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Research Article

Fuzzy PID Feedback Control of Piezoelectric Actuator with Feedforward Compensation

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Piezoelectric actuator is widely used in the field of micro/nanopositioning. However, piezoelectric hysteresis introduces nonlinearity to the system, which is the major obstacle to achieve a precise positioning. In this paper, the Preisach model is employed to describe the hysteresis characteristic of piezoelectric actuator and an inverse Preisach model is developed to construct a feedforward controller. Considering that the analytical expression of inverse Preisach model is difficult to derive and not suitable for practical application, a digital inverse model is established based on the input and output data of a piezoelectric actuator. Moreover, to mitigate the compensation error of the feedforward control, a feedback control scheme is implemented using different types of control algorithms in terms of PID control, fuzzy control, and fuzzy PID control. Extensive simulation studies are carried out using the three kinds of control systems. Comparative investigation reveals that the fuzzy PID control system with feedforward compensation is capable of providing quicker response and better control accuracy than the other two ones. It provides a promising way of precision control for piezoelectric actuator.

1. Introduction

As is known, human enters the world of micro/nanolevel with the inventions of scanning tunneling microscopy (STM) [1] and atomic force microscope (AFM) [2]. One key technology in STM and AFM is micro/nanopositioning. Actually, micro/nanopositioning has been applied in more and more fields nowadays. Regarding the drive principle in micro/nanopositioning system, piezoelectric actuator is popular because of its high stiffness, fast response, and several other outstanding features. However, piezoelectric actuator introduces some obvious limitations, such as hysteresis, creep, and vibration characteristics. How to realize the precise control of piezoelectric actuator is a hot research topic in recent years.

Generally, under open-loop voltage control, the piezoelectric actuator produces 10%–15% error with respect to full range [3]. With the increase of the input signal frequency, the error will even reach to 35% [4]. So, the hysteresis characteristics of piezoelectric actuator are the main problem to be overcome. In the literature, a physical explanation for the hysteresis phenomenon from a macroscopic viewpoint was given by Chen and Montgomery [5]. Yet, piezoelectric actuator exhibits more complex hysteresis nonlinearity [6]. In particular, the output signal not only depends on the input signal, but also relates to the history of the system state. Thus, for the same input signal under different states, the output signal will be different. In addition, previous studies have shown that the frequency of the input signal also affects the output signal and error.

To realize the control of the piezoelectric actuator to cater for the requirement of micro/nano positioning, appropriate mathematical models can be established to characterize the piezoelectric hysteresis. Researchers have established various models from different perspectives to describe the hysteresis nonlinearity of piezoelectric actuator. As shown in Figure 1, the hysteresis models can be mainly classified into two types: physics-based models and phenomenological models. Physics-based models are used to describe the basic physical principle of material and the hysteresis models are obtained in view of the relations of energy, displacement,

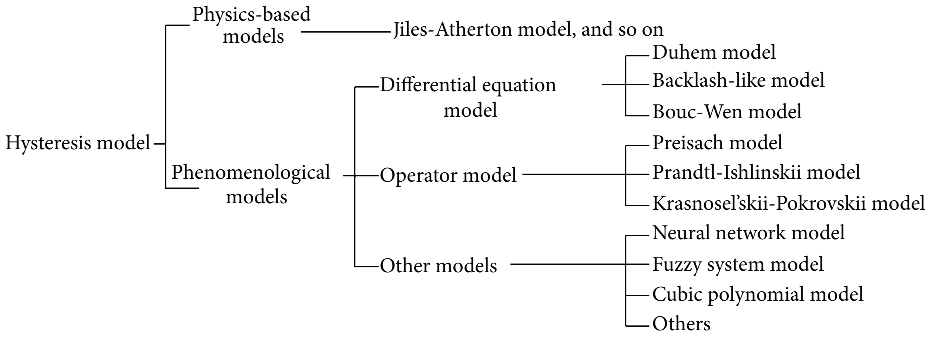


Figure 1: The classification of hysteresis models.

and so on [7–9]. Alternatively, phenomenological models start from the characteristic of hysteresis curve. They are employed to describe the hysteresis curve by using the effective math model directly, without paying attention to the physical meaning [10–13]. Specifically, Preisach model is a popular phenomenological hysteresis model, and it has been widely used. It is able to give an accurate description of the characteristics of the hysteresis nonlinearity. In this research, the Preisach model is used to describe the hysteresis nonlinearity of a piezoelectric actuator.

Concerning the control scheme of hysteresis nonlinear system, the inverse model of hysteresis nonlinearity is usually obtained first. Then, the inverse model is used to construct a feedforward controller to compensate for the hysteresis effect of the system. Using the inverse model as the feedforward compensation directly is a simple and effective method. The inverse compensation model and the piezoelectric actuator, which are connected in series, can be considered as a linear system. In order to achieve this goal, a lot of previous works have been conducted in the literature. To name a few, Leang and Devasia [14] adopted iterative learning control strategy to solve the Preisach model's inverse compensation control issue. Krejci and Kuhnen [15] derived the inverse analytical expression of traditional Prandtl-Ishlinskii (P-I) model and reduced the tracking error by one order of magnitude. Xu and Wong [16] built an inverse hysteresis model using support vector machines for compensating the hysteresis nonlinearity of piezoelectric actuator and then demonstrated that it is more effective than Bouc-Wen model and P-I model via experimental studies.

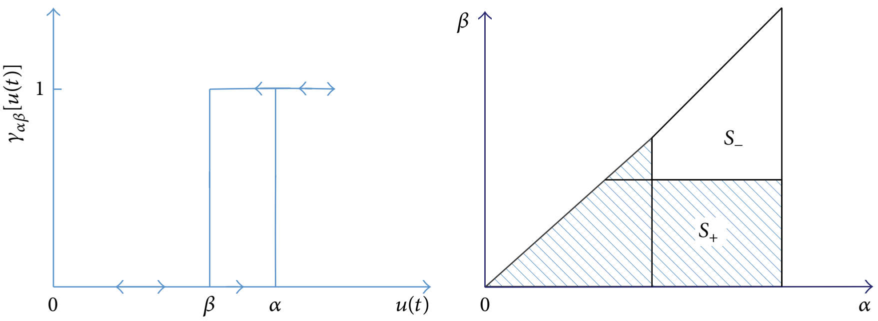
Control method based on inverse hysteresis model is simple and intuitive, but it has many drawbacks, such as heavy computational burden and complicated system structure. In particular, because of the complexity of the hysteresis model, finding out the analytic inverse model directly is difficult. Most of the time, numerical inverse model is used to approximate the exact model; thus it appears that the inverse model is not unique. Moreover, a standalone feedforward control is not sufficient to totally cancel out the positioning error because there always exist certain degrees of model error. Hence, a closed-loop feedback control can be designed to combine with the feedforward control in order to further mitigate the control error. Particularly, PID control is widely used because of its simple construction [17]. In the literature, Tan et al. [18] proposed a learning type of PID controller and tried to enhance the robustness of the system. Additionally, intelligent controllers based on fuzzy logic and neural networks have been applied extensively in the control of piezoelectric actuator [19, 20]. The inverse Preisach model can also be used as a feedforward compensation which is added to PID feedback control [21]. Moreover, this compound control method has also been applied in the joint angle control of a manipulator driven by pneumatic artificial muscles [22]. In addition, Chen et al. [23] proposed a control method which combines the inverse Preisach compensation model with the indirect adaptive controller. An adaptive inverse model has also been proposed which is updated by least mean square algorithm [24]. Recently, more different control methods for piezoelectric actuator have been proposed [25–27]. The whole purpose of these control approaches is to achieve a precise and stable control.

As an important branch of intelligent control, fuzzy control is a control method on the basis of fuzzy set theory, fuzzy language variables, and fuzzy logic reasoning. It spans a wide application in various fields of control and automation. As a combination of fuzzy control and PID control, the fuzzy PID control is a popular control approach. Although both fuzzy control and fuzzy PID control have been widely used, it is unclear how fuzzy control performs in comparison with fuzzy PID control in piezoelectric actuator control. In this research, a comparison study of fuzzy control and fuzzy PID control with feedforward compensation is conducted for precision motion control of a piezoelectric actuator. Through a series of simulation comparative studies, some useful conclusions are derived.

The following parts of the paper are organized as follows. Section 2 gives a brief review of the Preisach model. Three kinds of controllers are then constructed in Section 3. Section 4 performs simulation studies of the three controllers. Some conclusions are drawn in Section 5.

2. Preisach Model

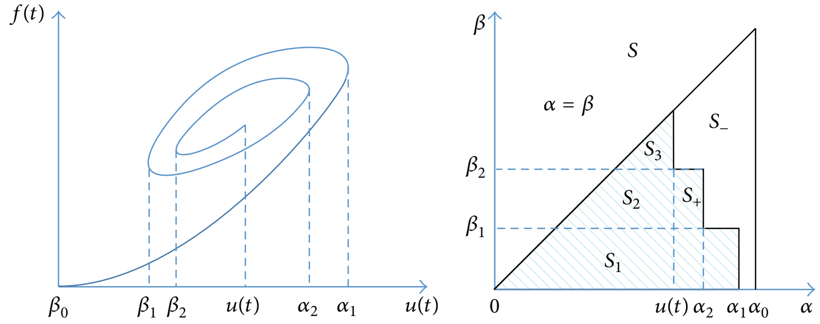
Preisach model was originally used to study the physical principle of magnetic hysteresis characteristics in phenomenon of



(a) Preisach operator

(b) Domain of integration

Figure 2: Schematic of Preisach model.



(a) Input signal

(b) Domain of integration

Figure 3: Discretization of the model of the Preisach model.

magnetization [10, 28]. After forty years of its development, the mathematicians Krasnosel'skii and Pokrovskii [29] separated the physical meaning of Preisach model in the 70s of the 20th century, gave a kind of pure mathematics characteristic model definition, and expanded the application field of the Preisach model. Nowadays, Preisach model has become one of the most widely used hysteresis models.

2.1. Model Expression. The mathematical description of classic Preisach model is shown as follows:

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

where $f(t)$ is the input of system; $u(t)$ is the output of system; $\mu(\alpha, \beta)$ is weighting function; α, β are the "rise threshold" and "fall threshold," respectively; and $\gamma_{\alpha\beta}[u(t)]$ is hysteresis operator with the value of $+1$ or -1.

Generally, Preisach model solves the current input response through the integration of historical input operations, and it has the characteristics of the global memory. In order to characterize the hysteresis of piezoelectric actuators, the Preisach model can be established as follows.

As shown in Figure 2, based on the rule of Preisach model $\alpha \geqslant \beta$, the integral area of (1) constructs the right triangle S. The right triangle vertex is (α_0, β_0), and the hypotenuse is the straight line $\alpha = \beta$. Any point (α, β) within S corresponds to a hysteresis operator $\gamma_{\alpha\beta}$. When $\gamma_{\alpha\beta} = 1$, its S_+ part lies in area S; when $\gamma_{\alpha\beta} = 0$, its $S\_$ part lies in area S. $\mu(\alpha, \beta)$ is a distribution function which is defined within the triangle S and its value obeys the statistical law. In addition, $\mu(\alpha, \beta) = 0$ lies in the area outside S.

From Figure 3, the corresponding output of piezoelectric actuators can be calculated as

$$\begin{aligned} f(t) &= \iint_{S_+} \mu(\alpha, \beta)\, \gamma_{\alpha\beta}[u(t)]\, d_\alpha d_\beta \\ &\quad + \iint_{S_-} \mu(\alpha, \beta)\, \gamma_{\alpha\beta}[u(t)]\, d_\alpha d_\beta \\ &= \iint_{S_+} \mu(\alpha, \beta)\, d_\alpha d_\beta. \end{aligned} \tag{2}$$

2.2. Model Discretization. It is found that although (2) can be used to calculate the output displacement, it is very difficult to solve. So, it is necessary to discretize this equation in order to facilitate its usage.

When the input $u(t)$ starts from 0 and increases to α_κ, the output is $f(\alpha_\kappa, \alpha_\kappa)$. Then, $u(t)$ monotonically decreases to β_κ, which produces an output $f(\alpha_\kappa, \beta_\kappa)$. The change of the output is defined as $F(\alpha_\kappa, \beta_\kappa)$:

$$F(\alpha_\kappa, \beta_\kappa) = f(\alpha_\kappa, \alpha_\kappa) - f(\alpha_\kappa, \beta_\kappa). \tag{3}$$

As shown, Figure 3(a) is the trajectory of input signal and Figure 3(b) is the domain of integration. S_+ and S_- are departed into S_1, S_2, and S_3. From this, the final output can be calculated:

$$\begin{aligned} f(u(t)) = {} & \iint_{S_1} \mu(\alpha,\beta)\, d_\alpha d_\beta + \iint_{S_2} \mu(\alpha,\beta)\, d_\alpha d_\beta \\ & + \iint_{S_3} \mu(\alpha,\beta)\, d_\alpha d_\beta. \end{aligned} \tag{4}$$

Combining (4) with the definition in (3) yields

$$\begin{aligned} f(u(t)) = {} & [f(\alpha_1,\beta_1) - f(\alpha_1,\beta_0)] \\ & + [f(\alpha_2,\beta_2) - f(\alpha_2,\beta_1)] \\ & + [f(u(t)) - f(u(t),\beta_2)]. \end{aligned} \tag{5}$$

When $u(t)$ is increasing,

$$\begin{aligned} f(t) = {} & \sum_{k=1}^{n} [f(\alpha_\kappa,\alpha_\kappa) - f(\alpha_\kappa,\beta_{k-1})] \\ & + [f(u(t)) - f(u(t),\beta_n)]. \end{aligned} \tag{6}$$

When $u(t)$ is decreasing,

$$\begin{aligned} f(t) = {} & \sum_{k=1}^{n-1} [f(\alpha_\kappa,\alpha_\kappa) - f(\alpha_\kappa,\beta_{k-1})] \\ & + [f(\alpha_n,u(t)) - f(u(t),\beta_{n-1})]. \end{aligned} \tag{7}$$

Through (6) and (7), the response of the output signal can be found out at any time. It is notable that only the nonmemory part needs to be considered to obtain an expression for the input signal based on this algorithm [30].

For illustration, a simulation result is shown in Figure 4. This figure clearly shows the Preisach curve after discretization. The upper one's simulation calculation time is $n = 10$; the lower one is $n = 100$. We can see that the discretization curve can be used to describe the hysteresis loop.

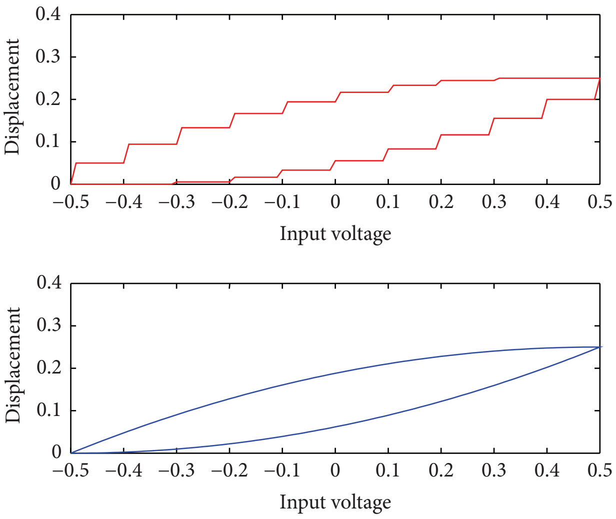


Figure 4: Simulation result of Preisach model.

3. Controller Design

3.1. Feedforward Compensation. The purpose of feedforward compensation is to cancel out the hysteresis behavior using the inverse hysteresis model. Because the Preisach model is in a recursive form, the inverse model is difficult to solve. To overcome this issue, researchers have proposed some other algorithms. For instance, Ge and Jouaneh [3] introduced an input correction iteration algorithm based on the main hysteresis loop. Basically, it puts the output displacement x_d into the fitted curve and finds out the needed u_d. Then, x_r is obtained based on Preisach model and the input value u_d. If $x_d - x_r \neq 0$, then the input u_d is adjusted till $x_d - x_r = 0$. It can realize a feedforward compensation. The flowchart of the compensation algorithm is shown in Figure 5.

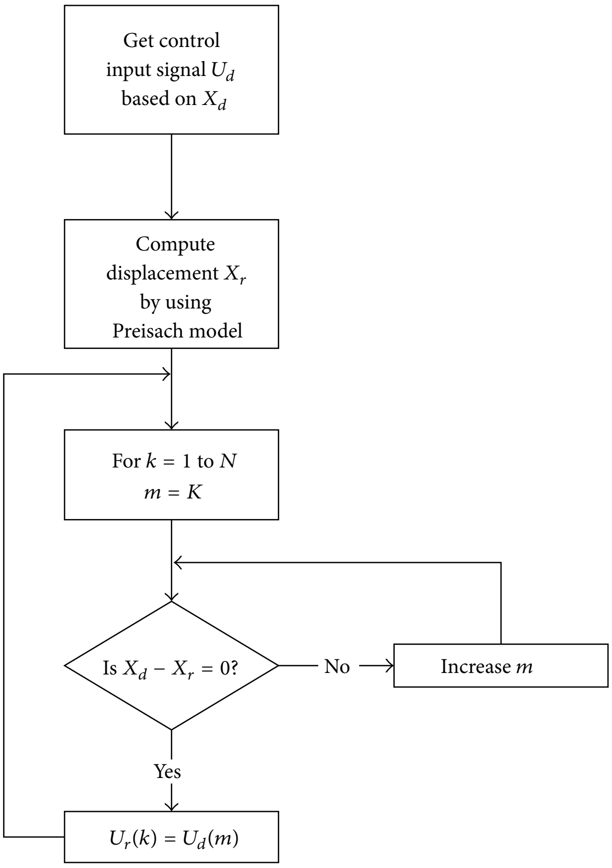


Figure 5: Flowchart of feedforward compensation algorithm.

To sum up, a feedforward controller is designed based on the inverse Preisach model. By using the expected output displacement as input, the compensator gives a compensation control signal for the piezoelectric actuator. This can reduce the effects of the hysteresis phenomenon and make the controlled model close to linear. The effectiveness of this control design has been demonstrated by Ge and Jouaneh [3].

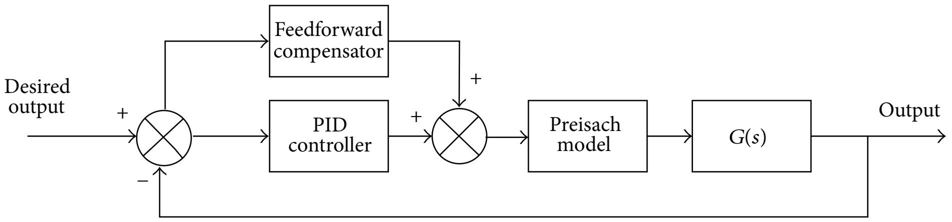


Figure 6: PID tracking control with feedforward compensation.

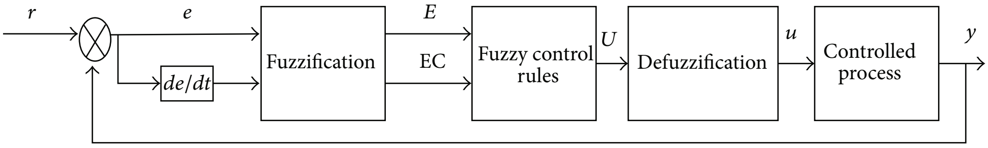


Figure 7: Fuzzy control system block diagram.

3.2. Closed-Loop Feedback Control. By cascading the inverse hysteresis compensator and piezoelectric actuator, a linear model is obtained approximately. Furthermore, feedback control can be employed to improve the control precision and enhance the robustness of the system. There are many popular feedback control methods in the literature. This paper employs PID control, fuzzy control, and fuzzy PID control. Moreover, the feedforward control based on the inverse Preisach model and feedback control are combined together to improve the control performance.

Without loss of generality, the transfer function $G(s)$ of the plant is represented by a second-order mode. Its expression is shown below:

$$G(s) = \frac{4}{s^2 + 29s + 8}. \qquad (8)$$

To represent the nonlinear plant of the piezoelectric actuator, a Preisach model is connected in series with the transfer function $G(s)$ to describe the dynamics system with hysteresis characteristics. The combination of these two components is taken as the controlled plant.

3.2.1. PID Control with Feedforward Compensation. A PID controller in the continuous time domain can be described as follows:

$$u(t) = K_p \left[e(t) + \frac{1}{T_i} \int_0^t e(\tau)\, d\tau + \frac{T_d d}{dt} e(t) \right]. \qquad (9)$$

A popular formula for the digital PID control realization is

$$\begin{aligned} \Delta u(n) = {} & K_p [e(n) + e(n-1)] + K_i e(n) \\ & + K_d [e(n) - 2e(n-1) + e(n-2)], \end{aligned} \qquad (10)$$

where K_p, K_i, and K_d are the proportional coefficient, integral coefficient, and differential coefficient, respectively. $\Delta u(n)$ is the corresponding increment value. In addition, $K_i = K_p (T/T_i)$, $K_d = K_p (T_d/T)$, and T is sampling period.

The block diagram of PID control with feedforward compensation is given in Figure 6.

Considering the system stability, response speed, overshoot, and steady-state precision, the tuning roles of K_p, K_i, and K_d are given as follows.

(a) If K_p is too small, it will reduce the accuracy. The response speed is slow too. And it will extend the settling time and degrade the system performance.

(b) The role of K_i is to eliminate the steady-state error of the system. The static error in the system will be reduced faster when K_i is increased. But if K_i is too high, it will produce larger overshoot amount. If K_i is too low, it is difficult to eliminate steady-state error; this will reduce the precision of the system.

(c) The effect of K_d is to improve the system's dynamic characteristics. It could suppress the change of the error. But if K_d is too high, it will extend the settling time and reduce the robustness of the system.

3.2.2. Fuzzy Control with Feedforward Compensation. Fuzzy control is a computer control method on the basis of fuzzy set theory, fuzzy language variables, and fuzzy logic reasoning. Fuzzy controller is the core of fuzzy control, and the key issue of fuzzy controller design is the determination of fuzzy control rules. Fuzzy control rule table is a series of control rules summed up by the expert or the operator according to their manual control experience.

The error e and error change rate ec are relatively easy to obtain in the control process. Hence, they are employed as the input language variables of the fuzzy controller. In addition, U is output linguistic variable. Thus, $U = F(e, ec)$. As shown in Figure 7, the designed fuzzy controller consists of the steps of fuzzification of inputs, making fuzzy control rules, and defuzzification. After adding the feedforward compensation, the fuzzy tracking control with feedforward compensation is depicted in Figure 8.

3.2.3. Fuzzy PID Control with Feedforward Compensation. The later simulation results show that fuzzy control with

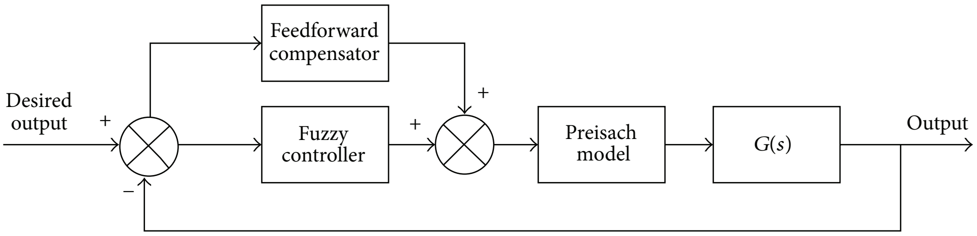


Figure 8: Fuzzy control with feedforward compensation.

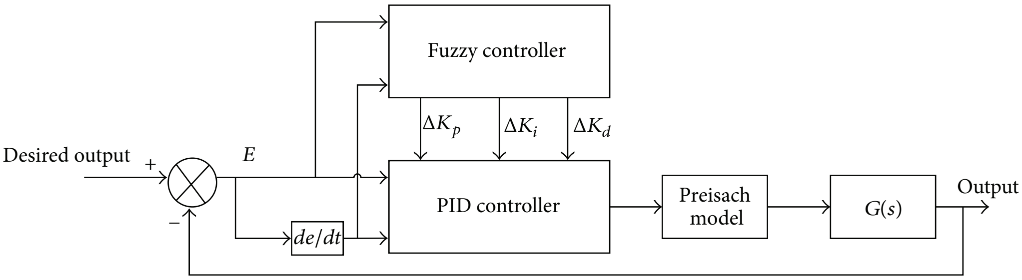


Figure 9: Block diagram of fuzzy PID control.

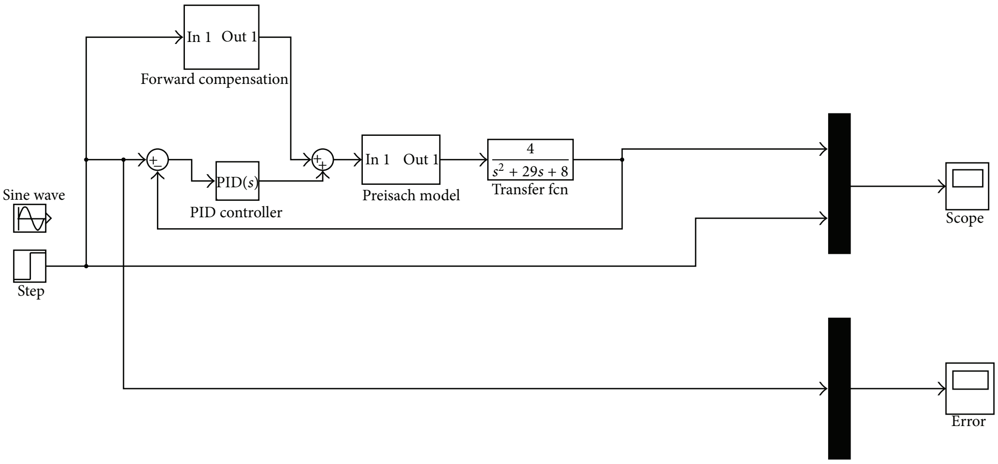


Figure 10: MATLAB simulation model of PID control with feedforward compensation.

feedforward compensation is not sufficient to produce a satisfactory result. In order to improve the control performance while ensuring the dynamic performance of system, the PID control and fuzzy control are combined together to reduce the shortcomings of each controller. The block diagram of the control scheme is shown in Figure 9.

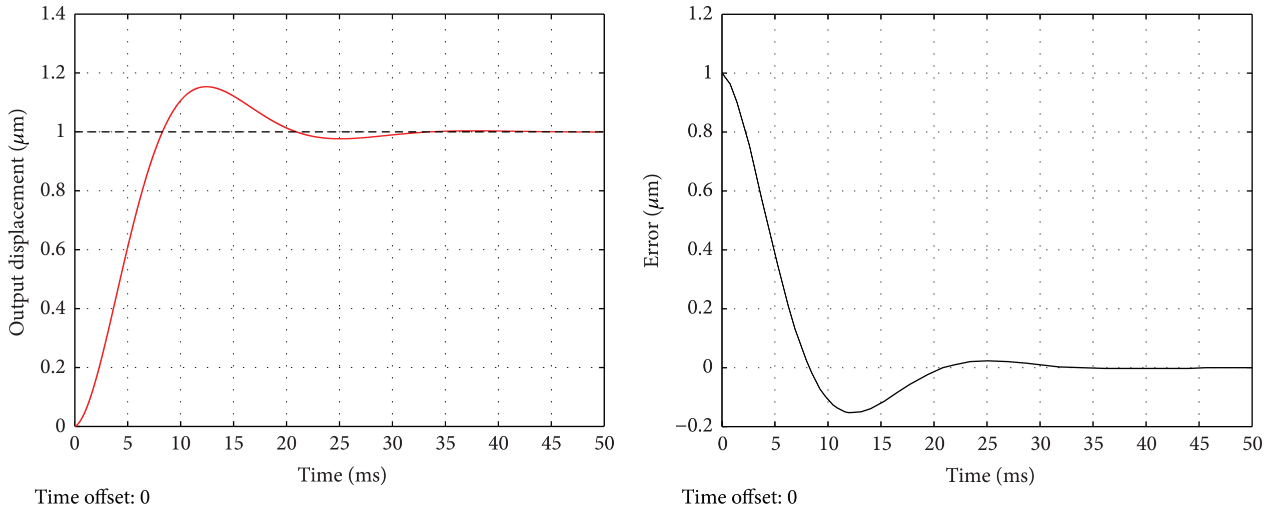
In this system, the error e and error change rate ec are input signals, and the correction values of PID (ΔK_p, ΔK_i, and ΔK_d) are the outputs. Based on the change of e and ec, ΔK_p, ΔK_i, and ΔK_d are modified at every time instant to enable the system good dynamic and static characteristics. At last, the values of PID control parameters are obtained.

In the following section, the three types of controllers are implemented and a comparison investigation is carried out through simulation studies. It is notable that, from herein until the end of this paper, $G(s)$ in each following figure is used to express the series connection of the second-order model and the Preisach hysteresis model.

4. Comparative Studies

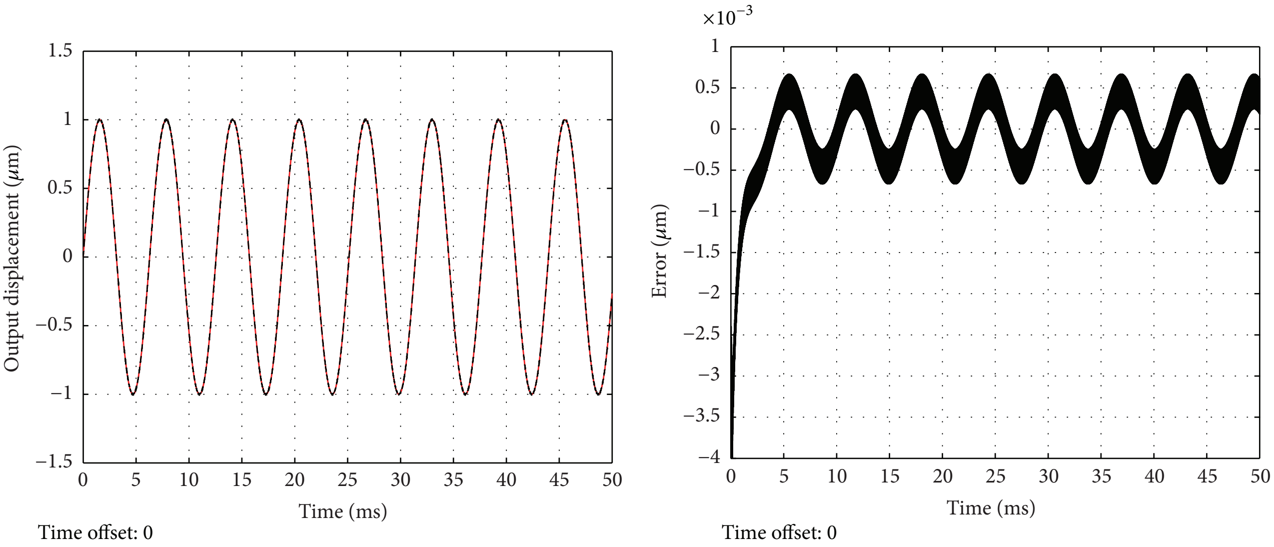
4.1. Results of PID Control with Feedforward Compensation. A PID control with feedforward compensation scheme is realized in MATLAB Simulink, as shown in Figure 10. The PID control parameters are adjusted according to the tuning rules as described in Section 3.2.1. Because of the manual adjustment, the tuning efficiency is low.

Figures 11 and 12 show the system responses to a step input and a sinusoidal input, respectively, where the dashed lines represent the reference inputs and the solid lines represent



(a) Step input signal response (b) Step response error

FIGURE 11: Step response of PID control with feedforward compensation.



(a) Sinusoidal tracking result (b) Sinusoidal tracking error

FIGURE 12: Sinusoidal tracking results of PID control with feedforward compensation.

the output responses. It can be seen that the system dynamic performance is not good enough, but the steady-state error is small as shown in both cases.

4.2. Results of Fuzzy Control with Feedforward Compensation. Based on the control block diagram, the MATLAB simulation model of the system is developed as shown in Figure 13.

To implement the fuzzy control, the practical values of input variables *e* and *ec* need to be converted into language variable values. This kind of translation is termed fuzzification, which relies on the membership functions as shown in Figure 14. Then, the language variable values are taken as input. By defining certain control rules, the output fuzzy sets are obtained. This process is called fuzzy inference, as shown in Figure 15. The control rule is derived from expert's experience of operation and control of the system, and they can be edited in the form of fuzzy conditional statement, as shown in Figure 16. At last, the fuzzy output is treated through defuzzification process, which makes the control decision of the system and completes the process of fuzzy control.

Figures 17 and 18 show the system responses to step input and sinusoidal input, respectively. It is seen that the step response of the system is very nice with a fast response, no overshoot, and almost no steady-state error. However, although the dynamic performance is improved, the error of the sinusoidal tracking is large and is not reduced much as compared with PID control.

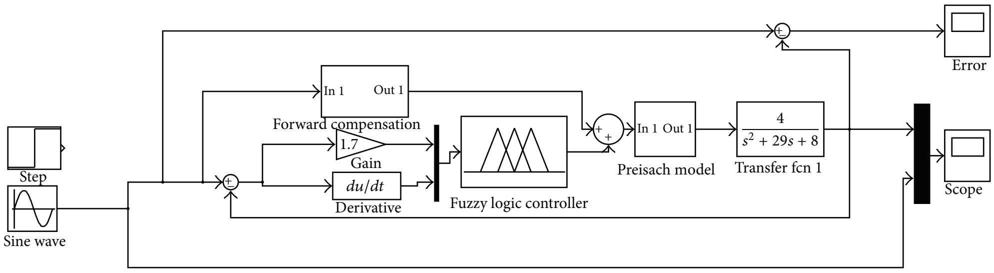


Figure 13: MATLAB simulation model of fuzzy control with feedforward compensation.

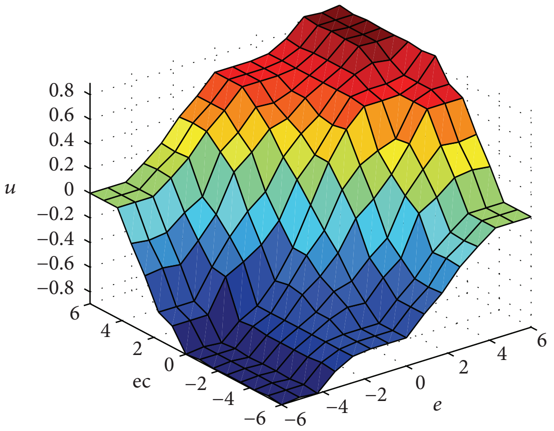
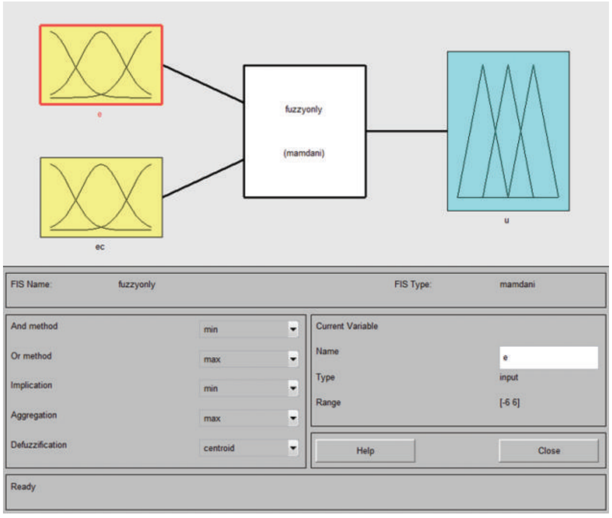


Figure 14: Membership function curves.



FIS Name: fuzzyonly FIS Type: mamdani

And method: min

Or method: max

Implication: min

Aggregation: max

Defuzzification: centroid

Current Variable

Name: e

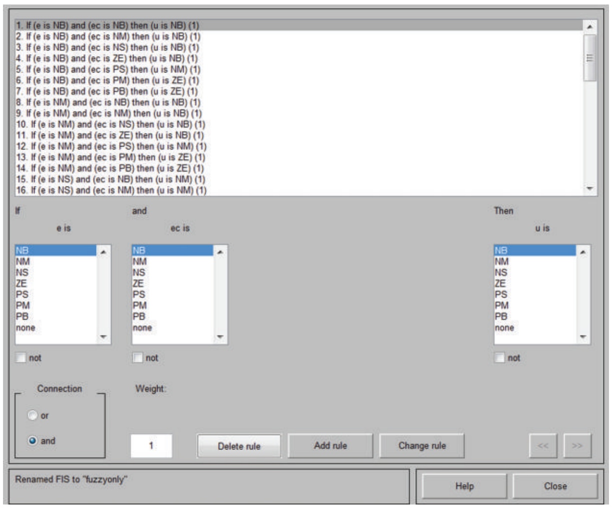
Type: input

Range: [-6 6]

Ready

Figure 15: The fuzzy inference system editor.

4.3. Results of Fuzzy PID Control with Feedforward Compensation. In this subsection, a fuzzy PID control is realized to further reduce the steady-state error of the system. The MATLAB simulation model of the fuzzy PID control with feedforward compensation is shown in Figure 19, where the embedded Simulink modules of PID controller and fuzzy controller are shown in Figures 20 and 21, respectively.



1. If (e is NB) and (ec is NB) then (u is NB) (1)
2. If (e is NB) and (ec is NM) then (u is NB) (1)
3. If (e is NB) and (ec is NS) then (u is NB) (1)
4. If (e is NB) and (ec is ZE) then (u is NB) (1)
5. If (e is NB) and (ec is PS) then (u is NM) (1)
6. If (e is NB) and (ec is PM) then (u is ZE) (1)
7. If (e is NB) and (ec is PB) then (u is ZE) (1)
8. If (e is NM) and (ec is NB) then (u is NB) (1)
9. If (e is NM) and (ec is NM) then (u is NB) (1)
10. If (e is NM) and (ec is NS) then (u is NB) (1)
11. If (e is NM) and (ec is ZE) then (u is NB) (1)
12. If (e is NM) and (ec is PS) then (u is NM) (1)
13. If (e is NM) and (ec is PM) then (u is ZE) (1)
14. If (e is NM) and (ec is PB) then (u is ZE) (1)
15. If (e is NS) and (ec is NB) then (u is NM) (1)
16. If (e is NS) and (ec is NM) then (u is NM) (1)

If e is: NB

and ec is: NB

Then u is: NB

Connection: ○ or ● and

Weight: 1

Renamed FIS to "fuzzyonly"

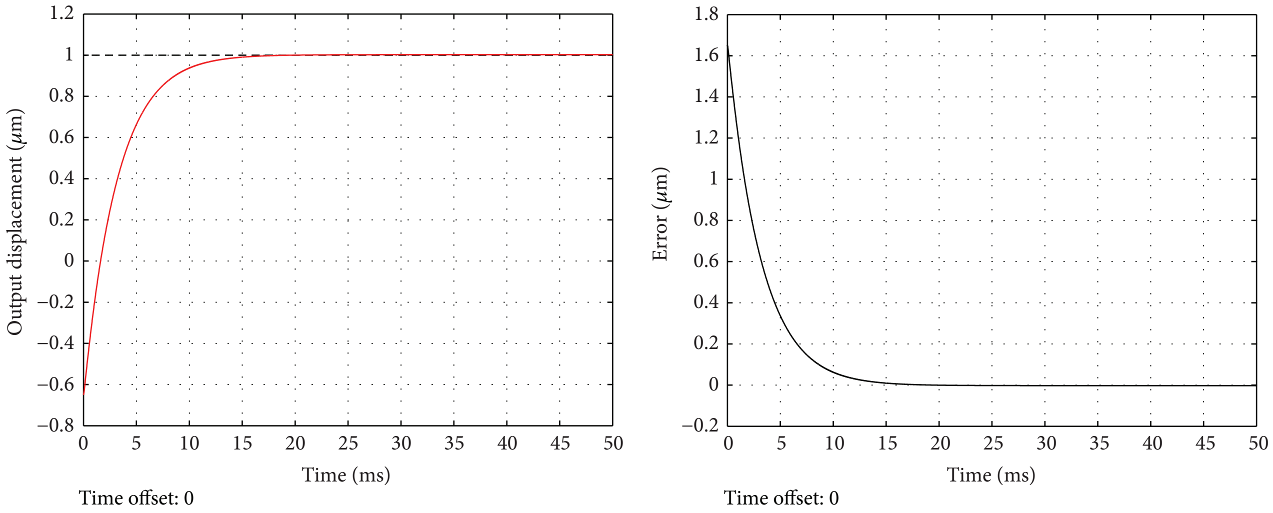
Figure 16: Fuzzy rules editor window.

Table 1: Fuzzy control rule table of parameter K_d.

e	ec						
	NB	NM	NS	Z0	PS	PM	PB
NB	PB	PM	PB	PB	PB	Z	NB
NM	PM	PS	PM	PM	PM	NS	NB
NS	PS	Z	PS	PS	PS	NM	NB
PS	NB	NB	PS	PS	PS	Z	PS
PM	NB	NS	PM	PM	PM	PS	PM
PB	NB	Z	PB	PB	PB	PM	PB

Generally, different values of e and ec require different PID parameter settings. The design objective of the fuzzy PID control is to greatly improve the steady-state control precision without losing too much dynamic performance. For these reasons, the fuzzy control rules are designed. For instance, the setting rules and language description of the parameter K_d are shown in Table 1. Similar rules are designed for parameters K_p and K_i. Figure 22 illustrates the MATLAB settings of the fuzzy control rules.

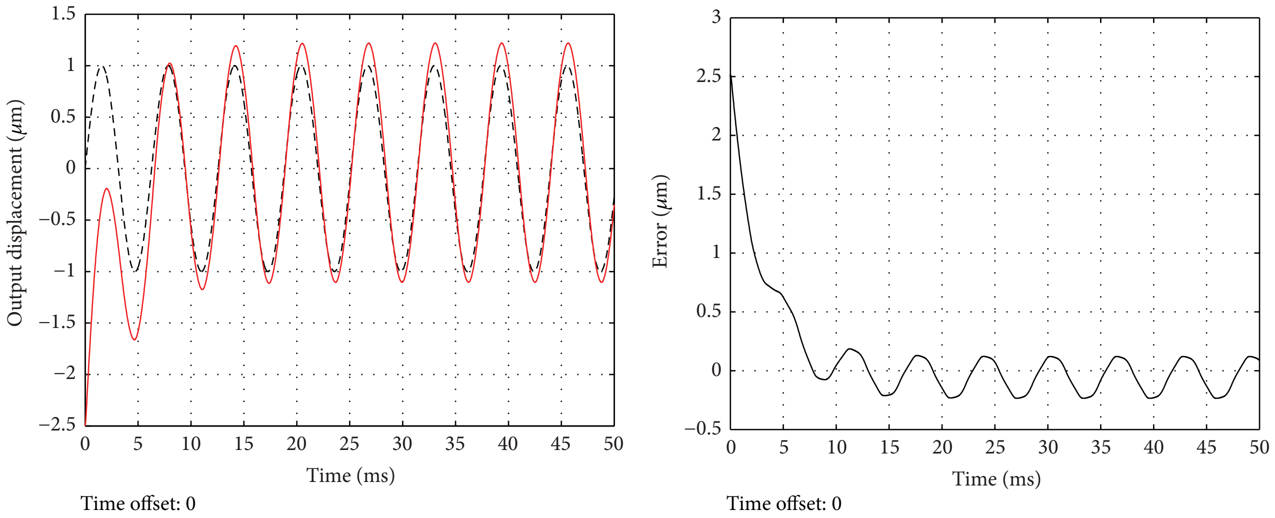
Moreover, Figures 23 and 24 illustrate the system response to step input and sinusoidal input, respectively. It is found that the system dynamic performance is very good. Most importantly, the sinusoidal signal tracking error is significantly reduced close to zero.



(a) Step input signal response

(b) Step response error

FIGURE 17: Step response of fuzzy control with feedforward compensation.



(a) Sinusoidal tracking result

(b) Sinusoidal tracking error

FIGURE 18: Sinusoidal tracking results of fuzzy control with feedforward compensation.

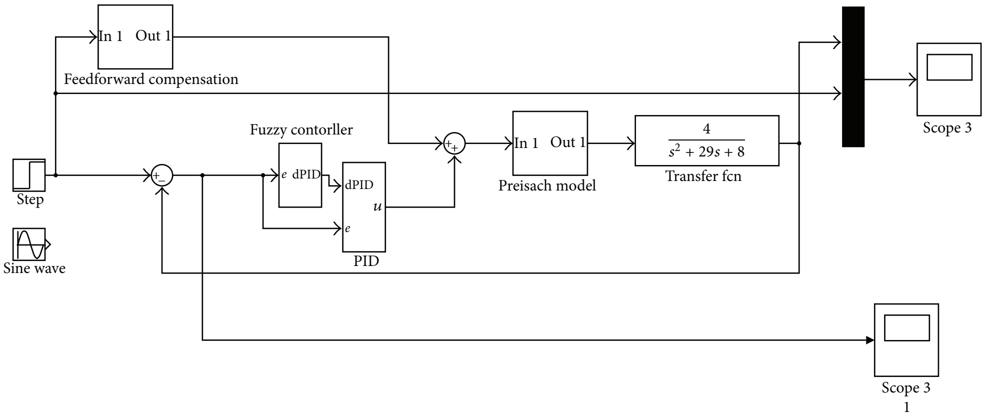


FIGURE 19: MATLAB simulation model of fuzzy PID control with feedforward compensation.

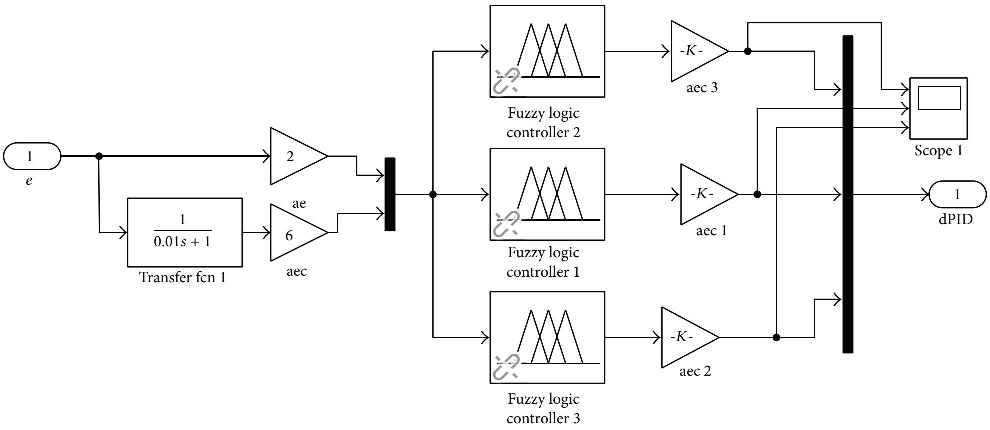


FIGURE 20: Simulink module structure of fuzzy controller.

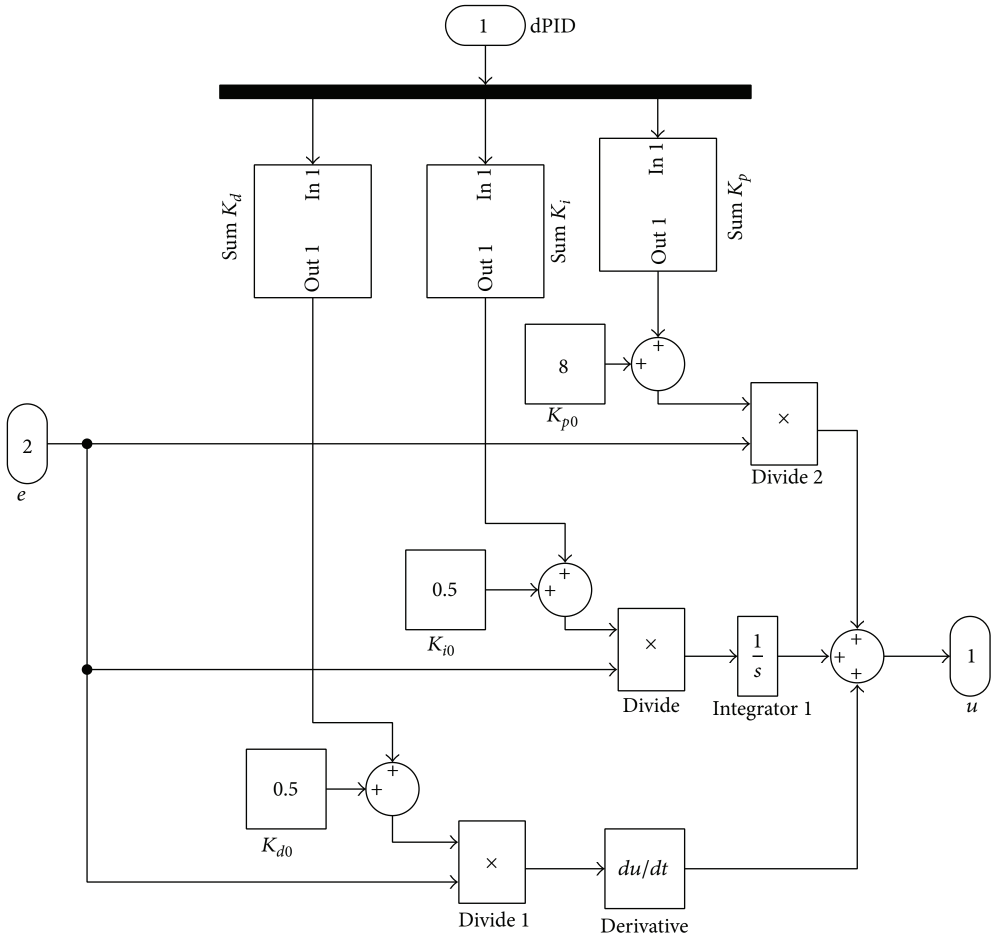
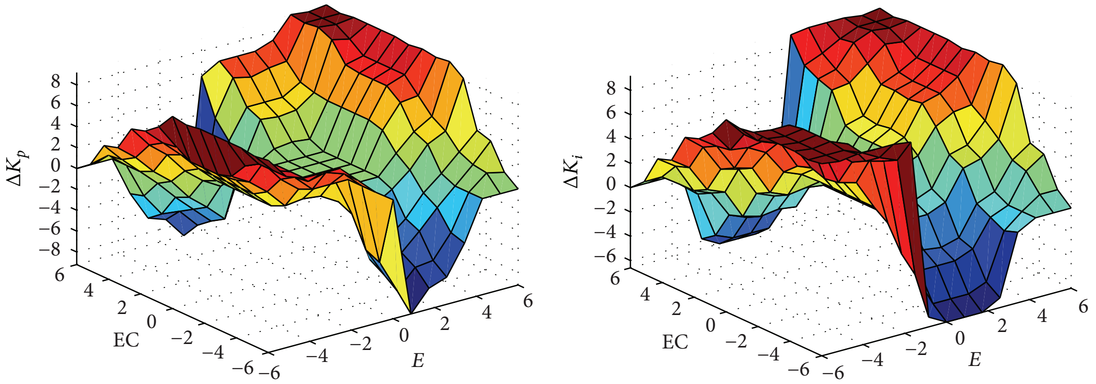


FIGURE 21: Simulink module structure of PID controller.

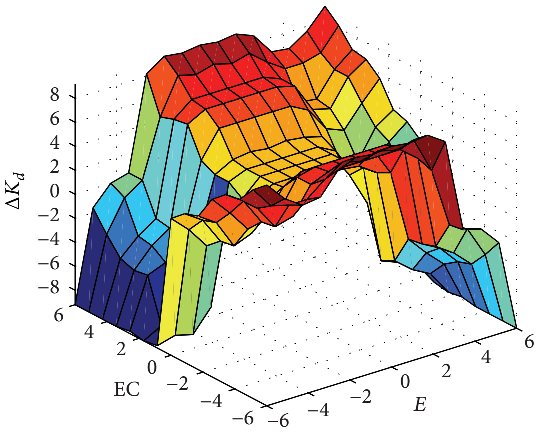
In order to further test the fuzzy PID control system with feedforward compensation, more simulation studies have been conducted to examine its performance under different frequencies (5x and 20x) of the input signal. The results are shown in Figure 25. In general, with the improvement of the input frequency, the response of the system will be degraded. But it can be seen from the diagram that the response of the fuzzy PID control system with feedforward compensation does not change much; it keeps a good control result.

4.4. Discussion on Control Results. Preliminary testing shows that the feedforward compensator based on inverse Preisach model is able to mitigate the influence of hysteresis greatly.



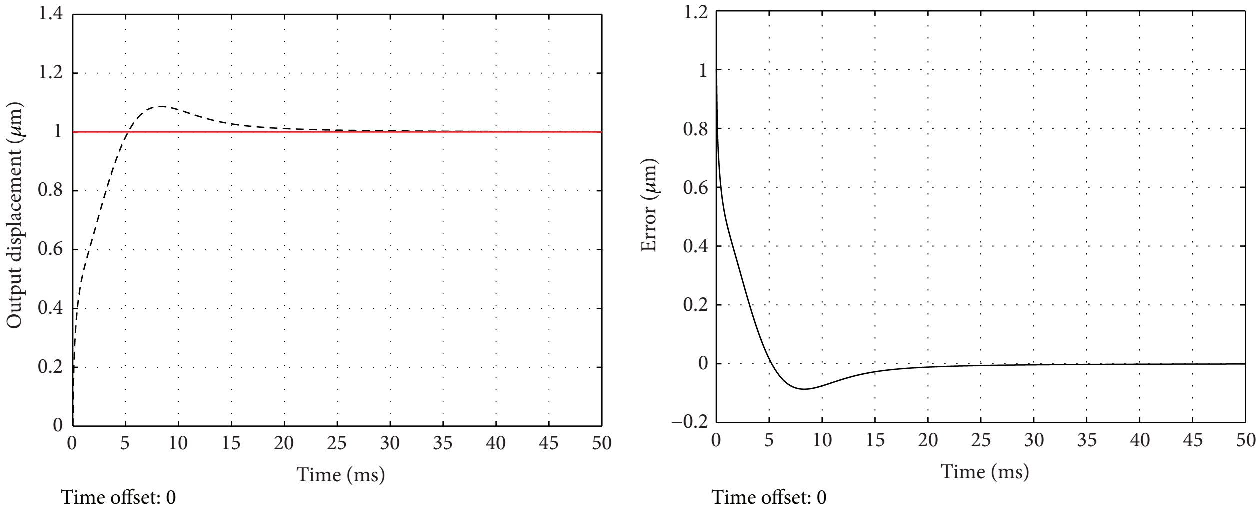
(a) Membership functions for K_p

(b) Membership functions for K_i



(c) Membership functions for K_d

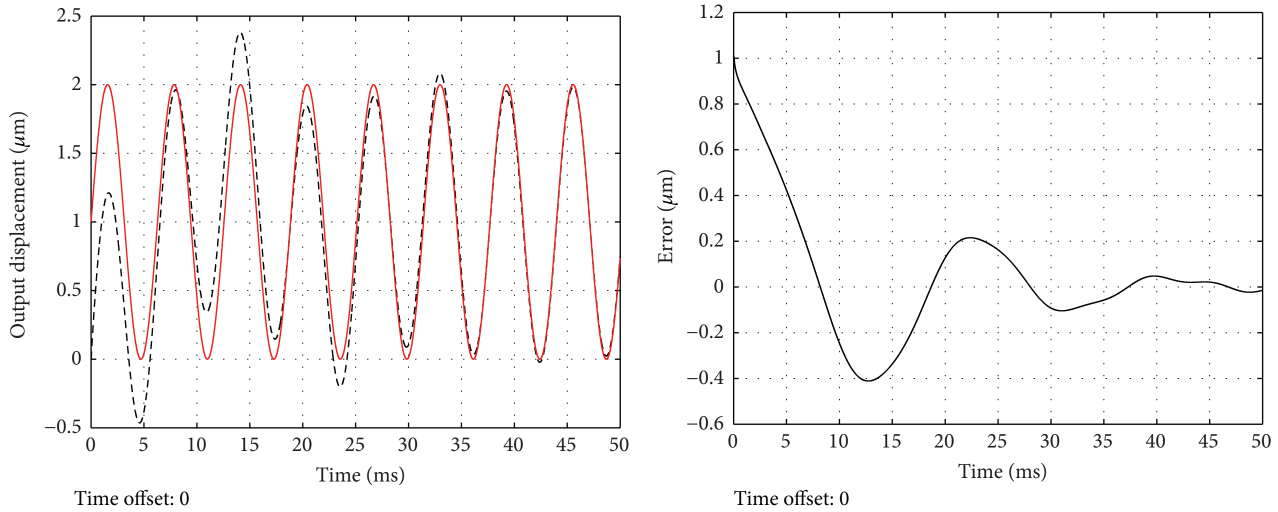
FIGURE 22: Illustrations of the membership functions.



(a) Step input signal response

(b) Step response error

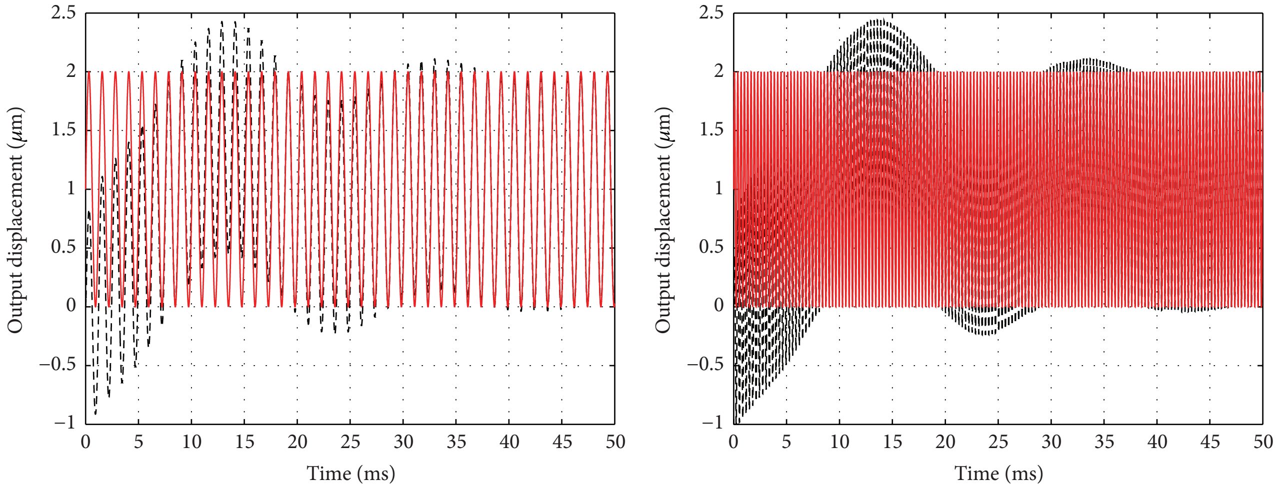
FIGURE 23: Step response of fuzzy PID control with feedforward compensation.



(a) Sinusoidal tracking result

(b) Sinusoidal tracking error

Figure 24: Sinusoidal tracking results of fuzzy PID control with feedforward compensation.



(a) Tracking results of input signal with 5 times of frequency

(b) Tracking results of input signal with 20 times of frequency

Figure 25: Responses under different frequencies of input sinusoidal signal.

Thus, the feedforward compensator is employed in the three types of feedback control systems in simulation testing. For a clear comparison, the simulation results of the three kinds of control systems are shown in Table 2.

It is found that the PID control with feedforward compensation delivers a small sinusoidal tracking error, but its dynamic performance is the worst as reflected by the step response results. In addition, the major problem is that the adjustment of PID parameters is a complicated process with low efficiency.

Besides, the fuzzy control with feedforward compensation has great dynamic response. However, its sinusoidal tracking ability is poor, and the control result is not accurate enough for the majority of applications.

Alternatively, the fuzzy PID control with feedforward compensation not only can realize the accurate control similar to PID controller, but also can improve the dynamic performance of system greatly. This is enabled by the designed fuzzy control rules, which are used to modify the PID parameters online, making the system have good learning ability and adaptability. The only problem with fuzzy PID control is that it demands a heavier computation than traditional way.

Additionally, in the aforementioned simulations, the fuzzy control rules are finely tuned to produce the overshoot as small as possible. This implies that the challenge of fuzzy control design lies in the tuning of these inference rules. To meet higher control requirements, more experiences on operation are needed to design more appropriate fuzzy rules.

Table 2: Comparison of the simulation results of the three controllers.

Controller	Step response Maximum overshoot (%)	5% settling time (ms)	Steady-state error (um)	Sinusoidal response Steady-state error bound (um)
PID control with feedforward compensation	18	18	0	$\pm 0.8 \times 10^{-3}$
Fuzzy control with feedforward compensation	0	13	0	±0.1
Fuzzy PID control with feedforward compensation	6	8	0	0

5. Conclusions

This paper presents the design and simulation study of fuzzy PID control with feedforward compensation for precision motion control of a piezoelectric actuator. An inverse Preisach model is developed to construct a feedforward compensator. Based on the feedforward compensation, three kinds of feedback controller are designed and realized. Comparative investigations reveal that the fuzzy PID control is superior over PID control and fuzzy control in terms of both step response and sinusoidal response performance. Future work will be conducted to tune the fuzzy rules automatically to reduce the work load of fuzzy control design.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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References

[1] S. Devasia, E. Eleftheriou, and S. O. R. Moheimani, “A survey of control issues in nanopositioning,” *IEEE Transactions on Control Systems Technology*, vol. 15, no. 5, pp. 802–823, 2007.

[2] A. A. Adly, I. D. Mayergoyz, and A. Bergqvist, “Preisach modeling of magnetostrictive hysteresis,” *Journal of Applied Physics*, vol. 69, no. 8, pp. 5777–5779, 1991.

[3] P. Ge and M. Jouaneh, “Tracking control of a piezoceramic actuator,” *IEEE Transactions on Control Systems Technology*, vol. 4, no. 3, pp. 209–216, 1996.

[4] R. Ben Mrad and H. Hu, “A model for voltage-to-displacement dynamics in piezoceramic actuators subject to dynamic-voltage excitations,” *IEEE/ASME Transactions on Mechatronics*, vol. 7, no. 4, pp. 479–489, 2002.

[5] P. Chen and S. Montgomery, “A macroscopic theory for the existence of the hysteresis and butterfly loops in ferroelectricity,” *Ferroelectrics*, vol. 23, no. 1, pp. 199–207, 1980.

[6] H. J. M. T. A. Adriaens, W. L. de Koning, and R. Banning, “Modeling piezoelectric actuators,” *IEEE/ASME Transactions on Mechatronics*, vol. 5, no. 4, pp. 331–341, 2000.

[7] D. C. Jiles and D. L. Atherton, “Theory of ferromagnetic hysteresis,” *Journal of Magnetism and Magnetic Materials*, vol. 61, no. 1-2, pp. 48–60, 1986.

[8] R. C. Smith and Z. Ounaies, “Domain wall model for hysteresis in piezoelectric materials,” *Journal of Intelligent Material Systems and Structures*, vol. 11, no. 1, pp. 62–79, 2000.

[9] R. C. Smith, *Smart Material System: Model Development*, vol. 32, SIAM, Philadelphia, Pa, USA, 2005.

[10] J. W. Macki, P. Nistri, and P. Zecca, “Mathematical models for hysteresis,” *SIAM Review*, vol. 35, no. 1, pp. 94–123, 1993.

[11] C.-Y. Su, Y. Stepanenko, J. Svoboda, and T. P. Leung, “Robust adaptive control of a class of nonlinear systems with unknown backlash-like hysteresis,” *IEEE Transactions on Automatic Control*, vol. 45, no. 12, pp. 2427–2432, 2000.

[12] Y.-K. Wen, “Method for random vibration of hysteretic systems,” *Journal of the Engineering Mechanics Division*, vol. 102, no. 2, pp. 249–263, 1976.

[13] Y. Shan, *Repetitive control for hysteretic systems: theory and application in piezo-based nanopositioners [Ph.D. thesis]*, University of Nevada, Reno, Nev, USA, 2011.

[14] K. K. Leang and S. Devasia, “Iterative feed forward compensation of hysteresis in piezo positioners,” in *Proceedings of the 42nd IEEE Conference on Decision and Control*, pp. 2626–2631, December 2003.

[15] P. Krejci and K. Kuhnen, “Inverse control of systems with hysteresis and creep,” *IEE Proceedings: Control Theory and Applications*, vol. 148, no. 3, pp. 185–192, 2001.

[16] Q. Xu and P.-K. Wong, “Hysteresis modeling and compensation of a piezostage using least squares support vector machines,” *Mechatronics*, vol. 21, no. 7, pp. 1239–1251, 2011.

[17] H. G. Xu, T. Ono, and M. Esashi, “Precise motion control of a nanopositioning PZT microstage using integrated capacitive displacement sensors,” *Journal of Micromechanics and Microengineering*, vol. 16, no. 12, article 031, pp. 2747–2754, 2006.

[18] K. K. Tan, T. H. Lee, and H. X. Zhou, “Micro-positioning of linear-piezoelectric motors based on a learning nonlinear PID controller,” *IEEE/ASME Transactions on Mechatronics*, vol. 6, no. 4, pp. 428–436, 2001.

[19] G.-R. Yu, C.-S. You, and R.-J. Hong, “Self-tuning fuzzy control of a piezoelectric actuator system,” in *Proceedings of the IEEE International Conference on Systems, Man and Cybernetics (SMC ’06)*, pp. 1108–1113, Taipei, Taiwan, October 2006.

[20] K. J. Åström and T. Hägglund, "The future of PID control," *Control Engineering Practice*, vol. 9, no. 11, pp. 1163–1175, 2001.

[21] X. Zhou, S. Yang, G. Qi, and X. Hu, "Tracking control of piezoceramic actuators by using preisach model," in *Control Systems and Robotics (ICMIT '05)*, vol. 6042 of *Proceedings of the SPIE*, Chongqing, China, September 2005.

[22] F. Schreiber, Y. Sklyarenko, K. Schlüter et al., "Tracking control with hysteresis compensation for manipulator segments driven by pneumatic artificial muscles," in *Proceedings of the IEEE International Conference on Robotics and Biomimetics (ROBIO '11)*, pp. 2750–2755, December 2011.

[23] Y. Chen, M.-T. Yan, and P.-L. Yen, "Hysteresis compensation and adaptive controller design for a piezoceramic actuator system in atomic force microscopy," *Asian Journal of Control*, vol. 14, no. 4, pp. 1012–1027, 2012.

[24] C. H. Ru, L. G. Chen, B. Shao, W. B. Rong, and L. N. Sun, "A hysteresis compensation method of piezoelectric actuator: model, identification and control," *Control Engineering Practice*, vol. 17, no. 9, pp. 1107–1114, 2009.

[25] G. Tao, J. O. Burkholder, and J. Guo, "Adaptive state feedback actuator nonlinearity compensation for multivariable systems," *International Journal of Adaptive Control and Signal Processing*, vol. 27, no. 1-2, pp. 82–107, 2013.

[26] Y. Zheng, C. Wen, and Z. Li, "Robust adaptive asymptotic tracking control of uncertain nonlinear systems subject to nonsmooth actuator nonlinearities," *International Journal of Adaptive Control and Signal Processing*, vol. 27, no. 1-2, pp. 108–121, 2013.

[27] Y. Xie, Y. Tan, and R. Dong, "Nonlinear modeling and decoupling control of XY micropositioning stages with piezoelectric actuators," *IEEE/ASME Transactions on Mechatronics*, vol. 18, no. 3, pp. 821–832, 2013.

[28] L. Mayergoyz, *Mathematical Models of Hysteresis and Their Application*, Elsevier Academic Press, New York, NY, USA, 2003.

[29] M. Krasnosel'skii and P. Pokrovskii, *Systems with Hysteresis*, Springer, Berlin, Germany, 1989.

[30] Z. Li, C.-Y. Su, and T. Chai, "Compensation of hysteresis nonlinearity in magnetostrictive actuators with inverse multiplicative structure for preisach model," *IEEE Transactions on Automation Science and Engineering*, vol. 11, no. 2, pp. 613–619, 2014.