Received: 18 December 2023 | Revised: 19 May 2024 | Accepted: 8 June 2024

IET Science, Measurement & Technology

DOI: 10.1049/smt2.12209

The Institution of Engineering and Technology WILEY

ORIGINAL RESEARCH

Induced voltage in piezoelectric tube driven segments and their use in nanopositioning, an assessment

Morteza Mohammadzaheri[1] | Reza Tafreshi[2] | Mohsen Bazghaleh[3] | Steven Grainger[4] | Mohammad Khorasani[5]

[1]College of Engineering, Birmingham City University, Birmingham, UK

[2]Mechanical Engineering Department, Texas A&M University, Doha, Qatar

[3]Accenture, Australia, Sydney, Australia

[4]School of Electrical and Mechanical Engineering, University of Adelaide, Adelaide, Australia

[5]Engineering Solutions QSTP LLC, Doha, Qatar

Correspondence
Morteza Mohammadzaheri, College of Engineering, Birmingham City University, UK.
Email: morteza.mohammadzaheri@bcu.ac.uk

This paper is a revised and extended version of our paper published in 8th IEEE-GCC conference, Muscat, Oman, 1–4 February 2015.

Abstract

A piezoelectric tube actuator has a number of segments or electrodes. The induced voltage and the piezoelectric voltage, two easy-to-measure electrical signals in piezoelectric tubes, have been used in position estimation of these actuators since 2006 and 1982. However, since introduction, the induced voltage has never been compared with the piezoelectric voltage for piezoelectric tubes' position estimation. In addition, only linear models have been used to present the relationship between the induced voltage and the position of piezoelectric tubes. In other words, in the literature, it has been practically assumed that (1) the relationship between the induced voltage and the position is linear, and (2) the induced voltage can estimate the position more accurately compared to the piezoelectric voltage. This article assesses and nullifies both these assumptions. In this research, with the use of the experimental data, both aforementioned voltage signals were mapped into the position through linear and nonlinear models. It was shown that the position can be estimated less accurately with the induced voltage compared to the piezoelectric voltage, and the relationship of the position with the induced voltage presents higher and non-negligible nonlinearity compared to the one with the piezoelectric voltage.

1 | INTRODUCTION

Piezoelectric tubes are the foremost actuators in nanopositioning, precise position control at nanometre scale, and they are likely to be still widely used in the future [1]. The major source of expense and practical limits in nanopositioning are precise displacement/ position sensors. This has pushed researchers to estimate the position using easy to measure electrical signals [2–6].

A widely used and well-known signal to estimate the position of piezoelectric tube actuators is 'the piezoelectric voltage', i.e. the voltage across a combination of driver (excited) and internal segments of the actuator. This signal is used to estimate the position of piezoelectric actuators since 1982, if not earlier [7]. A driver segment is directly subject to an external voltage [1, 5]. Other external electrodes or segments of a piezoelectric actuator, not directly subject to an external voltage, are called driven (non-excited) segments. The voltage across these segments, caused by their deflection, is called 'the induced voltage' [1, 8]. The induced voltage signal was proposed in 2006 as an indicator of the position [9]. Some piezoelectric actuators, e.g. stacks, have only one electrode or segment; hence, the induced voltage is not available in such actuators [8].

Both piezoelectric and induced voltage signals have been directly used instead of position signal in initial micro/nanopositioning systems [9–12]. In more recent/ advanced research, both linear and nonlinear models were tried to map the piezoelectric voltage to the position in different piezoelectric actuators [6, 13–15]. However, the induced voltage signal has mapped to the position only through linear models [16, 17] or analogue circuits [18] equivalent to linear models, and its accuracy in position estimation has never been compared with the one of the piezoelectric voltage. In other words, in the existing literature, it has been practically assumed that the relationship between the induced voltage and position is linear and the induced voltage can estimate position more accurately compared to the long-known piezoelectric voltage signal.

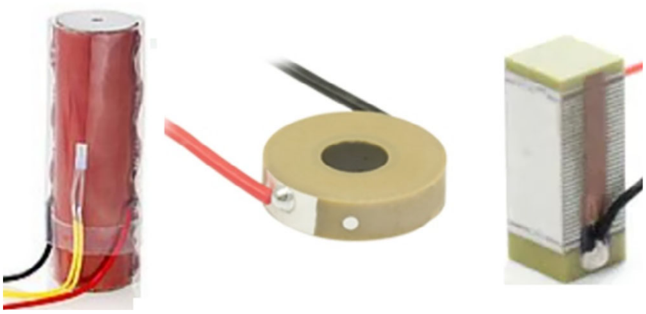

FIGURE 1 Samples of stack piezoelectric actuators with the shape of cylinder [30] (left), ring (middle) [31], and rectangular prism [32] (right).

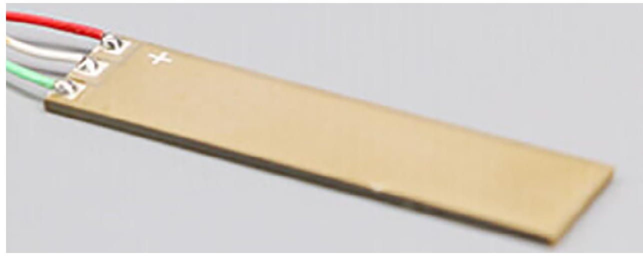

FIGURE 2 A piezoelectric bender [37].

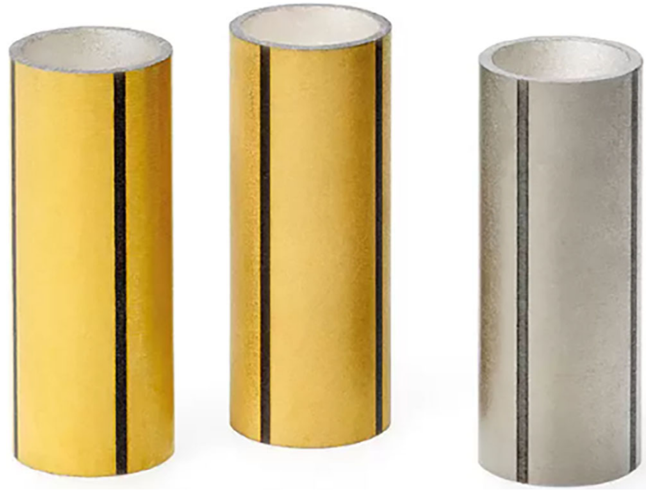

FIGURE 3 Piezoelectric tubes [41].

Considering the presented literature review, this research aims to answer two following research questions for a piezoelectric tube actuator:

1. How accurately the position can be estimated based on the piezoelectric or the induced voltage?
2. How nonlinear is the relationship of the piezoelectric or the induced voltage with the position?

2 | BACKGROUND- DIFFERENT TYPES OF PIEZOELECTRIC ACTUATORS FOR NANOPOSITIONING

Piezoelectricity, the interaction of mechanical and electrical quantities in piezoelectric materials, was discovered by Curie brothers in the 1880s [19]. The reason of piezoelectricity is the asymmetrical distribution of electrons within piezoelectric materials [20]. In these materials, exerting electric voltage leads to generation of deformation or force [21]; this phenomenon is named inverse piezoelectricity [22]. Piezoelectric actuators are devices, made with piezoelectric materials, purposely produced to use inverse piezoelectricity [23]. There are three types of piezoelectric actuators in the market with potential use in nanopositioning:

2.1 | Piezoelectric stacks

Layers of a piezoelectric material [24] are used to fabricate a stack, which is normally coated with a polymer material [25]. Stack piezoelectric actuators are stiff and have different shapes e.g. cylindrical [25], rectangular prism [26] or ring [27] as depicted in Figure 1. Piezoelectric stacks are widely used in precision positioning [28] and in piezoelectric motors [29].

Nonlinearity of the relationship between applied electric voltage on a stack piezo actuator and its position has been experimentally exhibited [26].

2.2 | Piezoelectric benders

Piezoelectric benders are fabricated with piezoelectric plate(s), occasionally together with thin layers of shim or metal [33] as depicted in Figure 2. Piezoelectric benders have been reported to be used in energy harvesting [34], non-destructive tests [35], force and position control [36] and other applications. The most prevalent piezoelectric benders for nanopositioning have one or two piezoelectric plate(s) and are called unimorph and bimorph, respectively [23]. Benders exhibit relatively high maximum deflection (e.g. 2 mm) and relatively low first natural frequency (e.g. below 100 Hz), compared to other piezoelectric actuators [25].

2.3 | Piezoelectric tubes

The core of a piezoelectric tube is a metal cylinder, internally covered by a layer of piezoelectric material. The outer layer of the metal cylinder is covered by a number of (e.g. 4 [6] or 12 [38]) piezoelectric layers, also known as segments or electrodes. Piezoelectric tubes with 4 segments are depicted in Figure 3. Tube piezoelectric actuators are essentially different from tube-shape piezoelectric stack actuators despite similarity in appearance [25]. The first natural frequency of piezoelectric tubes may vary from 200 Hz to 100s of kHz [39, 40]. These actuators may produce displacements of up to 100 micrometres [40].

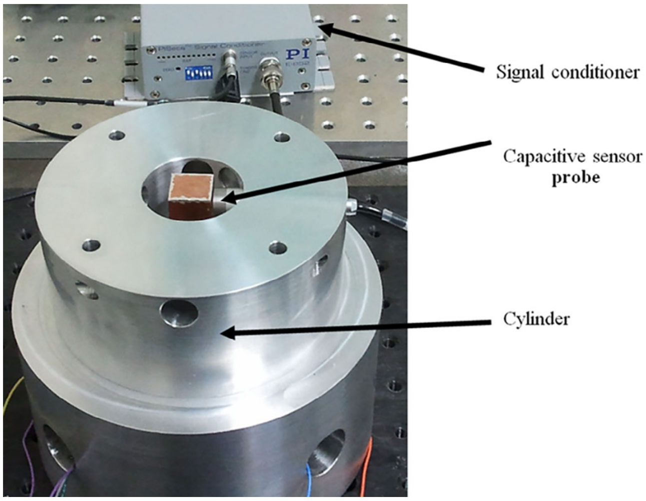

FIGURE 4 Experimental setup [43].

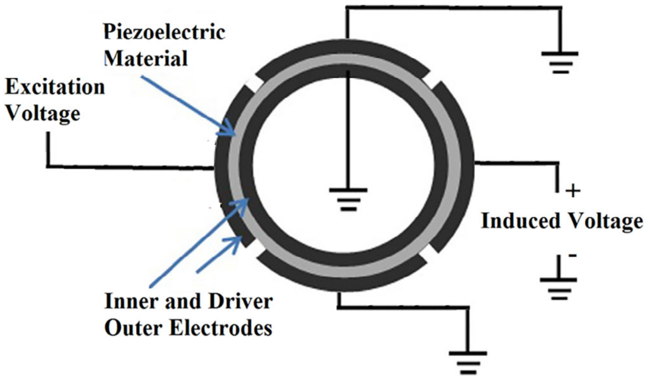

FIGURE 5 A schematic of the piezoelectric tube actuator, top view and measured voltages [43].

3 | EXPERIMENT AND DATA COLLECTION

In this research, a PI –PT130.24 piezoelectric tube was utilised. A PI-D-510 capacitive sensor together with an E-852.10 signal conditioner were used to measure the cubical end-effecter position [42]. During the experiment, the tube was placed inside an Aluminium cylinder (Figure 4).

The tube has one inner segment which is grounded and four equally distributed outer segments. Two opposite outer segments are grounded too to have a situation like scanning devices [40]. Excitation voltage was applied on one of non-grounded outer segments, i.e. the driver segment. The induced voltage in the other non-grounded segment was recorded as shown in Figure 5. The voltage across the driver and the internal segments is the piezoelectric voltage. In this research, as the internal segment is grounded, the piezoelectric voltage is same as the excitation voltage.

A DS1104 DSpace was used to connect the tube to a PC with MATLAB/Simulink. In different tests, excitation voltage, as different functions of time, was applied on the tube. Here are the utilised functions: a white noise with a maximum magnitude of 60 V and a series of triangular functions, with the magnitudes of 20 V, 40 and 60 V and the frequencies of 1 Hz, 10 Hz, 20 Hz, 30 Hz, 40 Hz, 50 and 60 Hz in the time period of 2s each. The data collected through triangular excitation with the amplitude of 40 V at 30 Hz were used for validation, the rest of the collected data were utilised for modelling.

4 | STRUCTURE OF THE MATHEMATICAL MODEL AND PROBLEM STATEMENT

Nonlinear auto-regressive models with exogenous inputs (NARX models), commonly used for system identification [44], were utilised in this research. Equation (1) shows the NARX structure, for a single input-single output (SISO) system [44],

$$y(t) = f\begin{pmatrix} u(t-t_{\mathrm{d}}), u(t-t_{\mathrm{d}}-t_{\mathrm{s}}), \dots, u(t-t_{\mathrm{d}}-r_{\mathrm{u}}t_{\mathrm{s}}), \\ y(t-t_{\mathrm{s}}), y(t-2t_{\mathrm{s}}), \dots, y(t-r_{\mathrm{y}}t_{\mathrm{s}}) \end{pmatrix}, \quad (1)$$

where y is the system output, u is the system input, t_{d} is the delay time, t_{s} is the sample (or sampling) time, and r_{u} and r_{y} are the input and output orders, respectively. f is a function. SISO NARX modelling aims to identify t_{d}, t_{s}, r_{u}, r_{y}, and f.

5 | DATA PREPARATION AND INITIAL PARAMETER SELECTION

In this research, data preparation comprises of normalisation and re-arrangement of the collected data.

5.1 | Normalisation

In input-output-data-based modelling, variables with larger (absolute) values than others may affect the modelling process more significantly [45]. Normalisation prevents this issue; the data columns were multiplied by coefficients so that the mean of squared values of all data columns are identical or very close to each other.

5.2 | Rearrangement

The normalised data should be re-arranged before identification of f. The collected data originally include two columns: Equation (1) the input (u, either the piezoelectric or the induced voltage) and Equation (2) the output (y, the position). Equation (3) shows a typical row of the prepared data (see Equation (1)).

$$\left[\overbrace{\begin{matrix} u(t-t_{\mathrm{d}}), u(t-t_{\mathrm{d}}-t_{\mathrm{s}}), \dots, u(t-t_{\mathrm{d}}-r_{\mathrm{u}}t_{\mathrm{s}}), \\ y(t-t_{\mathrm{s}}), y(t-2t_{\mathrm{s}}), \dots, y(t-r_{\mathrm{y}}t_{\mathrm{s}}) \end{matrix}}^{\text{input}}, \overbrace{y(t)}^{\text{output}}\right]. \quad (2)$$

In discrete presentation, Equation (2) is converted to Equation (3), where $r_d = t_d/t_s$ and $k = t/t_s$. The value of k should be higher than maximum of $(r_d + r_u)$ and r_y. r_d and k are called delay order and index, respectively.

$$\left[\overbrace{\begin{matrix} u(k-r_d), u(k-r_d-1), \dots, u(k-r_d-r_u), \\ y(k-1), y(k-2), \dots, y(k-r_y) \end{matrix}}^{\text{input}}, \overbrace{y(k)}^{\text{output}}\right]. \tag{3}$$

As to Equation (3), for the SISO system of Equation (1), the prepared modelling data is a matrix with r_u+r_y+1 input columns and one output column. Evidently, t_d, t_s, r_u, r_y need to be identified prior to arrangement.

Abramovich et al. recommended that the sampling frequency needs to be at least around 10 times greater than the first resonance frequency of the piezoelectric actuator [39]. The first resonant frequency of the tested actuator is around 1 kHz, so a sampling frequency of 10 kHz or a sample time (t_s) of 10^{-4}s was opted. To develop a discrete model of a physical system, the delay time (t_d) should be equal to or greater than the sample time [46]. No input delay is apparent in the system; therefore, the delay time is set equal to the sample time or 10^{-4}s, i.e. $r_d = 1$.

In this research, in order to have less complex and more comparable results, it was considered that

$$r_u + r_d = r_y \tag{4}$$

and r_y was considered as the order of the model. Then, modelling for various orders was carried out for comparison.

6 | SYSTEM IDENTIFICATION

In this research, a linear and a nonlinear model, or f in Equation (1), were developed and compared.

6.1 | Linear model

Equation (5) presents the linear model:

$$y(t) = \alpha_0 u(t-t_d) + \alpha_1 u(t-t_d-t_s) + \cdots + \alpha_{r_u} u(t-t_d-r_u t_s) + \beta_1 y(t-t_s) + \beta_2 y(t-2t_s) + \cdots + \beta_{r_y} y(t-r_y t_s) + \lambda. \tag{5}$$

The least square of errors (LSE) method was employed to identify the parameters of this model, presented by Greek letters. LSE provides the optimal linear model with the best possible fit to the modelling data [47].

6.2 | Nonlinear model

The employed nonlinear model is a semi-linear neural network [6, 48] with both linear and nonlinear activation functions in its hidden layer; this type of neural network particularly suits systems with slight nonlinearities. Selection of this type of model is based on the fact that linear models have been widely used to map both the piezoelectric and the induced voltages of tube piezoelectric actuators to the position [6, 38, 49]. That is, tube piezoelectric actuators are unlikely to be highly nonlinear.

Figure 6 depicts a semi-linear neural network with $r_d = r_y = 1$ and $r_u = 2$ (see Equation (3)), where

$$N(x) = \frac{2}{1+\exp(-2x)} - 1. \tag{6}$$

x represents any input to N function.

Other parameters shown in Figure 6 are the neural network connection weights.

Equation (6) presents the general form of a semi-linear neural network:

$$y(k) = R \times \left(\sum_{i=r_d}^{r_u+r_d} W_{Li} u(k-i) + \sum_{i=1}^{r_y} T_{Li} y(k-i) + b_L \right) + S \times N\left(\sum_{i=r_d}^{r_u+r_d} W_{Ni} u(k-i) + \sum_{i=1}^{r_y} T_{Ni} y(k-i) + b_N \right) + b. \tag{7}$$

This neural network can capture both linear and nonlinear behaviour of the system [48]. Nguyen–Widrow algorithm was employed for weight initialisation [50] and Levenberg–Marquardt–Batch-error back-propagation (as detailed in Appendix B of [51]) was used to identify the connection weights of the neural network.

7 | MODEL VALIDATION

The developed model should be cross-validated; that is, the identified model should return an acceptably low estimation error with the data never used in the process of model identification [51], i.e. the validation data detailed in Section 3.

In addition, a correct validation approach should be opted to calculate the estimation error. There are two different approaches to find the estimation error for model validation: (i) one-step prediction and (ii) simulation. One-step-prediction is generally accepted for models of static (memory-less) systems; the systems in which their output(s) at a time do not depend on the previous value(s) of the output(s) [52]. As a fairly common mistake, this approach has been frequently used to assess black box models of piezoelectric actuators, which are obviously dynamic systems, e.g. [53, 54].

In one-step-prediction, all the inputs to the model, at any time, are assumed to be available. Equation (8) shows the one-step-prediction output for the dynamic model presented in Equation (1):

$$\hat{y}(t) = f\left(\begin{matrix} u(t-t_d), u(t-t_d-t_s), \dots, u(t-t_d-r_u t_s), \\ y(t-t_s), y(t-2t_s), \dots, y(t-r_y t_s) \end{matrix} \right), \tag{8}$$

where the variable(s) with a hat signify estimated values. As shown in Equation (8), delayed (or previous values of the)

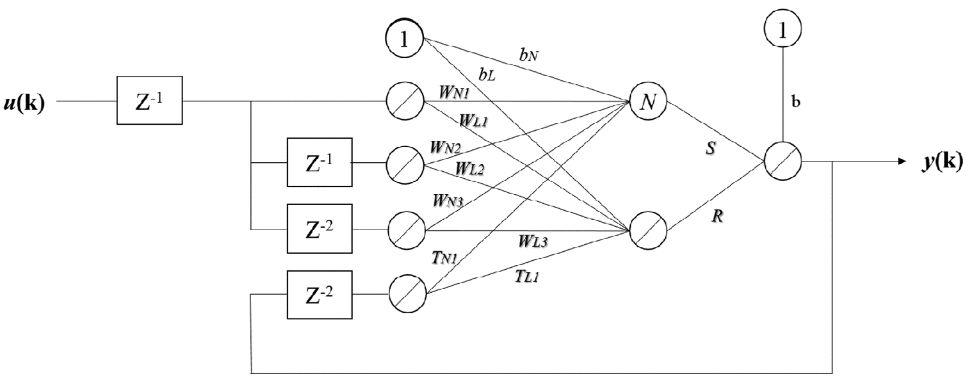

FIGURE 6 A semi-linear MLP.

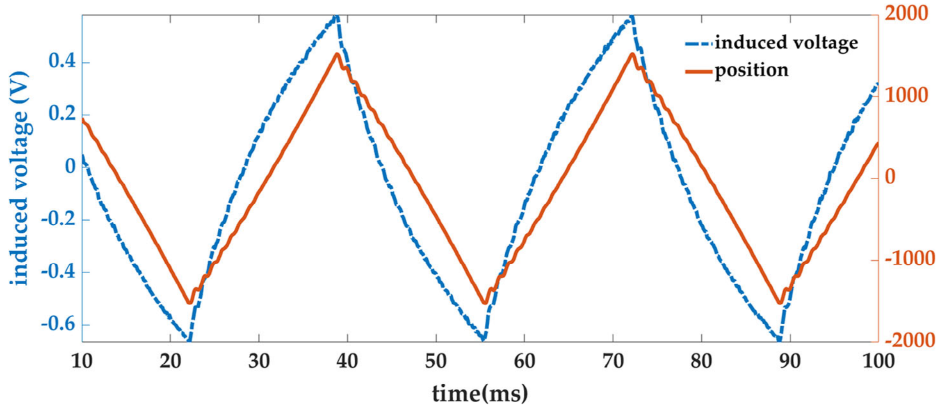

FIGURE 7 The induced voltage and the position versus time for the validation data.

output(s), which are inputs to the model, are assumed to be known in one step prediction, if used for dynamic models/systems. However, the models of dynamic systems are often used to estimate the output(s) for several steps ahead, in other words, for simulation. In this case, after the very first estimation, the delayed outputs will be unavailable from the collected data, and Equation (8) cannot be used.

Alternatively, in simulation approach to model validation, previously estimated values of system output(s) are fed to the model as inputs, as shown in Equation (9):

$$\hat{y}(t) = f\begin{pmatrix} u(t-t_{\mathrm{d}}), u(t-t_{\mathrm{d}}-t_{\mathrm{s}}), \ldots, u(t-t_{\mathrm{d}}-r_{\mathrm{u}}t_{\mathrm{s}}), \\ \hat{y}(t-t_{\mathrm{s}}), \hat{y}(t-2t_{\mathrm{s}}), \ldots, \hat{y}(t-r_{\mathrm{y}}t_{\mathrm{s}}) \end{pmatrix}. \quad (9)$$

Simulation approach is sensibly applicable for the validation of dynamic models, e.g. Equation (1). In this approach, the inevitable estimation error, associated with the estimated outputs, returns to the validation process and enlarges the resultant error. This is called "error accumulation" [55].

8 | EXPERIMENTAL RESULTS AND ANALYSIS

Figure 7 shows the validation data as introduced in Section 3, the induced voltage and the position caused by a triangular excitation voltage, respect to time, with the amplitude of 40 V and the frequency of 30 Hz. The piezoelectric voltage is same as the excitation voltage, as mentioned in Section 3. Interestingly, in the validation data, the range of the induced voltage is 64.25 times smaller than the range of the piezoelectric voltage. Please note that data recording started after having a stable sensor output rather than at the beginning of the operation.

Using the modelling data, detailed in Section 3, and models (5) and (7) detailed in Section 7, models were developed to map both the induced voltage and the piezoelectric voltage to the position for comparison. Table 1 presents the outcome of the comparison between the models. The result, for each model, is the mean of absolute error of position estimation in 500 sequential instants of operation (50 ms) calculated through simulation approach, detailed in Section 7. These results help to answer the research question proposed in the introduction. The results, presented in Table 1, clearly exhibit that 'induced voltage-position' models are less accurate than 'piezoelectric voltage-position' models in estimating the piezoelectric tube position.

In addition, in models mapping the induced voltage to the position, the minimum estimation error, across different orders, presented by non-optimal semi-linear (mathematically nonlinear) models is 25% smaller than the minimum error presented by optimal linear models. This clearly shows that the nonlinearity of induced voltage-position relationship is evident and

TABLE 1 The mean of absolute error (in nanometres) for the models estimating the position with different input signals and different orders; the range of the position is [−1500 1500] nanometres.

Input	Induced voltage		Piezoelectric voltage	
Order	Linear	Semi-linear	Linear	Semi-linear
1	444.801	427.381	85.718	66.117
2	199.093	158.057	40.957	36.636
3	230.463	208.963	27.867	19.100
4	220.900	172.080	19.410	23.186
5	198.534	136.453	20.237	20.309
6	169.922	127.236	20.927	18.426
7	409.331	332.582	21.043	20.355

TABLE 2 Two widely trusted assumptions about piezoelectric tube actuators in the literature and their assessment based on the results of this research.

Assumption	Verdict	Reason
Linear relationship between the induced voltage and the position	False	In Table 1, the smallest mean of absolute error in an optimal linear model is 25% greater than the same value for a non-optimal semi(non)-linear model
Higher position estimation accuracy with the induced voltage compared to the piezoelectric voltage	False	In Table 1, the smallest mean of absolute error with the use of the induced voltage is 691% greater than the same value for the piezoelectric voltage

unignorable. This conclusion cannot be extended to models mapping the piezoelectric voltage to the position, due to slight, i.e. 5%, discrepancy between the minimum estimation error presented by linear and nonlinear models, across different orders. This answers the second research question of the paper. As a result of this comparison, the piezoelectric voltage signal has less nonlinear relationship with the position and can estimate the position through models more accurately; therefore, it is more advantageous than the induced voltage in position estimation and control.

Table 2 summarises the major findings of this research through assessment of two assumptions, mentioned in Section 1, which have been widely trusted in the literature [9, 11, 16–18].

9 | CONCLUSIONS

This paper investigated the applicability of the induced voltage in driven segments of a piezoelectric tube actuator in estimation of its position. Here are the conclusions drawn with the use of semi-linear artificial neural networks, linear models and experimental data and their brief justifications:

(i) Both the induced and the piezoelectric voltages of a piezoelectric tube actuator were mapped to its position using linear and semi-linear (mathematically nonlinear) models. With the piezoelectric voltage as the input, linear and nonlinear models presented almost same minimum error in estimating position. However, the performance of the linear was meaningfully lower, where the induced voltage was the input. Consequently, the relationship between the induced voltage and the position, for the investigated tube, is unignorably nonlinear; while, piezoelectric voltage-position relationship was found to be much less nonlinear or nearly linear.

(ii) With use of the piezoelectric voltage of the investigated actuator, the mean of absolute error of position estimation was as low as low 18.426 nm in the test described in the paper. However, with use of the induced voltage, the lowest mean of absolute error of position estimation was 127.236 nm. That is, in comparison with the piezoelectric voltage, the induced voltage can estimate the position less accurately.

These conclusions suggest that the piezoelectric voltage is a better choice than the induced voltage for estimation of piezoelectric tube position. However, the use of the induced voltage, rather than the piezoelectric voltage, as an indicator of the position has been reported in several works in the literature. These works have not compared the suitability of the piezoelectric voltage and the induced voltage to estimate the position. Moreover, most of these reports are based on the assumption of a linear relationship between the induced voltage and the position which was proved false in this paper.

AUTHOR CONTRIBUTIONS

Morteza Mohammadzaheri: Conceptualization; formal analysis; investigation; methodology; validation; writing—original draft. **Reza Tafreshi**: Supervision; writing—review and editing. **Mohsen Bazghaleh**: Project administration; validation. **Steven Grainger**: Supervision; writing—review and editing. **Mohammad Khorasani**: Investigation.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data will be provided upon request.

ORCID

Morteza Mohammadzaheri https://orcid.org/0000-0002-8187-6375

REFERENCES

1. Mohammadzaheri, M., Soltani, P., Ghodsi, M.: Micro/nanopositioning systems with piezoelectric actuators and their role in sustainability and ecosystems. In: Ecomechatronics, pp. 233–250. Springer, Cham (2022)
2. Roshandel, N., Soleymanzadeh, D., Ghafarirad, H., Koupaei, A.S.: A modified sensorless position estimation approach for piezoelectric bending actuators. Mech. Syst. Sig. Process. 149, 107231 (2021)

3. Soleymanzadeh, D., Ghafarirad, H., Zareinejad, M.: Charge-based robust position estimation for low impedance piezoelectric actuators. Measurement. 147, 106839 (2019)
4. Mohammadzaheri, M., Grainger, S., Bazghaleh, M.: Fuzzy modeling of a piezoelectric actuator. Int. J. Precis. Eng. Manuf. 13, 663–670 (2012)
5. Mohammadzaheri, M., Grainger, S., Bazghaleh, M.: A comparative study on the use of black box modelling for piezoelectric actuators. Int. J. Adv. Manuf. Technol. 63, 1247–1255 (2012)
6. Mohammadzaheri, M., Grainger, S., Bazghaleh, M.: A system identification approach to the characterization and control of a piezoelectric tube actuator. Smart Mater. Struct. 22, 105022 (2013)
7. Newcomb, C.V., Flinn, I.: Improving the linearity of piezoelectric ceramic actuators. Electron. Lett. 18, 442–444 (1982)
8. Mohammadzaheri, M., Ghodsi, M., AlQallaf, A.: Estimate of the head produced by electrical submersible pumps on gaseous petroleum fluids, a radial basis function network approach. Int. J. Artif. Intell. Appl. 9, 53–62 (2018)
9. Fleming, A.J., Moheimani, S.O.R.: Sensorless vibration suppression and scan compensation for piezoelectric tube nanopositioners. IEEE Trans. Control Syst. Technol. 14, 33–44 (2006)
10. Dosch, J.J., Inman, D.J., Garcia, E.: A self-sensing piezoelectric actuator for collocated control. J. Intell. Mater. Syst. Struct. 3, 166–185 (1992)
11. Yong, Y.K., Moheimani, S.: Vibration control of a novel tube scanner using piezoelectric strain-induced voltage. In: Proceedings of IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM), pp. 1070–1075. IEEE, Piscataway, NJ (2009)
12. Tan, J.Y., Islam, S., Li, Y., Kim, A.: An optimization of perforation design on a piezoelectric-based smart stent for blood pressure monitoring and low-frequency vibrational energy harvesting. In: Proceedings of IEEE 36th International Conference on Micro Electro Mechanical Systems (MEMS), pp. 396–399. IEEE, Piscataway, NJ (2023)
13. Miri, N., Mohammadzaheri, M., Chen, L.: An enhanced physics-based model to estimate the displacement of piezoelectric actuators. J. Intell. Mater. Syst. Struct. 26, 1442–1451 (2015)
14. Yu, Y., Xiao, Z., Naganathan, N.G., Dukkipati, R.V.: Dynamic preisach modelling of hysteresis for the piezoceramic actuator system. Mech. Mach. Theory. 37, 75–89 (2002)
15. Li, P.-Z., Zhang, D.-F., Hu, J.-Y., Lennox, B., Arvin, F.: Hysteresis modelling and feedforward control of piezoelectric actuator based on simplified interval type-2 fuzzy system. Sensors. 20, 2587 (2020)
16. Yong, Y.K., Fleming, A.J., Moheimani, S.O.R.: A novel piezoelectric strain sensor for simultaneous damping and tracking control of a high-speed nanopositioner. IEEE/ASME Trans. Mechatron. 18, 1113–1121 (2012)
17. Raghunvanshi, D.S., Moore, S.I., Fleming, A.J., Yong, Y.K.: Electrode configurations for piezoelectric tube actuators with improved scan range and reduced cross-coupling. IEEE/ASME Trans. Mechatron. 25, 1479–1486 (2020)
18. Kuiper, S., Schitter, G.: Active damping of a piezoelectric tube scanner using self-sensing piezo actuation. Mechatronics 20, 656–665 (2010)
19. Minase, J., Lu, T.-F., Cazzolato, B., Grainger, S.: A review, supported by experimental results, of voltage, charge and capacitor insertion method for driving piezoelectric actuators. Precis. Eng. 34, 692–700 (2010)
20. Sabek, W., et al.: Experimental investigation of piezoelectric tube actuators dynamics. In: Proceedings of 2nd International Conference on Robotics and Mechatronics, pp. 139–143. IEEE, Piscataway, NJ (2015)
21. Mohammadzaheri, M., Al-Sulti, S., Ghodsi, M., Soltani, P.J.E.: Charge estimation of piezoelectric actuators: a comparative study. Energies 16, 3982 (2023)
22. Chopra, I.: Review of state of art of smart structures and integrated systems. AIAA J. 40, 2145–2187 (2002)
23. Rios, S., Fleming, A.: Control of piezoelectric benders using a charge drive. In: Proceedings of 14th International Conference on New Actuators, pp. 240–244. IEEE, Piscataway, NJ (2014)
24. Hussain, F., Khesro, A., Lu, Z., Wang, G., Wang, D.: Lead free multilayer piezoelectric actuators by economically new approach. Front. Mater. 7, 87 (2020)
25. PiezoDrive: Piezoelectric actuators. https://www.piezodrive.com/actuators/ (2021). Accessed 19 May 2024
26. Ahmadpour, H., Mohammadzaheri, M., Emadi, M., Ghods, V., Mehrabi, D., Tafreshi, R.: Neural modelling of a piezoelectric actuator inspired by the presiach approach. In: Proceedings of International Conference on Artificial Intelligence, Energy and Manufacturing Engineering, pp. 67–70. ISER, Amsterdam (2015)
27. Wang, G., Zhao, Z., Tan, J., Cui, S., Wu, H.: A novel multifunctional piezoelectric composite device for mechatronics systems by using one single Pzt ring. Smart Mater. Struct. 29, 055027 (2020)
28. Kanchan, M., Santhya, M., Bhat, R., Naik, N.J.T.: Application of modeling and control approaches of piezoelectric actuators: a review. Technologies 11, 155 (2023)
29. Kang, H., Shu, F., Li, Z., Yang, X.J.M.S., Processing, S.: Modeling of bonding piezoelectric stack using conductive adhesive with metal-coated polymer fillers. Mech. Syst. Sig. Process. 194, 110138 (2023)
30. Ceramics, P.: Stack actuators. https://www.piceramic.com/en/products/piezoceramic-actuators/stack-actuators/ (2021). Accessed 4 Apr 2024
31. Thorlabs: Piezoelectric ring chips and stacks. https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_ID=11059 (2023). Accessed 4 Apr 2024
32. Coremorrow: Pzt plate stack actuators. http://www.coremorrow.com/en/pro-9-1.html (2023). Accessed 4 Apr 2024
33. Piezo.com: Introduction to piezos. https://piezo.com/pages/introduction-to-piezos (2021). Accessed 4 Apr 2024
34. Ghodsi, M., Mohammadzaheri, M., Soltani, P.J.E.: Analysis of cantilever triple-layer piezoelectric harvester (CTLPH): non-resonance applications. Energies 16, 3129 (2023)
35. Iamchaturapatr, J., Piriyakul, K., Petcherdchoo, A.J.S.: Use of a piezoelectric bender element for the determination of initial and final setting times of metakaolin geopolymer pastes, with applications to laterite soils. Sensors 22, 1267 (2022)
36. Seethaler, R., Mansour, S.Z., Ruppert, M.G., Fleming, A.J.J.S., Physical, A.A.: Piezoelectric benders with strain sensing electrodes: sensor design for position control and force estimation. Sens. Actuators, A 335, 113384 (2022)
37. Piezodata: Piezo bender. https://www.piezodata.com/piezo-bender/ (2023). Accessed 4 Apr 2024
38. Moheimani, S.O.R., Yong, Y.K.: Simultaneous sensing and actuation with a piezoelectric tube scanner. Rev. Sci. Instrum. 79, 073702 (2008)
39. Abramovitch, D.Y., Andersson, S.B., Pao, L.Y., Schitter, G.: A tutorial on the mechanisms, dynamics, and control of atomic force microscopes. In: Proceedings of American Control Conference, pp. 3488–3502. IEEE, Piscataway, NJ (2007)
40. Moheimani, S.O.R.: Invited review article: accurate and fast nanopositioning with piezoelectric tube scanners: emerging trends and future challenges. Rev. Sci. Instrum. 79, 071101 (2008)
41. PI Ceramic: Pt230 Pt piezo scanner tubes. https://www.piceramic.com/en/products/piezoceramic-actuators/tube-actuators/pt230-pt-piezo-scanner-tubes-103150 (2023). Accessed 18 Dec 2023
42. Physik instrumente D-510 Piseca capacitive sensors, http://www.physikinstrumente.com/en/pdf/d510_datasheet.pdf Accessed 18 Dec 2023
43. Mohammadzaheri, M., Tafreshi, R., Mohammad-Khorasani, M., Bazghaleh, M., Grainger, S.: Evaluation of the induced voltage in driven electrodes of piezoelectric tube actuators for sensorless nanopositioning. In: Proceedings of 2015 IEEE 8th GCC Conference & Exhibition, pp. 1–5. IEEE, Piscataway, NJ (2015)
44. Nelles, O.: Nonlinear System Identfication. Springer-Verlag, Berlin, Heidelberg (2001)
45. Mohammadzaheri, M., Mirsepahi, A., Asef-Afshar, O., Koohi, H.: Neuro-fuzzy modeling of superheating system of a steam power plant. Appl. Math. Sci. 1, 2091–2099 (2007)
46. Mohammadzahri, M., Khaleghifar, A., Ghodsi, M., Soltani, P., AlSulti, S.: A discrete approach to feedback linearization, yaw control of an unmanned helicopter. Unmanned Syst. 11, 1–10 (2023)
47. Ljung, L.: System Identification, Theory for the User, 2nd ed. Prentice Hall, Upper Saddle River, NJ (1999)

48. Mohammadzaheri, M., Chen, L., Ghaffari, A., Willison, J.: A combination of linear and nonlinear activation functions in neural networks for modeling a De-Superheater. Simul. Modell. Pract. Theory. 17, 398–407 (2009)
49. Mohammadzaheri, M., Grainger, S., Kopaei, M.K., Bazghaleh, M.: IMC-based feedforward control of a piezoelectric tube actuator. In: Proceedings of IEEE Eighth International Conference on Intelligent Sensors, Sensor Networks and Information Processing, pp. 357–361. IEEE, Piscataway, NJ (2013)
50. Nguyen, D., Widrow, B.: Improving the learning speed of 2-layer neural networks by choosing initial values of the adaptive weights. In: Proceedings of International Joint Conference on Neural Networks, pp. 21–26. IEEE, Piscataway, NJ (1990)
51. Mohammadzaheri, M., Tafreshi, R., Khan, Z., Ghodsi, M., Franchek, M., Grigoriadis, K.: Modelling of petroleum multiphase flow in electrical submersible pumps with shallow artificial neural networks. Ships Offshore Struct. 15, 174–183 (2020)
52. Mohammadzaheri, M., Chen, L.: Intelligent modelling of mimo nonlinear dynamic process plants for predictive control purposes. IFAC Proc. Vol. 41(2), 12401–12406 (2008)
53. Dong, R.L., Tan, Y.H., Chen, H., Xie, Y.Q.: A neural networks based model for rate-dependent hysteresis for piezoceramic actuators. Sens. Actuators, A 148, 350–351 (2008)
54. Zhang, X.L., Tan, Y.H., Su, M.Y., Xie, Y.Q.: Neural networks based identification and compensation of rate-dependent hysteresis in piezoelectric actuators. Phys. B 405, 2687–2693 (2010)
55. Mehrabi, D., Mohammadzaheri, M., Firoozfar, A., Emadi, M.: A fuzzy virtual temperature sensor for an irradiative enclosure. J. Mech. Sci. Technol. 31, 4989–4994 (2017)

How to cite this article: Mohammadzaheri, M., Tafreshi, R., Bazghaleh, M., Grainger, S., Khorasani, M.: Induced voltage in piezoelectric tube driven segments and their use in nanopositioning, an assessment. IET Sci. Meas. Technol. 1–8 (2024). https://doi.org/10.1049/smt2.12209