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Frequency Response of Polypyrrole Trilayer Actuator Displacement

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ABSTRACT

Conducting polymer trilayers are attractive for use in functional devices, given low actuation voltages, operation in air and potentially useful stresses and strains; however, their dynamic behavior must be understood from an engineering perspective before they can be effectively incorporated into a design. As a step towards the identification of the actuator dynamics, frequency response analysis has been performed to identify the magnitude and phase shift of displacement in response to a sinusoidal voltage input. The low damping of the trilayer operating in air and the use of a laser displacement sensor has allowed the frequency response to be continuously identified up to 100Hz, demonstrating a resonant peak at 80Hz for a 10mm long actuator. Two linear transfer function models have been fitted to the frequency response of the trilayer displacement (i) a 3rd order model to represent the dynamics below 20Hz and (ii) a higher complexity 6th order model to also include the resonant peak. In response to a random input signal, the 3rd order model coarsely follows the experimental identified displacement, while the 6th order model is able to fully simulate the real trilayer movement. Step responses have also been obtained for the 3rd and 6th order transfer functions, with both models capable of following the first 4 seconds of experimental displacement. The application of empirical transfer function models will facilitate accurate simulation and analysis of trilayer displacement, and will lead to the design of accurate positional control systems.

Keywords: Conducting polymer, polypyrrole, actuator, modeling

1. INTRODUCTION

Conducting polymer laminates [1, 2] show promise as electrochemical actuators, given the low input voltages, potential biocompatibility [2] and scalability to the micro-scale [3]. Actuators comprised a single conducting polymer layer on a flexible substrate are termed bilayers and are generally confined to liquid environments, while trilayer configurations consist of two polymer films separated by an inert substrate. Early prototypes have used bilayer and trilayer actuators, based on polypyrrole (PPy), to manipulate sub-millimetre objects [4, 5], suggesting these laminates are suitable for micro-scale applications. Trilayers are attractive given their operability in air, but their dynamic behavior must be modeled and controlled before effective devices can be designed.

Models of polypyrrole trilayer displacement have been developed, using curvature to charge ratios [6, 7], finite element simulation [8] and phenomenological [9] approaches to estimate the static bending angle, typically accepting step voltages as inputs. To effectively simulate the behavior of conducting polymer actuators and control position, dynamic models for actuator displacement are required, capable of predicting actuator displacement for arbitrary inputs over time.

Frequency response analysis is one technique capable of identifying the dynamics of the trilayer actuator, examining the displacement generated by the actuator as a function of input signal frequency. If the frequency response of a system is known, then the performance of the system can be quantified, the displacement predicted and a control system designed. A method of mathematically describing the system response is using a ratio of the output signal to the input signal, in a form known as a transfer function [10]. Two avenues exist for obtaining the frequency response and transfer function –

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(i) an analytical approach, where differential equations describing the physics of the system are identified and combined, or (ii) empirically, where a model is estimated from experimentally obtained input and output signals.
As a step towards the understanding and modeling of conducting polymer trilayers, this paper presents the experimentally identified frequency response for polypyrrole trilayer actuator. Two empirical transfer functions of differing complexity have been fitted to this frequency response, which are then used to simulate the displacement of the actuator. It is shown that the model accurately represents the actuator displacement, providing a tool for actuator simulation and development that will lead to the development of model-based control systems.

2. EXPERIMENTAL SETUP

2.1. Trilayer structure

The conducting polymer device used for this study is a laminated structure [11], comprising of two polypyrrole layers separated by a porous poly(vinylidene fluoride)(PVDF) substrate (Fig. 1(a)). The PVDF serves as both an insulator between the two PPy layers and an electrolyte reservoir, allowing it to operate in air. Application of a potential across the device generates differing strains in each of the conducting polymer layers, causing it to bend (Fig. 1(b)).

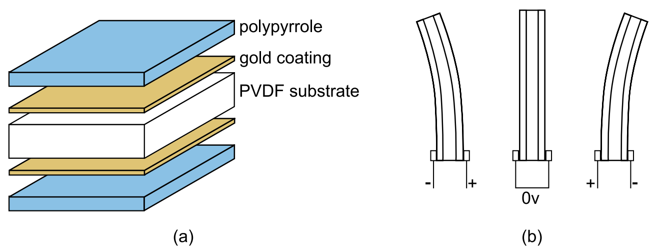


Fig. 1: (a) exploded structure and (b) bending behavior for the polypyrrole trilayer used in this study

2.2. Trilayer preparation

Trilayer bender actuators were prepared using an electrochemical deposition process [11]. A bare PVDF (Millipore Immobilon) membrane was sputter coated with gold on both sides and fitted to a spring loaded frame (Fig. 2 (a)). The PVDF and frame were then placed in the polymerization cell (Fig. 2(b)), containing a polymerization solution of 0.1M lithium bis(trifluoromethanesulfonimde) (LiTFSI, 3M), 0.1M pyrrole (Merck) and 1w/w% water in Propylene Carbonate (PC) (Aldrich) that had been deoxygenated with N_2 for 20 minutes. The gold coated PVDF was used as the working electrode and two stainless steel mesh sheets held parallel to PVDF were used as counter-electrodes. The cell was then chilled to -35°C and polymerization initiated using a galvanostat (Princeton Applied Research, model 363) applying a constant current density of 0.1mA/cm^2 for 12 hours. Upon completion of the polymerization, the PPy coated PVDF was removed from the cell and first washed with acetone and then soaked in the actuation electrolyte, consisting of 0.1M LiTFSI in PC. Trilayer actuators were cut to size from the as grown bulk sheet using a scalpel.

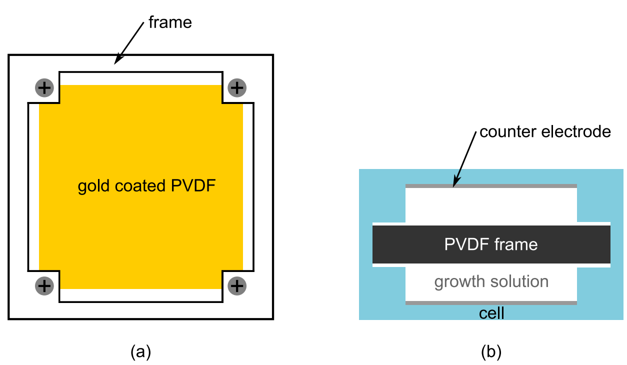


Fig. 2: Schematic of (a) PVDF stretching frame and (b) top view of the polymerization cell

2.3. Measurement of trilayer displacement and frequency response

The trilayer was gripped between two platinum contacts, allowing a potential to be applied across the two layers. An eDAQ potentiostat (EA161), operating in a 2-electrode configuration, was connected to the platinum contacts to drive the actuator. The voltage and current applied to the trilayer was recorded using an eDAQ datalogger (ED821). The reference signal applied to the potentiostat was generated using a National Instruments DAQ (NI6229) and custom LabView software.

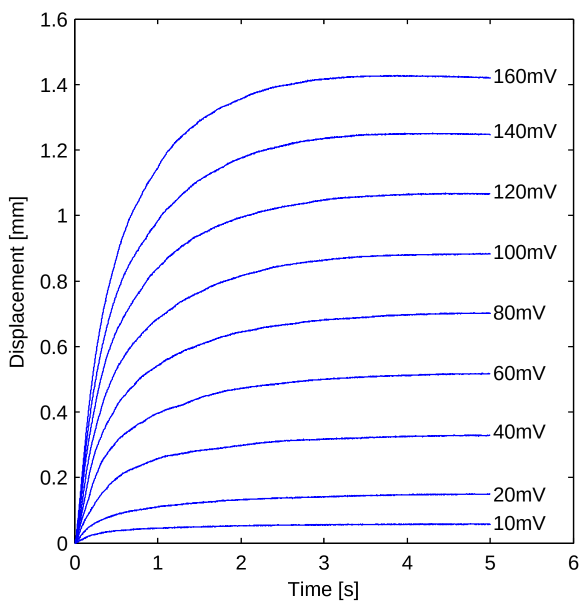
A laser displacement sensor (micro-epsilon NCDT-1700-10) with a 10mm range and 0.5 um resolution was mounted on an XY micrometer stage and focused perpendicular to the actuator, 0.5mm from the tip. A voltage signal proportional to displacement was generated by the sensor and measured using the datalogger. The digital conversion circuitry in the displacement sensor introduces a 2ms delay between the displacement and the output voltage, contributing a 0.7°/Hz phase shift to the trilayer phase response.

The Chart software package was used to interface with the datalogger, storing the time domain data and converting it to a delimited text file. From this data, the frequency response was identified using MATLAB, and the transfer function estimated using the Signal Processing toolbox. The System Identification toolbox was then used to estimate the transfer function and simulate displacement using the model.

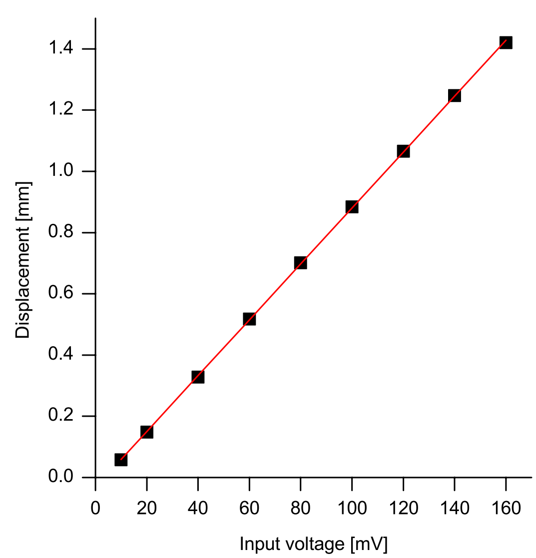
3. RESULTS

3.1. Step Response Linearity

To confirm the linearity of the trilayer actuator output, step responses were obtained for a number of different input amplitudes between 50mV and 150mV, as shown in Fig. 3(a). The displacement measured at 5 seconds is presented in Fig. 3(b) with a linear trendline fitted.



(a)



(b)

Fig. 3: (a) Displacement response of a trilayer actuator in response to increasing amplitude step voltages, and (b) displacement at 5 seconds as a function of input voltage. A linear trendline has been fitted to (b) with the equation y = 0.0091*x* + 0.032.

3.2. Frequency Response

Using the experimental technique detailed in Section 2.3, the displacement of the trilayer can be identified in terms of input frequency, as shown in Fig. 4 for a 10mm long, 2mm wide actuator. The output is expressed in gain and is calculated by dividing the actuator displacement with the input voltage at each frequency.

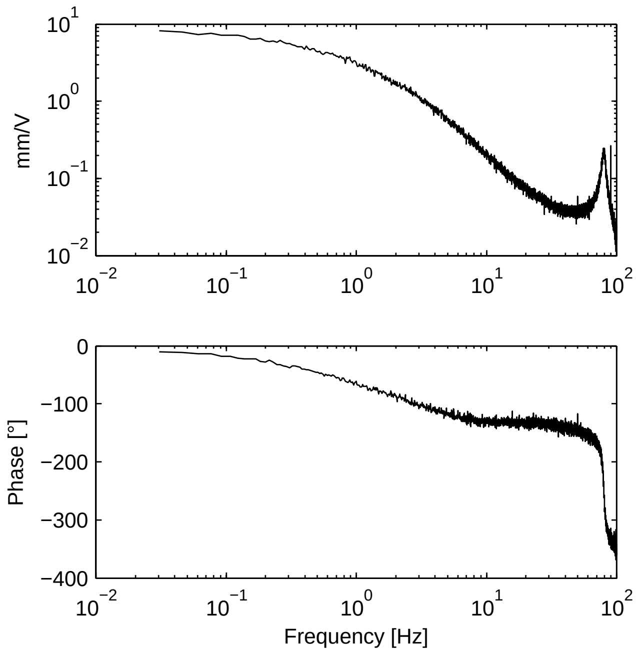


Fig. 4: Example frequency response for a 10mm long, 2mm wide actuator

The trilayer actuator also demonstrates a resonant peak, seen in Fig. 4 at approximately 80Hz, corresponding to the first mode of actuator resonance. For a sinusoidal input with amplitude of 1V, the displacement at the resonant peak is 0.23mm, as compared to 7.1mm at 0.1Hz.

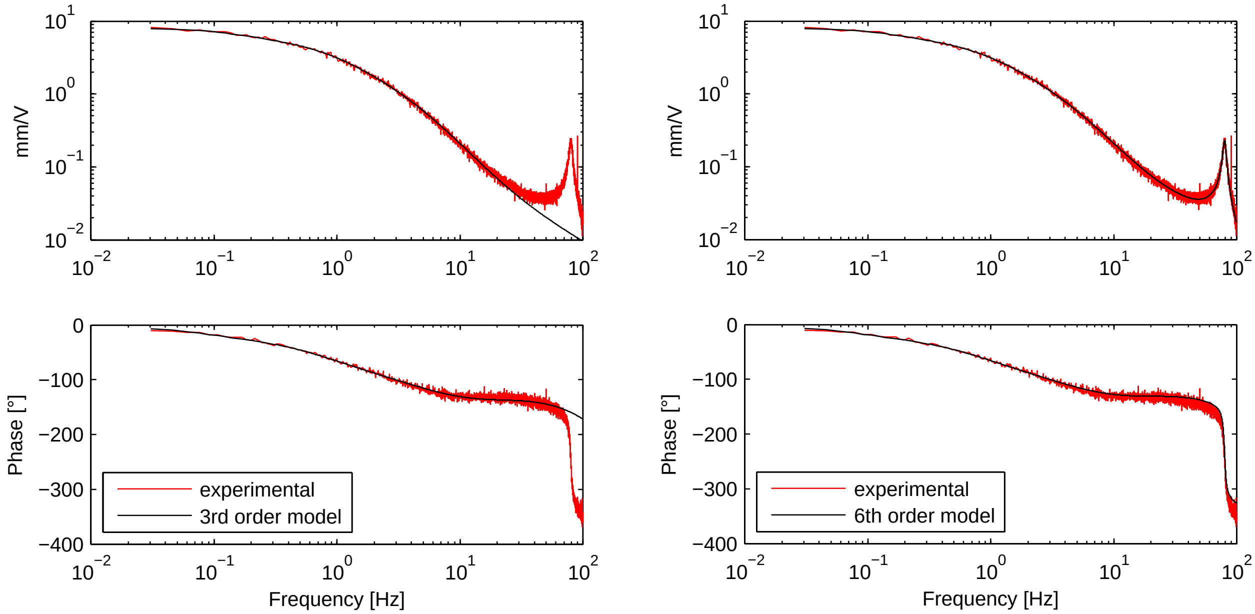
3.3. Frequency response modeling

3.3.1. Transfer function fitting

Linear transfer functions have been fitted to the identified frequency response, as shown in Fig. 5 for a 10mm long, 2mm wide trilayer actuator. Two different transfer functions have been obtained – a 3^{rd} order function (Fig. 5(a)) fitted to the low frequency region and a 6^{th} order function (Fig. 5(b)) to fit both the low frequency region and higher frequency resonance. The 3^{rd} order transfer function is shown in (1) and the 6^{th} order fitted transfer function in (2). In both instances, a delay of 2ms was included to model the phase lag introduced by the laser displacement sensor.

$$G_1(s) = e^{-0.002s} * \frac{5.8097\ (s+152)\ (s+1.293)}{(s+36.52)\ (s+4.516)\ (s+0.8632)} \quad (1)$$

$$G_2(s) = e^{-0.002s} * \frac{0.28806\ (s+1619)\ (s+125.7)\ (s+1.325)\ (s\text{^}2 + 2564s + 3.154e006)}{(s+898)\ (s+33.97)\ (s+4.583)\ (s+0.8791)\ (s\text{^}2 + 27.23s + 2.486e005)} \quad (2)$$

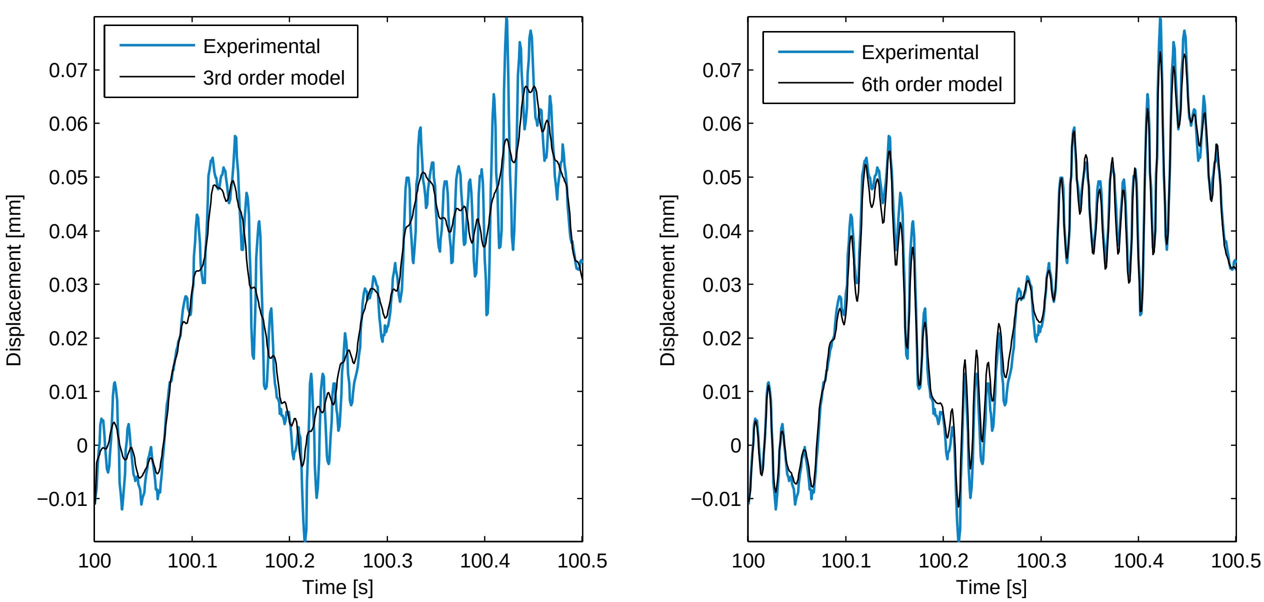


(a) (b)

Fig. 5: Experimentally identified frequency response and fitted (a) 3rd order transfer function and (b) 6th order transfer function

3.3.2. Transfer function validation

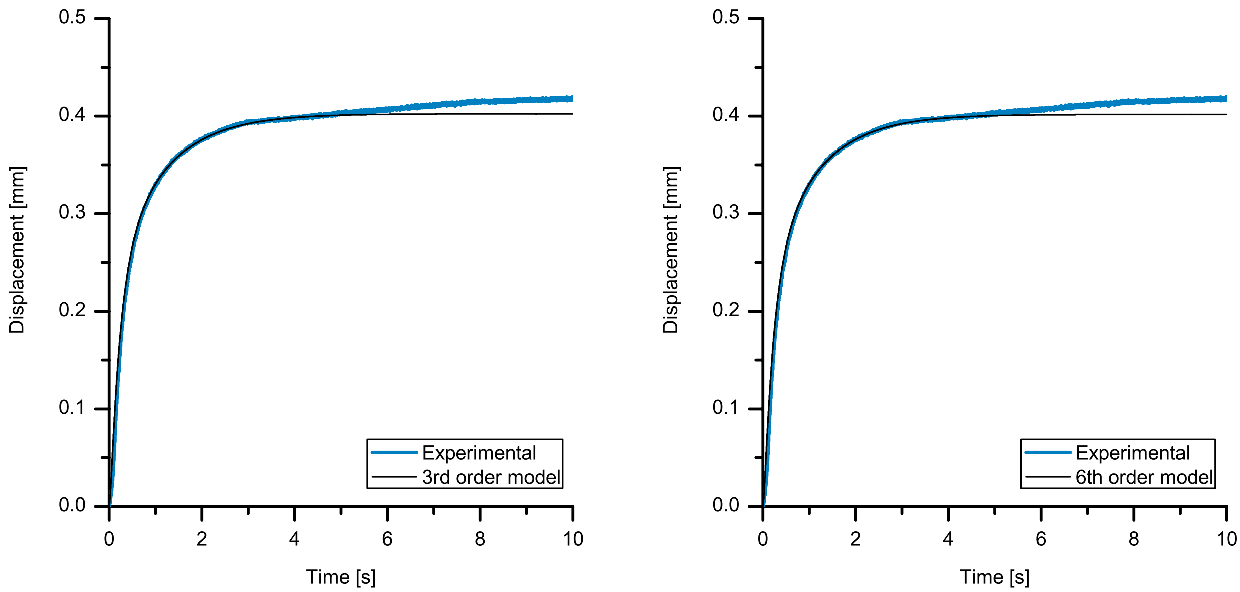
To validate the fitted transfer function, the random input signal was applied to the fitted model and the simulated output compared with the experimentally identified displacement. A 0.5s sample of the typical experimental and model output is shown in Fig. 6.



(a) (b)

Fig. 6: Experimentally observed response of a 10mm long, 2mm wide trilayer actuator to a random input voltage and simulated displacement from (a) a 3rd order and (b) a 6th order fitted transfer function.

A step voltage of 50mV was also applied to the trilayer actuator for 10 seconds and the response measured. The simulated response to the same signal was obtained from the 3rd and 6th order transfer functions, shown in Fig. 7.



(a) (b)

Fig. 7: Experimentally observed and simulated (a) 3rd order and (b) 6th order step responses for a 50mV step voltage, applied to a 10mm long, 2mm wide trilayer actuator.

4. DISCUSSION

4.1. Linearity

The displacement response of the actuator at 5 seconds was found to be linear within the range of step voltages considered, as indicated in Fig. 3(b). This follows the trends previously reported in literature for bender displacement [4, 8] and can be used to estimate the steady state position of the actuator tip; however, this relationship can not predict the time or displacement leading to the steady state.

4.2. Frequency response

A typical frequency response was identified for a 10mm long and 2mm wide actuator, as shown in Fig. 4. The frequency response plot indicates the magnitude of the displacement in response to the input voltage at a specific frequency, here between 0.03Hz to 100Hz. The two areas of the frequency response that are of interest are low frequencies below 20Hz and the high frequencies around the resonance (centered at 80Hz in Fig. 4).

4.2.1. Low frequency

The low frequency region is characterized by the sharp decrease in gain with frequency, starting at a maximum of 8.2mm/V (0.03Hz) and decreasing to 0.07mm/V (20Hz), beyond which displacement is negligible in the macro-scale. The larger gains at low frequencies indicate that the actuator movement is controlled by this region. The decrease in gain with frequency indicates displacement is driven by time-dependent internal processes, as there is less time for these internal processes to occur at higher frequencies, producing less strain.

The bending of the trilayer actuator is driven by differing levels of strain in each of the two PPy layers. For single films, it has been shown that the change in redox state is not immediate, instead progressing through the film with time [12, 13]. When the input frequency is increased, the time-dependent processes are activated for shorter periods before reversing, resulting in a smaller proportion of the conducting polymer changing state. As the redox level has been linked to the strain generated in the conducting polymer, the time-dependent change in state may explain the decrease seen in the tip displacement.

4.2.2. High frequency

The second region of interest is the high frequency response, particularly the resonant frequency, identified by the sharp peak in the frequency response (approximately 80Hz in Fig. 4). The displacement of laminated actuators have been studied in terms of frequency [11, 14, 15] and resonant frequencies of 90Hz detected [11], but the use of the laser displacement sensor and lower damping in the air environment has allowed the full frequency range to be accurately identified.

The force output of polypyrrole trilayer actuators is typically low (<10mN) [4, 11] and similarly prepared benders take approximately 1s to reach peak force output [11]; this suggests the force generated by the actuator at high frequencies and at resonance is small (<1mN). Low force output will limit the potential macro-scale applications of the bender at higher frequencies, but this limitation is less significant for low-force applications, such as micromanipulation [4].

4.3. Transfer function

Linear transfer functions have closely fitted to the frequency response of the conducting polymer actuator, using a 3rd order function to capture only the low frequency dynamics and a 6th order function to model the entire measured range, as shown in Fig. 5. The transfer functions are empirical models and based on experimental data only; the functions do not necessarily correspond to physical processes.

The validity of the identified transfer functions were tested by applying specific input signals to the experimental system and the models, then comparing the output. Random noise was used as an input signal as it theoretically contains equal power over a very large number of frequencies. The 3rd order model was fitted only to the low frequency portion of the identified spectrum; this restriction is evident in the simulated output (Fig. 6(a)), where the model coarsely follows the slower changes in displacement, failing to reproduce the higher frequency oscillations. By including the resonance in the 6th order model, all characteristics of the dynamic actuator displacement can be simulated (Fig. 6(b)).

The response of the trilayer to a 50mV step voltage was obtained experimentally, and compared to the response simulated by the fitted models (Fig. 7(a) and (b)). The response of the 3rd and 6th order models are similar, closely matching the experimental curve up to 4 seconds, as the dominant time constants of both models are nearly equal. The displacement of the actuator continues to increase after 4 seconds, while the transfer function models have reached steady state. It is known that the displacement of conducting polymer trilayers continues to increase at longer time periods, due to effects such as creep [4, 16] or slower changes in redox state, which are not accounted for in the fitted transfer functions models.

The estimated transfer functions are advantageous as they represent the dynamics of the system under consideration, and can simulate the trilayer displacement accurately, suitable for system analysis and design; however, as this is an empirical model and not based on the physics of actuation, each change to the actuator requires a new transfer function to be fitted.

5. CONCLUSION

This paper has presented a frequency response of a polypyrrole trilayer actuator up to 100Hz, obtained using a laser displacement sensor. The frequency response has been shown to have significant gain below 20Hz, related to the strain generation in the polymer, and a high frequency resonance. It has been shown that two transfer functions can be fitted to the identified frequency response, with a low order model suitable for coarse displacement simulations and a higher order model capable of predicting actuator displacement. While steady-state nonlinearities are omitted from the model, this transfer function is capable of accurately simulating the dynamic displacement of the trilayer and represents a useful tool for displacement analysis and accurate positioning through control system design.

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