ADAPTIVE CONTROL FOR A PIEZOELECTRIC-ACTUATING TABLE BASED ON LUGRE FRICTION MODEL WITH FUNCTIONAL APPROXIMATION COMPENSATION

1SHIUH-JER HUANG, 2KUAM-LIAN HER

1, 2Department of Mechanical Engineering, National Taiwan University of science and technology
E-mail: 1sjhuang@mail.ntust.edu.tw, 2ml10603430@mail.ntust.edu.tw

Abstract - A long range friction actuating mechanism was designed by using piezoelectric material to generate high frequency oscillation for actuating a finger tip which contacted with a slide to induce the back and forth motion. The LuGre friction model is chosen to simulate the dynamics of this friction actuating mechanism. However, this piezoelectric actuating system has obvious nonlinear and time-varying dead-zone offset control voltage due to the static friction and preload. It is difficulty to establish an accurate dynamic model for model-based precision control design. Hence, the functional approximation (FA) scheme is employed to compensate the system modeling error. The Lyapunov-like design strategy is adopted to derive the adaptive laws and the system stability criterion. The dynamic experimental results of the proposed controller are compared with that of a model-based PID controller.

Keywords - Piezoelectric actuator, LuGre friction model, FA based adaptive control.

I. INTRODUCTION

Due to the precision manufacturing requirements of semi-conductor related industry, the precise position control technology and positioning mechanism are important developing targets. Hence, the piezoelectric actuating element is the key component of micro/nano level positioning system. Piezoelectric material has the advantages of small size, quick response speed, high transformation efficiency between mechanical and electric properties, and accurate resolution. It has been widely selected as an actuator of micro positioning table. However, it has the disadvantages of small travel, serious hysteretic behavior and small tension or torsion capability.

In order to improve the defects of small travel and low tension capability, a friction actuating mechanism was designed by choosing piezoelectric material to generate high frequency oscillation for actuating a finger tip which contacted with a slide to induce the back and forth motion. This piezoelectric actuating X-Y table is manufactured by Nanomotion Ltd. Company with 100 mm travel range. Under a designed 39.6 KHz sinusoidal input voltage wave form, the combination of the PZT element longitudinal and bending deformations will induce the finger tip back and forth motion. The friction force between the front head of the finger tip and the slide contact surface is used to drive the linear motion of the slide. However, the static friction due to preload and motion contact between the finger tip and slide has caused an obvious starting offset control voltage. It is called as dead-zone offset control voltage in this study. It is a time-varying and temperature dependent value. If this friction phenomenon has not appropriately modeled and considered in the controller design, it will cause the oscillation and large tracking error in transient response and steady state error. The literature reviews of friction problem study and friction models investigation were proposed in [1].

The friction behaviors can be divided into static friction, coulomb friction, stick friction stricbeck effect and hysteretic phenomenon. Dahl [2] proposed a Dahl model to describe the spring-like starting friction behavior. However, it can not describe the stricbeck friction effect. Canudas et al. [3] extended Dahl model to include stricbeck effect, hysteretic and varying break-away force and proposed a LuGre friction model. It is widely employed in the friction simulation and model-based control compensation.


The friction force is considered as a time-varying unknown estimation component without model information. Lin and Peng [12] designed a model-free neural controller for handling the problem of friction force is function of local position and operation temperature. But it has about 0.5 mm error appearing at the acceleration discontinuous location. Wai et al.
Adaptive Control for a Piezoelectric-Actuating Table Based on LuGre Friction Model with Functional Approximation Compensation

[13] proposed a robust fuzzy neural network controller to compensate the nonlinear friction behavior of this piezoelectric actuating table to reach 0.08mm accuracy. Mainali et al. [14] designed a hybrid sliding mode control and iterative learning control methods and then used to learn the friction disturbance repeatedly. Tan et al. [15] employed an exponential friction model to design a learning nonlinear PID controller. These model-free approaches need long period of learning for improving the control accuracy.

In order to improve the controller designing facility, a LuGre friction model is chosen and identified for this PZT actuating X-Y table for model-based adaptive controller design. Since the friction behavior of this experimental system has nonlinear and time-varying features, the functional approximation (FA) scheme [16] is employed to compensate the system modeling error of LuGre model. The control performances of a PID and the proposed adaptive control are compared based on experimental results.

II. THE EXPERIMENTAL SYSTEM STRUCTURE

A PC based controller is developed for this experimental system. This X-Y table has two independent axes x and y actuated by two different piezoelectric actuators. The experimental layout of this positioning system is shown in Fig. 1. This positioning table can be used in micro or/sub-micro level optical axis alignment of laser diode and lithography applications.

The control voltage is calculated in PC, which is converted from digital to analog signal by a D/A interface card, and sent to the piezoelectric actuator’s driver unit to actuate a piezoelectric motor. This X-Y table’s displacements are measured by linear encoders, and sent back to PC through encoder card for closed loop control. The resolution of linear encoder is 0.1 μm, and the maximum measuring range is 100mm. HR2 motor was used to actuate axis x, and HR4 motor was used to actuate axis y.

If the offset control voltage used to compensate the friction dynamics is deducted from the control law, there is a linear response feature between the piezoelectric mechanism sliding velocity and the driver control voltage. The actuator and driver can be modeled as a DC-motor with internal friction, which is driven by a voltage amplifier, as Fig. 2. When a command voltage within ±10V is sent to the driver unit, the driver generates a 39.6KHz sinusoidal wave for driving the actuator with an amplitude function of the command voltage. This constant oscillation frequency is generated from the driver unit which was supplied by Nanomotion Ltd.

where Vin is the command voltage of the driver (-10 ~ +10V) and offset is the dead zone voltage value (V). This offset voltage is a position dependent time-varying value which will be discussed in the next section. Kf is the force constant (N/V) and Kfv is the velocity damping factor (N×sec/m). Vel is the slide velocity (m/sec) and M is the moving mass (kg). S is the Laplace variable.

III. FRICTION MODEL OF THIS PIEZOELECTRIC ACTUATING TABLE

The main friction force components of this PZT actuating table can be divided into static friction and stiction effect viscous friction. If the control voltage is increased slowly from zero, the control voltage used to overcome the mechanism stick friction and preload can be found when it begins to move. This starting control voltage has nonlinear characteristic, and it is function of position, moving direction and temperature. It is called the dead-zone offset voltage.

If the experimental payload is small comparing to the 36N nominal preload, and the specified moving speed is much less than the 250 mm/sec maximal allowable velocity, the linear inversely proportional behavior of actuating force with respect to velocity can be ignored. The slide motion speed will be linearly increased with respect to the control voltage increasing. Hence, this dead-zone stick friction control voltage can be measured by experimental testing. Fig. 3(a) and 4(b) are the measured motion speed with respect to control
Adaptive Control for a Piezoelectric-Actuating Table Based on LuGre Friction Model with Functional Approximation Compensation

The model parameters of this LuGre dynamic model, equation (1-3) and static LuGre model, equation (4) can be identified based on experimental data by using nonlinear optimal operation scheme. Firstly, the steady state friction model is rewritten as:

\[ F_{ss} = (\alpha_0 + \alpha_1 e^{-v_i/v}) \text{sgn}(v) + \sigma_v v \]

(5)

The parameters \( \alpha_0 \), \( \alpha_1 \), \( \sigma_v \) and \( v_s \) can be estimated from the experimental friction-velocity curve. The friction force is calculated from the control voltage and the \( K_f \) (N/V) value of PZT data sheet. The constant velocity experimental data is obtained by designing a PI controller for speed control. The cost function is defined as:

\[
\min_{\alpha_0, \alpha_1, \sigma_v, v_s} \sum_{i=1}^{n} \left[ F_{ss}(v_i) - F_{ss}^0(v_i) \right]^2
\]

(6)

The function “fminunc” of Matlab optimization toolbox is used as the optimization scheme for estimating the steady state friction model parameters. For example, the parameters for the x direction axis are:

Positive velocity: \( \hat{\alpha}_0 = 0.6113, \hat{\alpha}_1 = 0.0699, \hat{\sigma}_v = 0.0108, \hat{v}_s = 0.1035 \)

Negative velocity: \( \hat{\alpha}_0 = 0.6337, \hat{\alpha}_1 = 0.1349, \hat{\sigma}_v = 0.019, \hat{v}_s = 0.1857 \)

IV. MODEL-BASED PID CONTROL AND ADAPTIVE FUNCTIONAL APPROXIMATION COMPENSATION CONTROL

In order to investigate the feasibility of using this identified LuGre friction model for designing model-based controller, a sinusoidal wave trajectory is planned to evaluate the tracking control performance of a traditional model-based PID controller. The PZT system dynamics can be represented as:

\[ m \ddot{x} = K_f (K_p \dot{e} + K_p e + \sum K_i \delta - F_{friction} + d(x,t)) \]

(7)

Where \( m \) and \( K_f \) are known mass and force/voltage gain of this PZT actuating system. \( F_{friction} \) and \( d(x,t) \) are the estimated LuGre friction force and unknown disturbance, respectively. The PID control gains are \( K_p = 10 \), \( K_i = 0.007 \) and \( K_d = 0.0002 \). The dynamic response trajectory, tracking error and the friction force for tracking a 0.5Hz 1mm amplitude sinusoidal wave are shown in Fig. 4. It can be observed that the tracking error has obvious peak appearing in the motion direction (velocity) change. That means the LuGre model based PID control of this specific PZT friction actuating mechanism cannot correct the error on-time at these positions. Hence, the concept of Karnopp’s model [1] is adopted to modify the LuGre friction model as:

![Fig. 3 Dead-zone offset voltage of real movement](image-url)
\[ F_{\text{fict}} = \begin{cases} 
-\mathbf{u} & |x| < \delta, |y| < f_{\text{max}}, |y| > \phi \\
-\max_{\mathbf{x}} \mathbf{c}(\mathbf{u}) & |x| < \delta, |y| > f_{\text{max}}, |y| > \phi \\
\text{LuGre model} & |x| \geq \delta, |y| \geq f_{\text{max}}, |y| > \phi 
\end{cases} \]

(8)

Where \( f_{\text{max}} \) and \( u = K_y \dot{y} \) are the maximum static friction force and actuating force of the PZT actuator, respectively. The dynamic response trajectory, tracking error and the friction force for tracking a 0.5Hz 1mm amplitude sinusoidal wave by using the modified LuGre model are shown in Fig. 5. It can be observed that the tracking errors at the motion direction (velocity) change positions have been reduced significantly from 0.08mm to 0.03 mm. Since this PZT friction actuating mechanism has large static friction and time-varying behavior, the LuGre model can not always accurately track this plant slow speed dynamics. Hence an adaptive functional approximation scheme is adopted to model this friction modeling error. The system dynamics can be written as

\[ m\ddot{x} + K_y \ddot{y} - \tilde{F}_{\text{fict}} + d(x,t)e = K_y \ddot{y} - \tilde{F}_{\text{fict}} + f(x,t) \]

(9)

If the control law is designed as

\[ \dot{u} = \frac{1}{K_y} [m\ddot{x} + \tilde{F}_{\text{fict}} - \tilde{f} + k_0 e + k_1 \dot{e}] \]

(10)

Where \( e = x_d - x \) and \( \tilde{f} \) is the estimated value of the friction modeling error and dynamics uncertainty by using finite terms functional approximation function. The unknown time-varying function \( f(x,t) \) in equation (9) can be approximated by a linear combination of finite orthogonal basis functions \( Z(t) \) to arbitrarily prescribed accuracy as long as \( n \) is larger enough [16].

\[ \tilde{f}(x,t) \approx W_f^T Z_f(t) \]

(11)

where \( Z_f(t) \) is an orthogonal basis function vector and \( W_f \) is a weighting coefficient vector. If the number of basis functions is large enough, equation (11) can be described as the following approximation form.

\[ f(X, t) = W_f^T Z_f(t) \]

(12)

where \( Z_f(t) = [Z_0(t) \ Z_1(t) \ ... \ Z_n(t)]^T \), and \( W_f = [W_0 \ W_1 \ ... \ W_n]^T \). This functional approximation equation (12) can be used to represent an unknown function with uncertainty and disturbance. The time-varying vector \( Z_f(t) \) is a known function and the vector \( W_f \) is an unknown regulating constant. A proper Lyapunov function can be selected to find the update laws for these unknown constants based on Lyapunov stability theory. The Lyapunov-like function is chosen as the summation of the square of system output error and parameters error \( \dot{V}(\Theta, W_f) \).

\[ V(E, \dot{W}_f) = E^T PE + \dot{W}_f^T Q_f \dot{W}_f \]

(13)

Taking the time derivative of equation (13) and substituting the dynamic equations (9-10), the function parameters update law and Lyapunov-like function converging properties can be derived as:

\[ \dot{W}_f = Q_f^{-1} Z_f b^T PE - \sigma \dot{W}_f \]

(14)

\[ \dot{V} = -E^T Q E \leq 0 \]

(15)

Where \( b^T = [0, K_y / m] \) is this dynamic system input gain vector and the right hand side second term of equation (14) is used to improve the parameter convergence property. That means this adaptive control system has globally stable property and the tracking error will be converged into certain error bound, which depends on the modeling accuracy.

V. EXPERIMENTAL RESULTS

In order to achieve a smooth motion response, the 3rd order polynomial is chosen to plan the ideal moving trajectory between two positions.

\[ L(t) = a_0 t + a_1 t^2 + a_2 t^3 \]

(16)

The boundary conditions are

\[ L(t_i) = L_i, \ \dot{L}(t_i) = \dot{L}_i \]

(17)

\[ L(t_f) = L_f, \ \dot{L}(t_f) = \dot{L}_f \]

(18)

Then the coefficients of equation (4) can be solved as

\[ a_0 = L_i, a_1 = \dot{L}_i, a_2 = \frac{3(L_f - L_i) - T(2\dot{L}_i + \dot{L}_f)}{T^2}, a_3 = \frac{-2(L_f - L_i) + T(\dot{L}_i + \dot{L}_f)}{T^3} \]

(19)

where \( L_i \) is the initial position of a trajectory, \( L_f \) is the final position of a trajectory, \( t_i \) is the initial time, \( t_f \) is the final time and \( T = (t_f - t_i) \) is the motion time.

In previous literatures, the control objective of a micro-positioner is focused on the steady state accuracy of a step input response [17-18]. Usually, the transient response between each step change is not investigated for slow micro-stepping motion. If the moving speed and the step change are increased, the
transient response should be concerned, too. Since this piezoelectric actuating table is driven by a PZT actuating finger tip instead of PZT directly, it has larger moving travel. Hence both the steady state accuracy and the transient state tracking error need be investigated in this study. In order to evaluate the control performances of the LuGre friction model based PID control and the modified LuGre model with adaptive functional approximation compensation controller, different moving speeds and travels are planned for experimental evaluation. The 400 Hz sampling frequency was chosen for the following experiments.

(A) LuGre friction model based PID control
The appropriate control gains of this PID controller are chosen as \( K_p = 10 \), \( K_d = 0.007 \) and \( K_i = 0.0002 \) after a trial-and-error test. The modified LuGre friction model, eq. (8) is employed. The average velocity of a moving trajectory with 3rd order polynomial is specified as 2mm/sec. The tracking response, error history and control voltage of x axis by using a PID control are shown in Fig. 6(a), 6(b) and 6(c), respectively. Although the final steady state error is less than 5\( \mu \)m, the maximum middle lag is 18 \( \mu \)m, and the initial periods has a 12 \( \mu \)m oscillation due to the dead-zone offset control voltage chattering. In addition, the control gains need be searched by a trial-and-error process for each different motion situation to obtain reasonable control performance. It is not convenient for practical implementation. For example, the experimental results of tracking a 3rd polynomial with 5mm/sec average speed by using this PID controller are shown in Fig. 7. It can be observed that the maximum middle lag is 70 \( \mu \)m, and the initial and settling periods have a 20 \( \mu \)m oscillation. The control voltage is smooth except at the initial starting area with moving directions change due to dead-zone offset control voltages.

(B) Modified LuGre model with adaptive functional approximation compensation
The LuGre friction model, eq. (8) is employed and the adaptive functional approximation control parameters are listed in Table 1. The tracking control experimental responses of this piezoelectric actuating table by using the proposed adaptive FAT controller of x axis are shown in Fig. 8 with 5 mm/sec average planning speeds. It can be observed that the steady state error is less than 0.3\( \mu \)m and the initial learning period tracking error is less than 20 \( \mu \)m. The maximum middle lag is less than 10 \( \mu \)m. The control voltage chattering phenomenon only appears at initial learning and final stop positions. The proposed adaptive FAT LuGre friction model based controller can be employed in different moving speeds without trial-and-error effort for finding control parameters. The dynamic response and tracking error history of Y axis for tracking a sinusoidal wave with 1 mm amplitude are shown in Fig. 9. It can be observed that the tracking error always keep within 35 \( \mu \)m and the steady state error can reach 0.5 \( \mu \)m positioning accuracy. It can be concluded that the proposed adaptive FAT LuGre friction model based controller can effectively controlled this heavy friction and nonlinear PZT actuating mechanism to reach sub-micro level precision control accuracy. It also can be observed from these experimental results that the steady state error can converge into 0.3\( \mu \)m finally for each case. In addition, the chattering phenomenon of control voltage is improved by using the modified hybrid Karnopp + LuGre friction.

VI. CONCLUSION
The LuGre friction model is chosen to model the friction dynamics of a piezoelectric actuating system. The concept of Karnopp’s model is adopted to modify the LuGre friction model for model-based PID controller. The FAT is employed to design an adaptive control loop for compensating the modeling error and system dynamics uncertainty. The adaptive law is derived from the Lyapunov-like stability criterion to obtain the system converging property and stability. The tracking errors of a 3rd polynomial trajectory and a sinusoidal wave trajectory are kept within 20 \( \mu \)m and the final steady state error is less than 0.3 \( \mu \)m for both axes by using the proposed adaptive FAT hybrid LuGre model controller. These dynamics performances are better than that of a LuGre friction model based PID controller. In addition, the proposed adaptive controller can be employed to monitor different planning trajectory and speeds with the same control structure and parameters. In addition, the chattering phenomenon has been improved significantly by using the proposed adaptive controller.

REFERENCE
Adaptive Control for a Piezoelectric Actuator with Mismatched Uncertainties

Adaptive Functional Approximation Control

Table I Adaptive Functional Approximation Control Parameters

Fig. 4 The dynamic response trajectory, tracking error and the friction force for tracking a 0.5Hz 1mm amplitude sinusoidal wave by using PID control.

Fig. 5 The dynamic response trajectory, tracking error and the friction force for tracking a 0.5Hz 1mm amplitude sinusoidal wave based on modified LuGre model.

Fig. 6 The tracking response, error history and control voltage of axis x by using a PID control with 2 mm/sec average speed.

Adaptive Control for a Piezoelectric-Actuating Table Based on LuGre Friction Model with Functional Approximation Compensation
Adaptive Control for a Piezoelectric-Actuating Table Based on Lagre Friction Model with Functional Approximation Compensation

Fig. 7 The tracking response, error history and control voltage of axis x by using a PID control with 5 mm/sec average speed.

Fig. 8 The dynamic response, tracking error histories, control voltage, and estimated driving force for 5 mm/sec average speed.

Fig. 9 Dynamic response and tracking error of y axis with 1 mm amplitude sinusoidal wave by using proposed adaptive FAT Lagre model compensation.