MODELLING AND VIBRATION CONTROL OF PIEZOELECTRIC ACTUATOR

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This project is dedicated to my beloved late mother Gambo, late father Bala Muhammad, my brothers my sisters for their encouragement and blessing, support and caring.

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ABSTRACT

The piezoelectric actuator is a voltage spring system that behaves in similar characteristic to mechanical mass spring system. It converts electrical signal to physical displacement. The displacements profile of the piezoelectric actuator shifts due to hysteresis and creep during actuation. Static models of piezoelectric actuator were developed with different equations in the past. However, static (non-dynamic) piezoelectric actuator models were not represented by single transfer function. Furthermore, the modelling of dynamic (vibrating) piezoelectric actuator was not considered. In this work, we presented the behaviour of the piezoelectric actuator in terms of mechanical displacement from applied electric potential. The transfer function mathematical model was generated representing the actuator characteristics. The vibration model that can vibrate at desired frequency of the actuator was also developed. The models were developed by system identification from experimental results. A high resolution microscope together with the image processing technique was used to obtain the system characteristics. Simulation using Matlab simulink was used to validate the experiment (The hysteresis was reduced by 90 % and the vibration was reduced to 97 %.). These models can be used to develop the controller for controlling vibration profile. It can also be used for desired micro actuation. It can also be used for desired micro actuation.

ABSTRAK

Penggerak piezoelektrik ialah satu sistem spring voltan yang mempunyai ciri yang sama dengan sistem spring jisim mekanikal. Ia menukarkan isyarat elektrik kepada perpindahan fizikal. Profil perpindahan penggerak piezoelektrik beranjak disebabkan oleh histeresis dan rayapan semasa pergerakan. Sebelum ini, model statik penggerak piezoelektrik telah dibuat menggunakan persamaan yang berlainan. Walaubagaimanapun model statik (bukan dinamik) penggerak piezoelektrik tersebut tidak diwakili oleh fungsi perpindahan tunggal seterusnya. Permodelan penggerak piezoelektrik dinamik (getaran) tidak dipertimbangkan. Dalam hal ini, kelakuan penggerak piezoelektrik ditunjukkan dalam segi perpindahan mekanikal daripada potensi elektrik yang diaplikasikan. Perpindahan fungsi model matematik tersebut dihasilkan bagi mawakili ciri-ciri penggerak. Model getaran yang boleh bergetar pada frekuensi penggerak yang diinginkan juga telah dibuat. Model tersebut telah dihasilkan dengan identifikasi sistem daripada hasil eksperimen. Mikroskop yang mempunyai resolusi tinggi dan juga teknik pemprosesan gambar telah digunakan bagi mendapatkan ciri-ciri sistem tersebut. Simulasi telah dijalankan menggunakan Matlab & Simulink bagi mengesahkan eksperimen tersebut (Histeresis telah dikurangkan sebanyak 90 % dan gerakan juga telah dikurangkan kepada 97 %). Model-model ini boleh digunakan untuk menghasilkan pengawal bagi mengawal profil getaran. Selain itu, ia juga boleh digunakan untuk gerakan mikro yang diinginkan.

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CARMA	-	Controlled Autoregressive Moving Average
DC	-	Direct Current
LR	-	Inductor Resistor
MVSTDR	-	Minimum Variance Self-tuning Direct Regulator
MOC	-	Model Predictive Controller
NARMAX	-	Nonlinear Autoregressive Moving Average with Exogenous input
PID	-	Proportional Integral and Derivative
PZT	-	Piezoelectric Actuator

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Piezoelectricity is the electricity resulting from pressure. It derived from Greek piezo or piezein which mean to squeeze or press. Piezoelectric actuator is a displacement transducer that converts electrical signals to physical displacement. Many physical models have been used for modelling piezoelectric actuators [1]. Piezoelectric materials are made of crystals (e.g. Quartz), ferroelectric polycrystalline ceramic substances, piezoceramics (e.g. Barium titanate (BaTio3) and lead zirconate titanate (PZA). All these materials respond to mechanical force/torque or electrical voltage/charge in a short time; they also can couple electrical and mechanical properties to each other. These materials are employed in different structures such as piezoceramic thin flat patches, piezoelectric stacks, piezoelectric tubes and piezoelectric strips embedded into a polymer matrix [2]. The piezoelectric actuator is over-damped second order system. The displacement of the actuator is proportional to the voltage applied. The frequency bandwidth is proportional to stiffness and inverse proportional to damping constant and mass [3]. There are two types of piezoelectric actuator namely strip actuator and stack actuator. Resin coated type of stack actuator offer low displacement than metal case type. Some of the applications of piezoelectric actuator are as follows. It is used in disk drived head positioning system with reliable performance [4]. Sizeable displacement and reasonable force are provided by piezoelectricmicroactuator for efficient mechanical microactuation mechanism which offers application in microoptics, micro relays and micro grippers [5]. It is used as pump actuators in lab on chip in microfluidic system as well as in inkjet printed actuators that have applications on lab on chip technology [6],[7]. Vibration energy can be harvested from piezoelectric devices with harvesting efficiency of more than two fold as compared to quasi-resistive impedance matching. It is possible to control vibration and harvest energy in piezoelectric actuator [8],[9]. It is used in cell wall cutting [10]. Three phenomena are observed in piezoelectric actuators behaviour; [2].

i. Hysteresis: is regarded as having different output values of a system with an identical input value.

ii. Creep: The decrease of the amplitude of piezoelectric actuator displacements by time while the input voltage is maintained is called creep which can cause error in long operations.

iii. Structural vibration: Piezoelectric actuators vibration is a function of mechanical properties of the actuator such as mass, stiffness and damping. Structural vibration is more significant close to resonance frequencies.

Figure 1.1 shows the affect of hysteresis as a result of varying stress in ferromagnetic material, ferroelectric material as well as in deformation of some materials such as rubber bands and shape-memory alloys. Figure 1.2 shows the effect of creep on the piezoelectric actuator. The same voltage gives different amplitude at different time. The Amplitude decrease from 2.25 to 2.125 while the input voltage remains 90 V. Figure 1.3 display piezoelectric effect, where mechanical energy is converted to electrical energy and inverse piezoelectric effect, where the electrical energy is converted in to mechanical energy. Figure 1.4a shows the pressure applied to the piezoelectric material causes decrease in size. The material shrinks and the voltage is generated on the circuit. Figure 1.4b shows the DC voltage applied to the piezoelectric material causes the material to expand. Figure 1.5 shows stripe actuator deflection offers a large stroke and a very limited blocking force when compared to a stack actuator Figure 1.6 shows stack actuators offer low stroke and a high blocking force. Table 1.1 shows the type of stack actuator and their rated temperature. Metal coated usually rated high temperature and high displacement than resin coated type. Figure 1.7 shows resin coated type that was used in the experiment. It structure is composed of ceramic, insulator, internal and external electrodes.

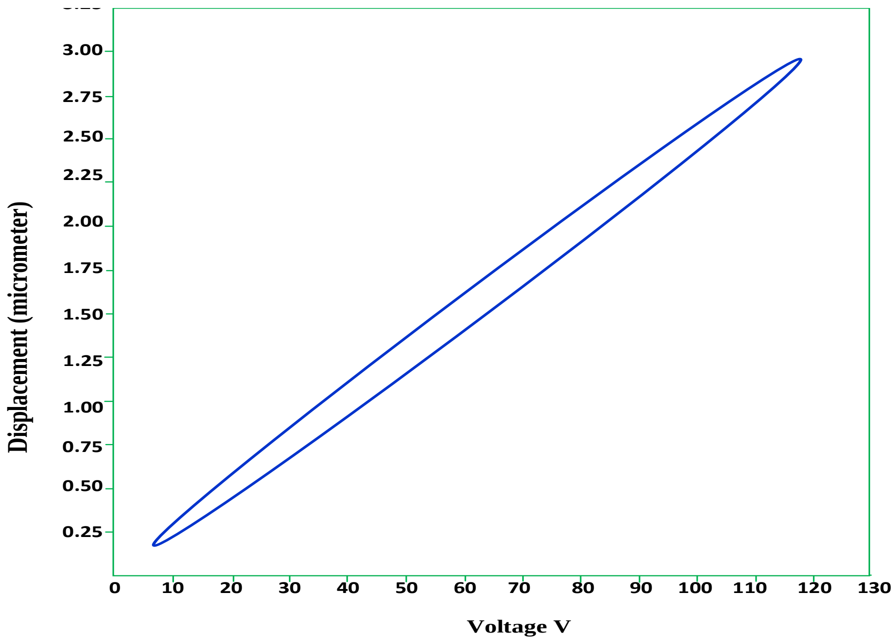

Figure 1.1 Hysteresis the actuator display different profile during loading and unloading phase.

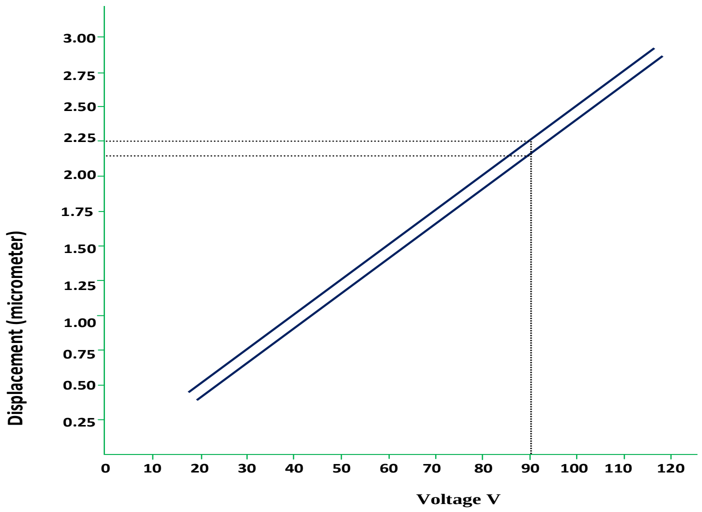

Figure 1.2 Piezoelectric Actuator Creeps, at constant voltage of 90 V the displacement decrease from 2.25 micrometre to 2.125 micrometre with time.

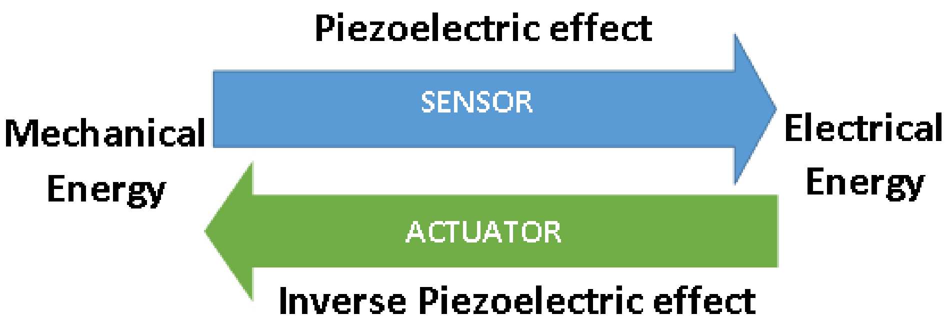

Figure 1.3 Piezoelectric properties. Piezoelectric effect converts mechanical energy is to electrical energy whereas inverse piezoelectric effect converts electrical energy to mechanical energy.

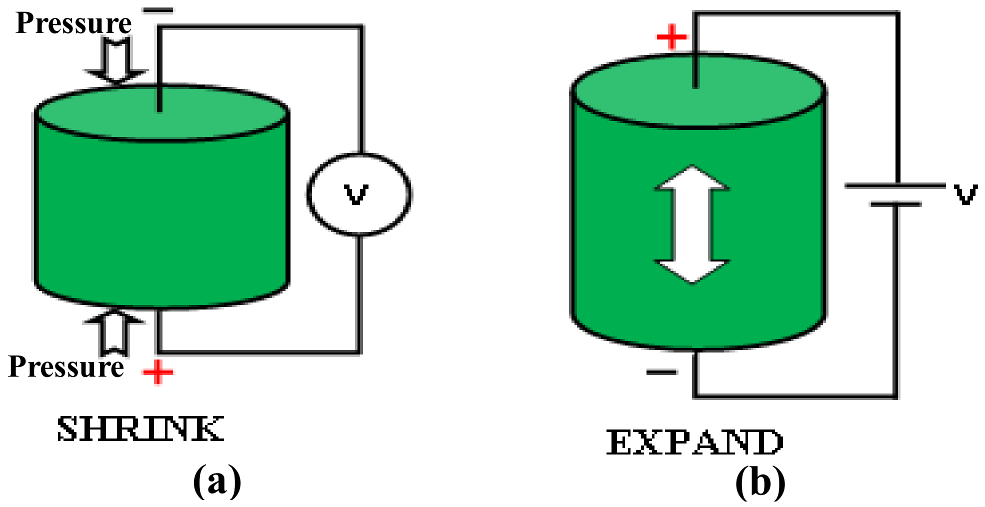

Figure 1.4 (a) Sensor uses the principle of piezoelectric effect to convert applied pressure into electrical signal while (b) Actuator uses inverse piezoelectric to increase the size of the piezoelectric material by converting voltage into displacement.

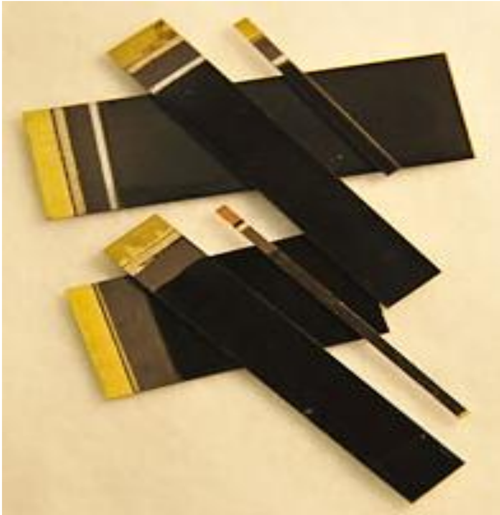

Figure 1.5 Strip actuator, which offers large stroke with limited blocking force.

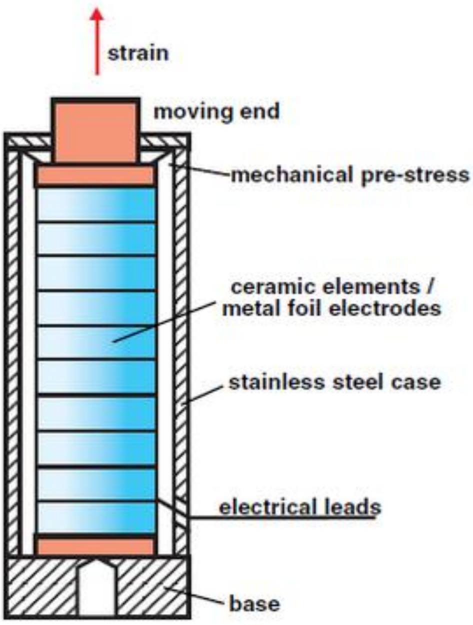

Figure 1.6 Stack actuator consists of ceramic element, electrical leads and stainless steel case.

Table 1.1 General Purpose

Rated temperature (^{0}C)	Resin coated	Metal case high performance
85	AE	ASB
150		ASL
		AHB (High displacement)

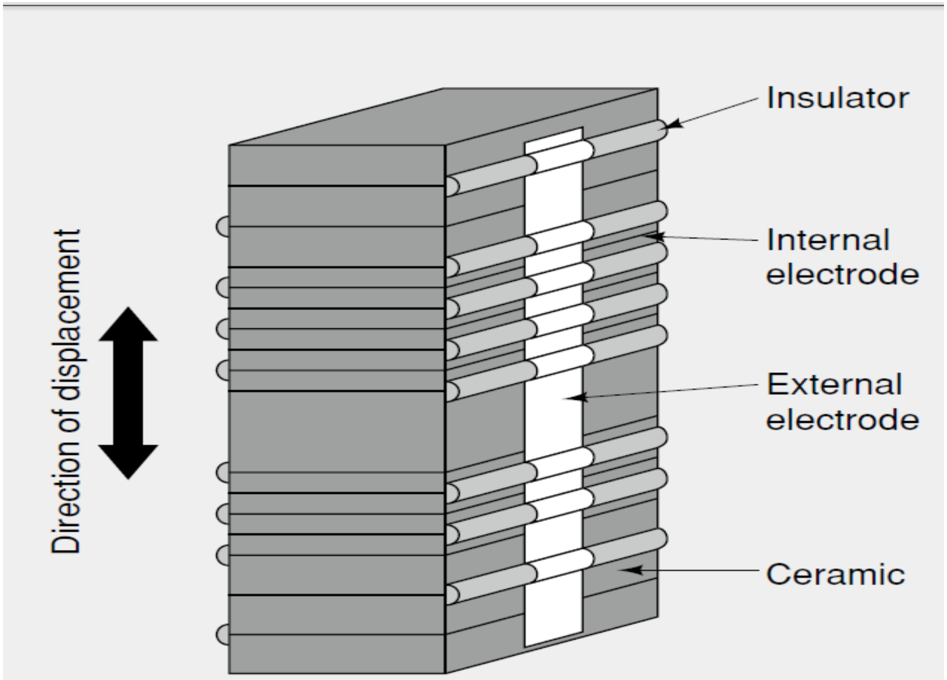

Figure 1.7 Architecture of PZT which consists of internal electrode, external electrode and insulator.

1.2 Background of the Study

The piezoelectric actuator has similar characteristics with mechanical mass spring damper system. The mass spring damper extends by the action of mass on the system while the piezoelectric actuator extends by the action of voltage on the system. Therefore it can be referred to as voltage spring system. Figure 1.8 the mechanical system generate force by action of mass on the system. Figure 1.9 the electrical system generates force by voltage acting on the piezoelectric actuator. Where F= applied force, K=stiffness, m=mass, b=damping force, x=distance extend by the force.

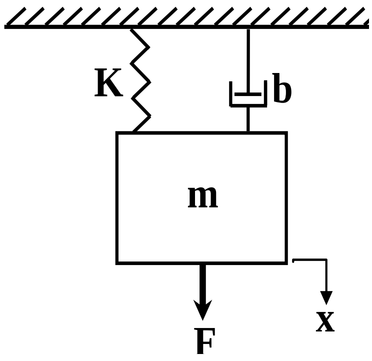

Figure 1.8 Mass spring damper system, K is stiffness, b is the damping force, m is the mass, F is the applied force and x is the displacement.

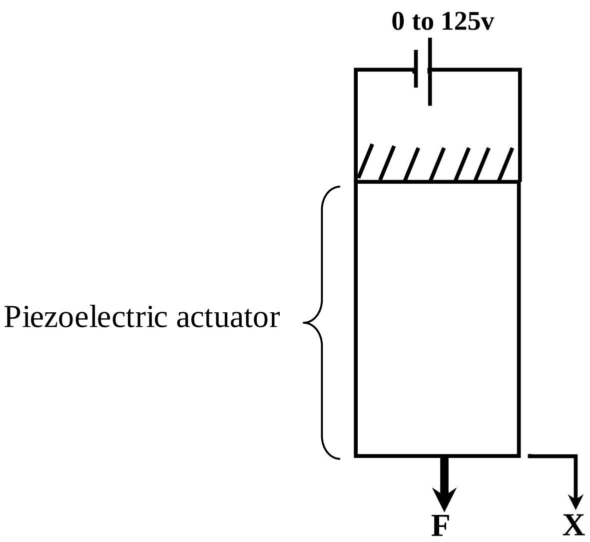

Figure 1.9 Piezoelectric actuator. F is the applied force and x is the displacement.

1.3 Problem Statement

The main problems of piezoelectric actuator are hysteresis, creep, structural vibration and associated nonlinearities. There is structural vibration which is associated with natural frequency. The static (non-dynamic) piezoelectric actuator models were not represented by single transfer function. The modelling of dynamic (vibrating) piezoelectric actuator was not previously considered. This project will emphasise on modelling piezoelectric actuator. Generating vibration at desire frequency and modelling of vibrating piezoelectric actuator. The project will also highlight controller design to control both hysteresis and vibration of the piezoelectric actuator.

1.4 Objectives

The main objective of this project is to control the piezoelectric actuator for accurately producing a vibration actuation. The above main objective can be divided into four sub-objectives as outline below:

i. To develop a model of both static (non-vibrating) and dynamic (vibrating) piezoelectric actuator using system identification technique.
ii. To implement the PID controller for hysteresis minimization using simulation.
iii. To implement the PID controller for vibration control using simulation.

1.5 Scopes of the Study

This project focused on modeling of piezoelectric actuator and modeling of vibrating piezoelectric actuator using system identification technique. The first PID controller was designed based on verified model to minimize the hysteresis. The second PID controller was designed to control vibration actuation. Due to the difficulties in dealing with nonlinear system of the piezoelectric actuator, the linear system model was used for analysis. The performances of the PID controllers were realized through simulation.

1.6 Significances and Original Contributions of the Study

The main contribution of this project is provides a means of precise control and manipulation of piezoelectric actuator to be used for micro and Nano-technology applications. The vibration of the actuator can also be used for precise cutting at micro level.

1.7 Project Outline

This project report is organized in four chapters. Chapter one gives an overview of the system, objectives and scope of the project and also gives introduction regarding the problem to be solved. Chapter two reviews some previous research and literatures related to this project. Chapter three provides steps of the methodology and description of each procedure to be followed in order to solve the problem at in view. Chapter four presents discussion of the results. Chapter five presents conclusion on the achievements of the project and also set forth some recommendations for further future works.

REFERENCES

[1] N. Miri, M. Mohammad Zaheri, L. Chen, S. Grainger, and M. Bazghaleh, "Physics-based modelling of a piezoelectric actuator using genetic algorithm," in *IEEE Symposium on Industrial Electronics & Applications*, 2013, pp. 16–20.

[2] N. Miri and M. Mohammad Zaheri, "A comparative study of different physics-based approaches to modelling of piezoelectric actuators," in *2013 IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, 2013, pp. 1211–1216.

[3] P. Li, J. Fu, Y. Wang, Z. Xing, and M. Yu, "Dynamic Model and Parameters Identification of Piezoelectric Stack Actuators," in *26th Chinese Control and Decision Conference (CCDC)*, pp. 1918–1923, 2014.

[4] Z. He, H. T. Loh, M. Xie, S. Member, G. Guo, and N. E, "A Reliability Model for Piezoelectric Actuators," *7th Int. Power Eng. Conf.*, pp. 1–6, 2005.

[5] T. Freyhold and U. Wallrabe, "Development of Miniaturized Piezoelectric Actuators for Optical Applications Realized Using LIGA Technology," *IEEE Jounal Microelectromechanical Syst.*, vol. 8, no. 3, pp. 258–263, 1999.

[6] O. Pabst, J. Perelaer, E. Beckert, U. S. Schubert, R. Eberhardt, and A. Tünnermann, "All inkjet-printed piezoelectric polymer actuators : Characterization and applications for micropumps in lab-on-a-chip systems," *Org. Electron.*, vol. 14, no. 12, pp. 3423–3429, 2013.

[7] O. Pabst, S. Hölzer, E. Beckert, J. Perelaer, U. S. Schubert, R. Eberhardt, and A. Tünnermann, "Inkjet printed micropump actuator based on piezoelectric polymers : Device performance and morphology studies," *Org. Electron.*, vol. 15, no. 11, pp. 3306–3315, 2014.

[8] I. S. Method, "A Self-Powered Piezoelectric Vibration Control System With Switch Precharged," *IEEE Trans. Mechatronics*, vol. 20, no. 2, pp. 773–781, 2015.

[9] J. Sankman and D. Ma, “A 12- μ W to 1 . 1-mW AIM Piezoelectric Energy Harvester for Time-Varying Vibrations With 450-nA I Q,” *IEEE Trans. Power Electron.*, vol. 30, no. 2, pp. 632–643, 2015.

[10] M. Habibur Rahman, Abdul Hafis mat Sulaiman, Ridzuan Ahmad, “Finite Element Analysis of Single Cell Wall Cutting by Piezoelectric-Actuated Vibrating Rigid Nanoneedle,” *IEEE Trans. Nanotechnol.*, vol. 12, no. 6, pp. 1158–1165, 2013.

[11] H. Jiang, H. Ji, J. Qiu, and Y. Chen, “A modified Prandtl-Ishlinskii model for modeling asymmetric hysteresis of piezoelectric actuators.,” *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 57, no. 5, pp. 1200–1210, 2010.

[12] Z. Wei, B. L. Xiang, and R. X. Ting, “Online parameter identification of the asymmetrical Bouc–Wen model for piezoelectric actuators,” *Precis. Eng.*, vol. 38, no. 4, pp. 921–927, 2014.

[13] I. M. Bahadur and J. K. Mills, “A new model of hysteresis in piezoelectric actuators,” in *IEEE International Conference on Mechatronics and Automation*, vol. 1, pp. 789–794, 2011.

[14] A. K. Kottari, A. E. Charalampakis, and V. K. Koumousis, “A consistent degrading Bouc–Wen model,” *Eng. Struct.*, vol. 60, pp. 235–240, 2014.

[15] F. Ikhouane, V. Mañosa, and J. Rodellar, “Dynamic properties of the hysteretic Bouc-Wen model,” *Syst. Control Lett.*, vol. 56, no. 3, pp. 197–205, 2007.

[16] C. Hui, T. Yonghong, Z. Xingpeng, D. Ruili, and Z. Yahong, “Identification of Dynamic Hysteresis Based on Duhem Model,” in *Fourth International Conference on Intelligent Computation Technology and Automation*, pp. 810–814, 2011.

[17] R. Ouyang and B. Jayawardhana, “Absolute stability analysis of linear systems with Duhem hysteresis operator,” *Automatica*, vol. 50, no. 7, pp. 1860–1866, 2014.

[18] Y. Bernard, E. Mendes, and F. Bouillault, “Dynamic hysteresis modeling based on Preisach model,” *IEEE Trans. Magn.*, vol. 38, no. 2, pp. 885–888, 2002.

[19] A. Matsubara, M. Maeda, and I. Yamaji, “Vibration suppression of boring bar by piezoelectric actuators and LR circuit,” *CIRP Ann. - Manuf. Technol.*, vol. 63, no. 1, pp. 373–376, 2014.

[20] T. Zhang, H. G. Li, and G. P. Cai, “Hysteresis identification and adaptive vibration control for a smart cantilever beam by a piezoelectric actuator,” *Sensors Actuators A Phys.*, vol. 203, pp. 168–175, 2013.

[21] C. Abis, F. Unal, and A. Mugan, "Active vibration control with piezoelectric actuator on a lathe machine with a gain controller," in *IEEE International Conference on Mechatronics*, pp. 19–22, 2011.

[22] C.-Y. S. and M. O. Jian Wang, "Theoretic Modeling and Adaptive Control for Two Degree-of-Freedom Piezo-Electric Actuated Chatter Suppression System," in *42nd IEEE Conference on Decision and Control*, pp. 4315–4320, 2003.

[23] H. Numasato and M. Tomizuka, "Settling control and performance of a dual-actuator system for hard disk drives," *IEEE/ASME Trans. Mechatronics*, vol. 8, no. 4, pp. 431–438, 2003.

[24] W. M. Chen and T. S. Liu, "Modeling and experimental validation of new two degree-of-freedom piezoelectric actuators," *Mechatronics*, vol. 23, no. 8, pp. 1163–1170, 2013.

[25] F. M. and A. S. M. khaled Joujou, "Experimental fuzzy logic active vibration control," in *5th International Symposium on Mechatronics and its Applications (ISMA08)*, pp. 6–12, 2008.

[26] Z. Kai, D. Xinghui, and W. Dongsheng, "Intelligent vibration control of piezo-electric truss structure using GA-based fuzzy neural network," *8th World Congr. Intell. Control Autom.*, pp. 5136–5139, 2010.

[27] W. Li and X. Chen, "Compensation of hysteresis in piezoelectric actuators without dynamics modeling," *Sensors Actuators A Phys.*, vol. 199, pp. 89–97, 2013.

[28] F. Heidary and M. Reza Eslami, "Piezo-control of forced vibrations of a thermoelastic composite plate," *Compos. Struct.*, vol. 74, no. 1, pp. 99–105, 2006.

[29] Y. Cao, L. Cheng, X. B. Chen, and J. Y. Peng, "An Inversion-Based Model Predictive Control With an Integral-of-Error State Variable for Piezoelectric Actuators," *IEEE/ASME Trans. Mechatronics*, vol. 18, no. 3, pp. 895–904, 2013.

[30] K. Ogata, *Modern Control Engineering*, 5th ed. New Jersey, USA: Pearson Education Incorporation, 2012.