this research, a bio-mimetic flapping actuator module operated at the resonant frequency is developed by using IPMC actuator based on the bio-mimetic design approach. First, the flapping mechanisms of flying insects such as butterfly, dragonfly and bee, are studied to determine the design requirements of the flapping actuator (flapping amplitude and frequency, actuation force, wing geometry and loading).Second, IPMC actuator is fabricated and fundamental characterization tests were conducted to investigate the mechanical characteristics of IPMC as the driving actuator. The performance of the IPMC actuators, deformation, blocking force and natural frequency depending on the input voltage and actuator dimensions, are then obtained from static and dynamic tests. Second, the analytical model of the IPMC actuator is established by using the performance results. By using analytical model, IPMC actuator is designed to adjust the design requirements, flapping frequency and actuation force. The natural frequency of the actuator module is selected as the operating frequency to increase the actuation efficiency, and the analysis results of the actuator module are compared with the experimental data. Finally, the flapping-wing system consisting of the IPMC actuator and a flexible insect wing are manufactured on the basis of the design requirements and the IPMC model. The dynamic characteristics and efficiency of the flapping-wing system are investigated and improved.

EAP as actuator for a gripper with variable curvature

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Correct microsystems are mostly made of silicon, but, in order to improve their performance and fulfill all their potential applications, the development of hybrid MEMS is strongly recommended. Hybrid systems are made of several components linked together. The main advantage of this approach is the possibility of using the most appropriate material and fabrication techniques for each component. On the other hand, due to the incompatibility of the processes, this approach requires suitable operations to assemble the components together.

The varying phase of microscopic components is a hard task and it represents the strength limit of the current fabrication of hybrid microsystems. Indeed, at microlevel, as a result of the high surface to volume ratio, surface forces become dominant with respect to other forces (weight, internal forces, external loads, and so on) and real physical phenomena occur. For this reason, the manipulation of microscopic components cannot be done through the procedures used for macrosystems; the failure of some theories and principles of these procedures often occurs when downscaled, therefore, the development of new handling techniques is strongly recommended.

On the other hand, the small dimensions and the low mass of microsystems allow the use of physical principles not suitable for the manipulation of macrocomponents. Corresponding to this perspective, numerous gizmos have been developed in the last years.

In this context, innovative handling systems have been studied at ISTA and the possibility of controlling and exploiting superficial interactions have been analyzed. In particular, the contact force has been investigated and an original handling system, based on capacitive force, has been conceived. Theoretical analyses were followed by simulations and modeling studies in order to develop a first prototype of a gripper with variable curvature. It was experimentally tested and showed a good reliability in being able to perform basic operations of pick and place of objects with a significant variety of shapes and weights. Due to the low stiffness of the complex object-finger, axial compliance can be exploited for ensuring safety operations. Moreover, the choice of an adhesive gripping system favors the manipulation of fragile components.

The results obtained with this prototype encourage the development of a real prototype, which, according to the theoretical predictions, would be suitable for the reduction of debris of the device. Therefore, smart materials for the actuation of the gripper have been investigated. Specifically, a novel configuration based on electroactive polymers (EAP) has been conceived. Indeed, due to the large displacement that can be obtained with EAP, their low mass, low power and, in general, their low voltage, they seem to be one of the most suitable materials for this purpose. Therefore, to understand their behavior and performance for actuation purposes, deep studies for the realization of a gripper with such an actuator have been investigated and presented in this paper.

A linear actuator from a single ionic polymer-metal composite (IPMC) strip

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Ionic polymer-metal composite (IPMC) bending actuators have a number of important characteristics that make them useful for use as artificial muscles and actuators. These include low weight, low volume, and low actuation force. At the same time, application areas also have robustness and low weight and actuation force. Thus, the linear actuator actuator has been developed, which can be used as an IPMC actuator actuator. This actuator is designed to satisfy the requirements for a linear actuator. Therefore, new actuator designs are necessary, including mechanical features such as sliding arms, flexible tape joints, rotating and linear Constraints and so on. These mechanical features are undesirable because they introduce mechanical weaknesses, cool weight, or make manufacturing more difficult.

In this paper, we present a novel linear actuator that, in its simplest form, is constructed from a single IPMC bending actuator that actuates into the form of a double-armed buckled beam. The buckled beam structure is that bending moment in the two halves of the beam cancels each other. As a result, only one bending actuator is needed to form a single linear actuator. Consequently, the newly designed actuator is mechanically simple and requires fewer actuator components. The non-normative nature of the bending in the double-armed buckled beam also means that joining multiple elements to increase the bending moment is trivial.

Actuation of the linear actuator element with a single driving voltage forces it to deform from a flat relaxed shape into a double-curved buckled beam shape. Axial deflection of the end points and sideways deflection of the mid point thus results in two linear actuation strokes. These complex curved shape is made possible by segmenting the electrodes on the surface of the actuator and applying reverse polarity voltages to successive segments. By segmenting the actuator into three segments we gener-