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# 快速伺服刀架迟滞特性的 Preisach 建模

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**摘要:** 使用压电陶瓷作驱动元件的快速伺服刀架是一种新的加工手段。本文介绍了基于 Preisach 模型快速伺服刀架迟滞特性建模方法。作为快速伺服刀架的驱动元件, 压电陶瓷微位移器自身的迟滞、蠕变等非线性特性严重影响了快速伺服刀架的动态性能。为了精确建立快速伺服刀架的迟滞模型, 给出了 Preisach 模型的数字表达方式, 通过一系列实验测得的数据证明快速伺服刀架系统具有一致特性与擦除特性, 满足 Preisach 模型的两个必要条件, 最后在实验数据的基础上建立了基于 Preisach 模型的迟滞特性模型。实验表明, 该迟滞模型可以很好地预测快速伺服刀架的迟滞位移曲线, 其预测误差不超过  $0.65 \mu\text{m}$ 。

**关键词:** 快速伺服刀架; 压电陶瓷微位移器; Preisach 模型

**中图分类号:** TN384 **文献标识码:** A

## Preisach modeling of hysteresis for fast tool servo system

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**Abstract:** A fast tool servo mechanism with a piezoelectric actuator has attracted more attention for its excellent machining way and high resolution. In this paper, the classical Preisach hysteresis modeling for a Fast Tool Servo (FTS) system subjected to the dynamic voltage excitations is presented. As a universal driving element for the FTS system, the piezoelectric actuator exhibits specific nonlinearity from the hysteresis effect between the displacement and the applied electric field, which is a key factor limiting the dynamic performance of the FTS system. To establish a mathematical model to describe the hysteresis for the FTS system, the numerical expressions of the classical Preisach model are presented in details, and a series of test are conducted to study the hysteresis property and to find out the congruency and wipe-out properties of the FTS system. Finally, the classical Preisach model is applied to simulate the hysteresis behavior of the FTS system. Experimental results indicate that the measured curves are good agreement with the predicted curves, which shows that the classical Preisach model can offer excellent modeling accuracy less than  $0.65 \mu\text{m}$  and can provide many applications for requiring voltage excitation signals with narrow band frequencies.

**Key words:** fast tool servo; piezoelectric actuator; Preisach model

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## 1 Introduction

In recent years, ultra-precision machining techniques have been successfully implemented in the field of optical surface generation<sup>[1]</sup>. With the advent of improved machines, a fast tool servo mechanism has been attracting more and more interest to increase the capability and capacity of existing machines<sup>[2-4]</sup>. The purpose of the fast tool servo system is to move the tool small distance into and out of the workpiece several times, so it generates nonaxisymmetric surfaces or corrects for errors. Diamond turning using a fast tool servo is one of the most popular techniques in micro-machining because of its shorter machining time, better repeatability and easy setup. In order to achieve high resolution and high stiffness, piezoelectric actuator is used as the universal driving base of the fast tool servo system. However, piezoelectric actuators exhibit hysteresis in their response to an applied electric field<sup>[5]</sup>. Hysteresis in piezoceramic material is a form of nonlinearity with memory<sup>[6-8]</sup> depending on the history of excitation, so one of many possible expansions can be the result of a specific voltage applied to the piezoceramic.

This paper presents the classical Preisach model of the hysteresis for a fast tool servo system. Firstly, the numerical expressions of the classical Preisach model are presented in details for different input variations. A series of tests are conducted to study the hysteresis properties of the piezoelectric actuator. To implement this model, the congruency property has to be satisfied and a set of first-order hysteresis reversal curves are measured with the driving voltage starting from zero. Then the classical Preisach model is applied to simulate the static hysteresis behavior of the FTS system. This study can also provide means to assess whether the classical

Preisach model is useful for hysteresis compensation. The good accordance found between the measured and calculated curves shows that the classical Preisach model is an effective mean to model the hysteresis of the FTS system.

## 2 Classical Preisach model for hysteresis

Now the Preisach model has been primarily known in the area of Magnetics<sup>[2]</sup>. The mathematical expression of the classical Preisach model can be written as

$$f(t) = \iint_{\alpha \geq \beta} \mu(\alpha, \beta) \gamma_{\alpha, \beta}[u(t)] d\alpha d\beta, \quad (1)$$

where  $f(t)$  is the system output,  $\mu(\alpha, \beta)$  is a weighting function,  $\gamma_{\alpha, \beta}[u(t)]$  is the hysteresis operator having an output of  $+1$  or  $-1$ , and  $\alpha, \beta$  correspond to "up" and "down" switching values of the input  $u(t)$ , respectively. The output of  $\gamma_{\alpha, \beta}[u(t)]$  is set to  $+1$  or  $-1$  if the input exceeds the switching value  $\alpha$  or drops below the switching value  $\beta$ .

To develop the expressions of the classical Preisach model,  $f_{M_i}$  is defined as the output when the input monotonically increases to  $M_i$  from  $u_{\min}$  (Fig. 1). Similarly,  $f_{M_i, m_j}$  refers to the output when the input monotonically increases to  $M_i$  from  $u_{\min}$  and then monotonically decreases to  $m_j$ . Then, based on the classical Preisach model, the piezoelectric actuator expansion  $f(t)$  subjects to an excitation voltage  $u(t)$ <sup>[2]</sup>:

$$\dot{u}(t) > 0: f(t) = \sum_{k=1}^{n-1} [f_{M_k m_k} - f_{M_k m_{k-1}}] + f_{u(t)} - f_{u(t) m_{n-1}}, \quad (2)$$

$$\dot{u}(t) < 0: f(t) = \sum_{k=1}^{n-1} [f_{M_k m_k} - f_{M_k m_{k-1}}] + f_{M_i u(t)} - f_{u(t) m_{n-1}}, \quad (3)$$

where  $n-1$  presents the number of maxima  $M_k$  and minima  $m_k$  pairs of the input signal sequence.

In order to implement the model equations (2)

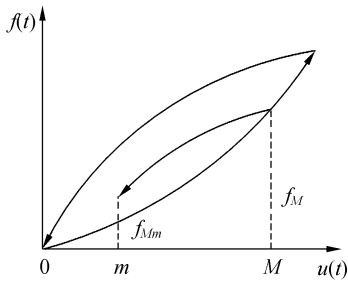


Fig. 1 Reversal curves attached to ascending branch

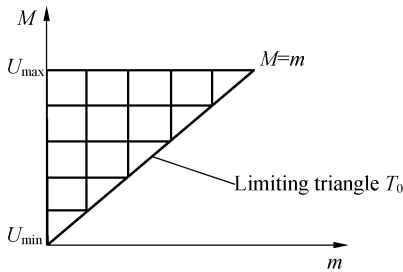


Fig. 2 Limiting triangle  $T_0$

and (3), a series of used functions  $f_M$  and  $f_{Mm}$  for the specific piezoelectric actuator need to be experimental determined for all pairs  $(M, m)$  which represents a node within the limiting triangle  $T_0$  (Fig. 2). The output  $f(t)$  can be predicted using (2) or (3) if the experimental data  $f_{M_i}$  and  $f_{M_i m_j}$  are known. For points of the  $(M, m)$  plane lying within any of the squares or triangles, they can be approximated by interpolation equations as follows:

$$f_{Mm} = c_0^{Mm} + c_1^{Mm} M + c_2^{Mm} m + c_3^{Mm} Mm, \quad (4)$$

$$f_{Mm} = d_0^{Mm} + d_1^{Mm} M + d_2^{Mm} m. \quad (5)$$

The constants in the interpolation equations (4) and (5) are estimated based on the measured functions at the nodes within  $T_0$ .

### 3 Experimental results and simulation of FTS hysteresis properties

#### 3.1 Experimental setup

The fast tool servo system designed in this in-

vestigation is composed of a main body, a tool holder, a moving part, a capacitive displacement sensor and a piezoelectric actuator. The piezoelectric actuator is of stacked type, 50 mm in length and 16 mm in outer diameter, which is preloaded by four flexure hinges in the main body. A capacitive displacement sensor is used to measure the displacement of the piezoelectric actuator. The block diagram of the entire experimental system setup is shown in Fig. 3.

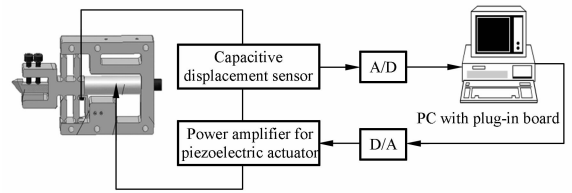


Fig. 3 System block diagram

#### 3.2 Voltage-to-displacement dynamics in fast tool servo system

To demonstrate the hysteresis properties of the FTS system, a series of first order reversal curves are tested for the system. Fig. 4 shows the experimental voltage-to-displacement curves, from which we can see that the ascending curves almost coincide.

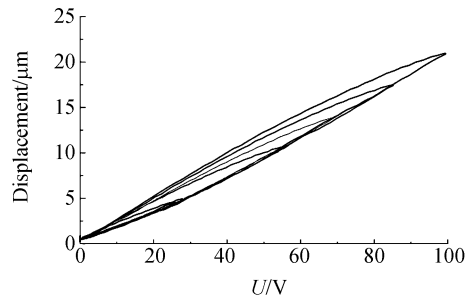


Fig. 4 Hysteresis loops for 0.01 Hz input signals

In order to use the classical Preisach model to represent the hysteresis nonlinearity, the congruency and wipe-out properties have to be satisfied<sup>[2]</sup>. To investigate the congruency property of the FTS system, the input signals are designed as shown in Fig. 5. The corresponding displacement outputs are given in Fig. 6, from

which we can see that the minor loops are not exactly congruent, however, the difference is insignificant.

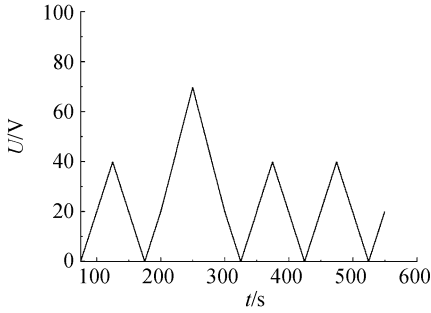


Fig. 5 0.1 Hz input signals for investigating congruency property

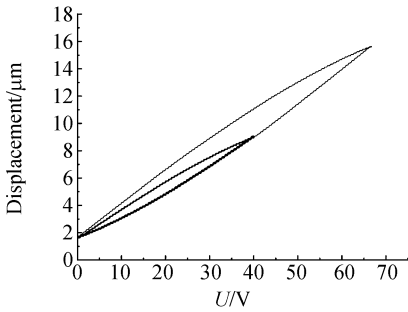


Fig. 6 FTS displacement-congruency property

To investigate the wipe-out property of the FTS system, input signals used in the experiments are shown in Fig. 7. The displacement outputs corresponding to the input signals are presented in Fig. 8, from which we can see that the displacements overlap from 160 – 210 s. Thus, in the first experiment the previous input extremum of 55 V does not have any influence on the output once the input reaches another ex-

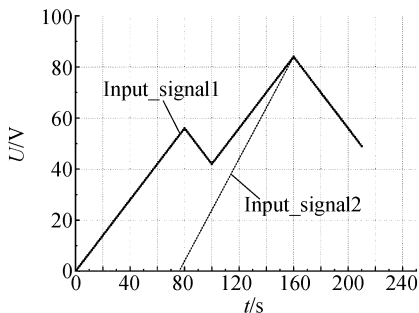


Fig. 7 Input signals for investigating wipe-out property

tremum of 85 V. In other words, the previous extremum is wiped out.

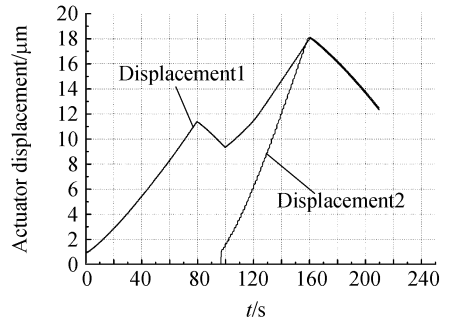


Fig. 8 FTS displacement-wipe-out property

### 3.3 Comparison of experimental and simulated behavior of the tool servo system

Based on the experimental data, the values of  $f_{M_i}$  and  $f_{M_{m_j}}$  ( $i, j = 1, 2, \dots, n$ ) can be determined, and then the output  $f(t)$  is predicted using (2) or (3). Classical Preisach model is then numerically implemented to predict the displacement outputs of the FTS system.

For an arbitrary input signal, varying from 0 V to 80 V, the displacement data predicted by the classical Preisach model and the experimental data are compared in Fig. 9. The good match between the simulated curve and the experimental curve shows that the classical Preisach model works well for simulating the displacement of the FTS system and the classical Preisach model is suitable for hysteresis modeling for the FTS system.

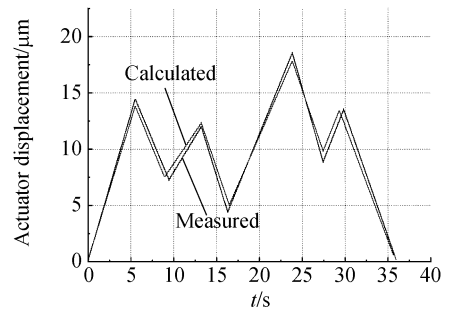


Fig. 9 Comparison of measured and CPM calculated data for FTS

## 4 Conclusions

This paper presents the classical Preisach modeling of the hysteresis for a fast tool servo system. A series of tests are conducted to study the hysteresis properties of the piezoelectric actuator.

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To implement this model, the congruency property and wipe-out property have been asserted to hold for the FTS system. The good agreement found between the measured and calculated curves shows that the classical Preisach model is an effective mean for modeling the hysteresis of the FTS system.

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