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Response Characterization of Electroactive Polymers as Mechanical Sensors

Gursel Alici, Geoffrey M. Spinks, John D. Madden, *Member, IEEE*, Yanzhe Wu, and Gordon G. Wallace

Abstract—The characterization of the dynamic response (including transfer function identification) of trilayer polypyrrole (PPy) type conducting polymer sensors is presented. The sensor was built like a cantilever beam with the free end stimulated through a mechanical lever system, which provided displacement inputs. The voltage generated and current passing between the two outer PPy layers as a result of the input was measured to model the output/input behavior of the sensors based on their experimental current/displacement and voltage/displacement frequency responses. We specifically targeted the low-frequency behavior of the sensor as it is a relatively slow system. Experimental transfer function models were generated and verified experimentally for sensors with different dimensions. The models can be used to understand the dynamic behavior and sensing ability of the polymers as mechanical sensors. The effect of the active sensor length on the voltage and current outputs has demonstrated that the shorter is the sensor length, the higher are the voltage output and the current passed for the same mechanical input. Also, their current and voltage responses under an impulse displacement stimulus were experimentally measured to show their dynamic sensing response and to estimate the current and voltage sensing bandwidths. Further, an energy balance method has been proposed to estimate the sensor output. Based on the novel experimental and analytical results, the contribution of this study is the first comprehensive investigation into the response analysis and characterization of the PPy-type conducting polymers as mechanical sensors, to the best of authors' knowledge.

Index Terms—Conducting polymer sensors and actuators, sensors, system identification/characterization.

I. INTRODUCTION

ELECTROACTIVE polymers have many distinctive features that can be exploited to establish electromechanical actuators and sensors. Especially knowing that their actuation ability improves significantly makes the polymers ideal candidates for miniaturized actuators and perhaps sensors. In a common configuration, they have a composite structure with

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two polymer layers separated from each other with an electronically insulating film, which is the passive layer in the overall configuration. When the right stimulus, which is usually a very small voltage—typically 1 V—or a current, is applied to the polymer layers, a net volume change occurs in the polymer layers due to the movement of ionic and solvent species in and out of the polymer layers. The volume change shows itself as a bending displacement; the electrochemical energy is converted into mechanical energy. More details on the working principle of conducting polymer actuators can be found in [1]–[3]. As a result, a considerable amount of research has been devoted to modeling and understanding their behaviors in order to improve their performance so that they can be reliable actuators for practical applications [1]–[12]. Recently, the reverse actuation response of these laminate structures has been reported [13], [14]. In this arrangement, a bending displacement induces a voltage difference between the conducting polymer electrodes. This behavior can be exploited to use the conducting polymers as mechanical sensors. In this paper, we present experimental frequency response and impulse results and their implications for polypyrrole (PPy) based trilayer conducting polymer sensors, which operate in a nonaqueous medium, i.e., air. A mechanical stimulus such as a displacement is applied to the free end of the sensor. This puts the top layer of the sensors in tension and the bottom layer in compression such that (it is surmised) while the electrolyte ions enter the upper polymer layer, they will leave lower layer polymer. This is analogous to applying a potential difference between the polymer layers such that while the upper layer expands as a result of the transfer of the ions from the insulating film into it, the lower layer contracts as a result of losing ions. The movement of the ions in and out of the polymer layers generates electric current and potential difference.

In our previous work on polymer actuators [6]–[12], we aimed to establish various mathematical models and their experimental validation in order to characterize the actuators' behavior and exploit these behaviors in useful applications. We built a two-finger robotic gripper to manipulate objects as heavy as 50 times the total mass of the polymer actuators used [3]. This study is the extension of our continuing efforts to understand the behavior of the polymer actuators and sensors and pave the way toward real functional devices. Although a significant amount of work has been dedicated to conducting polymer actuators, very little has been devoted to the conducting polymers as mechanical sensors. While polymer actuators convert the electrical energy into the mechanical energy, they do the opposite when they are used as sensors. In our theory, as soon as a mechanical input such as a displacement is applied, the dopant ion concentration

in the polymer layers changes temporarily, and hence, generates a potential difference across the sensor structure. The results are new in the sense that the mechanism behind the operation of polymer actuators and sensors is further elaborated through the frequency response results. Based on the results, the transfer functions of the sensors are established for subsequent use in understanding and evaluating the effect of various parameters on their sensing behavior.

The work most relevant to this study includes that of Takashima *et al.* [15] and Wu *et al.* [13], [14]. Takashima *et al.* [15] reported on the mechanically induced current observed in polyaniline films under a tensile load, without considering the effect of dopant ions. The mechanism behind this “mechanochemoelectrical” behavior is said to be the stretching of the film that changes the polymer density, and hence, induces a redox current. The induced charge is proportional to the axial stress applied to the film. Wu *et al.* [14] have investigated the same type of PPy trilayer sensor described in this paper. The polarity and magnitude of the voltage generated under a mechanical input depend on the size of dopant ions. A small mobile dopant, such as ClO_4^- , and the large immobile DBS^- dopant have produced negative (out of phase) and positive (in phase) voltages, respectively. Furthermore, the potentiostatic mode (current output) is more sensitive than the galvanostatic mode (voltage output) to employ the polymer as a displacement sensor. This is in agreement with the fact that while conducting polymers are excellent charge generators, they produce low voltages, as opposed to piezoelectric materials/generators [16]. A complete mechanism describing the sensor response of conducting polymers is not yet developed. We present in this paper experimental frequency and impulse results for PPy trilayer sensors, and discuss the implications of these results in terms of the sensing mechanism and practical applications for the sensor.

II. EXPERIMENTAL EVALUATION AND RESULTS

The structure of the polymer sensor considered in this study is shown in Fig. 1. The sensor has five layers. The outmost two layers that are PPy with the thicknesses of $30\ \mu\text{m}$ are the electroactive elements providing actuation or sensing. The middle layer is polyvinylidene fluoride (PVDF) with a thickness of $110\ \mu\text{m}$, an inert, nonconductive, porous polymer. It serves as a separator for the two PPy layers and the reservoir for electrolyte tetrabutylammonium hexafluorophosphate (TBA.PF_6) $0.05\ \text{M}$ in solvent propylene carbonate (PC). The electrolyte and the solvent need to be stored in the PVDF layer in order to operate the sensor/actuator in air. Otherwise, it has to be operated in a liquid medium consisting of the electrolyte and the solvent. Thin layers of platinum of $10\text{--}100\ \text{\AA}$ are sputter coated on both sides of PVDF to enhance the conductivity between PPy layers and the electrolyte and allow electrodeposition of the PPy onto the PVDF. A schematic comparison of a polymer actuator and a sensor is provided in Fig. 2.

The experimental system is shown in Figs. 3 and 4, where the input is provided by a mechanical lever system and the output voltage and current are recorded separately to obtain

Fig. 1. (a) Schematic structure of the conducting polymer sensor/actuator. (b) Schematic representation of the bending principle.

Fig. 2. Comparison of the conducting polymer actuators and sensors.

Fig. 3. Configuration of the lever and sensor.

current/displacement and voltage/displacement responses in the frequency domain.

As shown in Fig. 4, a dual-mode lever arm system (Model 300B-LR, Aurora Scientific, Inc.) was used to provide the input displacement. The induced electrical signals (voltage and current) in the sensor due to mechanical stimulation were conditioned with an *eDAQ Potentiostat*, a three-electrode preamplifier. The signals to be measured were connected to the inputs of the *eDAQ e-corder unit*, which was interfaced with a PC for data acquisition.

Fig. 4. Schematic representation of the experimental setup.

TABLE I
AMPLITUDE AND FREQUENCY OF THE SINUSOIDAL DISPLACEMENT INPUT

Amplitude	Frequency (Hz)
± 1 mm	0.01, 0.015, 0.02, 0.025, 0.03, 0.035, 0.04, 0.045, 0.05, 0.055, 0.06, 0.065, 0.07, 0.075, 0.08, 0.085, 0.09, 0.095, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20

For the three sensors with the dimensions of (7.5 mm, 10 mm, 12.5 mm) $\times$ 1 mm $\times$ 0.17 mm, frequency response experiments were conducted under sinusoidal inputs with the amplitude of ± 1 mm and frequencies ranging from 0.01 to 20 Hz. The frequency steps are presented in Table I.

A biased displacement of 2 mm was applied to the sensor to keep it in contact with the lever during measurements. Based on the measured response (current and voltage) and the input sinusoidal displacement, the magnitude ratio G and phase angle ϕ are calculated using (1) and Fig. 5. The resulting magnitude ratio and phase angle data against the frequency are presented in Figs. 7–12. When a dynamic system is subjected to a sinusoidal input $p(t)$, the steady-state output $x(t)$ of the system is also sinusoidal with a different amplitude and a phase lag/or lead, as schematically presented in Fig. 5(a). With reference to Fig. 5(b), the magnitude ratio and the phase angle (in radians) are determined from

$$|G(j\omega)| = \frac{A_1}{P}, \quad \phi = (\omega) \delta t \quad (1)$$

where ω is measured in radians per second.

III. MODELING AND ESTIMATION RESULTS

The output/input behavior of the sensors has been modeled using the experimental current/displacement and voltage/displacement frequency responses of the sensors. Assuming

Fig. 5. (a) Schematic representation of the response of a dynamic system under a sinusoidal input. (b) Relationship between the input and the response.

that the transfer functions to be identified are in the form of [17]

$$G(s) = \frac{B(s)}{A(s)} = \frac{b_n s^{n-1} + b_{n-1} s^{n-2} + \dots + b_1}{s^m + a_m s^{m-1} + \dots + a_1}, \quad m > n. \quad (2)$$

The transfer function, whose coefficients will be estimated using the experimental transfer function $G_{\text{exp}}(j\omega)$, is described by

$$G_{\text{exp}}(j\omega) = \begin{bmatrix} R_1 + jI_1 \\ R_2 + jI_2 \\ \vdots \\ R_k + jI_k \end{bmatrix}, \quad \text{for } \omega = \begin{bmatrix} \omega_1 \\ \omega_2 \\ \vdots \\ \omega_k \end{bmatrix} \quad (3)$$

where k is the number of amplitude ratio and phase measurements, which is greater than the total number of the parameters in (2). From the equivalence of the theoretical and experimental transfer functions described by (2) and (3), the following set of

Fig. 6. Structure of the OE model.

equations is obtained:

$$\frac{b_n (j\omega_1)^{n-1} + b_{n-1} (j\omega_1)^{n-2} + \dots + b_1}{(j\omega_1)^m + a_m (j\omega_1)^{m-1} + \dots + a_1} = R_1 + jI_1$$

$$\frac{b_n (j\omega_2)^{n-1} + b_{n-1} (j\omega_2)^{n-2} + \dots + b_1}{(j\omega_2)^m + a_m (j\omega_2)^{m-1} + \dots + a_1} = R_2 + jI_2$$

$$\vdots$$

$$\frac{b_n (j\omega_k)^{n-1} + b_{n-1} (j\omega_k)^{n-2} + \dots + b_1}{(j\omega_k)^m + a_m (j\omega_k)^{m-1} + \dots + a_1} = R_k + jI_k. \quad (4)$$

Equation (4) can be rewritten in a matrix-vector form including a vector of the unknown coefficients, which can be determined using a classical least squares estimation method. It must be noted that we have initially chosen a transfer function with eight poles and eight zeros, and then, calculated a cost function describing the fit between the experimental and theoretical transfer functions until a reasonably good fit has been obtained. The numbers of poles and zeros have been decreased systematically until a transfer function with minimum numbers of poles and zeros is extracted

$$P([\omega_1, \omega_2, \dots, \omega_k], [R_1, I_1, R_2, I_2, \dots, R_n, I_k]) \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_n \\ a_1 \\ a_2 \\ \vdots \\ a_m \end{bmatrix} = Q([\omega_1, \omega_2, \dots, \omega_k], [R_1, I_1, R_2, I_2, \dots, R_k, I_k]). \quad (5)$$

This transfer function estimation is accomplished using output error (OE) model estimation in the MATLAB *Identification Toolbox*. The structure of the OE model is depicted in Fig. 6, where the main advantage is that if the input-output data are collected for a system under no feedback control, the Fourier transform techniques can extract only the relevant frequency content, and the transfer function $G(s) = B(s)/A(s)$ can be identified correctly with any type of error or the disturbance [17]. Autoregression with exogenous signal (ARX), OE and Box-Jenkins (BJ) models have been identified and compared with the experimental data that the OE has produced the best fit. This could be due to the fact that while, with the OE, the error affects the output directly without considering any error model, and hence, the primary focus is on the accurate identification of the

Fig. 7. Estimated and experimental voltage/displacement frequency response of the sensor with the dimensions of 7.5 mm × 1 mm × 0.17 mm.

Fig. 8. Estimated and experimental current/displacement frequency response of the sensor with the dimensions of 7.5 mm × 1 mm × 0.17 mm.

system parameters, with the other estimation methods, the error affects the output through a transfer function, and therefore, it is likely to less accurately identify the system parameters.

A. Estimated Transfer Functions

The experimental and estimated magnitude and phase plots for the three sensors with the dimensions of 7.5 mm × 1 mm × 0.17 mm, 10 mm × 1 mm × 0.17 mm, and 12.5 mm × 1 mm × 0.17 mm are depicted in Figs. 7–12. The identified transfer functions are provided in Table II. It must be noted that the identified transfer functions do not describe the low-frequency behavior (<0.1 Hz) as good as the higher frequency behavior (>0.1 Hz). The transfer functions with higher numbers of poles and zeros have resulted in a better fit for the low frequencies. However, we had to make a compromise between the order of

Fig. 9. Estimated and experimental voltage/displacement frequency response of the sensor with the dimensions of 10 mm $\times$ 1 mm $\times$ 0.17 mm.

Fig. 11. Estimated and experimental voltage/displacement frequency responses of the sensor with the dimensions of 12.5 mm $\times$ 1 mm $\times$ 0.17 mm.

Fig. 10. Estimated and experimental current/displacement frequency response of the sensor with the dimensions of 10 mm $\times$ 1 mm $\times$ 0.17 mm.

Fig. 12. Estimated and experimental current/displacement frequency response of the sensor with the dimensions of 12.5 mm $\times$ 1 mm $\times$ 0.17 mm.

the transfer functions and the overall fit of the transfer functions to the experimental results.

The transfer function identified for the sensor 7.5 mm $\times$ 1 mm $\times$ 0.17 mm was employed to estimate the voltage output of the sensor at different frequencies, which are shown in Fig. 13. The close correspondence between the experimental and estimated voltage outputs demonstrates that the transfer function is effective enough to estimate electrical output of the sensor. Similar close correspondence has been obtained with experimental current data, which are not provided here for the sake of brevity. Experiments were conducted to determine whether the current and voltage responses show a linear relationship with the amplitude of the sinusoidal displacement inputs. As depicted in Fig. 14, there is approximately a linear relationship between the responses and the inputs. This finding supports our

approach to mimic the dynamic behavior of the sensors with transfer functions.

IV. DISCUSSION OF CHARACTERIZATION RESULTS

With reference to the frequency response models presented in Figs. 7–12, the peak current and voltage occurs at approximately 2 Hz for the three sensors considered. The results presented in this study are in agreement with the finding in the literature [6] that the actuation ability of the conducting polymers significantly depends on the polymer layer thickness rather than on the length. Using the voltage output and current generated for each of the sensors, the internal impedance of the sensor was estimated. At frequencies above 0.1 Hz, the phase difference between the current and the voltage is close to zero, suggesting that the internal impedance of the cell is primarily resistive in

TABLE II
SUMMARY OF THE ESTIMATED TRANSFER FUNCTIONS FOR THE 7.5, 10, AND 12.5 mm SENSORS IN LENGTH IN THE SECOND, THIRD, AND FOURTH ROWS, RESPECTIVELY

Voltage/Displacement Transfer Functions	Current/Displacement Transfer Functions
$14.15 \frac{s + 0.6144}{(s + 54)(s + 3.0215)}$	$16.81 \frac{s + 0.2705}{(s + 52.295)(s + 2.824)}$
$16.12 \frac{s + 1.2416}{(s + 75.394)(s + 5.132)}$	$21.23 \frac{s + 0.5142}{(s + 66.777)(s + 3.898)}$
$5.892 \frac{s + 0.875}{(s + 28.059)(s + 3.66)}$	$10.07 \frac{s + 0.3634}{(s + 31.313)(s + 3.098)}$

Fig. 13. Comparison of the experimental and estimated voltage outputs for the sensor (7.5 mm × 1 mm × 0.17 mm) under different input frequencies. (a) 0.01 Hz. (b) 0.1 Hz. (c) 3 Hz.

Fig. 14. Influence of the input amplitude on the current and voltage outputs of a 10 mm × 1 mm × 0.17 mm sensor.

Fig. 15. Resistance (top plot) and the electrical power generated (bottom plot) by the three sensors.

nature. This estimated sensor resistance reaches a minimum at 2 Hz, as depicted in Fig. 15. An upper bound on electrical power (voltage open circuit × current short circuit) generated during the frequency response measurements is calculated for the three sensors. The power results indicate that the shorter is the length, the higher is the power generated, as shown in the bottom plot of Fig. 15. The shape of the “resistance” curve suggests an RC limited response with the capacitance increasingly dominating the impedance at frequencies below 10 Hz. Such a capacitive response is expected in PF_6^- doped PPy [18].

We have repeated the frequency response experiments with *other sample* (with a different electrolyte LiTFSI, 0.1 M in PC) of polymer sensors with a 2 mm width and a range of lengths (thickness unchanged), and found that the shorter is the sensor length, the higher are the amplitudes of the voltage output and the current passed, as shown in Figs. 16 and 17

Fig. 16. Variation of the amplitudes of the current output with the active sensor length under sinusoidal displacement inputs.

Fig. 17. Variation of the amplitudes of the voltage output with the active sensor length under sinusoidal displacement inputs.

for the [1, 2, 3, 4, 5] Hz sinusoidal displacement inputs. This conclusion is also supported by the current and voltage magnitude responses provided in Figs. 7–12. It must be noted that while the current outputs at all frequencies considered have a consistent trend, the voltage outputs do not show quite the same consistency. The increase in response with shortened actuator length is not surprising. The strain induced in the shorter beams is higher at a given beam displacement. The amplitude of displacement is fixed in the experiments, resulting in larger strain in short beams, and an expected increase in response. The strain is approximately proportional to the inverse square of the length. The amount of charge transferred might be expected to be proportional to the length. As a result, it might be predicted that the current would increase in inverse proportion to length and the voltage as the inverse square of length.

Fig. 18. Dynamic electrical sensing response of a 20 mm × 4 mm × 0.17 mm sensor under an impulse displacement.

Further, their current and voltage responses under an impulse stimulus (i.e., displacement) are experimentally measured for the same samples a number of times. The results indicate that the dynamic sensing response is quite noticeable and repeatable; one of the results is shown in Fig. 18.

We propose to use this experimental impulse response to generate the transfer function models of the sensors, and estimate their bandwidths and other dynamic characteristics, as an alternative method to the frequency response experiments. It must be noted that the impulse responses shown in Fig. 18 show an underdamped response as opposed to the transfer functions identified for the results in Figs. 7–12, which indicate an overdamped response due to the separate real poles of the transfer functions.

A. Estimation of Bandwidth of Underdamped Sensors

The current and voltage responses shown in Fig. 18 are analogous to a damped harmonic response of a mechanical system. For such responses, there is a simple logarithmic relation with successive amplitudes [19]. This relation is known as the logarithmic decrement δ , which is a measure of the decrease in the amplitude of the response with time

$$\delta = \frac{1}{n} \ln \frac{Q_0}{Q_n} \quad (6)$$

where Q_0 and Q_n are the amplitudes of the logarithmically decreasing response at time $t = t_0$ or at the beginning of the response and after n cycles, respectively. The logarithmic decrement given by (6) is expressed in terms of the damping ratio ζ of the response

$$\delta = \frac{2\pi\zeta}{\sqrt{1-\zeta^2}}. \quad (7)$$

The time between successive cycles is the period τ_d of the damped response, which can be measured from two successive peaks in Fig. 18. The undamped natural frequency ω_n of the

Fig. 19. Experimental current/displacement and voltage/displacement magnitude plots of the 20 mm $\times$ 4 mm $\times$ 0.17 mm sensor. The X-coordinate reading is the bandwidth.

system is related to the damped natural frequency $\omega_d = 2\pi/\tau_d$

$$\omega_d = \omega_n \sqrt{1 - \zeta^2}. \quad (8)$$

The bandwidth ω_b of a second-order underdamped system is given by [20]

$$\omega_b = \omega_n \left(1 - 2\zeta^2 + \sqrt{4\zeta^4 - 4\zeta^2 + 2} \right)^{1/2}. \quad (9)$$

Using the impulse response in Fig. 18 for $n = 4$, the current data ($Q_0 = -0.0026268$ mA, $Q_4 = -0.00280592$ mA, $\tau_d = 0.045$ s) and the voltage data ($Q_0 = -0.0034803$ V, $Q_4 = -0.00362728$ V, $\tau_d = 0.0447 \cong 0.045$ s) are acquired. The current sensing and voltage sensing bandwidths of the polymer are estimated as $(\omega_b)_{\text{current}} = 216.83$ rad/s and $(\omega_b)_{\text{voltage}} = 218.31$ rad/sec, respectively. As expected, both bandwidths are approximately the same. This bandwidth is likely a consequence of beam inertia and is not a limitation on the sensor response mechanism itself. A reduction in length of the sensor leads to a higher bandwidth for the same mechanical input. Using the same experimental setup described in Section II, we conducted current frequency response experiments for the same sensor sample to verify the bandwidth estimation method. As shown in Fig. 19, the bandwidths estimated from the frequency response experiments are very close to the estimated ones, which prove that the logarithmic-decrement-based method is valid.

V. ESTIMATION OF SENSOR OUTPUT

When an external load is applied to the polymer sensor, one might expect that it would also have an influence on the ion content of the polymer. A compressive load might tend to push ions out, while a tensile load would tend to make it easier for ions to be inserted. The expulsion or insertion of ions however leads to a change in voltage across the electrode. At some point, the electrical penalty for this ion exchange balances the reduction in mechanical energy and equilibrium is reached. The total

Fig. 20. Voltage and force responses of a 10 mm $\times$ 2 mm $\times$ 0.17 mm sensor under a step displacement of 2 mm.

energy density is the sum of the electrochemical and mechanical energies

$$U_{\text{total}} = U_{\text{mechanical}} + U_{\text{electrochemical}} = \int \sigma d\varepsilon + \int V \cdot d\rho \quad (10)$$

where V is the electrode voltage, ε is strain, σ is stress, and ρ is the charge density. The mechanical energy can be changed by inserting or expelling ions, which is assumed to lead to a strain $\varepsilon = \alpha \cdot \rho$. Here, α is the strain to charge density constant (in cubic meters per coulomb). Inserting this expression for strain into (10) and minimizing the energy with respect to charge density leads to

$$V = \sigma \alpha. \quad (11)$$

The corresponding current can be calculated if the impedance is known. In this study, we conducted experiments to measure the voltage generated as a result of a step displacement. The contact force F between the lever arm and the polymer sensor was also measured, as shown in Fig. 20, to verify (11). The bending stress induced by the force is calculated from

$$\sigma = \frac{Mc}{I}, \quad M = F \times L, \quad I = \frac{bh^3}{12}, \quad c = \frac{h}{2} \quad (12)$$

where L , b , and h are the length, width, and overall thickness of the sensor, respectively. The voltage output of the sensors can be estimated using (11), provided that the strain to charge density constant α and the bending stress σ are known for that particular sensor. From the experimental results in the top plot and the middle plot of Fig. 20, the net voltage output and the net force are read to be 0.096 mV and 0.3953 mN, respectively. Using (12), the induced bending stress is calculated to be 0.41 MPa for a sensor with the dimensions of 10 mm $\times$ 2 mm $\times$ 0.17 mm. This follows that

$$\alpha = \frac{V}{\sigma} = 2.34 \times 10^{-10} \text{ m}^3/\text{C}. \quad (13)$$

Fig. 21. Voltage and force responses of a 10 mm × 2 mm × 0.17 mm sensor under step displacements to verify the sensor voltage output.

We repeated the same experiments with the same sensor, but pushing the polymer sensor down with the lever, rather than pushing it up. These experimental results are shown in Fig. 21. For the first step displacement, we estimate the voltage output to be $1.163\text{e}-004$ V, using (11) and the strain to charge density constant α in (13). The corresponding real voltage output is acquired from the top plot of Fig. 21 as $1.15\text{e}-004$ V, which match the estimated value perfectly. To verify the voltage estimation method further, the voltage output due to the opposite 1.5 mm step displacement is estimated to be $9.8984\text{e}-005$ V. The real voltage is acquired from Fig. 21 to be $9.0000\text{e}-005$ V. These two results are also in good agreement. It must be noted that the voltage output from Fig. 20 (0.096 mV) is lower than the voltage output from Fig. 21 (0.115 mV), with only difference being the direction of the displacement input. Ideally, the same voltage outputs are expected in displacing the sensor up and down by the same amount, provided that the thickness of the polymer layers is exactly the same. With reference to our previous work [10], this is not always the case due to the polymer synthesis anomalies.

The maximum bending stress described by (12) occurs at the fixed end of the sensor. The strain ε in a cantilever beam is given by [21]

$$\varepsilon = \frac{2}{3} \frac{h(L-x)}{L^3} z_{\text{tip}} \quad (14)$$

where x is the location of the strain along the beam, measured from the fixed end. For the strain at the fixed end of the sensor, $x = 0$. The effective modulus of elasticity $E = \sigma/\varepsilon$ of the cantilever polymer sensor can be estimated using (12) and (14). For the experimental results in Fig. 20, the maximum bending stress is 0.41 MPa and the corresponding strain for the tip displacement of 2 mm is calculated to be $2.27\text{e}-03$ mm/mm. This results in the effective modulus of elasticity of $E = 180.9$ MPa for the trilayer polymer sensor. This result can be

Fig. 22. Dimensional parameters of the flexural rigidity formulation.

verified using [8]

$$EI = E_{\text{PPy}} I_{\text{PPy}} + E_{\text{PVDF}} I_{\text{PVDF}} = E_{\text{PPy}} \frac{2b(h_2^3 - h_1^3)}{3} + E_{\text{PVDF}} \frac{2bh_1^3}{3} \quad (15)$$

where EI is known as the flexural rigidity of the beam. The dimensional parameters in (15) are shown in Fig. 22. For $E_{\text{PPy}} = 80$ MPa and $E_{\text{PVDF}} = 440$ MPa [7], the effective modulus of the elasticity of the sensor is calculated to be $E = 177.53$ MPa. This result matches the modulus of elasticity calculated earlier, using (13) and (14).

VI. CONCLUSION

We have presented our experimental investigation into the behavior of mechanical polymer sensors in order to identify the transfer functions describing the electrical outputs of the conducting polymers, which can be used as mechanical displacement and/or force sensors. The identified transfer functions can satisfactorily mimic the behavior of the polymer sensors up to 20 Hz. The dynamic sensing behavior of the sensors is characterized through impulse current and voltage responses, which show an underdamped response characteristic. We proposed a method to determine the current and voltage sensing bandwidths of the sensors. The voltage output is estimated using an energy balance approach, which has been successfully validated through a set of experimental results. Based on the novel experimental and analytical results, the contribution of this study is the first comprehensive investigation into the response characterization of the conducting polymers as mechanical sensors. The future work includes: 1) identifying more descriptive analytical mathematical models covering the effects of all geometric parameters (width, thickness, and length), from which we plan to determine analogous electrical circuit models in order to shed more light on the actuation and sensing mechanisms of conducting polymers, and their similarities and differences, and 2) build sensorized polymer actuators and test the performance of the mechanical polymer sensors under realistic conditions.

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