MODELING AND CONTROL OF PIEZOELECTRIC STACK ACTUATORS WITH HYSTERESIS

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ABSTRACT

Piezoelectric actuators are popularly applied as actuators in high precision systems due to their small displacement resolution, fast response and simple construction. However, the hysteresis nonlinear behavior limits the dynamic modeling and tracking control of piezoelectric actuators. This thesis studies a dynamic model of a moving stage driven by piezoelectric stack actuator. The Bouc-Wen model is introduced and analyzed to express the nonlinear hysteresis term of the piezoelectric stack actuator, where the values of the parameters of the model have been taken from a previous work. The simulated results using MATLAB/Simulink demonstrate the existence of the hysteresis phenomenon between the input voltage and the output displacement of the piezoelectric stack actuator, and validate the correctness of the model. Moreover, a Luenberger observer is designed to estimate the hysteresis nonlinearity of the system, and then combined with the voltage input signal to form a Luenberger-based feedforward controller to control the displacement of the system. Furthermore, a Proportional-Integral-Derivative (PID) feedback controller is integrated with the feedforward controller to achieve more accurate output displacement, where the gains of the PID controller are optimized using Particle Swarm Optimization. Several performance index formulas have been studied to get the best solution of the PID's gains. An Integral Time Squared Error plus Absolute Error performance index formula has been proposed to achieve zero overshoot and steady-state error. The simulated results accomplished using MATLAB/Simulink show the ability of the designed controllers to vastly reduce the amount of error of the output displacement and the response time of the system.

ABSTRAK

Pemacu piezoelektrik popular digunakan sebagai pemacu system berketepatan tinggi memandangkan ia memberikan resolusi sesaran yang kecil, tindak balas yang cepat dan konstruksi yang mudah. Namun, sifat histerisis yang tidak linear menghadkan pemodelan dinamik dan penjejakan bagi pemacu ini. Tesis ini mengkaji model dinamik bagi pemacu bergerak berperingkat dipacu oleh aktuator piezoelektrik bertingkat. Model Bouc-Wen diperkenalkan dan dianalisis untuk menyatakan terma histerisis tidak linear bagi aktuator piezoelektrik bertingkat, di mana nilai parameter yang digunakan bagi model ini diambil daripada projek yang terdahulu. Keputusan simulasi dengan menggunakan MATLAB/Simulink menunjukkan tentang kewujudan fenomena histerisis antara voltan input dan sesaran output bagi pemacu piezoelektrik berlapis, dan mengesahkan kesahihan model. Tambahan pula, pemerhati Luenberger telah direka untuk menganggarkan histerisis tidak linear bagi sistem dan kemudian menggabungkan dengan isyarat input voltan membentuk satu pengawal suapbalik hadapan berasaskan Luenberger untuk mengawal sesaran sistem. Tambahan pula, satu pengawal suapbalik berasaskan Perkadaran-Pembezaan-Kamiran (PID) disepadukan dengan pengawal suapbalik hadapan untuk mencapai sesaran output yang lebih tepat, di mana peningkatan pengawal PID dioptimumkan menggunakan Particle Swarm Optimization. Beberapa indeks prestasi telah dikaji untuk mendapatkan penyelesaian yang terbaik untuk nilai gandaan PID. Formula gabungan indek kamiran ralat kuasa dua dan indeks ralat mutlak telah dicadangkan untuk mencapai lajakan sifar dan ralat keadaan mantap sifar. Keputusan-keputusan simulasi yang diperoleh dengan menggunakan MATLAB/Simulink menunjukkan keupayaan pengawal yang direka dengan mengurangkan jumlah ralat sesaran output yang besar dan mengurangkan masa tindak balas sistem.

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LIST OF ABBREVIATIONS

AE	-	Absolute Error
IAE	-	Integral Absolute Error
ISE	-	Integral Squared Error
ITAE	-	Integral Time Absolute Error
ITSE	-	Integral Time Squared Error
ITSE+AE	-	Integral Time Squared Error Plus Absolute Error
PI	-	Proportional-Integral
PID	-	Proportional-Integral-Derivative
PSO	-	Particle Swarm Optimization

CHAPTER 1

INTRODUCTION

Piezoelectric actuators are widely used for micro/nano manipulation systems [1], micro-robots [2], vibration active control [3], precision machining [4], and atomic force microscopy [5]. This is due to their special characteristics such as high resolution in nanometer range, fast response, and high stiffness. The major advantage of using piezoelectric actuators is that they do not have any frictional or static characteristics, which usually exist in other types of actuators. However, the main disadvantage of piezoelectric actuators is the nonlinearity that is mainly due to hysteresis behavior, creep phenomenon and high frequency vibration [6].

1.1. Piezoelectricity

Piezoelectric effect was discovered for the first time in 1880 by the brothers Pierre and Jacques Curie. They noticed, that a mechanical deformation in certain directions causes opposite electrical surface charges at opposite crystal faces. This effect, which was also found afterwards in quartz and other crystals without symmetry center, has been called piezoelectric effect by Hankel. The prefix 'piezo-' is derived from the Greek word 'piezein', which means 'press'. Thus, the word piezoelectricity means electricity resulting from pressure [7]. In 1881, Lippmann predicted the existence of the inverse piezoelectric effect from thermodynamic considerations, and then Pierre and Jacques Curie verified this in the same year [8].

Piezoelectric effect happens due to the existence of polar axes within the piezoelectric material structure. This means that there is an electrical dipole moment in axis directions caused by the distribution of the electrical charge in the chemical bond of the cell structure of the piezoelectric material. Figure 1.1 shows the cell structure of quartz.

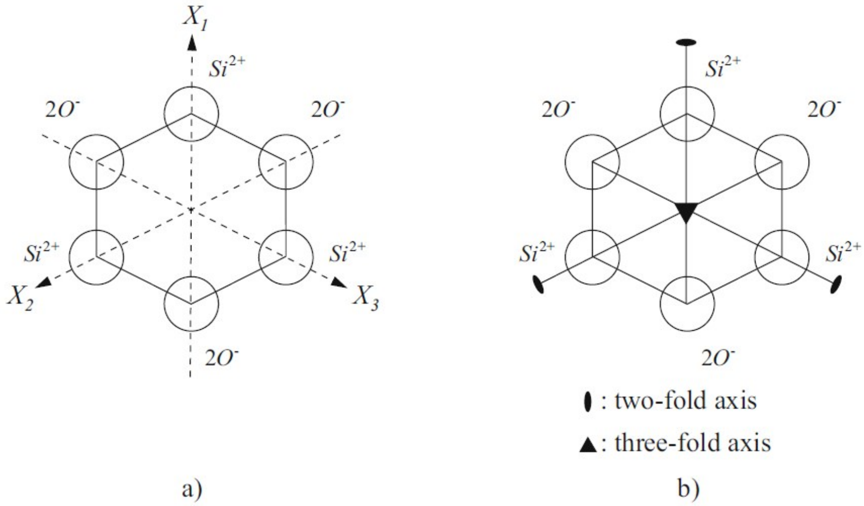

Figure 1.1. Simplified cell structure of quartz. - (a) arrangement of Si- and O-ions with the main crystal axes; (b) two- and three-fold axes.

The cell consists of negative charged O-ions and positive charged Si-ions and has three two-fold polar rotation axes X_1, X_2 and X_3 in the drawing plane and a three-fold rotation axis Z vertical on the drawing plane. If there is a deformation of the quartz structure along the polar X_1-axis, an additional electrical polarization P performs along this axis. The electrical polarization is caused by the displacement of the positive and negative ions of the crystal net against each other, resulting an electrical charge on the appropriate crystal surfaces that is vertical on the X_1-axis, and thus an outside electrical polarization voltage. This effect is called direct longitudinal piezoelectric effect. Applying compression or tensile stresses vertically on the X_1-axis results an additional electrical polarization in an opposite sign on X_1-axis direction. This behavior is called direct transversal piezoelectric effect. Figure 1.2 shows the direct piezoelectric effect in a cell structure of quartz [8].

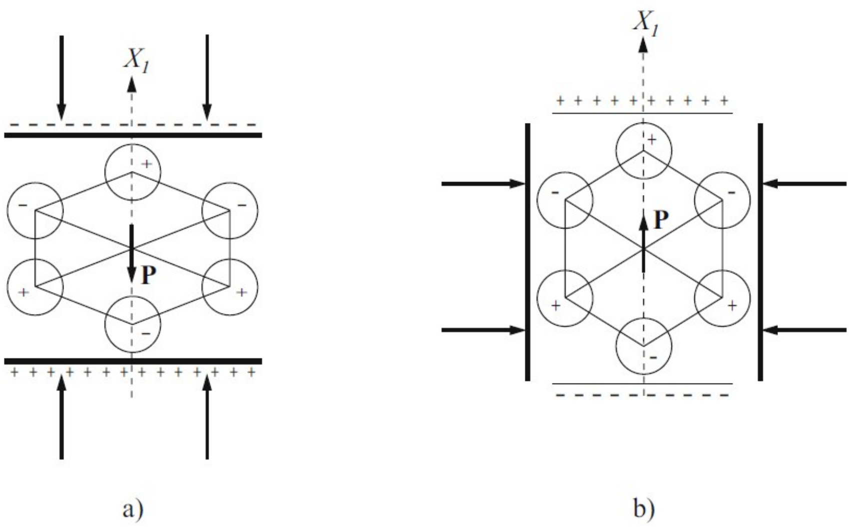

Figure 1.2. Direct piezoelectric effect in a cell structure of quartz. - (a) longitudinal piezoelectric effect; (b) transversal piezoelectric effect.

Both longitudinal piezoelectric effects and transversal piezoelectric effect are reversible. This means that a contraction or an extension of the quartz structure can be achieved under the influence of electrical fields. This effect is called inverse piezoelectric effect [8, 9]. This effect is the working principle of all piezoelectric actuators. Piezoelectric materials can be divided into the following three types:

1. Single crystals, such as quartz.
2. Piezoelectric ceramics, such as lead zirconate titanate.
3. Polymers, such as polyvinyl fluoride.

Single crystals and polymers show a weak piezoelectric effect, which makes them limited to be used in sensor applications, while piezoelectric ceramics have large electromechanical coupling, which makes them suitable for actuator applications [10].

1.2. Piezoelectric Actuators

Piezoelectric actuators are specific actuators using piezoelectric materials as active materials. They are several types of piezoelectric actuators, such as stacks, benders, flextensional, langevin transducers and various motors. The most popular ones are stacks and benders. A stack contains a pile of piezoceramic layers and electrodes mounted electrically in parallel and mechanically in series, which increases the maximum displacement. The focus of this study is piezoelectric stack actuators. Figure 1.3 shows a schematic of piezoelectric stack actuator [7, 11].

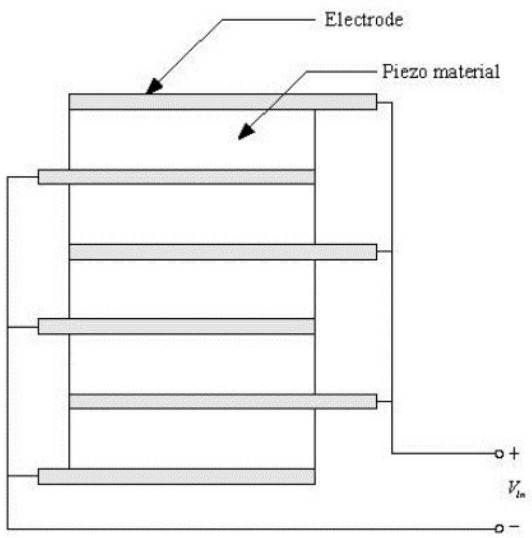

Figure 1.3. Schematic of piezoelectric stack actuator.

Benders have mechanical motion amplification, where two piezoceramic layers are attached with opposing polarization, which makes the first layer expands while the other shrinks under voltage excitation. This causes the structure to bend, and the overall motion on the actuator tip is greater than the strain of the ceramics [7]. Figure 1.4 shows a schematic of piezoelectric bender actuator.

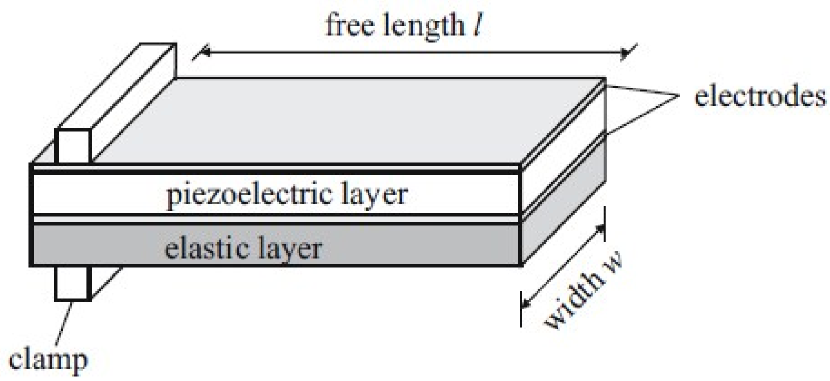

Figure 1.4. Schematic of piezoelectric bender actuator.

1.3. Nonlinearities in Piezoelectric Actuators

Piezoelectric actuators exhibit nonlinear behavior caused by hysteresis, creep and vibration. Hysteresis in piezoelectric actuators causes that the displacement depends on the current and the previous excitation voltage. Hysteresis phenomenon is based on the crystalline polarization effect and molecular friction [12]. The displacement generated by piezoelectric actuator depends on the applied electric field and the piezoelectric material constant which is related to the remnant polarization that is affected by the electric field applied to piezoelectric material. The deflection of the hysteresis curve depends on the previous value of the input voltage, which means that piezoelectric materials have memory because they remain magnetized after the external magnetic field is removed [13]. Figure 1.5 shows the hysteresis curve of piezoelectric actuators.

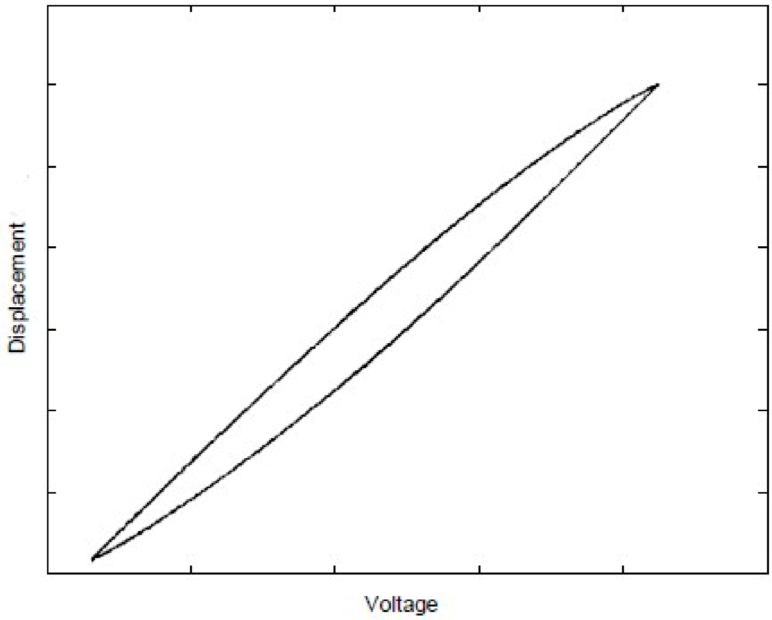

Figure 1.5. Hysteresis curve of piezoelectric actuators.

Creep is a drift of the output displacement for a constant applied voltage, which increases over extended periods of time during low-speed operations. Creep is related to the effect of the applied voltage on the remnant polarization of the piezoelectric actuator. If the operating voltage of a piezoelectric actuator is increased, the remnant polarization continues to increase. This manifests itself in a slow creep after the voltage change is complete [14]. Figure 1.6 shows the creep curve of piezoelectric actuators.

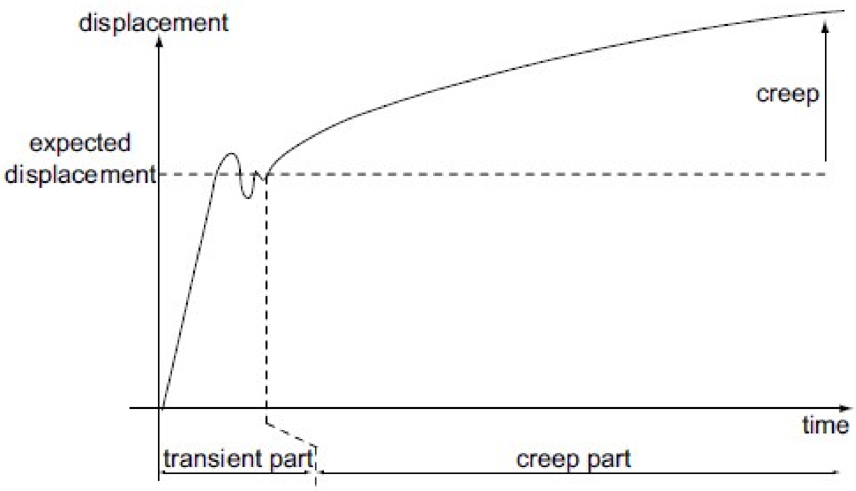

Figure 1.6. Creep curve of piezoelectric actuators.

Vibration effect is caused by exciting the resonant modes of the system. To avoid vibration effect, the frequency of the applied voltage should be smaller than the lowest resonant peak of the piezoelectric actuator [15].

The focus of this study is on hysteresis modeling of piezoelectric actuators, since creep and vibration can be negligible in high speed and low frequency applications [15].

1.4. Displacement Control of Piezoelectric Actuators

Piezoelectric actuators are commonly used in applications requiring high resolution and precision. Their suitable dynamic properties extend the application areas into high speed areas. However, nonlinearities in piezoelectric actuators and external load effect decrease the open-loop positioning accuracy. If a high accuracy is required, nonlinearities and disturbances have to be compensated. The compensation is usually accomplished using six control types [7]:

1. Feedforward voltage control, where nonlinear models are normally used.
2. Feedback voltage control, where several displacement sensors are used.
3. Feedforward and feedback voltage control.
4. Feedforward charge control, where the operating current is controlled.
5. Feedback charge control, where charge is measured and controlled.
6. Feedforward and feedback charge control.

This study focuses on feedforward and feedback voltage control.

1.5. Thesis motivations

Piezoelectric stack actuators are popularly applied as actuators in high precision systems due to their small displacement resolution, fast response and simple construction. However, the hysteresis nonlinear behavior limits the dynamic modeling and tracking control of piezoelectric actuators.

An accurate hysteresis model is needed to present the hysteresis nonlinear behavior of piezoelectric stack actuators, and effective controllers are required to achieve high precision and fast displacement of the systems that are driven by piezoelectric stack actuators.

1.6. Problem Statement

Hysteresis has a high nonlinear effect on piezoelectric stack actuators. This effect causes difficulties in modeling and controlling piezoelectric stack actuators, and limits their applications in high precision positioning systems.

Development of an accurate model and efficient control of piezoelectric stack actuators is needed to achieve precise accuracy and better dynamic performance.

1.7. Research Objectives

The objectives of this study are:

1. To derive a dynamic model of a moving stage driven by piezoelectric stack actuator with hysteresis.
2. To study the effect of hysteresis on the behavior of the systm

3. To design a feedforward controller with Luenberger observer, and a feedback PID controller to control the displacement of the moving stage.

1.8. Scope of Work

This study focuses on the hysteresis modeling of a moving stage driven by piezoelectric stack actuator. Bouc-Wen hysteresis model is used to model the hysteresis in the system. The model is studied, derived and then implemented using MATLAB Simulink. A feedforward with Luenberger observer is designed and then combined with a PID controller that is tuned using PSO method. These two combined controllers are then used to control the displacement of the system.

1.9. Organization of the Thesis

This thesis is organized as follows: Chapter 1 introduces the topic of this thesis. Chapter 2 discusses a literature review about the topic of this thesis. Chapter 3 presents the methodology that is used in this project. The results of modeling are presented and discussed in Chapter 4, while the results of control and optimization are presented and discussed in Chapter 5. Finally, a conclusion and future work are introduced in Chapter 6.

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