行政院國家科學委員會專題研究計畫成果報告

微奈米壓電平台之數位控制系統

Digital control system of a piezo-positioning nanostage

計畫編號： NSC 96-2221-E-009-237

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1. Abstract

This report presents an approach for modeling hysteresis nonlinearity in a piezo actuator, and a hybrid controller is designed combining inverse hysteresis compensator and NCTF tuned PID controller. A feedforward neural network is defined to describe the Preisach model. This model is extended with two additional inputs--- input extrema and input rate, to identify the piezo actuator's rate-dependent hysteresis behavior throughout the major loop and minor loops. An NCTF tuned PID controller augmented with inverse hysteresis model is then developed to compensate the hysteretic behavior, modeling error, and disturbance to improve the positioning/tracking stability and accuracy. The effectiveness of this algorithm is experimentally verified through the tracking control of a piezo actuator.

Keyword:

Piezo, rate-dependent hysteresis, feedforward neural networks, NCTF tuned PID

中文摘要

本計劃研製壓電平台數位控制器。一種結合反遲滯補償和 NCTF 調整型 PID 的控制器已經設計出來。在反遲滯補償上，使用類神經網路或取描述 Presisach 模型。經由加上極值和速率，對於遲滯的主迴路和次迴路都可以附有速率相關的行為。NCTF 調整型 PID 的控制器可以清除干擾的影響，進而改善位置和追蹤控制的精度，還能兼顧系統穩定性。這種壓電平台數位控制器已經經過實驗的驗證。

關鍵字：

壓電致動器，速率相關遲滯，類神經網路，特徵軌跡跟隨控制器。

2. Introduction

The so-called smart materials, for example piezo-ceramic material and ferromagnetic material, have interested more and more researchers because of their special properties considered useful applications.

Hysteresis is a kind of non-smooth nonlinearity, naturally existing in a wide range of disciplines such as piezo actuators, damper-spring systems and gear box, etc. Hysteresis can produce multiple output states for a given input state, thus it may frustrate the performance of the control system leading to close-loop instability and complicate the task of controller design and analysis [1]. Also, it may generate the undesired amplitude-dependent phase shifts and harmonic distortions, which reduce the effectiveness of feedback control [2].

Hysteresis has been studied for decades, and various models have been proposed to efficiently capture the hysteretic characteristics [3], such as the Preisach model (PM), the Maxwell slip model, and the Prandtl-Ishlinskii (PI) operator. By developing a look up table and interpolator based on the measurement of first-order reversal curves, PM has become one of the most popular models for its well defined and reliable experimental identification procedure.

Preliminary experiment shows that the hysteresis behavior of a piezo actuator is rate-dependent, increasing with the rate of control input. Therefore, the performance of the system with hysteresis will be poor if the system without using the corresponding mechanism to compensate for the hysteresis behavior. The classical PM is a rate-independent model possessing Wiping-out and congruency properties that must be modified to adequately describe piezo's hysteresis and frequency dependent behavior.

Based on the geometric similarities between PM and feedforward neural network (FNN) that's much easier to identify the weighting functions of FNN [4]. An FNN, with two consecutive input extrema and the rate of input between the extrema as additional inputs, is developed to address the issue of rate-dependent hysteresis in piezo actuator.

Althought, open-loop feedforward inverse control can be chosen for its simplicity and guaranteed stability, the robustness of a feedforwad inverse control system is susceptible to the modeling error and unmeasured disturbance. To combat this problem, a nominal character trajectory following (NCTF) controller tuned PID controller combining feedforward compensation is used to overcome the residual hysteretic behavior of the piezo actuator. This algorithm is experimentally verified through the tracking control of a piezo actuator.

The report is organized as follows. The classical Preisach model is briefly presented in Section II. The rate-dependent hysteresis model and the corresponding identification method by FNN are presented in section III. An NCTF tuned PID controller is introduced in section IV. Finally, experimental implementation and conclusions are summarized in Section V and VI.

3. Problem Formulation

The existence of nonlinear multi-path hysteresis in piezo-ceramic material complicates the control of a piezo actuator in high precision applications. Previous experiment shows the maximum hysteretic error is typically about 15% in static positioning applications. Still worse, the hysteresis is rate-dependent, increasing with the rate of control input, as shown in Fig. 1.

Feedback controller with function of hysteresis compensation is an effective way to solve the phase lag phenomena of a precision positioning system. That is to find a mathematical model that closely describe the hysteresis behavior of a piezo actuator, and then feed forward the inverse hysteresis model to linearize the actuator's response.

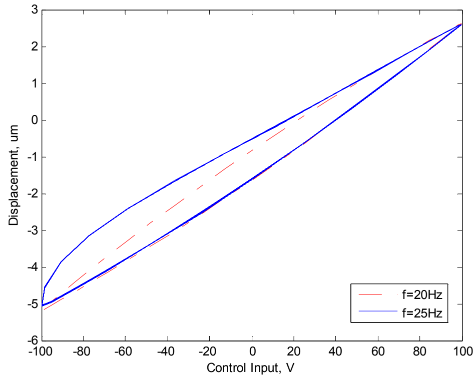

Fig. 1. Hysteresis of piezo-ceramic material is rate-dependent. The plot shows the response of a piezo actuator at two different driving frequencies.

4. Proposed Method

4.1 Brief introduction of the Classical Preisach Model

The classical Preisach model (PM) is the most popular model for its well defined and reliable experimental identification procedure based on the measurement of first-order reversal curves. The classical Preisach model can be expressed as

$$H[v](t) = \iint_{(\alpha,\beta)\in s} \mu(\alpha,\beta)\gamma_{\alpha,\beta}[v](t)\,d\alpha\, d\beta \qquad (1)$$

Where $\gamma_{\alpha,\beta}$ is the hysteresis operator, responses as a relay element with "up" and "down" switching value α and β whose values are determined by the input-voltage signal $v(t)$ as shown in Fig.2. The function $\mu(\alpha,\beta)$ is the weighting function estimated from measured data and is called the Preisach function.

The double integration in expression (1) is performed in the limited triangle S in α,β-plane, graphically described in Fig. 2, where $S = \{(\alpha,\beta) | v_{\min} \le \beta \le \alpha \le v_{\max}\}$, $v_{\min}$ and $v_{\max}$ are the minimal and maximal values of the input respectively. The implementation of the Preisach model can be simplified to a problem of developing a method to experimentally estimate the weighting function $\mu(\alpha,\beta)$ for a given piezo actuator. By properly assigning weighting functions, the sum of model's output will approach a hysteresis curve.

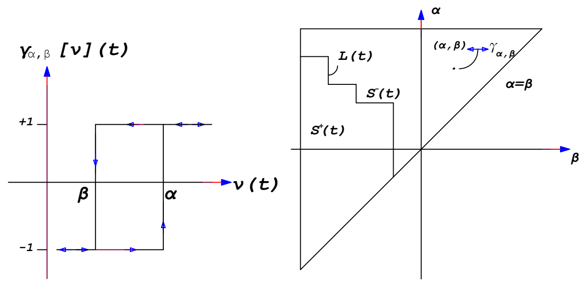

Fig. 2. An elementary hysteresis operator $\gamma_{\alpha,\beta}[v](t)$ and a geometric interpretation of the Preisach model

4.2 Neural network identification procedure

By using an approach with the fact that Preisach models have some similarities to neural networks configurations, Adly et. al. [4] introduces a method for solving the identification problem of the classical Preisaxh model in the (partial) absence of the congruency property.

This case considers a four-layer feedforward network, as depicted in Fig. 3, and the back-propagation (BP) training algorithm is applied to multilayer FNN consisting of processing elements with continuous differentiable activation functions [4~7]. The basis for this weight update algorithm is simply the gradient-descent method.

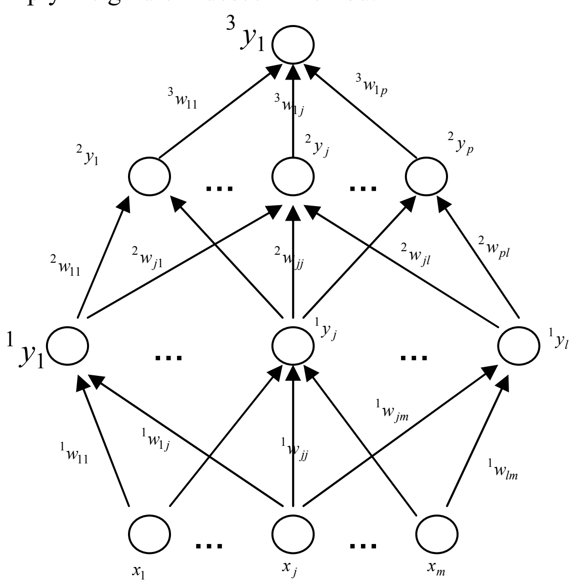

Fig. 3 Four-layer back-propagation network

First, assumes each perceptron element in this network has a bipolar sigmoid activation function,

$$y = a(net) = \frac{2}{1 - e^{-\lambda net}} \qquad (2)$$

where "*net*" is the net input defined as the weighted summation of the input values and $\lambda = 1$ [6]. Each element q in the hidden layer receives a net input of and produces an output of

$$ {}^{q}y_i = a({}^{q}net_i) = a(\sum_j {}^{q}w_{ij}\, {}^{q-1}x_j) \qquad (3) $$

where ${}^{q}net_i$ and ${}^{q}y_i$ denote the net input and output of the i_{th} unit in the q_{th} layer, ${}^{q}w_{ij}$ denote the connection weight from ${}^{q-1}y_j$ to ${}^{q}y_i$. The network has m input nodes and one output node.

Second, consider the error signals and their back propagation to update the connection weights. The error value and error signals are defined as follows:

$$ E(\mathbf{W}) = \frac{1}{2}\sum_{i=1}^{n}\left(d_i - {}^{Q}y_i\right)^2 \qquad (4) $$

$$ {}^{Q}\delta_i = \left(d_i - {}^{Q}y_i\right)a'\left({}^{Q}net_i\right) \qquad (5) $$

$$ \Delta^{q}w_{ij} = \eta\, {}^{q}\delta_i\, {}^{q-1}y_i \qquad (6) $$

$$ {}^{q}w_{ij}^{new} = {}^{q}w_{ij}^{old} + \Delta^{q}w_{ij} \qquad (7) $$

$$ {}^{q-1}\delta_i = a'\left({}^{q-1}net_i\right)\sum_j {}^{q}w_{ji}\, {}^{q}\delta_j \qquad (8) $$

where $q = Q, Q\text{-}1, \ldots, 2$.

4.3 Control system design

To compensate the bounded modeling error and external disturbance, an NCTF tuned PID feedback controller with function of hysteresis feedforward compensation is employed. First, a FNNs model shown in Fig. 4 is setup for inverse hysteresis. The obtained inverse model will be augmented with feedback control to compensate the effect of hysteresis.

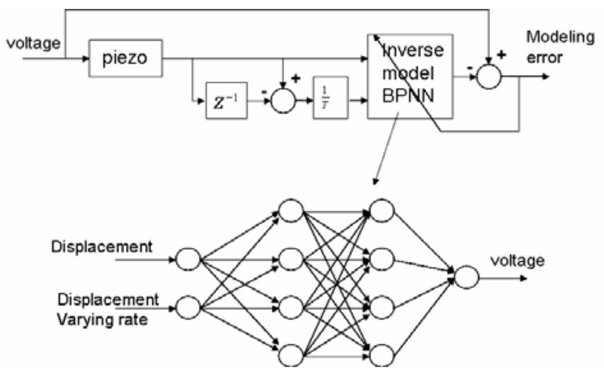

Fig. 4 FNNs inverse hysteresis model

PID controllers have been widely used in industrial processes because of their simple structure and robust performance in a wide range of operating conditions. However, the design of PID controllers requires specification of three parameters: proportional gain, integral time constant and derivative time gain. To determine these parameters, the certain knowledge of control processes is required. To avoid setting up a complicated controller, a nominal characteristic trajectory following (NCTF) controller has been proposed as a practical controller for point-to-point (PTP) positioning system [9-10]. The structure of NCTF controller, shown in Fig. 5, consists of a nominal characteristic trajectory (NCT) and a compensator. The basic concept of NCTF controller is to drive the state of a plant to tracking the phase plane trajectory by a state feedback control scheme where the feedback is a continuous function of time. Signal shown in Fig. 5 represents the difference between the actual error rate $\dot{e}$ and that of the NCT. The compensator, PI controller, is used to make the object follow the NCT and end at the origin of the phase plane (e, $\dot{e}$). However, the actual error rate of plant could be noisy and that flusters the output of compensator.

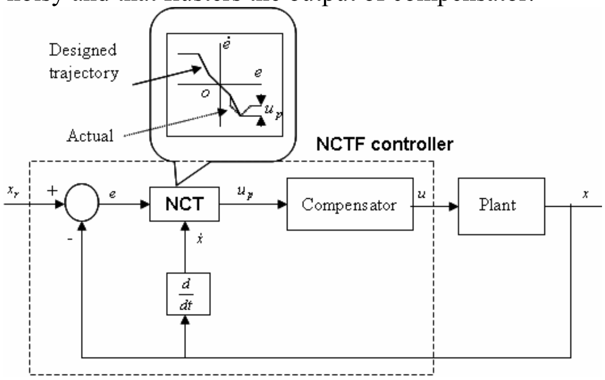

Fig. 5 Structure of the NCTF control system.

In this research, an NCTF tuned PID controller is implemented, as Fig. 6, by taking the advantage of both NCTF and PID to reach good control performances. The proportional gain of PID controller is dynamically tuned by the output signal of NCTF. The phase trajectory of the object is expected to track the designed phase trajectory.

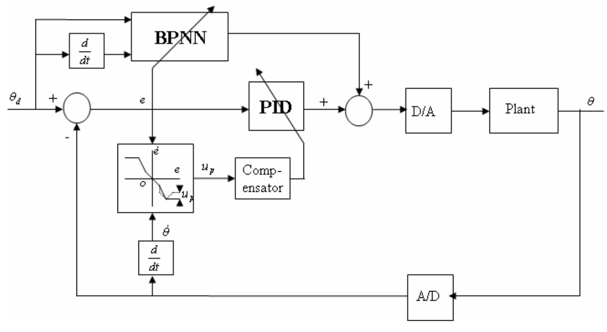

Fig. 6 Structure of the NCTF-based PID control system.

5. Implementation

The schematic diagram of experimental device u_p is shown in Fig. 7. The closed loop control system includes piezo actuator, high voltage driver, position sensor, A/D-D/A converters and controller. The training data was generated by exciting a piezo actuator with the exciting voltage signal with fixed-magnitude decreasing-frequency, decreasing-magnitude decreasing-frequency and decreasing-magnitude increasing frequency, as shown in Fig. 8(a)(b) and (c) respectively.

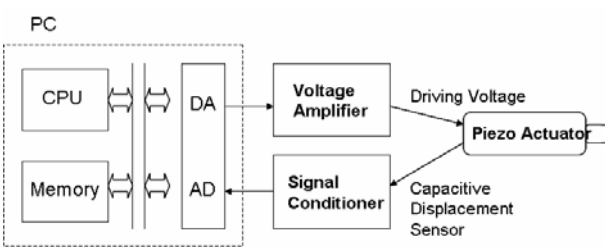

Fig. 7 Block diagram of the experimental device.

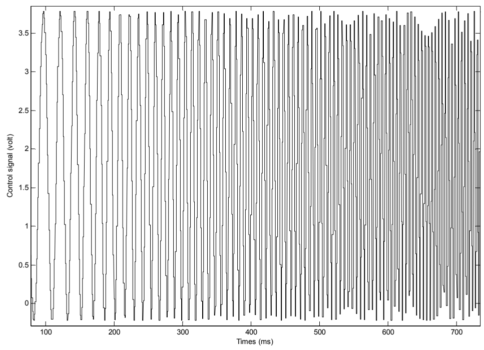

Fig. 8(a) Excitation decreasing-frequency and fixed-magnitude

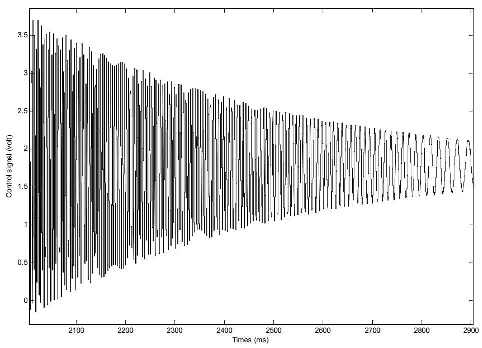

Fig. 8(b) Excitation decreasing-frequency and decreasing-magnitude

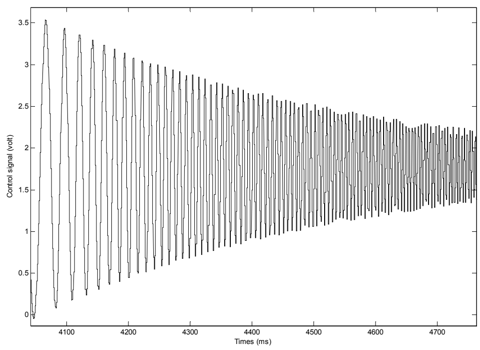

Fig. 8(c) Excitation increasing-frequency and decreasing-magnitude

To investigate the effectiveness of the proposed control design, the displacement tracking responses of the piezo actuator is demonstrated using the PC-based control system. The experimental results due to step and chaotic time series are shown in Fig. 9 and Fig. 10(a); a microscopic view of the tracking response is shown in Fig. 10(b); the tracking error is shown in Fig. 10(c). From the experimental results shown in Fig. 9 ~ Fig. 10(c), the tracking performance of the NCTF tuned PID controller augmented with inverse hysteresis model is good for the tracking command.

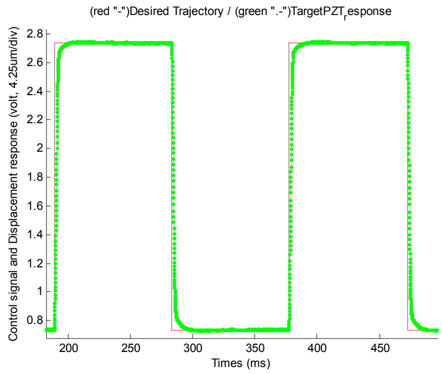

Fig. 9 The step responses of piezo actuator with the inverse hysteresis compensator and NCTF tuned PID controller

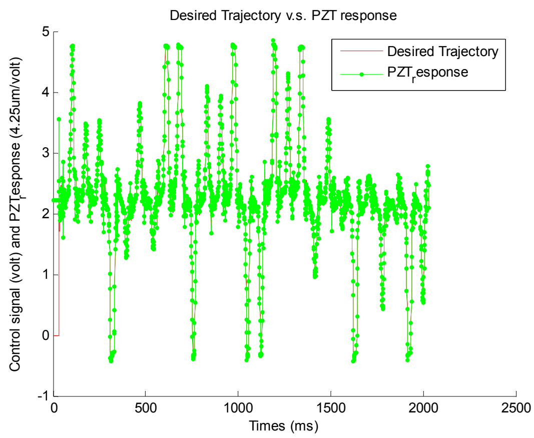

Fig. 10(a) The tracking performance

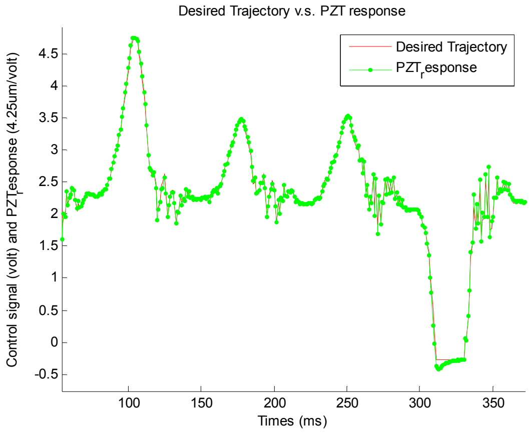

Fig. 10(b) A microscopic view of tracking performance

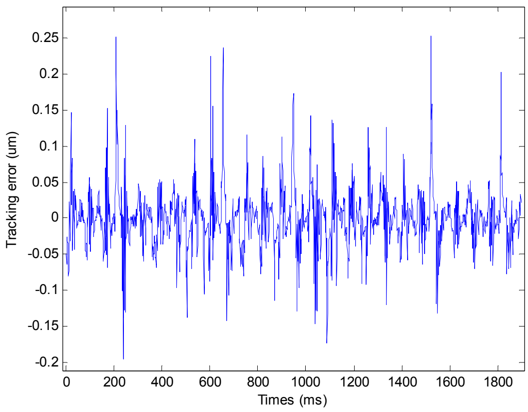

Fig. 10(c) The compensation of tracking performance

6. Conclusions

In this report, an approach for modeling hysteresis nonlinearity in a piezo actuator is investigated with control input extrema and rate. A hybrid controller is designed combining inverse hysteresis compensator and NCTF tuned PID controller to overcome the bounded modeling error and external disturbance. The proportional gain of PID controller is continuously scheduled based on the NCTF information without chattering and high frequency oscillation caused by some discontinuous control signals. As a result, the high-precision tracking ability is obtained.

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附件二

可供推廣之研發成果資料表

☐ 可申請專利　☐ 可技術移轉　日期：97 年 10 月 27 日

國科會補助計畫	計畫名稱：微奈米壓電平台之數位控制系統 計畫主持人：林錫寬教授 計畫編號：NSC 96-2221-E-009-237　學門領域：控制學門
技術/創作名稱	結合反遲滯補償和 NCTF 調整型 PID 的控制器
發明人/創作人	黃煥祺與林錫寬
技術說明	中文： 一種結合反遲滯補償和 NCTF 調整型 PID 的控制器。在反遲滯補償上，使用類神經網路或取描述 Presisach 模型。經由加上極值和速率，對於遲滯的主迴路和次迴路都可以附有速率相關的行為。NCTF 調整型 PID 的控制器可以清除干擾的影響，進而改善位置和追蹤控制的精度，還能兼顧系統穩定性。這種壓電平台數位控制器已經經過實驗的驗證。
	英文： A hybrid controller is the combination of the inverse hysteresis compensator and NCTF tuned PID controller. A feedforward neural network is defined to describe the Preisach model. This model is extended with two additional inputs--- input extrema and input rate, to identify the piezo actuator’s rate-dependent hysteresis behavior throughout the major loop and minor loops. An NCTF tuned PID controller augmented with inverse hysteresis model is then developed to compensate the hysteretic behavior, modeling error, and disturbance to improve the positioning/tracking stability and accuracy. The effectiveness of this algorithm is experimentally verified through the tracking control of a piezo actuator.
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