2020 IEEE/ASME International Conference on
Advanced Intelligent Mechatronics (AIM), Boston, USA
(Virtual Conference), July 6-9, 2020

Self-sensing of Dielectric Tubular Actuator and Its Validation in Feedback Control

Shengbin Wang, Theophilus Kaaya, and Zheng Chen*

***Abstract*— Dielectric elastomer (DE) materials, a category of electroactive polymers, can be used to design actuators that are flexible, resilient, lightweight, and durable. However, due to the uncertainties in its actuation dynamics, DE actuators always rely on feedback control to perform accurate and safe operations. In this paper, a tubular dielectric elastomer actuator (DEA) with self-sensing capability is developed. It does not require external devices to measure displacement for feedback control. The displacement of the actuator is controlled using a proportional-integral controller with the capacitance measured at high probing frequency as the self-sensing mechanism component of the actuator. By superimposing actuation and probing voltage and applying them to the DE tube, the actuation voltage activates the movement of the DE tube and the probing voltage is used for self-sensing. Fast Fourier Transform (FFT) is then used to filter a given frequency of the probing current and voltage and then calculate the capacitance from the probing current and voltage during each time window. With the relationship between capacitance and displacement of the DE tube, the displacement output is estimated online and self-sensing without an external sensor is achieved. The self-sensing signal is then used as a feedback signal in a closed-loop design to follow a reference signal for tracking. The experimental results validate the self-sensing of the DE actuator in feedback control.**

Keywords— Dielectric elastomer(DE), Capacitance, Tubular actuator, Self-sensing

I. INTRODUCTION

Dielectric elastomer material shows desirable performance and ideal characteristics for soft robotics such as having high energy density and being lightweight [1], not requiring large amounts of space to operate [2]. They have been studied as artificial muscles for many years because their internal actuation properties are close to natural muscles. They are easy to be manufactured, and the material is readily available. In addition, they can offer a large amount of strain with high voltage applied across the membrane. It is easy to change the shape and size of the DE material with as high voltage applied on the surface of the membrane. The DE material can be used to mimic the movement of muscles to design bionic robots to help the disabled people recover their movement [3]. Some heavy machinery can also be replaced with lightweight soft robots that are fabricated by DE material [4]. With all these benefits and promising applications in robotics, however, the DE actuators are challenging to be modeled since their behaviors are unpredictable in certain configurations [5].

*This work was supported in part by the National Science Foundation under Grant CMMI #1747855.

S. wang, T. Kaaya, Z. Chen are with the Department of Mechanical Engineering, University of Houston, 4800 Calhoun Rd, Houston, TX 77004, USA (Corresponding author e-mail: zchen43@central.uh.edu).

A feedback control is needed to make sure that the control system is robust to those uncertainties. Thus a compact and reliable sensor is needed to provide feedback information. The major restriction of feedback control for DE actuator is the requirement of some external sensors. DE material has also been treated as a potential candidate for sensor applications as its electrical impedance changes when a stretching load is applied on it. Because of its built-in sensing and actuation mechanism, a DE actuator can work as sensor and actuator simultaneously based on the fact that the DE electrical behavior (capacitance or resistance) can be measured instantly during its actuation process.

Many self-sensing methods for DE actuator have been developed in recent literature, such as impedance measurement and online identification algorithms, some research work was focused on resistance [6], some was focused on the current [7], and others have measured the capacitance [8] as variables to predict displacement. These electrical features could be calculated with different algorithms and used to predict the displacement of the DE actuator. The challenges in most experiments in establishing good performance for feedback control mostly stem from the self-sensing model combined with a robust controller. To get good results with less noise, Hoffstadt *et al.* extracted the probing signal from the combined signal to calculate the capacitance of the DE actuator, which reduces the influence of the noise produced by outside experimental equipment [9].

In this paper, we present a novel DE tubular actuator which acts as a small displacement measuring device without the need for any external measurement devices. The novel tubular DE actuator can hold air inside when the two end sides are closed by the tape material and can save space comparing with the same volume plane actuator. The actuator utilities the advantage that its change in displacement during actuation has a relationship with the capacitance under a fixed frequency of the input signal. This allows for the creation of a feedback loop to help the actuator sense displacements in low frequency and follow the desired reference signal closely.

For the DE tube, little research has been done with measuring the displacement for self-sensing due to the challenges involved in fabricating the DE tube as well as the difficulties in filtering the noise from the experiment without loss of data. A further aspect, which has not been investigated so far, is filtering the noise information of the DE actuator. In this paper, we mainly focus on the DE tube actuator by selecting suitable VHB material and a certain size to make the DE tube, by combining actuation and probing voltage. The current, resistance, reactance, and capacitance of the actuator are changed with the movement of the DE material. By simplifying the actuator as an RC circuit, and choosing an optimal time window, filtering the probing signal from the actuation signal through Fast Fourier Transform (FFT), we can get the magnitude of the probing current and voltage. Thus, the resistance and reactance of the DE tube during each time window can be calculated. The capacitance of the DE for a specific frequency probing signal can then be extracted from the reactance. It is reasonable to propose a model to build a reliable relationship between the displacement and capacitance under a given frequency. The relationship between capacitance and displacement has been demonstrated in many articles [10].

The area of feedback control with DE actuator has already gained increasing attention during recent years. However, several recent papers introduce experimental investigation of self-sensing capabilities of DE tube actuator. In this paper, we propose a model and stable experiments to show the certain relationship between the capacitance and displacement of the DE tube, then combine the self-sensing model and controller to accomplish feedback control in real-time. We also present some tracking control results with different reference signals at different actuation frequencies. There are two major steps included in experimental validation of the self-sensing method in feedback control. In the first step, we get the self-sensing model from a given data set to predict the displacement with the changing capacitance during the movement of the DE tube. The self-sensing results are then compared with the displacement measured by the laser sensor with different input signals that are applied on the DE actuator. In the second step, we finish the closed-loop control using the self-sensing displacement as the feedback signal when applying different reference signals, then comparing the self-sensing model prediction results with the laser sensing results to verify the self-sensing model. All the experiments are carried out online and the real-time capacitance output from the self-sensing model can be used for calculating the displacement of the actuator from one time window to another time window. The demonstration from different types of reference signals shown excellent performance with small error between the reference signal and measured data under low frequency and small displacement. This work implemented on a DE tubular actuator is the first effort to analyze the capacitance change with FFT method. This work will benefit us for further research in the bionic artificial muscles enabled by DE.

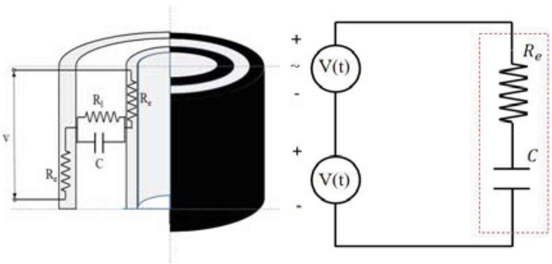
The rest of the paper is organized as follows: Section II talks about the self-sensing mechanism. Section III provides the system identification and validation of the self-sensing model as well as the actuation model. Section IV shows the experimental results for validation of self-sensing in closed-loop feedback control with a PI controller. Section V discusses the conclusion.

II. Self-sensing mechanism

The self-sensing requires the use of electrical parameter measurements to predict the DE tube deformation. From the electrical aspect, the DE tubular actuator acts as a cylindrical capacitor, the capacitance between the two surfaces changes as the tube is stretched in length under a load since the thickness decreases.

In order to measure the electrical impedance, a high frequency probing signal is added on the top of a low frequency actuation signal. To describe the probing voltage and current response, we simplify the DE circuit to an RC series circuit which is a leakage-free model, as shown in Figure 1. The DE tube circuit includes two-electrode resistors R_e and the cylinder capacitance C connected in parallel with the leakage resistor R_l. The leakage resistor R_l can be neglected at high frequency [11]. Since $R_l \gg R_e$, the voltage on the cylindrical capacitor can be calculated as:

$$V_{DE} = \frac{R_l}{2R_e + R_l} V \tag{1}$$



(a) (b)

Fig. 1. (a) DE tube actuator circuit; (b) simplified model with combined probing and actuation signals.

When the combined voltage is applied to the DE tube, the current and voltage undergo a fast dynamics due to the high-frequency probing signal, while the reactance and capacitance undergo relatively slow changes during the same time period. So we assume the capacitance of the DE tube to be the same during each small sampling time T_s, and during this time, we adopt all of the data for FFT and then filter the probing voltage *v(t)* and current *i(t)*. Since the low-frequency actuation voltage and the high-frequency probing voltage are combined together, the low frequency voltage is used as the actuation signal to make the DE tube move with high voltage, and the high frequency voltage is used as the probing signal to measure the current accurately with low voltage. The DE circuit is designed with a high pass filter attribute. As such, the current from the low frequency actuation voltage are filtered out. This method is focused on the probing signal to calculate the capacitance to predict the displacement of the DE tube. Also, the probing signal does not influence the movement of the DE tube since the probing signal is set at a high frequency while the dynamics of DE actuator behave as a low-pass filter [12].

With the circuit shown in Fig. 1, we have

$$v(t) = v_R(t) + v_C(t) = i(t)R + i(t)\frac{1}{j\omega C} \quad (2)$$

where ω is the angular frequency of the AC voltage source. The impedance Z is thus given by

$$Z = R + \frac{1}{j\omega C} = \sqrt{R^2 + (\frac{1}{j\omega C})^2} e^{(j\theta)}, \quad (3)$$

$$R_c = \frac{1}{2\pi f C}. \quad (4)$$

R_c is the reactance of the DE tube for a given frequency *f*. In this paper, the frequency of the probing signal is *f*. The phase angle θ between the voltage *v(t)* and current *i(t)* is

$$\cos\theta = \frac{R}{\sqrt{R^2 + (\frac{1}{\omega C})^2}}. \quad (5)$$

For the cylindrical capacitor DE tube, there is a voltage difference between the two sides of the conductors when a voltage is applied across them. Let the length of the tube be L with inner radius r and outer radius R. λ is the charge per unit length on the surface of each side. The total charge on one side of the cylinder is $Q=\lambda L$. The voltage between the cylinder can be found by integrating the electric field along a radial line. By applying Gauss' Law to the cylindrical capacitor in a vacuum, the electric field can be calculated. The capacitance of the DE tube is calculated as:

$$C = \frac{Q}{V} = \frac{2\pi\varepsilon_r\varepsilon_0 L}{\ln(\frac{R}{r})}, \quad (6)$$

where ε_0 is permittivity of free space, and ε_r is the relative permittivity of the medium in-between the two DE electrodes. When the actuator undergoes a displacement, it causes a change in the thickness of the membrane and hence a change in the capacitance. We assume that ε_0 and ε_r does not change. The length of the DE tube and the inner and outer radius are not negligible for small displacements. The final capacitance C_f when the DE undergoes a certain displacement can be estimated as:

$$C_f = \frac{2\pi\varepsilon_0\varepsilon_r(L + \delta L)}{\ln(\frac{R+\delta R}{r+\delta r})}, \quad (7)$$

where δL is the change in the length of the DE membrane, δR and δr are the changes in the inner and outer radius of the DE membrane. All of the changes are decided by the change in the thickness of the DE tube. Let z be the displacement of the DE tube. It can be seen that there exists a relationship between the change of the thickness of the DE tube δd and the displacement z. So we assume:

$$\delta L = f_1(\delta d), \delta R = f_2(\delta d), \delta r = f_3(\delta d). \quad (8)$$

$$z = f_4(\delta d), \quad (9)$$

Combining Eqn. 7, Eqn. 8 and Eqn. 9, we can conclude the displacement of the DE tube as shown below

$$z = f(C). \quad (10)$$

From Eqn. 4, the capacitance can be calculated from the reactance under a certain frequency, so the final displacement z can be derived as long as the self-sensing model based on Eqn. 10 is found.

III. System Identification

A. Experimental Setup

Relevant geometrical parameters of the DE tube are shown in Table I. The actuator is made from VHB material of 10 cm by 5.6 cm size cut from a tape roll. Both sides are fixed on plastic cylinders. The edges of the sides are then covered with insulating tape to avoid short circuit between the two electrodes. Graphite powder is pasted on both sides of the DE membrane uniformly, and a load of 20 g is fixed on the lower side to contribute a vertical pre-stretch of 37.5 %. The final length of the DE tube is 110 mm. The DE tube membrane actuator with two plastic supports and the load are shown in figure 2, the blue cylindrical tubes are made from plastic material with 15 mm diameter, the black tube represents VHB tape with carbon powder painting on the inside and outside surfaces. When a high voltage is applied to the DE tube, the free side, with the 20 g load, of the DE actuator will undergo some displacement and change the shape of the actuator. The original position represents the bottom of the DE membrane when there is no load applied on the free side.

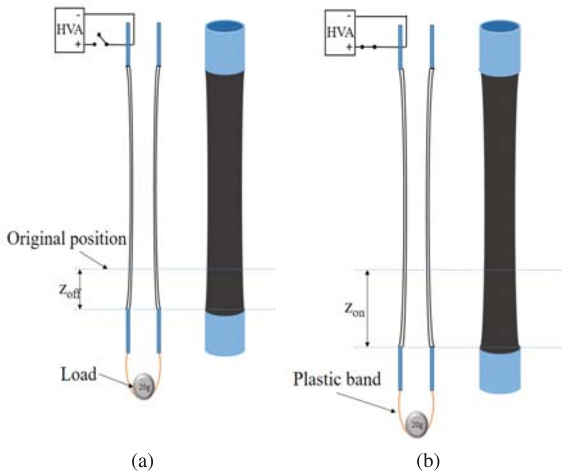


Fig. 2. DE tube actuator (a) without high voltage and (b) with high voltage.

TABLE I

DE tube geometry parameters.

Parameter	Value	Unit
Average radius	7.5	(mm)
Average Thickness	0.254	(mm)
Height	80	(mm)
Relative permittivity	2∼10	

The full experimental setup is shown in Figure 3, where there are the DE tube holder and the inner and external electrodes, with the laser sensor measuring the movement of the DE tube by measuring the displacement between the laser sensor and the balance plate medium.

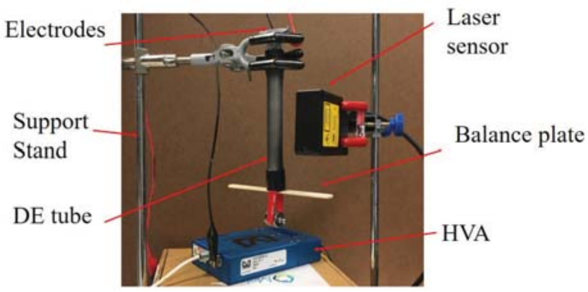


Fig. 3. Experimental setup.

B. Actuation Model Identification

To determine the characteristics of the tubular actuator, we perform system identification to estimate the transfer function of the actuator. This is achieved by analyzing the system's frequency response of the actuator over the range of 0.02 Hz to 8 Hz with a sinusoidal input signal of amplitude 2 kV. The response is then plotted on the bode magnitude and a transfer function is fitted onto the data. The frequency response is shown in Figure 4, where we can find that the probing signal does not have a big influence the dynamics of the actuator especially during the low frequency. Probing voltage and current can be used as variables to calculate the reactance of the DE circuit from which the capacitance can be obtained. The capacitance is chosen as the feature used to predict the displacement of the DE tube.

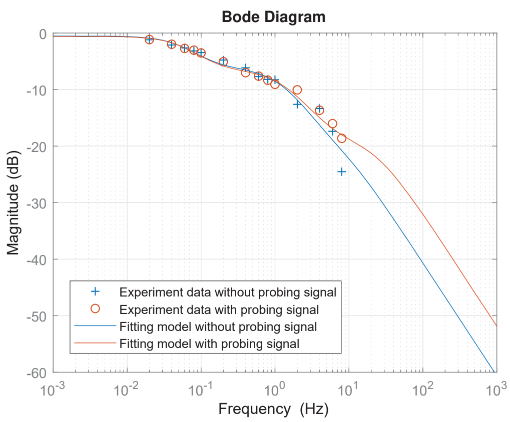


Fig. 4. Frequency response with probing and without probing signal

The actuation voltage is provided by a high voltage amplifier (HVA 5HVA24-BP1-F), the real displacement of the DE tube is measured by a laser sensor (Baumer OADM 20I6441/S14F). Data acquisition and control for self-sensing are implemented in real-time by using Simulink and dSPACE (DS1104, dSPACE Inc.). Since the inherited length of the FFT for MATLAB should be 2^n, the frequency with which we collect the data is set to 1,024 Hz. Then we use FFT (Fast Fourier Transform) method to get the magnitude of the probing signal. The time window of the FFT is inferred from the default setting in Matlab from the function:

$$F_n = \frac{(n-1)F_s}{N}, \tag{11}$$

where F_n is the frequency of the probing signal, F_s is the sampling frequency, n is the number of the order we want, and N is the number of the data points we choose to run FFT. For continuous two time windows of data, half of which are overlapping, the data will be double compared to the case when there is no overlapping [13]. This serves to increase the accuracy in capacitance measurement. The optimal value for F_n is 32 Hz, and N is 64 so that we can get integer n to get the magnitude of current during each time window, which we use to calculate capacitance. We also use a bandwidth filter in Simulink. The bandwidth pass frequency is from 31 Hz to 33 Hz. Fig 5 shows the experimental results, where the first row of the figure is the voltage applied to the DE tube, the second row is the current in the DE tube circuit measured by the HVA, the third row is the capacitance of the DE tube measured by an algorithm built-in Simulink, and the last row is the displacement measured by the laser sensor which shows there is a good relationship between displacement with the capacitance. We therefore choose capacitance as the variable to be used for self-sensing of the actuator to get a model to predict the displacement of the DE tube.

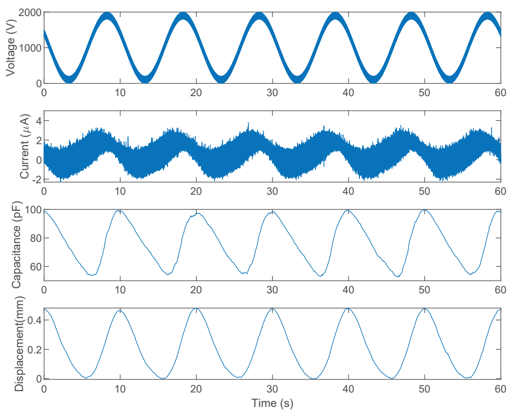


Fig. 5. Closed-loop control of DE tubular actuator with self-sensing mechanism.

C. Sensing Model Identification

To find the model to predict the displacement of the DE tube, a sinusoidal actuation voltage with frequency of 0.05 Hz and amplitude 2 kV was applied to the circuit. The probing signal frequency is set to 32 Hz with a magnitude of 100 V. The capacitance and displacement of the DE tube are recorded and a third-order polynomial function is used to fit the data. Calibration is performed on both self-sensing and the laser sensor data as shown in Figure 6.

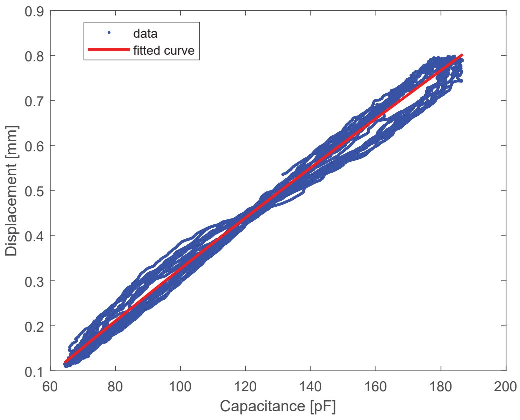


Fig. 6. Third order polynomial fitting curve of probing signal.

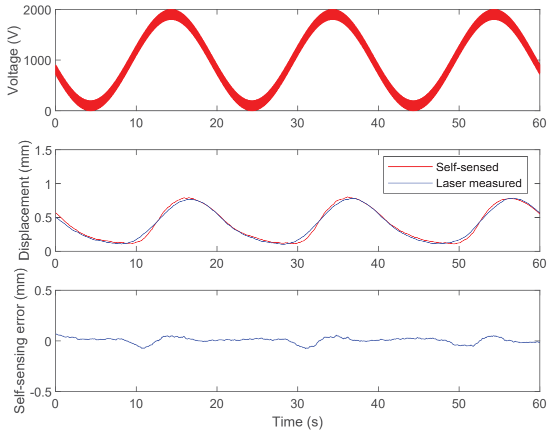


Fig. 7. Self-sensing validation at 0.05 Hz sine wave.

TABLE II

SELF-SENSING ERROR WITH DIFFERENT FREQUENCIES AND WAVEFORMS.

Waveform	**Sinusoid**	**Sinusoid**	**Sinusoid**
Frequency (Hz)	**0.02**	**0.05**	**0.1**
Error (%)	3.16	0.96	4.4
Waveform	**Sawtooth**	**Square**	
Frequency (Hz)	**0.05**	**0.05**	
Error (%)	1.93	0.93	

This model is used to test its performance at predicting the displacement of the tube with the same frequency actuation input signal of 0.05 Hz. The result is shown in Figure 7. The model developed is then used to test two different frequency sinusoidal input signals with the frequency at 0.02 Hz and 0.1 Hz, respectively. We also test the model with two different types of input signals having the same actuation frequency of 0.05 Hz. The first one is a saw-tooth signal and the second a square signal. All of the signals have the same range from 0 V to 2,000 V. Root Mean Square (RMS) of the displacement from the laser sensor and self-sensing model are chosen as the measurement standard to calculate the average error. Table II shows the average error between the laser sensor and the self-sensing model. It can be observed that the self-sensing model obtained from a specific frequency input signal is the best fit for predicting the displacement of the DE actuator with the same frequency input signal. Changing the frequency of the input signal leads to a decrease in the accuracy of self-sensing which shows that the model is sensitive to the frequency input. However, the average error is still under a reasonable value which means the model has a robust prediction capability. The exact self-sensing model can be obtained once the model function is trained from the corresponding frequency input signal. This paper focuses on the 0.05 Hz input signal.

It can be observed that the error is relatively small (less than 2%) for the same frequency input signal (0.05 Hz), even under a different type of signal (saw-tooth and square signal). This model could also be used to predict sudden changes from the input reference signal or input voltage even under the influence of the viscosity of the DE material and the weight of the load under the DE tube. Thus the identified self-sensing model shows good performance in estimating the displacement, as can be seen from the above experiments. The model can predict most displacements with different input signals, which allows us to implement a feedback control in real-time.

IV. VALIDATION OF SELF-SENSING IN CLOSED-LOOP FEEDBACK CONTROL

To validate the self-sensing mechanism in closed-loop feedback control, we develop a single-loop feedback control system where a proportional-integral controller is used for voltage input control with the feedback displacement signal for reference tracking. The PI controller also provides the benefit of avoiding noise generation during the experiment [14]. A block diagram representation of the final experimental setup is shown in figure 8.

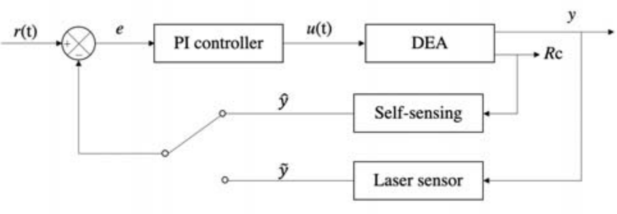


Fig. 8. Closed loop control with self-sensing block diagram.

With the same probing signal and self-sensing model, the PI controller gains are fine-tuned manually to achieve the desired control performance. The reference signals, sinusoidal, saw-tooth, triangular, and square, are set to have a minimum of 0.2 mm and the highest value set at 0.6 mm. The experimental results including voltage, current, and capacitance for each experiment, the average error of the performance is shown in Table III, the results also include the displacement of both the self-sensing and laser sensor measured. The output results show good performance with the closed-loop model.

TABLE III

TRACKING ERROR WITH DIFFERENT INPUT SIGNAL.

Waveform	Sinusoid	Sawtooth	Square	Triangular
Frequency (Hz)	**0.05**	**0.05**	**0.05**	**0.05**
Error (%)	3	3.55	2.6	1.24

For the last experiment we test the model with a random input reference signal, which is our final goal, and control the movement of the DE tube according to our requirements. The reference signal is set as the sum of two sinusoidal waves

$$r(t) = 0.05\sin(0.1\pi t) + 0.05\sin(0.02\pi t + \pi) + 0.3. \quad (12)$$

Figure 9 shows the output results with the PI controller and the self-sensing model for reference tracking. The average tracking error is around 1.19%, which shows that the self-sensing model with PI control can predict very well.

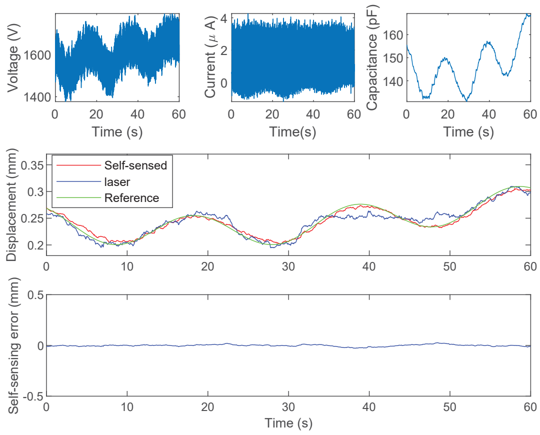


Fig. 9. Multiple-frequency signal tracking results.

As can be seen above, the model can follow most of the reference signals with different input signals. This is of great importance as the non-linear behavior of the system does not influence the model for small displacement measurements. For higher frequency actuation, the loss in the capacitance measurements has to be accounted for and this is possible with the frequency response model which is a topic to be discussed later. It is important to note that for drastic changes in the actuation signal such as at the peaks or sharp locations of the signal (saw, triangular, and square), the self-sensing mechanism does not capture the peaks precisely due to the slow response of the membrane from its viscous effects. One way to improve the responsiveness of the actuator is to increase the voltage to be applied to the actuator. However, there is a ultimate voltage limit based on the value of the electrical-mechanical failure of the actuator.

V. CONCLUSION

The experimental results have shown that the displacement of the DE tube can be predicted by the integrated self-sensing mechanism without any external sensor. The DE tubular actuator can be used to generate vertical vibrations that track some random input signals with a self-sensing mechanism and PI controller. The error between displacement from the laser sensor and self-sensing is small for continuous actuation without sudden changes in dynamics. A polynomial function is used to model the relationship between the displacement of the membrane and the change in the capacitance. The PI controller is then used to perform feedback control to follow a reference displacement signal using the self-sensing mechanism. The polynomial model developed is able to fairly predict the displacement of the DE actuator for self sensing within a displacement range of 0.4 mm.

REFERENCES

[1] L. Li, J. Li, L. Qin, J. Cao, M. Kankanhalli, and J. Zhu, "Deep reinforcement learning in soft viscoelastic actuator of dielectric elastomer," *IEEE Robotics and Automation Letters*, vol. PP, pp. 1–1, 02 2019.

[2] P. Brochu and Q. Pei, "Advances in dielectric elastomers for actuators and artificial muscles," *Macromolecular rapid communications*, vol. 31, pp. 10–36, 01 2010.

[3] B. Massa, S. Roccella, M. C. Carrozza, and P. Dario, "Design and development of an underactuated prosthetic hand." in *Proceedings ICRA '02, IEEE International Conference on Robotics and Automation*, vol. 4, 01 2002, pp. 3374–3379.

[4] J. Lai, M. Schoen, A. Perez-Gracia, D. Naidu, and S. Leung, "Prosthetic devices: Challenges and implications of robotic implants and biological interfaces," *Proceedings of the Institution of Mechanical Engineers. Part H, Journal of engineering in medicine*, vol. 221, pp. 173–83, 03 2007.

[5] J.-S. Plante and S. Dubowsky, "Large-scale failure modes of dielectric elastomer actuators," *International Journal of Solids and Structures - INT J SOLIDS STRUCT*, vol. 43, 04 2006.

[6] C. Nguyen, D. Thuy, J. Park, K. Duksang, J. Koo, Y. Lee, J. Nam, and H. Choi, "A dielectric elastomer actuator with self-sensing capability," *Proc. SPIE*, vol. 6927, p. 69270V, 03 2008.

[7] Z. Ye and Z. Chen, "Self-sensing of dielectric elastomer actuator enhanced by artificial neural network," *Smart Materials and Structures*, vol. 26, 07 2017.

[8] K. Jung, K. Kim, and H. Choi, "A self-sensing dielectric elastomer actuator," *Sensors and Actuators A: Physical*, vol. 143, pp. 343–351, 05 2008.

[9] T. Hoffstadt and J. Maas, "Model-based self-sensing algorithm for dielectric elastomer transducers based on an extended kalman filter," *Mechatronics*, vol. 50, 10 2017.

[10] P. Zanini, G. Rizzello, S. Seelecke, J. Rossiter, and M. Homer, "Self-sensing for robust automatic charge management of dielectric elastomer generators," in *Electroactive Polymer Actuators and Devices (EAPAD) XX*, 03 2018.

[11] G. Rizzello, M. Hodgins, D. Naso, A. York, and S. Seelecke, "Modeling of the effects of the electrical dynamics on the electromechanical response of a DEAP circular actuator with a mass–spring load," *Smart Materials and Structures*, vol. 24, no. 9, p. 094003, aug 2015.

[12] Z. Ye and Z. Chen, "Modeling and control of 2-dof dielectric elastomer diaphragm actuator," *IEEE/ASME Transactions on Mechatronics*, vol. PP, pp. 1–1, 01 2019.

[13] Y. Lin, J. Krischer, K. Vehik, H.-S. Lee, and S. Huang, "A rule-based prognostic model for type 1 diabetes by identifying and synthesizing baseline profile patterns," *PloS one*, vol. 9, p. e91095, 06 2014.

[14] C. Jiang, K. Takagi, T. Suzuki, H. Shigeyuki, A. Nozawa, and K. Hashimoto, "Experimental study of position control with tube-type dielectric elastomer actuator," in *Proceedings of the 2013 International Conference on Advanced Mechatronic Systems*, 09 2013, pp. 352–356.