Fully Coupled Simulation Model for Transient Response of Mechanical Sensors using Electro-active Polymers

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1 Introduction

The conducting polymer(CP) showed a multitude of potentials as a novel material and exhibited prospective characteristics: low voltage, high sensitivity, miniaturization, lightweight, easy access, flexible, silent and chemically stable properties. The CP has attracted attention as a candidate of actuators or sensors [2-6].

The aim of the present study is to develop a computational system for design and control of the mechanical CP sensors. The CP sensors, responding to mechanical stimulation, show transient behaviors with the relaxation of reaction forces. When a bending deformation occurs as shown in Fig.1, ions and solvent are pushed out from compressive sides and enter into the tensile sides. The transport reduces reaction force and causes instant electric potential by charge density gradient, and then the electric potential decreases [4].

Even though the CP sensors, conversely to the well-known CP actuators, generate an electrical voltage when a displacement is enforced, the output voltage from the input displacement is very much smaller than the input voltage to the same displacement [5,6]. Hence, the computational model of the CP sensors has not been well established even though many researchers have conducted the analysis of the CP actuators.

For the estimation of the sensor output, the simplified model [8] was developed from the observation that output voltage is proportional to mechanical solid stress. However, the simplified model cannot express the transient behavior of the CP sensor. Furthermore, it cannot explain the aforementioned difference of input-output relation between the actuator and sensor. In order to overcome this problem, the present study focused on the interactions between solid, fluid and ion transport in the polymer matrix. First, the mechanical behavior of the sensor is assumed as the bending of layered Timoshenko beam model. Second, the fluid pressure in the polymer matrix is obtained by Biot poro-elastic model with electric potential and solid strain. Third, ion concentration and electric potential are calculated by Poisson-Nernst-Planck equations with the fluid pressure. Therefore, the transient response with the relaxation is numerically simulated. Lastly, the numerical results are compared with experimental results.

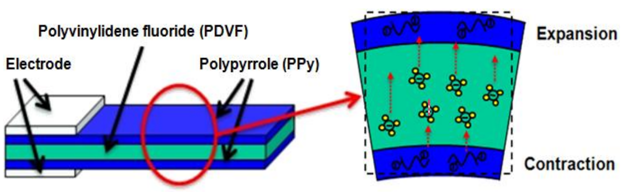

Fig. 1 Mechanical sensor using conducting polymer

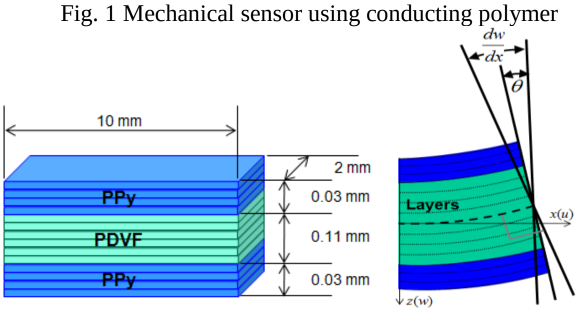

Fig. 2 Layered Timoshenko beam model|

2 Formulation

2.1 Layered Timoshenko Beam Model

The CP sensor consists of different layers having different properties, and its mechanical deformation can be assumed as the bending of a beam in solid mechanics[3,6]. Therefore, layered Timoshenko beam theory [7] is employed as shown in Fig.2.

2.2 Biot Poro-elastic Model

The CP has two phases, a polymer matrix and electrolyte. The polymer matrix is solid, and the electrolyte is fluid in the polymer matrix. When the CP sensor is deformed, the induced pressure difference of the matrix causes fluid flow through the pores of the matrix. For the analysis of the porous CP saturated with fluid, Biot poro-elastic model [1] is employed. In case of isotropy, Biot linear stress-strain relations for Timoshenko beam with no leakage of fluid on boundary, is obtained as follows.

$$\sigma_x = E\varepsilon_x - bp = E\frac{\partial u}{\partial x} - bp = E\left(-z\frac{d\theta}{dx}\right) - bp \tag{2.2.1}$$

$$\tau_{zx} = \alpha G\gamma_{zx} = \alpha G\left(\frac{\partial w}{\partial x} + \frac{\partial u}{\partial z}\right) = \alpha G\left(\frac{dw}{dx} - \theta\right) \tag{2.2.2}$$

where, σ_x is nominal stress, ε_x is nominal strain, τ_{zx} is transverse shear stress, γ_{zx} is transverse shear strain; p is pore pressure, u is axial displacement, w is lateral displacement, θ is rotation of the normal section, z is distance from neutral axis, E is elastic modulus, G is shear modulus, b is Biot coefficient, and α is shear correction factor.

Next, the fluid pressure can be obtained by Darcy law in which Biot linear stress-strain relations are embedded so that the flux of the fluid in the porous media can be obtained. Adding electric force into the Biot poro-elastic model, leads to the following differential equation of the pore pressure in the CPs.

$$\frac{\kappa_h}{\eta}\left(\frac{\partial^2 p}{\partial z^2} - \beta FC\frac{\partial^2 V}{\partial z^2}\right) = \frac{3(\nu_u - \nu)}{2GB(1+\nu)(1+\nu_u)}\frac{\partial}{\partial t}\left(\sigma_x + \frac{3}{B}p\right) \tag{2.2.3}$$

where, κ_h is hydraulic permeability, η is dynamic viscosity, β is porosity, F is Faraday constant, C is ion concentration, V is electric potential, B is Skemptom coefficient, ν is drained Poisson's ratio, and ν_u is undrained Poisson's ratio.

2.3 Poisson-Nernst-Planck (PNP) Model

CP molecules and large dopants are immobile, so the movement of mobile ions causes voltage as sensor output [3,5]. Therefore, PNP equations [3] are employed to the analysis of the ion transport in electric field. Adding the pore pressure into the PNP equations, ion concentration distribution and electric potential are obtained with the below equations.

$$\frac{\partial C}{\partial t} = \frac{\kappa_h D}{\eta}\left\{\frac{\partial^2 C}{\partial z^2} - nC\left(\frac{F}{RT}\right)\frac{\partial^2 V}{\partial z^2}\right\} - C\frac{\kappa_h}{\eta}\frac{\partial^2 p}{\partial z^2} \qquad (2.3.1)$$

$$\frac{\partial^2 V}{\partial z^2} = \frac{FC}{k_e} \qquad (2.3.2)$$

where, n is species charge of mobile ion, R is the gas constant, T is absolute temperature, k_e is electric permittivity, and D is diffusivity coefficient.

Using the layered Timoshenko beam, Biot poro-elastic and PNP models, the interactions between fluid pressure, bending stress, and electric field at each time step are fully coupled.

3 Numerical Results

A typical conducting polymer sensor in Figs.1 and 2 was selected in this simulation. The physical parameters of the aforementioned models for the CP are determined by experiments in macro-scale. The reservoir for electrolyte is TBA.PF6 of 0.05M in solvent propylene carbonate. The ion movement is much more dominant factor than oxidation-reduction reaction, because of the dependence of the polarity of voltage on the type of counter-ions [5]. Furthermore, the ion flux applies only to mobile ions and excludes the polymer molecules and large dopants [3]. A monotonic case of a prescribed displacement enforced at the beam was simulated and its results are shown in Fig.3~6.

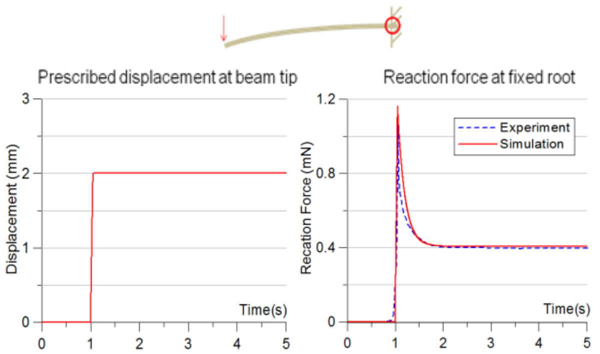

Fig. 3 Time history of tip displacement and reaction force

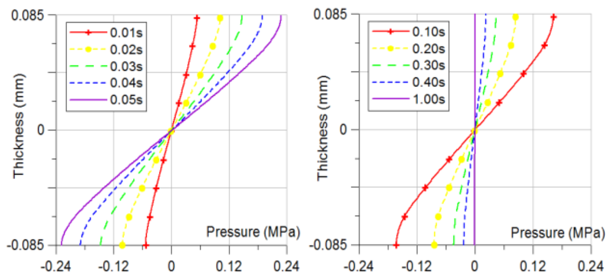

Fig. 4 Pressure distribution over thickness at beam tip during loading(left) and relaxation(right)

As shown in Fig.3, when the prescribed displacement is enforced, the reaction force elastically responses and then gradually reduced with time. As illustrated in Fig.4, the fluid pressure was obtained with the interactions between fluid pressure, bending stress, and electric field. These results reveal that the relaxation of the reaction force is due to the change of the fluid pressure which means the fluid flow in the pores of the polymer matrix. The mobile ion concentration in Fig.5 is also changed with the fluid pressure. Finally, electric potential are obtained with the mobile ion concentration as shown in Fig.6. As a result, mechanical deformation results in differences of ionic charge and voltage as sensor output. Furthermore, the transient behavior and relaxation were numerically expressed.

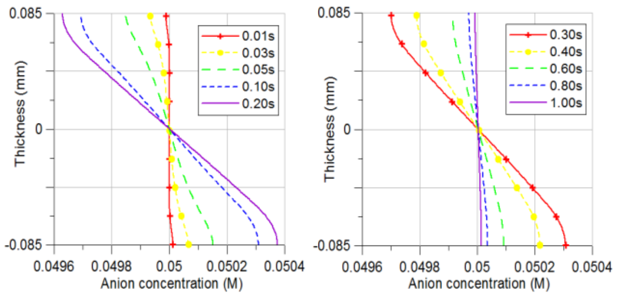

Fig. 5 Mobile ion concentration over thickness at beam root during loading(left) and relaxation(right)

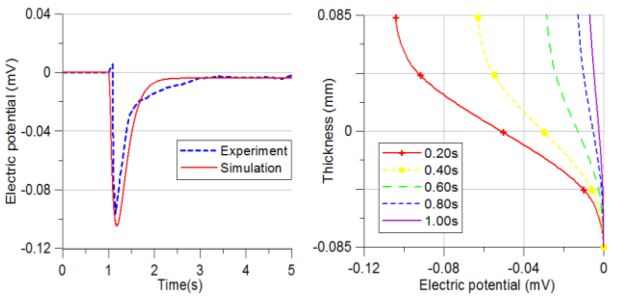

Fig. 6 Electric potential output with respect to time(left) and electric potential over thickness at root(right)

4 Conclusion

In the present study, the interactions of solid stress, fluid pressure, ion transport and electric potential were fully coupled and the transient response with the relaxation of the reaction force was analyzed with the time-marching. As a result, the mechanism of the CP sensor was understood through the numerical analysis. Mechanical factors, especially porosity, have a large effect on the responses. Above all, the non-invertible problem between actuator and sensor models, in which the current black box model cannot be used for both of sensor and actuator, was solved through the present model using the same theories in the actuation models.

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