Adaptive Fuzzy Control of Electrostrictive Polymer Actuator for the Endoscopic Microcapsule*

Kyoil HWANG** and Hunmo KIM***

This paper deals with modeling and control of electrostrictive polymer (EP) for endoscopic microcapsule. The EP is so flexible that we considered it as a flexible membrane. And the EP has time variant variable. It is the reason that the elastic modulus of EP is very small and changes during deformation of EP. But an electronics, polymer science and mechanics must be considered at the same time to have exact model of EP. So a control algorithm was used. The control algorithm must overcome the limit of modeling. So the algorithm of adaptive fuzzy algorithm was used to control the actuator exactly.

**Key Words**: Electrostrictive Polymer (EP), Endoscopic Microcapsule, Adaptive Fuzzy Control, Flexible Membrane

1. Introduction

Now days, a micro scale system has been developed. In small scale systems, such as micro robot, conventional electromagnetic technologies generally have poor performance, due to physical scaling effects and fabrication difficulties. Such small scale systems could benefit from improved actuators. In general, the polymer is attractive as actuator materials because they are lightweight, easily fabricated in various shapes, low cost; and in addition the polymer their properties can often be modified as desired, by various chemical means.

This polymer actuation technology is based on the deformation of dielectric elastomeric polymers in the presence of an electric field. This dielectric elastomer technology does not necessarily produce the greatest performance in any one measure, however dielectric elastomers do have a large specific energy output, large strain response, fast response, and high energy efficiency.

The material of a micro-actuator that is made by polymers is as follows. Electrostrictive polymer (EP)(11)(17), piezoelectric polymer(18)(19), shape memory polymer(13), conducting polymer(12)(18) belong to these polymers. But many smart materials do not have all of the shortfalls of electromagnetics. These materials, including shape memory alloys and piezoelectric and magnetostrictive material, have been shown to be suitable for many new applications. However, each has specific shortcomings that prevent its usage in a wider range of applications. For example, piezoelectric materials are efficient and gave a fast response, but can produce only very small motions. Shape memory alloys have large strain and force outputs but are not energy efficient and are slow to respond. Because of these shortcomings, EP was developed. The EP does not harm to human body. So we make endoscopic microcapsules using the EP.

The mechanism of EP relies on electrostatic forces, the performance of EP is critically determined by the electrical, polymer science and mechanical properties. The quantity and the shape of the strain are changed by applied voltage in the EP, the boundary condition, and the Young’s modulus of the material.
The EP is a very flexible material\textsuperscript{17,19}. And the EP has a thickness, so it looks like a plate. But, when the voltage is applied in the EP, the thickness of EP changes. This causes for the stiffness of EP to change. At the same time, the tension of EP changes. So it is possible that EP is considered as a flexible membrane of which the tension is changed during deformation of EP.

The EP actuator was made using this EP membrane.

But the parameters of EP don't be exactly known clearly, the modeling doesn't exact. And it will work unknown surround, the tension is time variant variable. So we studied the algorithm of adaptive fuzzy control\textsuperscript{19-23}. So this paper deals with these modeling and control algorithm.

2. The Modeling of EP Actuator

The EP is used for material of actuator in endoscopic microcapsule. The experiments in our study were designed to measure the relation of voltage and strain. The EP needs the high voltage to work. So the high voltage power supplier was used. And the laser strain gauge was used to gauge strain exactly. These are shown in Fig. 1. When a voltage is applied to the electrodes, the film between the electrodes expands in area and contracts in thickness. The extended EP is shown in Fig. 2(a). The initial EP is shown in Fig. 2(b). The module of endoscopic microcapsule is shown in Fig. 3. The whole shape encoscopic microcapsule is shown in Fig. 4. The experiment was be basis for modeling.

2.1 Principle of operation in EP

The actuation of EP is based on the deformation of elastomeric polymer dielectrics. In this case the electrodes that produce the electric field are applied

![Laser strain gauge](image1)

![High voltage power](image2)

![The equipment of experiment](image3)

![A module of actuator](image4)

![A hole shape of actuator](image5)
directly to the surface of the polymer dielectric. When a voltage is applied across the electrodes, the polymer shrinks in thickness and expands in area, as shown in Fig. 5. The net volume change of the polymer materials is very small. The electrodes must be highly compliant so as not to restrain the motion of the film. The resultant strains produced in the polymer are dependent on the boundary conditions and loads on the polymer. In this paper, it is assumed that the constraint is applied in all edges and the electrode is applied in all of the area in the EP as shown in Fig. 6.

2.2 The modeling of tension

In this paper, it was assumed that the EP is almost the same as the flexible membrane. So the tension is an important factor in membrane. When a voltage is applied to the EP, the tension is changed.

The tension is a time variant variable. In this paper, the tension is marked, \( \tau(t) \). To model the equation of tension, geometry of the deformation was used on EP. The EP has the incompressibility and uniformity. The model of tension was derived using these properties. The deformation of EP is shown in Fig. 7. In Fig. 7, \( a, b, c \) are initial length, \( a', b', c' \) are the changing length. In this time, \( d' \) is represented as

\[
d' = d(1 - \delta_t) \tag{1}
\]

where \( \delta_t \) is thickness strain. To derived \( \delta_t \), Eq.(2) was used.

\[
P = \varepsilon\varepsilon_0 \left( \frac{V}{d'} \right)^2 = E \delta_t \tag{2}
\]

Where \( P \) is pressure that is applied in EP, \( d \) is thickness of EP, \( \varepsilon \) is permittivity, \( \varepsilon_0 \) is permittivity of free space and \( V \) is voltage that is applied in EP. So when voltage is applied to the EP, the thickness strain is defined. But the pressure has a time delay because the EP has a property which is one of capacitor-like properties. The Eq.(3.a) and Eq.(3.b) are about pressure. The former is Eq.(3.a) and Eq.(3.b) are about pressure. The former is applied voltage on EP and the later is not.

In these equation, the time delay is included at Eq. (2), the time delay was measured at experiment.

\[
P(t) = \varepsilon\varepsilon_0 \left( \frac{V}{d(t)} \right)^2 \left( 1 + \frac{1}{1 + e^{-\frac{t}{\tau}}} - 0.5 \right) \tag{3.a}
\]

\[
P(t) = \varepsilon\varepsilon_0 \left( \frac{V}{d(t)} \right)^2 2^n \left( 1 + \frac{1}{1 + e^{-\frac{t}{\tau}}} \right) \tag{3.b}
\]

The pressure is shown in the Fig. 8. In Fig. 8, the voltage is turned on in \( 0 < \text{time} < t_1 \), and off in \( t_1 < \text{time} < t_2 \). The \( a' \) and \( b' \) become Eq.(4) and Eq.(5).

\[
a' = a(1 + \varepsilon_{ab}) \tag{4}
\]

\[
b' = b(1 + \varepsilon_{ab}) \tag{5}
\]

Here, \( \varepsilon_{ab} \) is the strain of \( x \) and \( y \) coordinate. The strain of \( x \) and \( y \) coordinate are same. It is the reason that electrostrictive polymer has the uniformity. Now using the incompressibility, Eq.(6) is derived.

\[
\varepsilon_{ab} = \varepsilon_{ab}(1 - \delta_t)(1 + \varepsilon_{ab}) \tag{6}
\]

So \( \varepsilon_{ab} \) is like Eq.(7).

\[
\varepsilon_{ab} = \sqrt{\frac{1}{1 - \delta_t} - 1} \tag{7}
\]

\( \delta_t \) is derived in Eq.(2). So using this relation, the equation of tension is derived as Eq.(8).

\[
\tau(t) = E(t) - \sqrt{E(t)}(E(t) - P(t)) \tag{8}
\]

In Eq.(8), tension is the function of elastic modulus (stiffness) and pressure. The elastic modulus
(E(t)) is measured as experiment. When voltage is applied to EP, the tension becomes small. And voltage is preserved in EP, the tension is preserved, too. When voltage turns off, then the tension becomes large. This mechanism makes the displacement of EP to be changed.

2.3 The dynamics of EP

In this paper, EP is considered as a thin flexible membrane. It is shown in Fig. 8. The constraint is applied the edge in EP. And thickness is very thin, elastic modulus is very small. In Fig. 9, the system of deformation is shown. This is about a minuteness element in Fig. 10.

In Fig. 9, τ is a restitutive tension. θ is a deformation degree. The w(x, y, t) is amount of deformation. x₁, x₂ are position of the minuteness element. To derive two dimension equation, first we drive one dimension equation. It is shown at Eq. (11).

\[ -n \sin \theta + n \sin \theta \cdot f(x, t) \Delta x = \gamma \Delta x \frac{\partial^2 \omega(x, t)}{\partial t^2} \]  

(11)

Here, γ is mass per unit length.

The Eq. (11) is nonlinear function. But, if deformation degree, θ, is very small, then it is possible that Eq. (11) may be equal Eq. (12).

\[ \left( \frac{\partial \omega(x, t)}{\partial x} \right)_{x_1} \Delta x - \left( \frac{\partial \omega(x, t)}{\partial x} \right)_{x_2} \Delta x = \gamma \frac{\partial^2 \omega(x, t)}{\partial t^2} \Delta x \]  

(12)

The degree, in, x₂, may be represented using Taylor expansion. So Eq. (13) is made.

\[ \frac{\partial}{\partial x} \left( \frac{\partial \omega(x, t)}{\partial x} \right) = \gamma \frac{\partial^2 \omega(x, t)}{\partial t^2} \]  

(13)

Now, it is possible in y-coordinate, so Eq. (14) may be made.

\[ \frac{\partial \omega^2(x, y, t)}{\partial x^2} + \frac{\partial \omega^2(x, y, t)}{\partial y^2} = \frac{1}{c^2} \frac{\partial^2 \omega(x, y, t)}{\partial t^2} \]  

(14)

Here the c is \( \sqrt{\frac{\gamma}{\tau(t)}} \), E is elastic modulus, and γ is a mass per unit area of EP.

2.3.1 The mode shape

In Eq. (14), the PDE is usually solved using separation method. The separation was processed as Eq. (15).

\[ w(x, y, t) = X(x) Y(y) T(t) \]  

(15)

When Eq. (14) is separated about x, y, t, then Eq. (16) is derived

\[ \frac{X(x)''}{X(x)} = \frac{Y(y)''}{Y(y)} = \frac{1}{c^2} \frac{T(t)}{T(t)} \]  

(16)

In the Eq. (16), each term may be represented as Eqs. (17), (18) and (19).

\[ \frac{X(x)''}{X(x)} = -\alpha^2 \]  

(17)

\[ \frac{Y(y)''}{Y(y)} = -\beta^2 \]  

(18)

\[ \frac{T(t)'}{T(t)} = -\frac{\gamma}{c^2} \]  

(19)

The Eqs. (17) and (18) is the function about the mode shape. So using the Eqs. (17) and (18), the mode shape is derived as Eq. (20).

\[ X(x) Y(y) = (A \sin \alpha x + B \cos \alpha x) \times (C \sin \beta x + D \cos \beta x) \]  

(20)

To find the A, B, C, D, the boundary condition is used. The condition is shown in Eq. (21).
\[ w(a, y, t) = w(a, y, t) = 0 \]  
\[ w(x, 0, t) = w(x, b, t) = 0 \]

So the mode shape may be derived as Eq. (22).

\[ \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} \frac{\sin n\pi x}{a} \sin m\pi y = 0 \]

(22)

Here, \( a = n \pi, n = 1, 2, 3, \ldots, \infty \) and \( \beta = m \pi, m = 1, 2, 3, \ldots, \infty \).

2.3.2 The change in displacement in time

The Eq. (19) is the function about the time. So using Eq. (19), the change in displacement is derived as Eq. (23).

\[ \ddot{T}(t) + \frac{w_{ea}}{T^2} \dot{T}(t) = 0 \]

(23)

The Eq. (23) does not include a damping ratio, but the EP is visco-elastic material. So the damping ratio is a very important factor. The equation that includes damping ratio is shown in Eq. (24).

\[ \ddot{T}(t) + 2\xi w_{ea} \dot{T}(t) + \frac{w_{ea} \dot{T}(t)}{T} \dot{T}(t) = 0 \]

(24)

The result of mode shape is information of point of EP area. So the maximum number is “1”. That is the maximum displacement is \( T(t) \). And the maximum velocity is \( \ddot{T}(t) \). The Eq. (24) is time variant equation, a solution of Eq. (24) is too hard to solve in closed form. So in this paper, the numerical analysis method was used to solve the Eq. (24) using Eq. (25).

\[
\begin{bmatrix}
T_1 \\
T_2
\end{bmatrix} = \begin{bmatrix}
0 & 1 \\
-\frac{w_{ea} \theta(t)}{c^2} & -2\xi w_{ea}
\end{bmatrix} \begin{bmatrix}
T_1 \\
T_2
\end{bmatrix}
\]

(25)

Here, \( \sqrt{\frac{T(t)}{c^2}} = \theta(t) \).

2.4 The dynamics of EP actuator

A type of actuator that was developed is diaphragm. A module of actuator is shown in Fig. 10. Four modules of actuator are piled up, a whole actuator is made. The fabrication of actuator is that two EP films wrap in top and bottom side of a ball. The mechanism is that the transformation is occurred in direction of applying part when voltage is applied on each EP. So, in order to execute this modeling, it is required not only previous EP modeling but also new external force term that is occurred in ball. Figure 11 shows free body diagram of actuator.

2.4.1 Dynamics of EP actuator

Dynamic modeling of EP actuator is able to be assumed adding the force to simple modeling of EP in chapter 2. The equation of EP actuator model is shown in Eq. (26).

\[ \frac{\partial w(x, y, t)}{\partial x^2} + \frac{\partial^2 w(x, y, t)}{\partial y^2} + F(t) = \frac{1}{c^2} \ddot{w}(x, y, t) \]

(26)

The driving force at Eq. (26) is able to be induced by Fig. 11. The mechanism of this actuator is caused by difference of tension of EP, so it is able to induce as Eq. (27), therefore, model is analyzed substituting Eq. (27) for Eq. (26).

\[ F(t) = 2\tau(t) \cos \theta \]

(27)

2.4.2 Homogeneous solution

To get homogeneous solution, \( F(t) \) at Eq. (26) is assumed zero. It is same with EP membrane. The mode shape of EP actuator is like Eq. (28).

\[ X(x, y) = \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} \sin \frac{n\pi x}{a} \sin \frac{m\pi y}{b} \]

(28)

Beside, EP actuator is viscoelasticity, the equation of EP actuator that is about time is like Eq. (29).

\[ \ddot{T}(t) + 2\xi w_{ea} \dot{T}(t) + \frac{w_{ea} \dot{T}(t)}{T} \dot{T}(t) = 0 \]

(29)

Equation (29) is solved by numeric analysis because it contains a term of tension that is time variant variable.

2.4.3 Particular solution

Equation which contains the term of \( F(t) \) can’t solve with variable separation method. So displacement \( w(x, y, t) \) is regarded as Eq. (30).

\[ w(x, y, t) = W(x, y, t) + \phi(t) \]

(30)

Equation (31) is the result of putting the Eq. (30) into Eq. (26).

\[ \frac{1}{c^2} \frac{\partial^2 W(x, y, t)}{\partial t^2} - \frac{\partial^2 W(x, y, t)}{\partial x^2} + \frac{\partial^2 W(x, y, t)}{\partial y^2} + \frac{1}{\tau(t)} F(t) - \frac{\partial \phi(t)}{c^2} = 0 \]

(31)

To be a wave equation, Eq. (32) will be satisfied.

\[ \frac{1}{\tau(t)} F(t) - \frac{\partial \phi(t)}{c^2} = 0 \]

(32)

And the boundary condition, Eq. (33), is shown below.

\[ w(0, y, 0) = W(0, y, 0) + \phi(0) \]
\[ w(a, y, 0) = W(a, y, 0) + \phi(0) \]
\[ w(x, 0, 0) = W(x, 0, 0) + \phi(0) \]
\[ w(x, b, 0) = W(x, b, 0) + \phi(0) \]

If \( \phi(0) = 0 \), the formula is like Eq. (34)

\[ W(0, y, 0) = 0 \]
\[ W(a, y, 0) = 0 \]
\[ W(0, y, 0) = 0 \]
\[ W(0, b, 0) = 0 \]

(33)

(34)

(35)

to solve the particular solution, integrate about \( \phi(x) \) which is defined though the Eq. (35)

\[ \phi(t) = \int \left( c^2 F(t) \right) \frac{d\tau(t)}{\tau(t)} \]

(35)

Accordingly entire formula of EP actuator is the formula about \( W(x, y, t) \) which contains the term of

Fig. 11 Free body diagram
\( \phi(t) \). To integrate the Eq.(35), \( \phi(t) \) and \( \phi(t) \) is regarded as 0. This means a parallel movement of homogeneous solution about \( \phi(t) \). To get a particular solution, numeric analysis is used.

3. Adaptive Fuzzy Algorithm

The EP plays a part in capacity, so the electric modeling must be considered. And EP is viscoelastic material, so a polymer science must be considered. But in this paper, we just considered the EP is flexible membrane. So we developed a control algorithm to control EP actuator exactly.

We used an adaptive fuzzy control. The fuzzy algorithm was used to accept robustness. And the time variant variable (the tension) is included in the EP actuator, the adaptive algorithm was used. Even if the modeling does not exactly, the adaptive fuzzy control algorithm can control the EP actuator exactly.

3.1 Fuzzy model reference learning control

We used an FMRLC (Fuzzy Model Reference Learning Control) algorithm for a direct adaptive fuzzy controller in order to improve the performance of the system. The FMRLC has two parts basically: the fuzzy controller and the learning mechanism. The learning mechanism distinguishes an FRMLC from a fuzzy control. The schematic of the FMRLC is shown in Fig. 12.

3.1.1 Fuzzy controller part

We used triangular membership functions, the Min-Max inference engine, and central gravity defuzzification for the fuzzy controller part. They are shown in Eqs.(12), (13), and (14).

\[
U(e|a) = \frac{\prod_{i=1}^{n} \mu_{a_i}(a)}{\sum_{i=1}^{m} \sum_{j=1}^{n} \prod_{i=1}^{n} \mu_{a_i}(a) + \sum_{i=1}^{m} \sum_{j=1}^{n} \prod_{i=1}^{n} \mu_{a_i}(a)}
\]

(13)

\[
\hat{e} = \frac{\prod_{i=1}^{n} \mu_{a_i}(a)}{\sum_{i=1}^{m} \sum_{j=1}^{n} \prod_{i=1}^{n} \mu_{a_i}(a)}
\]

(14)

The linguistic values for input and output of the controller are shown below.

1) Input variable

(1) The error of displacement

The linguistic value for the error of displacement is \( e(kT) \). It is noted below.

\[
e(kT) = r(kT) - y(kT)
\]

(15)

where, \( T \) is the sampling time, 0.01 sec, and \( k \) is the sampling number. And \( r \) is input, \( y \) is actual displacement of actuator. So the error is the difference of reference input displacement and actual displacement. It is normalized between 0 and 10.

(2) The error change of displacement

The linguistic value for the error change of displacement is \( c(kT) \). It is noted below.

\[
c(kT) = \frac{e(kT) - e(kT-1)}{T}
\]

(16)

where, \( T \) is the sampling time and \( k \) is the sampling number. At \( t = kT \) the crisp change in error is the difference between present error and error in the previous time step \( t = kT - T \). It is normalized between 0 and 10.

2) Rule-base

The rule-base for the fuzzy controller that controls the displacement has rules of the form "IF-THEN".

\[
R: IF e \text{ is } E^i \text{ AND } c \text{ is } C^j \text{ THEN } v \text{ is } V^m
\]

where \( e \) and \( c \) denote the linguistic variables associated with controller input error of displacement, \( e(kT) \) and error change of displacement, \( c(kT) \), respectively. \( V \) denotes the linguistic variable associated with the controller output \( v \); it is a voltage, and \( E^i \) and \( C^j \) denote the \( i \)th (\( j \)th) linguistic value associated with \( e \) and \( c \), respectively. The error and error change of displacement are applied to the controller, the controller control the voltage in EP actuator. The rule-bases for the fuzzy controller are shown in Table 1.

3.1.2 Learning mechanism

The learning mechanism consists of two parts: a fuzzy inverse model and a rule-base modifier.

The linguistic values for input and output of the fuzzy inverse model are shown below.

1) Input variable

(1) The error between the reference model displacement and the actual displacement.

The linguistic value for the error between the reference model displacement and the rear actual displacement is \( y_e \). It is noted as

\[
y_e(kT) = y_m(kT) - y(kT)
\]

(17)
Table 1  Rule base before changing

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.1</td>
<td>1.1</td>
<td>1.32</td>
<td>4.3</td>
<td>4.725</td>
<td>5</td>
<td>5.275</td>
<td>5.7</td>
<td>7</td>
<td>9.225</td>
<td>9.235</td>
</tr>
<tr>
<td>1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.32</td>
<td>4.3</td>
<td>4.785</td>
<td>5</td>
<td>5.216</td>
<td>5.7</td>
<td>7</td>
<td>9.225</td>
<td>9.235</td>
</tr>
<tr>
<td>2</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>4.5</td>
<td>4.555</td>
<td>5</td>
<td>5</td>
<td>5.5</td>
<td>7</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>3</td>
<td>3.5</td>
<td>3.5</td>
<td>4.5</td>
<td>4.625</td>
<td>5.44</td>
<td>6.025</td>
<td>6.51</td>
<td>6.909</td>
<td>7</td>
<td>9.225</td>
<td>9.235</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>6</td>
<td>4.6</td>
<td>5</td>
<td>6.59</td>
<td>5</td>
<td>5.909</td>
<td>7.25</td>
<td>7</td>
<td>9.225</td>
<td>9.235</td>
</tr>
<tr>
<td>7</td>
<td>4</td>
<td>5</td>
<td>4.5</td>
<td>5.3</td>
<td>7.62</td>
<td>6.51</td>
<td>7.691</td>
<td>9</td>
<td>9.225</td>
<td>9.235</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>4.5</td>
<td>4.5</td>
<td>4.5</td>
<td>6.5</td>
<td>6.5</td>
<td>6.5</td>
<td>6.5</td>
<td>7</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
<td>5</td>
<td>4.5</td>
<td>6</td>
<td>6.74</td>
<td>8.93</td>
<td>8.93</td>
<td>9.33</td>
<td>9</td>
<td>9.225</td>
<td>9.235</td>
</tr>
</tbody>
</table>

where, \( T \) is the sampling time and \( k \) is the sampling number. And \( y_m \) is the displacement of reference model, \( y \) is the actual displacement of EP actuator. It is normalized between 0 and 10.

(2) The error change between the reference model displacement and the actual displacement.

The linguistic value for the error change between the reference model displacement and the actual displacement is \( y_e \). It is noted below.

\[
y_e(kT) = \frac{y_e(kT) - y_e(kT - T)}{T} \quad (18)
\]

where, \( T \) is the sampling time and \( k \) is the sampling number. It is normalized between 0 and 10.

2) Rule-base

The rule-base for the fuzzy inverse model has rules of the form “IF-THEN”.

\[ R: \text{IF } y_e \text{ is } Y_e^i \text{ AND } y_c \text{ is } Y_c^j \text{ THEN } \rho \text{ is } P^m \]

where \( Y_e^i \) and \( Y_c^j \) are linguistic values. The fuzzy membership function is moved by \( P^m \). The rule-bases for the fuzzy inverse model are shown in Table 2. The output \( \rho \) adapts the fuzzy controller, using the equation below and employing the fuzzy modifier.

\[
c_i(kT) - c_i(kT - dT) + p(kT) \quad (19)
\]

where \( c_i \) is the center of the fuzzy membership function for the \( i \)th output variable at \( kT \).

4. Result

4.1 Result of modeling

We considered the mode shape. The result is shown in Figs. 13, 14 and 15. The deformation of EP is changed by prestrain. The prestrain is same with initial tension. If the prestrain is small, then the deformation of EP is like Figs. 14 and 15. And if the

![Fig. 13 In case of n=1, m=1](image)

![Fig. 14 Mode shape in case of n=2, m=2](image)
prestrain is large, then the deformation of EP is like Fig. 13. In this paper, it is assumed the deformation of EP is like Fig. 13.

The material that is used in simulation is VHB4905. The VHB4905 is a kind of acryloyl. The VHB4905 has large displacement and force. First the change of tension that is reason of deformation is shown in Fig. 16. When the voltage is applied, then the tension is shrunken rapidly. Because the thickness of EP is shrunken, the tension shrunken. And the voltage is removed, the tension is returned to the original condition slowly. It is the reason the electric charge that is charged in EP is discharged slowly.

The deformation line of EP is shown in Fig. 17. The deformation line is about time. The result is accepted using numerical analysis, Runge Kutta method. The result of EP actuator is shown in Fig. 18. The result is accepted using numerical analysis, too. Some error is occurred between result of simulation and experiment. It is four reasons to occur error.

1. The change of degree was occurred between EP and ball when the actuator was fabricated. It made the change of force in EP actuator.

2. The pressure that is applied in EP is general equation. But the pressure is changed as using material. So pressure does not exact, then the tension too.

3. The result of simulation is accepted using numerical analysis, so it has error.

4. The mechanical, electronics, polymer theories are necessary to accept the exact model. But in this paper, the mechanical theory is only used. So the error is occurred.

But the deformation of EP actuator was known using the result of modeling.

### 4.2 Result of simulation

We processed the simulation of control for EP actuator. The input voltages are 3 kV and 4 kV. To compare performance of controller, random periodic reference input is given and tracking performance of controller is analyzed. Used material is VHB4905. The damping ratio is 0.9. The dimension is 50 mm × 50 mm × 0.5 mm.

We used the open inventor and visual C++ to simulate the EP actuator. We can make the imagination EP actuator, and simulate before making the EP actuator. The simulator is shown in Fig. 19. The simulator is composed of input properties and input voltage in left side. And in the middle side, the 3D imagination is shown, the result of control is shown in

---

**Fig. 15** Mode shape in case of $n=1$, $m=2$

**Fig. 16** Change of tension

**Fig. 17** A comparison between model and experiment (3 kV)

**Fig. 18** EP A comparison between model and experiment (2 kV)
4.3 Result of experiment

In this paper, we produced EP actuator in order to compare developed adaptive fuzzy controller. We materialized the adaptive fuzzy controller. There is an operating mechanism of whole system in Fig. 20. The devices can be divided into three parts. There are, EP actuator, control module that the adaptive fuzzy program is embedded and strain gauge. The control module is shown in Fig. 21. And the EP actuator and strain gauge are shown in Fig. 22. And High voltage power supply was used to apply to EP actuator. PC was used to gain the data. We experimented the performance of proposed algorithm with experiment devices.

To compare with simulation, the voltage was supplied 3 V and 4 V in experiment. In Fig. 23, the simulation is compared with experiment in displacement at 3 kV. In first cycle, both simulation and experiment don't trace reference model exactly. But, after two cycles, it estimates a reference model. There is error, because EP actuator responds slower than reference model. Even if displacement of reference model is zero, actual actuator isn't zero. Because response time of EP actuator is limited. Figure 24 shows control of velocity at 3 kV. Two cycles of velocity and one cycle of displacement are same scale. Velocity estimates reference model almost after third cycle.

---

Fig. 19 Simulator

Laser strain gauge

Controller

Actuator

Data storage

Fig. 20 Flow of experiment

Fig. 21 Controller of EP actuator

Fig. 22 Strain gauge and actuator

Fig. 23 A result of displacement control in 3 kV
Figure 25 represent to state of controlled displacement in cage of applying 4 kV to actuator. When input voltage is 4 kV, reference model is set up within the limit of capacity of actuator distinctively to 3 kV. In the result, it can notice that experiment result approximate to “0” if reference model become “0” differently to 3 kV. Figure 26 represent to state of controlled velocity in case of applying 4 kV to actuator. This result approximate to reference model nearby at third period as well.

It is means that the control rule base is be changed as adaptive rule base to trace the reference model. The initial rule base and changed rule base is shown in Tables 1 and 2. The error and change of error are converged to “0”, if means that the control algorithm is suitable.

5. Conclusion

In this paper, modeling and control algorithm about EP membrane and EP actuator were presented for endoscopic microcapsule. Modeling of EP and EP actuator were executed. But the properties (elastic modulus, damping ratio etc) and input pressure didn’t be considered exactly. And the electronics and polymer science were not considered, but these theories must be considered to get exact model. So the error is occurred between simulation and experiment. But this result became reference to make control algorithm.

We developed the control algorithm to overcome the error that is between simulation and experiment. The adaptive fuzzy control algorithm was used, because the tension is time variant variable. The result of control was suitable.

Acknowledgements

This work was performed under the management of institute of Nano-micro system by Sungkyunkwan University.

References

(8) Zhao, X., Bharti, V., Zhang, Q.M., Romotowski,


