論 文 の 内 容 の 要 旨

論文題目

Computational Modeling of Mechanical Sensors Using Ionic Electroactive Polymers
（イオン性電気活性ポリマーを用いた力学センサの計算モデリング）

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Electroactive polymers are polymers that show mechanical deformation when electrical simulation is applied. Electroactive polymers have shown potentials as a novel material in robotics, MEMS and biomechanics since the 1990s. Within electroactive polymers, there are two types, dielectric electroactive polymers and ionic electroactive polymers. Dielectric electroactive polymers are actuated by dielectric polarization and ionic electroactive polymers are actuated by ion transport process when electric field is applied. Ionic electroactive polymers are classified as conducting polymers and IPMCs (Ionic polymer metal composites). Conducting polymers are actuated by reaction and oxidation when electric field is applied. Polypyrrole is one of conducting polymers for actuators. IPMCs are the composites consisting of ionic polymer membrane and metal deposits. IPMCs are actuated by ion migration when electric field is applied. Flemion and Nafion belong to IPMCs.

The present study focuses on ionic electroactive polymers for mechanical sensors. Ionic electroactive polymers have attractive characteristics such as driven by low voltage (1~2V), micro-miniature, light weight, flexible and silent, durable and stable chemically and working in water or wet condition. Due to low voltage operation, ionic electroactive polymers have recently received amplified expectations as a novel material especially for artificial muscle. Their electroactive applications are based on actuating and sensing functions with mechanical and electrical measures, e.g. mechanical deformation is induced by electric voltage, and electric voltage is generated by mechanical deformation. Ionic electroactive polymers can be applied into both of actuators and mechanical sensors at the same time, but the functions are not compatible with each other. The generated voltage of sensing mode is very much smaller than the supplied voltage of actuating mode with respect to the same displacement and structure. Since the late 1990s, actuators using ionic electroactive polymers have been modeled and simulated, but the simulation of mechanical sensing behaviors has not been reported except for black box models. Hence, the present study newly attempts the numerical simulation of mechanical sensors using ionic electroactive polymers.

The mechanism of mechanical sensors using ionic electroactive polymers such as conducting polymers or IPMCs is explained as follows. When mechanical sensors using ionic electroactive polymer are deformed, the internal stresses of solid matrix is induced, and the pressure of ion-containing fluid filling the pores of the solid matrix is also induced. The induced pressure causes the pore fluid to be pushed out from shrunk side and to be sucked into dilate side, and then the transport of the pore fluid results in the gradual relaxation of reaction forces. At the same time, the migration of mobile ions causes the instant unbalance of the distribution of charge density, and the gradient of charge density results in electric potential difference. Subsequently, the mobile ion concentration is diffused, and the electric potential is gradually decreased to the neutralization of electric charges. As a result, the mechanical sensors generate electric voltage responding to mechanical deformation.

Mechanical sensors using ionic electroactive polymers show transient behaviors that reaction force and electric potential have relaxation and hysteresis. Responding to mechanical stimulation, the reaction force is immediately generated, and then gradually reduced even when the displacement remains constant. Electrical potential is also changed with mechanical reaction force and then gradually relaxed. Furthermore, the peak of electric potential is induced during the relaxation of reaction force and has time lag behind the peak of reaction force.

Numerical simulation to reproduce the electromechanical behaviors of ionic electroactive polymers is still difficult even though a lot of researches have been reported. For the estimation of the electromechanical behaviors, most researches employed simple black box models from experimental observations, e.g. an empirical relation between mechanical stress and electric voltage. Here, structure analysis becomes important to obtain the mechanical stress. In such backgrounds, the present study was started with a black box model and focused on structure analysis. This first attempt for the numerical simulation of the mechanical sensors is introduced in chapter 2. As the further research of chapter 2, more complicated model was developed for the mechanical sensors. The second attempt is introduced in chapter 3. Next, another type of ionic electroactive polymers for mechanical sensors is IPMCs. IPMCs show hydration effect that mechanical stiffness and volume are significantly changed as water is absorbed. The hydration effect is modeled, and the proposed model in chapter 3 is employed into IPMCs. This third attempt is introduced in chapter 4.

Chapter 2 introduces a computational system, using a simple black box model, for mechanical sensors using conducting polymers. The conducting polymers, which belong to ionic electroactive polymers, have attracted attention as a prospective material for mechanical sensing from stimulation to electricity. When stimulated by an external force, the mechanical sensors are elastically deformed and then show a large reduction of reaction forces that are induced by the movement of ions and solvent. The elastic deformation of the mechanical sensors, in response to mechanical stimulation, is analyzed with layered Timoshenko beam theory. The subsequent reduction of the reaction forces, quantitatively idealized with initial strain method, is calculated with finite element method. Therefore, the net reaction force is obtained and employed to estimate a generated potential as the response of the mechanical sensors. As the application of the proposed model, the mechanical sensing behaviors are simulated in cases of prescribed and stepwise loading conditions, and those results are compared with experimental results in order to validate the proposed model.

Chapter 3 introduces a more complicated model for mechanical sensors using conducting polymers which generate electricity in the transient response to mechanical stimulation. The generated electric potential in the mechanical sensors is very much smaller than the supplied electric potential of the actuators with respect to the same deformation and structure. The present simulation procedure modifies and integrates the existing theories, and then the features of the transient behaviors, e.g. the non-invertible relation between electrical potential and deformation, relaxation and hysteresis, are numerically simulated. The governing equations of the physical phenomena of the mechanical sensors coupled by embedding driving forces with physical parameters such as solid stress, fluid pressure, ion concentration and electric potential. The governing equations and the fields of the physical parameters are spatially simplified as one-dimensional in the thickness direction of the sensors, because their variations over thickness dominantly determine the behavior of the sensor. In addition, the numerical procedure is efficiently simplified as possible as the transient behaviors are expressed. Next, the undrained Poisson's ratio is modified with a correction factor, and its significant effect on the transient behavior is investigated. Lastly, the procedure of the present computational system for the mechanical sensors is introduced and fully coupled simulation is conducted. As a result, the present study reports the simulation results of the important physical quantities over the microscale thickness of the mechanical sensors.

Chapter 4 introduces the numerical simulation of mechanical sensors using IPMCs. IPMCs are also applied into both of actuators and mechanical sensors, but the existing models of the actuators cannot be inversely applied to the mechanical sensors. The mechanical sensors generate very much smaller electric potential compared to the supplied electric potential of the actuators with respect to the same displacement and structure. The non-invertible response of the mechanical sensors is numerically simulated, and the simulation considers hydration and transient behaviors. IPMCs have hydration effect that volume and mechanical stiffness are significantly changed with water uptake. In order to consider the volume swelling due to hydration, the total strains and pore pressure of IPMCs are respectively decomposed into stress-induced and hydration-induced parts. The hydration-induced strain is considered as eigen-strain, and the stress-induced strain and stress-induced pore pressure are employed into Biot poroelastic constitutive equations. The mechanical stiffness of a hydrated IPMC is expressed as empirical relations with water uptake. Furthermore, mechanical sensors using IPMCs show transient response with the relaxation and time lag of reaction force and electric potential. The transient response is modeled with a set of basic equations, e.g. layered Timoshenko beam model, Biot poroelastic model, Darcy-flow model, Poisson-Nernst-Plank model. The instantaneous peak of reaction force is estimated on undrained condition, the relaxation of reaction force is considered with pore pressure and its Poisson effect, and hydration-induced water migration is modeled with hydration potential. The hydration potential is modeled with an empirical chemical potential at free swelling equilibrium and is expressed as a function of water uptake. Next, discretization and numerical formulation with layered finite beam elements is introduced. Lastly, the transient responses of a Flemion-based mechanical sensor are numerically simulated with different deflections, and the distributions of stress, pore pressure, ion concentration and electric potential are obtained with time. Lastly, the numerical results are compared with experimental results.

The applications of the present study can be thought as follows. As mentioned before, mechanical sensors using ionic electroactive polymers such as conducting polymers or IPMCs show dependencies on time, initial condition, water uptake and so on. In order to analyze the behaviors of the mechanical sensors more precisely, the present computational system could be helpful. Until now, a lot of researches have been conducted based on black box model using linear relations between mechanical stress and electric voltage, but the present study attempted to overcome the black box model. Furthermore, the present study tried to analyze the continuous measurements of the mechanical sensors using the time history of electric potential. If the measured history of electric potential is reproduced by the present model, we can estimates the history of mechanical stimulation or verify the measurement. For fabrication or design of the mechanical sensors, more complicated model can give understanding and prediction, not only time-dependent response but also the distributions of important parameters over thickness, which are difficult to be measured, and their contributions on performance. For users, the data for time dependant responses has to be provided because of the relaxation and time lag and hydration effects on the performance of the mechanical sensors. The fundamental phenomena in the present study can be found in other materials and applications, e.g. transient responses, hydration and ion transport of porous materials.