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# Hysteresis Modeling of Piezoelectric Actuators and Feed-Forward Compensation Algorithm Research

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***Abstract***

*Piezoelectric ceramic actuators have wide application prospects in precision positioning and measurement technology, but its hysteresis characteristics cause a lot of restrictions to their applications. To solve this problem, this paper summary the hysteresis characteristic of piezoelectric ceramics, and collect the data through the experiment, analyze and research the piezoelectric ceramic hysteresis curves at different excitation signal effect, and the fitting curve is got based on the experimental data in order to establish hysteresis model of piezoelectric ceramic actuators by using of the curve fitting toolbox of MATLAB. Then the inverse model is obtained and the inverse compensation feed-forward control algorithm is proposed. The experiment results show that the piezoelectric ceramic actuators meet the basic linear relationship between the input voltage signal and the output displacement, and eliminate hysteresis nonlinear of the piezoelectric actuators.*

***Keywords:*** *Piezoelectric ceramic, Hysteresis characteristics, Data fitting, Inverse compensation, Feed-forward control*

## 1. Introduction

Piezoelectric ceramic actuator has many advantages, such as small size, compact structure, no mechanical friction, high bear capacity, high displacement resolution and so on. So it is an ideal micro-displacement driving device [1]. But the serious hysteresis nonlinearity characteristics of piezoelectric ceramic actuator greatly reduce its accuracy in the micro-positioning and micro-measurement technologies. Therefore, the hysteresis nonlinearity modeling has become one of the hot issues in the study of precision positioning. Now, for modeling the hysteresis characteristics of piezoelectric ceramic, research scholars at home and abroad generally have the following three categories: First, analyze the physical mechanism of the hysteresis characteristics of piezoelectric ceramic and then establish the model. Second, use various hysteresis operators to establish the model, such as Play operator [2], Preisach operator [3]. Third, use the method of curve fitting to fit the experimental data [4] and describe the hysteresis characteristics. The first method established a physical model based on the mechanism, it requires to predominate the detailed information of the materials microstructure, and to solve complex nonlinear partial differential equations. Therefore, it is difficult to obtain a satisfactory model. The second and the third modeling methods are relatively flexible, and on the one hand, they can effectively describe the input-output relationship of materials through experimental data regardless of its internal structure. On the other hand, their implementation process is relatively simple and straightforward with good practical value. In addition, it is also

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important to design corresponding controller to eliminate the hysteresis characteristics of piezoelectric ceramics. For different hysteresis models of the piezoelectric ceramics actuators, research scholars at home and abroad also do a lot of work to research its control methods [5-7], The traditional PID control algorithm has high control precision, but has no very good adaptability to nonlinear time-varying system. Most of intelligent control algorithms need to meet some prerequisites for a particular occasion and their implementation process is also complicated.

Therefore, for the hysteresis characteristics of piezoelectric ceramics, this paper collected experimental data, analyzed and researched the piezoelectric ceramic hysteresis curves at different excitation signals effect, and established the hysteresis model of piezoelectric ceramic actuator by fitting the experimental data. Then obtained its anti-inverse model and proposed the inverse compensation feed-forward control algorithm, this make the input voltage and the output displacement of piezoelectric ceramic actuators meet the basic linear relationship and achieve the goal of eliminating the hysteresis nonlinear of the piezoelectric actuators.

## 2. Research of the Hysteresis Characteristics

### 2.1. Overview of Hysteresis Characteristics

Hysteresis characteristics of piezoelectric ceramics [8] refers to a non-linear relationship between the input voltage and output displacements, shown in Figure 1, the frequency and amplitude of the input signal, and environmental factors are likely to affect the hysteresis characteristics. Additionally, different piezoelectric ceramics actuators have different hysteresis characteristics.

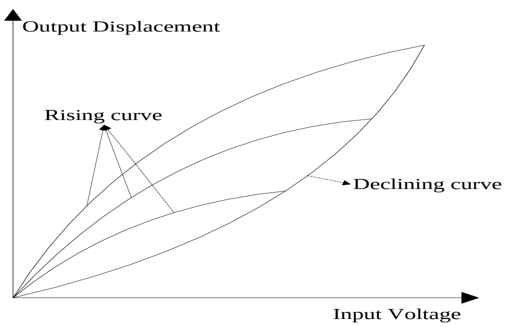



**Figure 1. Hysteresis Characteristic Schematic of the Piezoelectric Ceramic**

In order to establish hysteresis model of the piezoelectric ceramic, we collected data by experiment, the data acquisition system schematic diagram is shown in Figure 2:

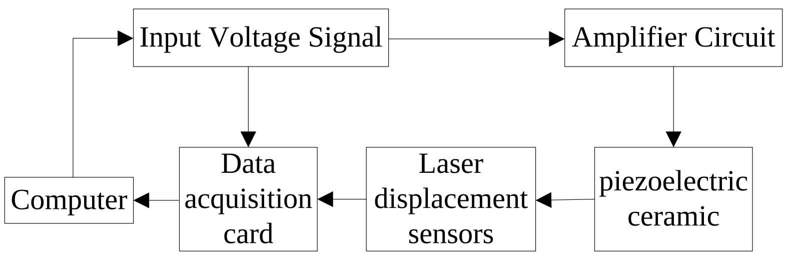



**Figure 2. The Experimental Schematic Diagram of Hysteresis Characteristic**

The data acquisition card used in the experiment is PCI 6221 data acquisition card of National Instruments (NI), shown in Figure 3, and the piezoelectric ceramic driving platform is shown in Figure 4:


**Figure 3. PCI 6221 Data Acquisition Card**

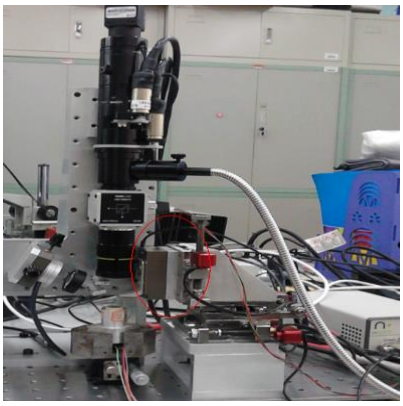


**Figure 4. PZT Driving Experimental Platform**

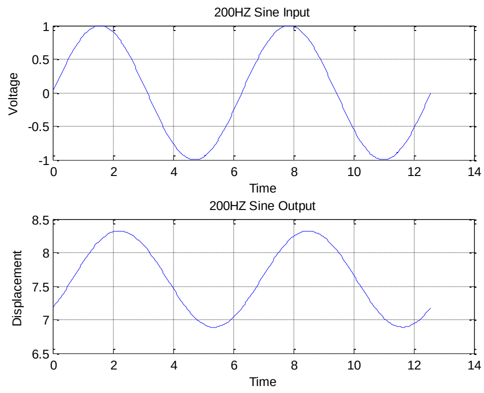
Where the PCI 6221 data acquisition card is a M Series data acquisition card (DAQ) that is low-cost and multifunctional, its resolution is 16-bit, sampling rate is 250kS/s, and 16-channel analog input can effectively meet our requirements. The experimental driving platform is NPX25A Nanometer positioning platform, it is a closed loop and monopodium Nanometer locator with 25 $\mu m$ Run Internet deals.

Generate a driving voltage signal required by the function generator, and after amplifying by the amplifier it is applied to the piezoelectric material. Due to the inverse piezoelectric effect of the piezoelectric material [9], the piezoelectric material produces a relatively large deflection displacement detected by the laser displacement sensor, collect the input voltage and displacement deflection using the data acquisition card, and they are simultaneously fed into the computer for processing. The collected data is processed in MATALB environment, and then analyze the hysteresis characteristics of piezoelectric actuators by the processing results.

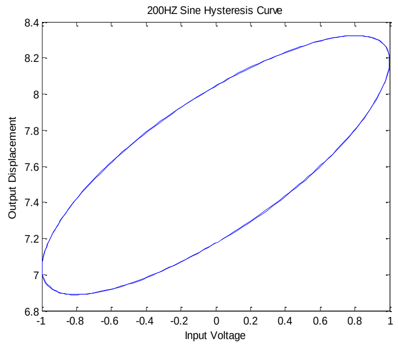
### 2.2. Experimental Analysis of Hysteresis Characteristics

Respectively in Sine, Square, Triangle, Step signal excitation, research the displacement response curve of piezoelectric ceramic. Through analyzing the output response and input excitations of the piezoelectric ceramic, we found that under the excitation of every signal, piezoelectric ceramics response widely presence hysteresis. As shown below:

(1) In the case of Sine signal excitation:



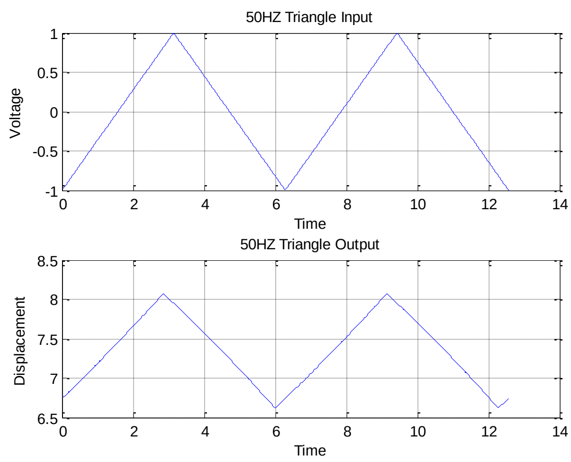

(A) 200HZ Sine Displacement Response Curve



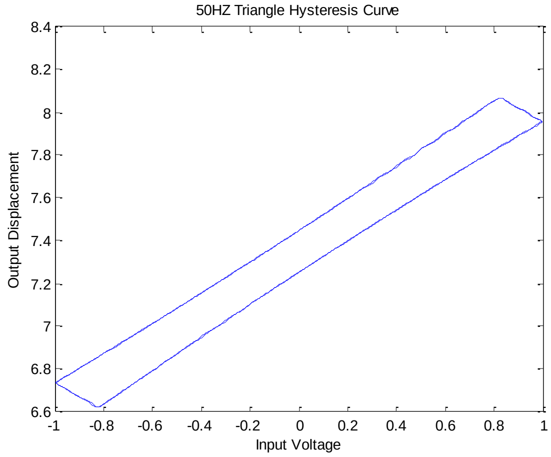

(B) 200HZ Sine Hysteresis Curve

**Figure 5. Displacement Response and Hysteresis Curves Under 9HZ Square Signal**

(2) In the case of Triangle signal excitation:



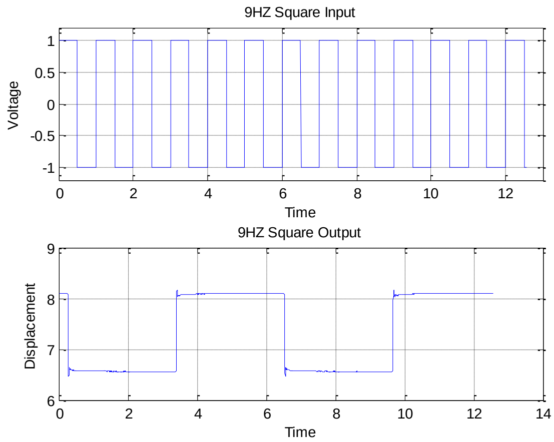

(A) 50HZ Triangle Displacement Response Curve



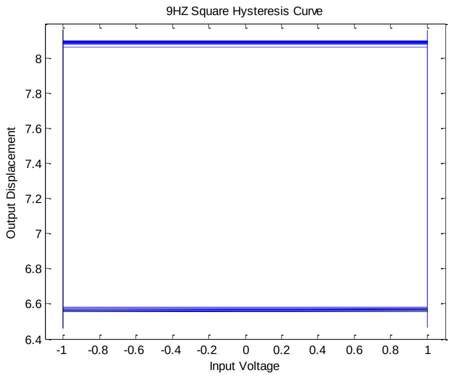

(B) 50HZ Triangle Hysteresis Curve

**Figure6. Displacement Response and Hysteresis Curves Under 9HZ Square Signal**

(3) In the case of Square signal excitation:



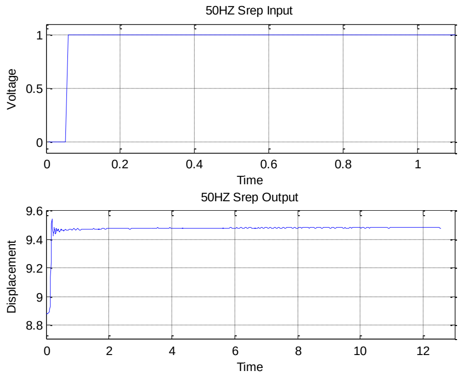

(A) 9HZ Square Displacement Response Curve



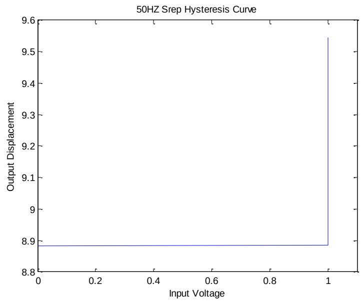

(B) 9HZ Square Hysteresis Curve

**Figure 7. Displacement Response and Hysteresis Curves Under 9HZ Square Signal**

(4) In the case of Step signal excitation:




(A) 50HZ Step Displacement Response Curve




(B) 50HZ Step Hysteresis Curve

**Figure 8. Displacement Response and Hysteresis Curves Under 50HZ Step Signal**

By the response curve of the piezoelectric ceramic at various excitation signals, the following conclusions can be found:

(1) Under the excitation of Sine, Triangle, Square and Step these basic signals, the response curves of piezoelectric ceramic showed a characteristic tracking the excitation signal, but not synchronous tracking. The displacement response curve has a certain lag with respect to the input curve.

(2) Where under the Sine and Triangle signals excitation, the response curves of the piezoelectric ceramic are the most stable and steady.

(3) Under the Sine, Triangle and Square signals excitation, the response curves of piezoelectric ceramic are approximated Sine, Triangle and Square curve, so piezoelectric ceramic driver model may be linear. But in the Step signal excitation, the response curve of the piezoelectric ceramic is not meet the conditions, it can be think of the response of the piezoelectric ceramic driving mechanism and modeling is more complex.

## 3. Mathematical Model of Hysteresis

Through above analysis, found that the piezoelectric ceramic itself has serious hysteresis characteristic [10, 11]. In order to establish piezoelectric ceramic hysteresis model, use data fitting method. Carry out the following experiment and collect the corresponding experimental data, when a voltage is exerted to the piezoelectric ceramic, gradually increased from 0V to 1V, each increment is 0.1V; and then gradually decreased from 1V to 0V, each reduction is 0.1V, the voltage - displacement data we collected are shown in Table 1.

**Table 1. The Rising/Descending Voltage - Displacement Sampling Data Sheet**

| Voltage/V | 0 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Rising displacement/ $\mu m$ | 0.00 | 0.03 | 0.08 | 0.14 | 0.21 | 0.30 | 0.41 | 0.53 | 0.67 | 0.82 | 0.98 |
| Descending displacement/ $\mu m$ | 0.00 | 0.21 | 0.36 | 0.49 | 0.60 | 0.69 | 0.78 | 0.85 | 0.91 | 0.97 | 0.99 |

Use the Curve Fitting Toolbox of MATLAB to fit the experimental data, select $SSE = 0.001$ (SSE represents the Sum of Squares for Error).

After validated, we find using a second-order polynomial to fit the experimental data on the rising phase, in which the fitting residual error ($SSE$) is 0.00007, and the error is much smaller than selected, the coefficient of determination ($R^2$) is as high as 0.9999, indicating that the fitting function can accurately reflect the relationship between the input voltage and output displacement of the piezoelectric ceramics.

Consequently, the mathematical model of rising phase is a second-order model:

$$y_{Rising} = f_1(x) = 0.7517x^2 + 0.231x + 0.0004895 \qquad (1)$$

Similarly, the mathematical model of descending phase is a third-order model:

$$y_{Declining} = f_2(x) = 0.4351x^3 - 1.434x^2 + 1.988x + 0.01084 \qquad (2)$$

Wherein, the fit residual error ($SSE$) is 0.0008, and the coefficient of determination ($R^2$) is 0.9992, which are also meet the selected fitting residual error.

Fitting curve and the sample data are shown in Figure 9. As can be seen from the figure, the fitting curve can fit the sampled data very well.

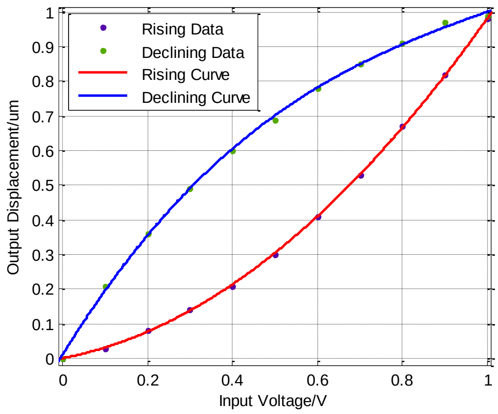



**Figure 9. The Hysteresis Curve of the Piezoelectric Ceramic**

## 4. The Controller Design of the Piezoelectric Actuators

The inverse model open-loop control [12] of piezoelectric ceramic actuator is a control method by solving the inverse function to revise the input voltage. Then apply the revised voltage signal to the piezoelectric ceramic actuator that is a method to connect the hysteresis inverse model of piezoelectric actuator in series before the inverse model of piezoelectric actuator to accomplish the feed-forward correction control. The control flow is shown in Figure 10.

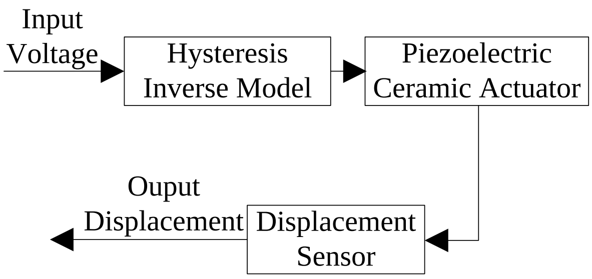



**Figure 10. The Control Flow Graph of the Feed-Forward Inverse Compensation Control**

According to the idea of fitting function formula and linear systems, use the method by solving inverse function to make the input voltage and output displacement approximately satisfy the linear relationship. First, described on the linearity of the piezoelectric ceramics actuators. Through the fitting model of the rising curve and the descending curve, we can obtain the linearity of the piezoelectric ceramics actuator is:

$$k = \frac{k_1 + k_2}{2} = \frac{0.9827 + 0.9582}{2} = 0.97045 \qquad (3)$$

Wherein $k_1$ and $k_2$ are linearity of rising curve and descending curve of the piezoelectric ceramics respectively.

According to the control requirement like $y = f[g(x)] = kx$, solve the inverse function of the fitting model to obtain the corresponding control equations, therefore the control equations of the rising curve and descending curve are:

$$g_{Ri\sin g}(x) = \sqrt{1.3305x + 0.023} - 0.1573 \qquad (4)$$

$$g_{Declining}(x) = \sqrt[3]{1.15x - 1.2 + \sqrt{(1.15x - 1.2)^2 + 0.0316}} - \frac{0.316}{\sqrt[3]{1.15x - 1.2 + \sqrt{(1.15x - 1.2)^2 + 0.0316}}} + 1.1 \qquad (5)$$

## 5. Experimental Analysis

In order to verify the feasibility of the control algorithm, connect the inverse model in series before the hysteresis model, the control schematic is shown in Figure 11.

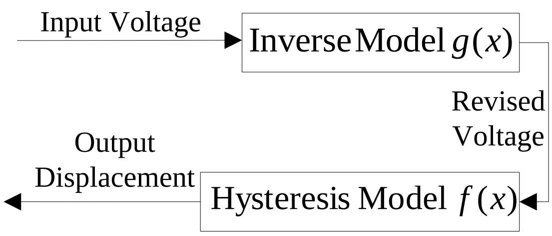



**Figure 11. The Control Schematic Diagram of Inverse Compensation**

The input voltage revised by the inverse model is used to drive the piezoelectric ceramic actuators, and the data of response displacements are measured through the displacement sensor, the fitting curve after inverse compensation is shown in Figure 12.

As can be seen from the figure, the rising curve and descending curve are essentially coincident, i.e. the input voltage and output displacement satisfy the linear relationship, and the linearity is:

$$k^{'} = \frac{k_1^{'} + k_2^{'}}{2} = \frac{1.007 + 0.9891}{2} = 0.9980 \qquad (6)$$

Obviously, $k^{'} > k$ and $k^{'}$ is very close to 1, this indicates that the inverse compensation control algorithm proposed in this paper achieve the purpose of eliminating the hysteresis characteristics of piezoelectric ceramic actuator.

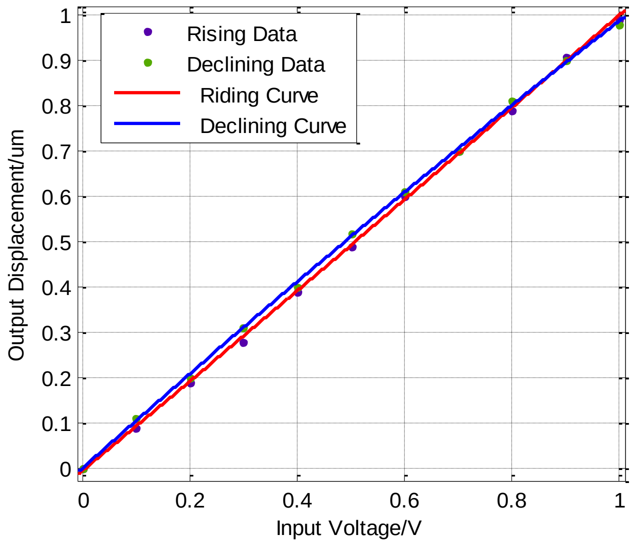



**Figure 12. The Hysteresis Curve between the Input Voltage-Output Displacement of the Piezoelectric Ceramic After Inverse Compensation**

## 6. Conclusions

In this paper studied the hysteresis characteristics of piezoelectric ceramics, collected the experimental data and process them with MATLAB to fit the hysteresis model of the piezoelectric ceramics. Combining the idea of inverse control, proposed the inverse compensation feed-forward control algorithm, Validation experiment shows that the above method can basically eliminate the hysteresis characteristics of piezoelectric ceramics actuators, make the input voltage and output displacement satisfy a linear relationship, which provides a new way to solve the hysteresis nonlinear characteristics of piezoelectric ceramics actuators based on precision positioning platform.

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## References


[1] G. Wang, "piezoelectric drive linear calibration technology research [D]", Graduate School of Chinese Academy of Sciences (Optoelectronic Technology Institute), **(2013).**

[2] C. Li, "Modeling and Control of AFM piezoelectric drive [D]", Shandong University, **(2010)**.

[3] W. Yanding and T. Huifeng, "Preisach model Researching of piezoelectric actuator hysteresis characteristics [J]", Piezoelectric and acousto-optic, vol. 26, no. 5, **(2004)**, pp. 364-367.

[4] Y. Zhu, W. Yong and J. Zhu, "The feedback control algorithm analysis of piezoelectric ceramic hysteresis characteristics [J]", Electrical and Mechanical Information, vol. 18, **(2013),** pp. 160-161.

[5] Z. Tan, "Study of piezoelectric actuator hysteresis' compensation method [D]", Harbin Institute of Technology, **(2008)**.

[6] Tan, Xiaobo and J.S. Baras, "Adaptive identification and control of hysteresis in smart materials [J]", Automatic Control, IEEE Transactions, vol. 50, no. 6**, (2005)**, pp. 827-839.

[7] G. Tao and P.V. Kokotovic, "Adaptive control of plants with unknown hysteresis [J]", Automatic Control, IEEE Transactions on, vol. 40, no. 2, **(1995)**, pp. 200-212.

[8] P. Krejci and K. Kuhnen, "Inverse control of systems with hysteresis and creep [J]", IEEE Proceedings Control Theory and Applications, vol. 148, no. 3, **(2001)**, pp. 185-192.

[9] M. Wang, "Based on piezoelectric ceramic micro-drive platform control technology [J]", Equipment Manufacturing Technology, no. 11, **(2008)**, pp. 25-27.

[10] W. Rong, D. Qu , L. Sun and J.X.C. Hegao, "Research of Piezoelectric ceramic micro displacement device hysteresis model [J]", Piezoelectric and acousto-optic, vol. 25, no. 1, **(2003)**, pp. 22-25.

[11] X. Zhang and Y. Tan, "The hysteresis dynamic intelligent modeling of piezoelectric ceramics based on dynamic preisach operator [J]", Journal of system simulation, vol. 9, **(2009), pp.** 2682-2686.

[12] S. Bo, "Research on the micro displacement driving control technology for piezoelectric ceramics [D]", Harbin Institute of Technology, **(2010)**.


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