Development of a novel multi-axis nano-positioning and the spiral tracking control


Keywords : Piezoelectric, Hysteresis, Capacitance Sensor, Sliding-mode control, Precision Stage

ABSTRACT

This paper presents the design of a sliding-mode controller for a piezoelectric-driven nanometer resolution stage. The nanometer resolution stage is developed using the features of a flexible structure, and is driven by piezoelectric actuators and also uses capacitance sensors for position feedback. The hysteresis characteristic of the piezoelectric actuators is one of the major deficiencies in a wide variety of precise tracking positioning controls. In order to design the control system, the open-loop characteristics of this nanometer resolution stage are investigated. According to the open-loop characteristics, each pair of piezoelectric actuator and capacitance sensor is treated as an independent system and modeled as a first order linear model coupled with hysteresis. When the model is identified, the hysteresis nonlinearity is linearized then the linear system model with uncertainty is used to design the controller. When designing the controller, the sliding-mode disturbance estimation and compensation scheme is used. The structure of the proposed controller is similar to the PID controller. Thus, it can be easily implemented.

INTRODUCTION

In recent years, as the result of rapid developments in various fields of precision engineering, there has been a big increase in the need for precision positioning. In the precision positioning applications, it is often required that actuators have nanometer resolution in displacement. Piezoelectric actuators are known for their unique features of quick response, high resolution, electrical mechanical coupling efficiency, and low heat. So, they are usually used in positioning technology to control the system and achieve nanometer resolution in displacement. The piezoelectric actuator has many advantages such as: 1. response is fast; 2. efficiency is high; 3. there is no moving parts; 4. the actuators can produce large forces; 5. they have almost unlimited resolution [1-7]. However, it also has some disadvantageous characteristics such as: 1. temperature dependence; 2. drift in time; 3. hysteresis behavior. The disadvantageous characteristics of hysteresis are usually nonlinearities and uncertainty. Therefore, it is difficult to obtain an accurate trajectory tracking control. In order to compensate for the hysteresis of the piezoelectric actuator, many methods have been studied. These methods can be separated into two approaches: feedforward control [8-13] and inverse control [14-18]. In 1996, Ge and Jouaneh used a combination of a proportional integral derivative (PID) feedback controller with a feedforward controller that included the Preisach model of hysteresis. Their experimental results showed that the tracking performance was improved greatly. However, the result in 1996 is only valid for a sinusoidal trajectory and the method in 1997 needs the model to be trained by using reference input before the control started. In 2000, Ku et al. combined a PID feedback controller with an adaptive neural network feedforward controller to control a nanopositioner that was actuated by a piezoelectric actuator. In the inverse control approach, Cruz-Hernandez and Hayward proposed a variable phase
method in 2001. They utilized an operator to shift the periodic input signal by a phase angle that depended on the amplitude of the input signal and then used this operator to reduce the hysteresis nonlinearity. In 2004, Huang and Lin proposed a new hysteresis model based on two first-order transfer functions in parallel with two parameters determined from experiment. Adaptive control is also an approach to the inverse control of plants with hysteresis behavior. In 1995, Tao and Kokotovic developed an adaptive hysteresis inverse and cascaded it with the system so that the effects of hysteresis nonlinearity could be reduced. In 1993, Xu utilized an adaptive neural network inverse controller to compensate the hysteretic behavior of a piezoelectric actuator and a PI controller in the outer loop to overcome the remaining nonlinear uncertainty. In 2001, Hwang et al. utilized an offline learned neural network model to reduce the effect of hysteresis then designed a discrete-time variable structure controller to overcome the remaining uncertainty. They also reinforced this method by using a recurrent neural network to improve the control performance. However, the computation burden of the controller that was designed by their method is heavy.

In this paper, an integral sliding-mode controller for a piezoelectric-driven system is presented. Firstly, the piezoelectric-driven system was modeled as a first order uncertain linear model coupled with an hysteresis nonlinearity. Then the hysteresis nonlinearity was linearized and the resulting uncertain linear model was used to design the sliding-mode controller. In this study, the sliding-mode uncertainty estimation and compensation scheme is used [19]. Since the model of the system is first order, the structure of the proposed controller is as simple as the PID controller. Therefore, it can be implemented easily. Finally, this design method was applied to the motion control of a nano-stage. The experimental results are presented that verify the usefulness of this method.

THE STRUCTURE OF THE NANOMETER STAGE

This paper uses the features of a flexible structure to develop a novel flexure hinge-based stack-type 5 DOF piezoelectric-driven nanometer resolution stage. It is composed of six piezoelectric actuators, six capacitance sensors, eight rotational flexure hinges, two micrometers, two preload adjustments and a rigid base. The structure of the stage is shown in Fig.1 [20].

![Fig. 1. Schematic drawing of the novel flexure hinge-based stack-type 5 DOF piezoelectric-driven nanometer resolution stage.](image)

There are many parts of the flexible structures in the nanometer resolution stage. These flexible structures were all assembled by a pre-baking process, and are all made the parts are out of medium carbon steel. The stage uses piezoelectric actuators instead of conventional actuators. The Piezomechanik GmbH PSt150/7/20 Vs12 is 28 mm long with an outside diameter of 12 mm. The electrodes of the actuator were deposited in the outside and inside surfaces of the PZT tube, which provided a maximum displacement of 20 µm with an excitation of 150V. The piezoelectric actuators were fastened at each end to the rigid base using the preload adjusting mechanisms. The nanometer resolution stage allows for 3 translational and 2 rotational motions, and is provided with six piezoelectric actuators – one on the X-axis, another on the Y-axis, and the others on the Z-axis. There are six high-resolution capacitance sensors provided inside the stage to measure the displacement of the nanometer resolution stage. The Physik Instrumente D-015 has a displacement resolution of 0.01nm. The total range of the capacitance sensors was 15µm with a sensitivity of 0.66V/µm.

THE MEASURING SYSTEM

In this nanometer resolution stage, the measuring system was developed using six capacitance sensors. All of the capacitance sensors were installed inside the structure of the nanometer resolution stage. Four capacitance sensors (Z1 sensor, Z2 sensor, Z3 sensor and Z4 sensor) were installed on the structure of the moving mechanism. Two capacitance sensors (X sensor and Y sensor) were installed on the side of the moving mechanism. The schematic drawing is shown in Fig.2.
The displacement characteristics of the output member of the nanometer resolution stage were measured with the built-in capacitance sensors. The performance of the x-axis and y-axis could be measured by the capacitance sensors (X sensor and Y sensor). The performance of the z-axis and the rotational mutation along the X-axis ($\theta_x$) and Y-axis ($\theta_y$) could also be measured by the capacitance sensors (Z1 to Z4).

The relation of the rotational angle $\theta_x$ and $\theta_y$ between the displacement measured by the capacitance sensors (Z1 to Z4) and the displacement of the center of the stage platform in the Z-axis can be obtained as:

$$Z1 = Z + r_1 \sin \theta_x + r_2 \sin \theta_y,$$

$$Z2 = Z + r_1 \sin \theta_x - r_2 \sin \theta_y,$$

$$Z3 = Z - r_1 \sin \theta_x - r_2 \sin \theta_y,$$

$$Z4 = Z - r_1 \sin \theta_x + r_2 \sin \theta_y,$$

respectively. The distance of $r_1$ or $r_2$ (51mm) is half the distance between the center of sensors Z1 and Z2 or Z3 and Z4. Note that $\theta_x$ is small, therefore, $\sin \theta_x \approx \theta_x$ and $\sin \theta_y \approx \theta_y$. The geometric relation is shown in Fig. 3. The relations between Z1, Z2, Z3, Z4, Z, $\theta_x$ and $\theta_y$ can be summarized as:

$$\begin{bmatrix}
X \\
Y \\
Z1 \\
Z2 \\
Z3 \\
Z4
\end{bmatrix}
= \begin{bmatrix}
1 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 \\
0 & 0 & 1 & -r & 0 \\
0 & 0 & 1 & r & 0 \\
0 & 0 & 1 & 0 & -r \\
0 & 0 & 1 & 0 & r
\end{bmatrix}
\begin{bmatrix}
X \\
Y \\
Z \\
\theta_x \\
\theta_y
\end{bmatrix}$$

(1)

THE CONTROL SYSTEM

The control system is shown in Fig. 4. It includes a personal computer, a Dspace card (DS1103), an analog amplifier (SVR 150/3), eight Piezoelectric actuators (PSt150/7/20 Vs12), a nanometer resolution stage, six capacitance sensors (PI, D-015) and a sensor signal processor (PI E-509). The control procedure used was the MATLAB software for compiling the control blocks and compiled the Dspace card (DS1103). By using the DSP card (DS1103), the control blocks could be executed and also the digital/analog signals processed. The amplifier (SVR 150/3) supplied the required voltage to the piezoelectric actuators (PSt150/7/20 Vs12) of the nanometer resolution stage. The axial displacement of the nanometer resolution stage could be measured by using the capacitance sensors (PI, D-015) and the signal was then sent to the signal processor (PI, E-509).
THE OPEN-LOOP DYNAMIC CHARACTERISTIC TESTING OF THE NANOMETER RESOLUTION STAGE

Before the controller could be designed, it was necessary to understand the open-loop characteristics of this nanometer resolution stage. In this study, the input voltage was increased from 0V to 150V and decreased from 150V to 0V. The displacement of the nanometer resolution stage could be detected via the capacitance sensors. The test results are shown in Fig. 5. From the results, it is found that the moving ranges of the X-axis, Y-axis, Z1-axis, Z2-axis, Z3-axis and Z4-axis are about 10.83µm, 11.67µm, 14.43µm, 15.2µm, 14.49µm and 13.95µm respectively. Moreover, the coupling effects between the X-axis, Y-axis, Z1-axis, Z2-axis, Z3-axis and Z4-axis are less than 27%.

THE SYSTEM MODELING AND CONTROLLER DESIGN

In the control system design, the whole control system was divided into six single-input-single-output sub-systems. Each sub-system consisted of a piezoelectric actuator and its corresponding capacitance sensors. Then, the controllers were designed for each sub-system independently and regarded the coupling effects between each sub-system as disturbances.

System Model

In order to control the nanometer resolution stage well, it is necessary to design the controller. According to the open-loop dynamic characteristic testing results described in previous section, the sub-system can be modeled by a first order uncertain linear system coupled with a hysteresis nonlinearity as shown in Fig. 6.

\[ u \rightarrow H \rightarrow Y \rightarrow T(1+\Delta(t))\dot{x} + x = v \rightarrow x \]

Fig. 6. Model of the sub-system.

Where \( u \) is the input, \( H \) describes the hysteresis behavior of the piezoelectric actuator, \( d \) represents the disturbance, and the first order differential equation

\[ T(1+\Delta(t))\dot{x} + x = v, \tag{2} \]

describes the dynamic behavior of the sub-system. Where \( x \) is the displacement, \( T \) is the nominal time constant and \( \Delta(t) \) represents the uncertainty. Parameter \( T \) and the bound of \( \Delta(t) \) can be determined by doing step response tests at various working points.

From Fig. 6, \( v \) can be represented as

\[ v = Ku + N(t) + d(t), \tag{3} \]

where \( K \) is the linearized gain of the hysteresis and \( N(t) \) represents the nonlinear uncertain part of the hysteresis. From (2) and (3), the following dynamic equation can be obtained:

\[ \dot{x} = -\frac{x}{T} + \frac{Ku}{T} + \phi(t), \tag{4} \]

where

\[ \phi(t) = \frac{\Delta(x - Ku) + N + d}{T(1+\Delta)}, \]

represents the disturbance and uncertainties.

Sliding-Mode Controller Design

This subsection describes how to design the sliding mode controller. In this study, the sliding mode disturbance (uncertainty) estimation and compensation scheme [14, 15] is applied to design the closed-loop controller for the sub-system.

Let \( x_d \) be the desired displacement, which may be time varying. Define

\[ e = x_d - x, \tag{5} \]

as the tracking error. From (4) and (5), the error dynamics can be obtained as

\[ \dot{e} = \dot{x}_d - \dot{x} = \dot{x}_d + \frac{x}{T} - \frac{K}{T}u - \phi(t), \tag{6} \]

Let the control law be

\[ u = \frac{x}{K} + \frac{T}{K}(\lambda e + \dot{x}_d) + u_d, \tag{7} \]

where \( \lambda \) is the feedback gain to be designed so
that the error dynamic will have the desired response while the system is free of disturbance and uncertainty, and $u_d$ is the uncertainty and the disturbance compensation component yet to be determined by the sliding mode estimator.

Defining the switching function as

$$ S = z - e, \quad (8) $$

with

$$ \dot{z} = -\lambda e - \frac{K}{T} u_d + \psi, \quad z(0) = e(0), \quad (9) $$

where $z$ is the state variable of this auxiliary process, $\psi$ is the switching action assigned as

$$ \psi = -\eta \text{sign}(S), \quad \text{sign}(S) = \begin{cases} 1 & \text{if } S > 0 \\ -1 & \text{if } S < 0 \\ 0 & \text{if } S = 0 \end{cases}, \quad (10) $$

and the positive constant $\eta$ satisfies

$$ \eta > |\phi(0)|, \quad (11) $$

Ensuring a sliding regime $S = 0$ requires consideration of the Lyapunov candidate $V = 0.5S^2$. Differentiating $V$ with respect to time and substituting (6-9) to obtain

$$ \dot{V} = S(\dot{z} - \dot{\psi}) = S[\phi(t) - 2\eta S\text{sign}(S) + \phi(t)], \quad (12) $$

From (11) and (12), it is seen that

$$ \dot{V} < 0 \quad \text{if } S \neq 0, \quad (13) $$

Thus the sliding condition is satisfied. Note that $z(0) = e(0)$, therefore

$$ S = 0 \quad \text{for } t = 0, \quad (14) $$

From (13) and (14), it can be concluded that the sliding mode exists at all times, i.e.,

$$ S = 0 \quad \text{for all } t \geq 0, \quad (15) $$

Denote the equivalent value of $\psi$ as $\psi_{eq}$. Since $S = 0$, $\psi_{eq}$ can be determined from (6), (8) and (9):

$$ \psi_{eq} = -\phi, \quad (16) $$

This means that the equivalent value of $\psi$ equals the uncertainties and disturbances. By selecting $u_d = \frac{T}{K} \psi_{eq}$, the uncertainties and disturbances can be compensated. It was shown in [15] that the equivalent $\psi_{eq}$ is equal to the average value measured by a first-order linear filter with the switched action as its input. Therefore, $u_d$ can be written as

$$ u_d = \frac{T}{K} \psi_{av} = \frac{T}{K} \psi_{eq}, \quad (17) $$

with

$$ \tau \psi_{av} + \psi_{av} = \psi, \quad (18) $$

The time constant $\tau$ should be made small enough that the plant and disturbance dynamics are allowed to pass through the filter without significant phase delay. Substituting (17) and (7) into (6) yields

$$ \dot{e} + \lambda e = -\psi_{eq} - \phi, $$

which is equivalent to $\dot{e} + \lambda e = 0$. This equation represents the desired error dynamics. Fig. 7 depicts the structure of this controller. It can be found that this controller is almost as simple as a PID controller.

![Fig. 7. Block diagram of the controller](image)

When designing the controllers, the gain for each actuator is obtained from Fig. 5 as 0.0722µm/V, 0.0778µm/V, 0.0962µm/V, 0.1013µm/V, 0.0966µm/V and 0.093µm/V respectively. The nominal time constant $T$ and the bound of uncertainty $\Delta$ can be obtained by step response tests. In order to obtain wider bandwidth, the $\lambda$ for each sub-system are chosen as large as possible. The controller parameters of the sub-system are shown in the Table 1.

<table>
<thead>
<tr>
<th>k</th>
<th>T(ms)</th>
<th>$\Delta$</th>
<th>$\lambda$</th>
<th>$\eta$</th>
<th>$\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-axis</td>
<td>0.244</td>
<td>3.6</td>
<td>2/3</td>
<td>550</td>
<td>9</td>
</tr>
<tr>
<td>Y-axis</td>
<td>0.262</td>
<td>3</td>
<td>2/3</td>
<td>500</td>
<td>9</td>
</tr>
<tr>
<td>Z$_1$-axis</td>
<td>0.339</td>
<td>3</td>
<td>2/3</td>
<td>550</td>
<td>8</td>
</tr>
<tr>
<td>Z$_2$-axis</td>
<td>0.361</td>
<td>4</td>
<td>2/3</td>
<td>550</td>
<td>8</td>
</tr>
<tr>
<td>Z$_3$-axis</td>
<td>0.346</td>
<td>3.6</td>
<td>2/3</td>
<td>550</td>
<td>8</td>
</tr>
<tr>
<td>Z$_4$-axis</td>
<td>0.333</td>
<td>4.2</td>
<td>2/3</td>
<td>550</td>
<td>8</td>
</tr>
</tbody>
</table>

THE TRACKING CONTROL RESULTS OF THE NANOMETER RESOLUTIONS STAGE

The experimental results of the piezoelectric-driven nanometer resolution stage are shown in Figs. 8-15. Fig. 8 and Fig. 9 show the tracking results of a 5 Hz sine wave with an
amplitude of 2.22µm amplitude. It can be seen that the X-axis and Y-axis can track the desired trajectory very well. Fig.10 shows the circular tracking control results of the X-axis and Y-axis and the triangle control result of the Z-axis. Fig.11 shows the tracking control errors of the X-axis, Y-axis and Z-axis. The tracking control error is about 20nm. Fig.12 shows the error analysis results of the circle tracking. Fig.14 and Fig.16 show the spiral tracking results. Fig.13 and Fig.15 show the spiral tracking results in the X-Z plane.

**Fig. 8.** The tracking control result of the X-axis.

**Fig. 9.** The tracking control result of the Y-axis.

**Fig. 10.** The circular tracking control result of the X-axis and Y-axis and the triangle control result of the Z-axis.

**Fig. 11.** The tracking control error of the X-axis, Y-axis and Z-axis.

**Fig. 12.** The error analysis results of the circle tracking.

**Fig. 13.** The tracking result in the X-Z plane (Upward).

**Fig. 14.** The spiral tracking result (Upward).

3.5
4
4.5
5
5.5
6
6.5
7
7.5
8
8.5
9
X ($\mu$m)
Z ($\mu$m)

X-Z plane
Z1
Z2
Z3
Z4
ref

Fig. 15. The tracking result in the X-Z plane (Downward).

Fig. 16. The tracking result of the spiral (Downward).

CONCLUSIONS

This paper used the state-space analysis and identification for the hysteresis to compensate the hysteresis error and also presented a sliding-mode controller of a five-degrees-of-freedom nanometer resolution stage. Experiments on tracking the sinusoidal waveforms, and triangle waveforms were carried out. From the results, it can be seen that the performance of the controller is good and 4nm circle tracking resolution can be obtained. The most important feature is that the proposed controller is as simple as a PID controller. Therefore, it can be implemented easily.

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一種創新多軸奈米定位平台建構與螺旋循軌控制

覺文郁 沈金鐘
國立虎尾科技大學自動化工程系

鄭友仁
國立中正大學機械工程學系

劉建宏
國立虎尾科技大學電光所

簡裕特
國立虎尾科技大學機械與機電所

王鴻澍
國立成功大學機械系

摘 要
本篇論文中藉由材料具有撓曲的特性，設計一創新多自由度奈米級微定位平台，並以壓電致動器作為驅動器以取代傳統的驅動方式，其平台內部並設計多組高解析度電容式探頭，針對微定位平台進行位移的檢測，而在控制器設計方面則採用順滑控制設計，針對微動平臺內部的壓電致動器進行遲滯建模與補償，使其微定位平臺能做到 3D 曲線循軌，並且循軌軌跡精度可達到 4 奈米。