Equivalent Mechanical Model for Conducting Polypyrrole Actuator

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Abstract. Conducting polypyrrole actuators are widely used in sensors and bionic robots because of their high conductivity, flexibility and biocompatibility. Based on the theory of cantilever beam, the equivalent mechanical model of conducting polypyrrole actuator is built, and the bending characteristics of different length actuators under different voltage are studied by using the bending characteristics test system of polypyrrole actuator, and the functional relationship between voltage and bending displacement. By lifting the weight with the actuator, it is verified that the free end of the actuator can withstand the force.

1. Introduction

Electroactive polymers are one group of smart materials with specific electrical, structural and mechanical features [1]. Conductive ionic polymer is a polymer composite material with polymer properties and conductive characteristics which has been developed since 1970s [2], conductive ionic polymer is one of the electroactive polymers has many promising properties, including light weight, low energy consumption, good flexibility, biocompatibility, and working ability in solution and air circumstances, and even in some properties very similar to natural muscles which is the best candidate for biomimetic muscles [3, 4]. It is widely used in medical equipment, bionic robot, MEMS, micro-mechanical equipment, sensor and other fields. So conductive ionic polymer is a kind of intelligent polymer material with great development potential. It has been shown that various conjugated polymers can be transformed into polymer materials with different conductivity by doping (e.g., polypyrrole, polythiophene and polyaniline). Polypyrrole (PPy) is considered to be the most widely used conductive polymer because of its conductivity, biocompatibility, strong mechanical properties, and redox properties.

In 1984, Burgmayer [5] reported the shape change of conductive ionic polymer under the action of electric field. The ability to work in solution and air circumstances and its stability under large volume changes are particularly important for conductive ionic polymer actuators. The working principle of actuator is based on the volume contraction or expansion caused by ion exchange in and out of the active conductive layer during the electrochemical reaction. Therefore, the electrochemical energy is converted into mechanical energy for the purpose of actuation. This material is widely used in bending actuators, such as cantilever beams, whose strain varies 0.5%~10%, and even up to 39%. Due to the limitation of driving and diffusion speed, its stress varies between 1~35mpa [4]. Because of this characteristic, the actuator is suitable for microswitches and microcantilevers, which can be used to
move and position, and manipulate biological samples [6-8].

Although such a system has been proven on a macro scale, few works on actuator miniaturization have been published. Han [6] synthesized [PPy/PTh/PPy] three-layer conductive polymer composite membrane. It has been proved that the three-layer conductive membrane (0.4 mg) can reversibly lift a copper wire (10 mg) from one position (0°) to another position (90°). However, this membrane can only operate in a specific aqueous medium, which provides the ion source needed to drive. Chen et al. [9] studied the physical model and electromechanical coupling characteristics of IPMC and DE materials respectively, and explored the application of the two materials in valveless micropumps and minimally invasive surgical arms. Xiong et al. [10] proposed a force-electricity coupling model for describing the driving and sensing characteristics of IPMC materials, and the mechanical and electrical properties of IPMC materials were better calculated by this model. Christophersen et al. [11] studied the characteristics and modeling methods of different-size double-layer bending actuators. Jager et al. [12] manufactured a serially connected miniature manipulator and a miniature robotic arm, which were successfully applied for single-cell manipulation.

In this paper, polypyrrole conductive polymer (PPy) is used as the research object, and a multilayer curved conductive polymer driver that can work in air is prepared. According to the working principle of the actuator, we propose an equivalent cantilever beam mechanical model. The model consists of two parts: (1) bending motion curve model, which is used to analyze the movement process of the actuator; (2) bending force model, which is used to verify whether it can support a certain load at the end of the actuator. Finally, the validity of the equivalent beam model was verified by the built experimental system, and the force at the top of the actuator was confirmed.

2. Actuator movement mechanism

The bending-type actuator considered consists of five layers (see Figure 1). The PPy layer is an electroactive element that provides driving, which is connected with two electrodes of the power supply, and the thickness of each PPy layer is about 30 μm. PVDF is an non-conductive material, which is used as a separator for electrochemical batteries with a thickness of 110 μm. It is also used as the storage solution of Li\(^{+}\)TFSI\(^{-}\) in the PC solvent at 0.5 M. The CuSn layer is sprayed on both sides of the PVDF with a thickness of 10 Å to 100 Å, which is used to increase the conductivity between the electrolyte and the PPy layer.

![Figure 1. Sectional structure diagram of the actuator.](image)

Normally, the molecules and ions are stably distributed in the actuator before the voltage is applied. When the voltage is applied to both sides of the PPy layer of the actuator, the redox reaction will take place in the film under the action of the electric field formed. TFSI\(^{-}\) as a PPy doped ion, the positive PPy layer is oxidized and expanded, and the negative PPy layer is reduced. To make the interior of the driver neutral, the anion TFSI\(^{-}\) will migrate from the electrolyte to the PPy side with positive charge, resulting in the volume expansion of the oxide layer, while the anion TFSI\(^{-}\) leaves the negatively charged PPy side, resulting in the volume shrinkage of the reduction layer. The volume change of the actuator is due to the static TFSI\(^{-}\) ions moving towards the anode under the action of the applied electric field; meanwhile. Meanwhile, because the hydrophilicity of TFSI\(^{-}\) ions is better, the hydrated water molecules will move to the anode together during the migration process, that is, the pressure difference will be formed, resulting in the bending deformation of the actuator in the negative
direction of the power supply, realizing the internal electrochemical energy is converted into mechanical work.

3. Equivalent Cantilever Beam Model

In the practical application of artificial muscle, it is usually necessary to analyze the kinematics and mechanics of the designed micromanipulator. Because the electro-chemical-mechanical characteristics of the actuator cannot be directly modeled, by referring to the structure and working mechanism of the conductive polymer actuator, and considering its own hysteresis expansion characteristics, the actuator can be equivalent to a cantilever structure from the practical application. In fact, the equivalent model belongs to the grey box model among the three theoretical models. It establishes the corresponding model according to the internal physical characteristics of the actuator when the internal laws of the system are not fully understood, and then the other basic parameters of the equivalent cantilever beam model are fitted according to the experimental data, and the stress field generated by the internal ion migration is assumed to be applied to the cantilever uniform load on the beam.

3.1. Bending motion curve model

The main purpose of the motion model study is to analyze the bending deformation of the substrate when the voltage (0 V ~ 1.0 V) is applied to the actuator. An internal bending moment based on the expansion or contraction of the PPy layer is derived through the bending curve model. Since the amplitude of applied potential varies in a limited range, the elastic modulus is considered to be a constant.

Figure 2 shows the bending motion curve of the actuator under the excitation voltage. The top position \((x_1, y_1)\) of the actuator is set. \(y_1\) is the displacement of the top of the actuator measured by the laser displacement sensor (1.0 mm from the top as the incident point). The upper micro segment \(ds\) of the actuator is intercepted with the coordinate position of \((dx, dy)\), \(d\theta\) is the rotation angle, \(\theta\) is the bending angle, and \(R\) is the curvature radius of the curve. The geometric model of top displacement \(x_1\) and curvature radius \(R\) is established by simple triangle similarity relation:

\[
R = \frac{y_1^2 + x_1^2}{2y_1} \quad (1)
\]

Referring to Euler-Bernoulli law, the relationship between bending moment and bending angle can be established by using the parameters shown in Figure 2:

\[
M = \frac{EI}{ds} \left( d \arctan\left( \frac{dy}{dx} \right) \right) \quad (2)
\]

Thus, the Bending rigidity of the actuator is:

\[
EI = E_{PPY}I_{PPY} + E_{PVDF}I_{PVDF} = \frac{2b \left( E_{PPY} (h_2^3 - h_1^3) + E_{PVDF} h_1^3 \right)}{3} \quad (3)
\]

By combining Eq. (1) - (3), the bending moment is:

\[
M = \frac{E_{PPY} (h_2^3 - h_1^3) + E_{PVDF} h_1^3 \cdot 4by_1}{3 \left( y_1^2 + x_1^2 \right)} \quad (4)
\]
Figure 2. Bending curve diagram of the actuator

Figure 3. Schematic diagram of stress and strain distribution of actuator cross section

Since there is no positive stress between the longitudinal segments, each segment is uniaxial tension or compression. When the material is in the range of homogeneity and linear elasticity, and the elastic modulus of tension and compression is the same, the physical relationship can be listed by Hooke’s law under uniaxial stress state

\[ \sigma = E\varepsilon = E_y \frac{d\theta}{ds} \]

Thus, the bending stress can be expressed as:

\[ \sigma = \frac{E_{PPy}(h_3^2 - h_1^2) + E_{PVDF}h_2^3}{3I} \cdot \frac{4bh_1}{y_1^2 + x_1^2} \]

where \( h \) is half of the actuator thickness.

3.2. Bending force model

The mechanical modeling method of polymer actuator has been studied, and the Timoshenko model described in references [13, 14] is the output force model extending to three-layer actuator. The equivalent model cannot simulate the movement of ions and molecules in the polymer. Under the quasi-static condition, the stress field generated by ion migration in the actuator can be assumed to be the uniform load applied on the cantilever beam. The relationship between the free end force and voltage of the actuator can be established through the equivalent uniform load.

Referring to Figure 4, the deflection curve equation of cantilever beam without force at the free end of actuator can be listed

\[ \omega = \frac{qx^4 + 6qx^2L^2 - 4Lqx^3}{24EI} \]

When \( x=L \), maximum deflection equation:
\[ \omega_{\text{max}} = \frac{qL^4 + 6qL^4 - 4qL^4}{24EI} = \frac{qL^4}{8EI} \]  

When only \( F \) acts on the free end of the actuator, the maximum deflection at free end can be expressed as:

\[ \omega_{\text{max}} = -\frac{FL^3}{3EI} \]  

According to Eqs. (8) and (9), the blocking force is:

\[ \frac{qL^4}{8EI} = -\frac{FL^3}{3EI} \rightarrow F = \frac{3}{8} qL \]

4. Experimental Results

4.1 Experimental Setup

The electrorstrictive effect of the actuator is mainly manifested in its own deformation. The low voltage of 0 V ~ 1.0 V is enough to cause large deformation of the free end of the actuator. After the actuator is electrified, the internal ion migration causes the volume change of the PPy layer, which indicates that the bending characteristics of the actuator are directly related to the ion migration in the material, and its deformation is relatively large compared with other intelligent materials. Even if the voltage is very small, the shape of the sensor is very small, but it is difficult to observe with the naked eye. Therefore, this experiment uses a non-contact laser displacement sensor to measure the electrical response of the driver under low voltage. The resolution of the laser displacement sensor is 20 μm ~ 80 μm, and the analog output is 0 V ~ 10 V voltage signal is converted into displacement value by proportion, and transmitted to computer through PCI data acquisition card. In order to study the bending motion characteristics of conductive polymer actuator, a physical test platform is built as shown in Figure 5.

![Figure 5. Schematic representation of the experimental setup](image)

4.2 Experimental Results and Discussion

To obtain the electrolyte concentration ratio which can make the actuator work stably for a long time and has the best bending effect, the actuator with the size of 6 mm x 2 mm x 0.17 mm is selected to test the PC solution containing 0.5 mol and 0.1 mol Li+TFSI respectively (see Figure 6). It can be seen that when the concentration ratio is 0.5 mol, the actuator can be in a stable state after working for 10 s when the voltage is 0.2 V, the bending displacement can reach 0.22 mm, and the time (> 22 s) required for the solution with concentration ratio of 0.1 mol to stabilize is significantly higher than the former. Combined with the comparison of different concentrations in Figure 6, the solution with concentration ratio of 0.5 mol was finally selected as the electrolyte for experiment, and it needs to be stored in the electrolyte for 30 minutes before each experiment until it was used.
According to the bending motion process of the actuator, the fitting bending motion curve of the actuator (8 mm×2 mm×0.17 mm) after applying low voltage (0.1 V ~ 1.0 V) is measured, as shown in Figure 7. The correlation coefficient $R^2 \geq 0.986$ of all fitting curves indicates that the fitting degree of the data is good and the fitting reliability is high. It can be seen from the figure that under different voltages, the bending trend of the actuator is basically the same, that is, the bending rate is fast at the initial stage, then gradually slows down, and finally tends to be stable. When the voltage reaches 0.8 V, the deflection amplitude of the actuator slows down, and when the voltage reaches 1.0 V, the deflection displacement can reach half of the length of the actuator, which is in accordance with the literature [8]. It can be considered that the bending effect is the best, and the solution with concentration ratio of 0.5 mol is also the best choice.

According to the bending curve motion model of the actuator, the free end deflection displacement of the actuator with a width of 2 mm is studied. As shown in Figure 8, the deflection displacement of the actuator is related to its own length. The longer the driver length, the greater the deflection displacement. The top displacement of the actuator has a linear relationship with the applied voltage, the larger the voltage, the greater the deflection displacement. This is because a higher voltage will mean that more energy or charge is provided to the moving ions in and out of the polymer active layer. Therefore, causing the contraction and expansion of the PPy layer.

Figure 6. Comparison of different concentration ratios

Figure 7. Bending motion fitting curve of actuator.
Figure 8. Deflection displacement of actuator under stable voltage.

With reference to the bending curve model of the actuator, combined with the displacement $y_1$ value of the actuator top measured by the laser displacement sensor in Figure 2, the radius of curvature of the actuator is calculated by Eq. (1), as shown in Table 1.

Table 1. The curvature radius $R$ at the top of the actuators (mm).

| Voltage (V) | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Long 6 mm  | 97  | 60  | 43  | 26  | 17  | 13  | 11  | 10  | 9   | 8   |
| Long 8 mm  | 129 | 70  | 43  | 30  | 21  | 16  | 13  | 11  | 10  | 9   |
| Long 10 mm | 166 | 78  | 48  | 35  | 24  | 20  | 15  | 13  | 13  | 12  |

The relationship between the curvature radius and the voltage can be fitted by the obtained data, as shown in Figure 9. It can be seen that with the increase of the voltage, the increase of the curvature of the actuator decreases gradually. The relationship between voltage and curvature radius is established:

$$R = \begin{cases} 
\frac{-U}{149.82768e^{0.19826}} + 6.537030 & \text{Long 6mm} \\
\frac{-U}{222.62007e^{0.15791}} + 10.33115 & \text{Long 8mm} \\
\frac{-U}{321.60758e^{0.13023}} + 14.55078 & \text{Long 10mm}
\end{cases}$$

Figure 9. Relationship between voltage and curvature radius

In this paper, the existence of the top force is verified by lifting the weight at the free end of the actuator. Using an electronic balance (FA1104A), the weight of the monolithic actuator strip (10 mm×2 mm×0.17 mm) was weighed at 4.5 mg. The micro magnet was fixed at 1.0 mm from the top of the actuator. The diameter of the magnet is 1.0 mm and the thickness is 0.5 mm. The total weight of
the eight magnets is 21.2 mg. Figure 10 shows the bending motion process of the actuator captured by the high-speed camera. The position of the actuator when it is not powered is shown in Figure 11. At this time, the vertical position of the weight from the fixture is $\delta =0.88$ mm. After the voltage is applied, the free end of the actuator bends counterclockwise direction. When the voltage reaches 0.6 V, the deflection height $\delta =1.83$ mm. The experimental results show that the actuator can lift a weight of about 5 times its own weight and move 2.71 mm, which verifies that the top of the drive can withstand the force.

Figure 10. Measurement of the bending motion of the actuator.

Figure 11. Deflection displacement of actuator under different voltage

Under the condition of load, when the voltage of 1.0 V is applied, the force test is carried out on the actuator with width of 2 mm, 2.5 mm, 3 mm and 4 mm (length of 10 mm) (see Figure 12). Finally, it can be concluded that the larger the actuator width is, the greater the displacement is, and the greater the top force is. Figure 12 shows the relationship between the displacement and the length of the 2 mm wide actuator tip. It can be seen that the longer the actuator length is, the smaller the displacement is and the smaller the tip force is.

Figure 12. Deflection displacement at different widths and lengths

5. Conclusions
In view of the structure, driving mechanism and excellent characteristics of the conductive polymer actuator, starting from the practical application of the actuator, the actuator is equivalent to a cantilever structure, and the bending motion model and bending force model are established. When low voltage (0 V ~ 1.0 V) is applied, the deflection displacement of the free end of the actuator increases with the increase of the excitation voltage. When the voltage is 1.0 V, the deflection displacement can reach half of the length of the actuator, and it is approximately linear. The magnet with a weight of 21.2 Mg can be lifted and moved by 2.71 mm by a single actuator bar (4.5 mg), which verifies that the top of the actuator can bear the force.

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