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Modelling trilayer conjugated polymer actuators for their sensorless position control

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ABSTRACT

In this paper, we present a new model to describe the displacement response of a trilayer conjugated polymer actuator that can operate in dry environments. The proposed model based on the working principle of conjugated polymer actuators includes diffusion impedances combined with double layer capacitors and charge transfer resistors. The parameters of the model are estimated by using a nonlinear least square estimation method by comparing simulation and experimental results. The proposed model is very useful in predicting the impedance as well as the displacement response of the polymer actuators accurately. Based on the proposed model, an inversion-based controller not requiring an external sensor for position feedback data is implemented and compared with the experimental results. The experimental position control results have confirmed the feasibility and efficacy of the proposed model in describing the time response of the actuators and their position control without using externally provided position data.

1. Introduction

The past decade has seen the rapid development of ElectroActive Polymers (EAPs) in both academia and industry because they can be used as artificial muscles, sensors, haptic devices [1,2]. Among EAPs, the trilayer conjugated polymer actuators [3,4] are a class of bending type EAP actuators that can operate in air under a low voltage. This class of actuators gives us great opportunities to develop real applications ranging from macro to micro applications.

Dynamic response of the actuator needs to be understood to improve its ability in following user-specified inputs such as a desired position. This is needed to establish functional devices activated by these actuators. For instance, we are interested in guiding a cochlear implant through a 3D spiral structure in the inner ear by using a trilayer conducting polymer actuator as the implant carrier. Such an advanced application and other bio-inspired applications require actuators with built-in sensors or control strategies not requiring external sensing data for accurate position control. Since the topology of the tri-layer EAP actuator we employ and the application we consider do not allow having a built-in sensor and/or external sensors for feedback control, there is a need for sensorless control of these actuators. One effective method for sensorless control is to employ inversion-based control methods based on an accurate mathematical model of the actuator [5]. In this paper, we establish a mathematical model of the actuator based on the physical phenomenon occurring in the actuator. The model parameters are experimentally identified and the model is verified with a new set of experimental data to demonstrate its efficacy in describing the time-domain and frequency domain dynamic behaviours of these actuators. It is the contribution of this paper to establish this more accurate mathematical model, its experimental verification, and its use for sensorless position control with a high accuracy.

The model presented in this study develops further various previously published models for conducting polymer actuators. A model of a bilayer conducting polymer actuator based on the diffusive-elastic-metal model reported by Madden [6] was extended to a trilayer actuator by Fang et al. [7]. In this model, the diffusive impedance was assumed to be connected in parallel with a double layer capacitor. However, the resistances of the conducting polymer layer as well as the charge transfer resistances have been neglected in this model. In some applications, a potential drop due to the resistance of conducting polymer and charge transfer resistance should be considered in determining the effect of the mass transport on the actuator impedance [8]. Further, to model the time response of a trilayer actuator, an electrical circuit equivalent to the 2-D impedance of a conducting polymer actuator has been proposed in [9]. The 2-D impedance includes a 1-D transmission line circuit which considers the ionic transport through the polymer film thickness. In this model, the transmission line circuit of capacitances and resistances were used to describe the

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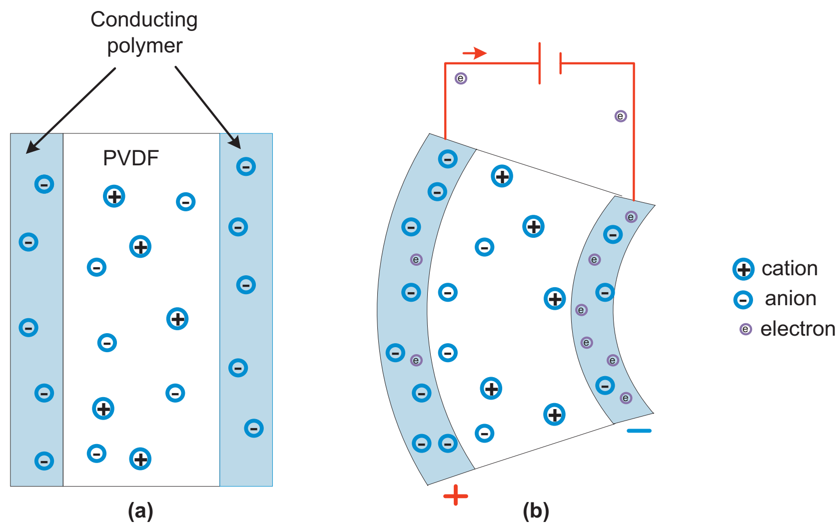

Fig. 1. Mechanism of trilayer conducting polymer actuator. (a) Cross-sectional view of actuators with polypyrrole conducting polymer layer coated onto a porous PVDF membrane that contains a liquid electrolyte; (b) bending of actuator when a voltage is applied.

movement of ions. However, the diffusive impedance was not taken into account in this model [9].

In this paper, we present a general model to combine important properties of the EAP actuators including diffusive impedance, double layer capacitance, conducting polymer resistance and charge-transfer resistance. The trilayer actuator is depicted in Fig. 1. Under an applied potential difference, ions move from the inside PVDF (polyvinylidene fluoride) layer [4] to the outer conducting polymer layers and vice versa [10]. This movement involves the electrical properties such as diffusive impedance, double layer capacitance and charge transfer resistance [8]. Therefore, we develop a new model of the actuators, extending the previously reported models [4,5] to describe the diffusion of ions, the capacitance and resistance of the charge transfer. We identify the model parameters from the experimental results by using a nonlinear least square estimation method.

The application of conventional and modern theories based on feedback sensors to control a trilayer conducting polymer actuator has faced some disadvantages due to the size of sensors. Fang et al. [7] have successfully implemented a robust controller based on an electrochemical model with a laser sensor. However, it is not practical to apply such a method to real applications because the size of a laser sensor is several times larger than the size of the actuator. For example, in bio-inspired applications, space is of paramount importance. As stated above, one effective method to control the position of a trilayer actuator is to employ an inversion based-controller. Previously, a black-box model of the trilayer conducting polymer actuator has been developed experimentally for its inversion-based position control [5]. The model was developed for a particular actuator – when the actuator size and other actuator properties were changed, a new model had to be identified for the accurate position control of the actuator. In the present study, we go one step ahead of our previous work to establish a comprehensive model to cater for various actuator properties, paving the way towards a mathematical model accurately describing the electro-chemo-mechanical behaviour of these actuators. Current literature still lacks such a model.

This paper is organized as follows. In Section 2, we briefly introduce the working principle of the trilayer EAP actuator. In Section 3, the proposed model will be presented and analysed. The experimental verification of the proposed model is provided in Section 4. The sensorless control of the actuator are presented in Section 5. Conclusions are presented in Section 6.

2. The conceptual model of trilayer conducting polymer actuator

2.1. The structure and operating principle of the actuator

The structure of the trilayer actuator considered here is illustrated in Figs. 1 and 2. There are three main layers in the structure: two polypyrrole (PPy) outer layers that are active components and an inner porous separator of PVDF that holds the liquid electrolyte. The electrolyte consists of lithium trifouromethanesulfonimide (Li^+TFSI^-) in the solvent of propylene carbonate (PC). The whole structure is like a one-end fixed, the other end free cantilever beam. It exhibits a large amplitude bending motion when a voltage is applied across the two PPy layers as the electrodes.

The working principle of the trilayer conducting polymer actuators has been described in detail previously [4,11,12]. When a voltage is passed between the two conducting polymer layers (PPy) of the actuator, as shown in Fig. 1(b), one conducting polymer layer is oxidized while the other is reduced. The redox process is described by [10]:

Oxidation: $PPy + TFSI^- \rightarrow PPy^+TFSI^- + e^-$

Reduction: $PPy^+TFSI^- + e^- \rightarrow PPy + TFSI^-$

When TFSI is used as a dopant ion for the polypyrrole, it is known that the oxidized layer absorbs anions and expands [10], while the reduced layer contracts due to the anions expelled from this layer. The overall result is that the cantilevered structure will bend towards the negative electrode/cathode, as depicted in Fig. 1. The volume change happens due to the movement of the charge balancing anions in and out of the polymer layers, and perhaps some solvent molecules move inside the polymer layers, due to osmotic effects to balance the ionic concentration. The charge transfer between the anode and cathode determines the total impedance of the actuator as well as the volume change.

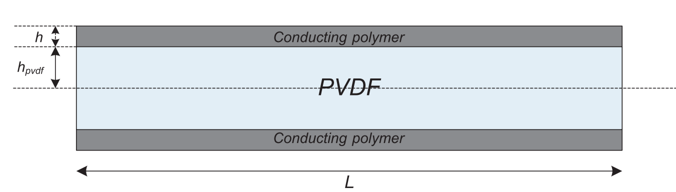

Fig. 2. The schematic diagram of the trilayer conducting polymer actuator.