Improving Tracking Precision of Piezoceramic Actuators Using Feedforward-Feedback Control

Guo-Ying Gu, Chun-Xia Li, Lei-Jie Lai, and Li-Min Zhu

State Key Laboratory of Mechanical System and Vibration,
Shanghai Jiao Tong University, Shanghai 200240, China
{guguoying,chunxia19881226,lailj,zhulm}@sjtu.edu.cn

Abstract. This paper presents a feedforward-feedback controller to improve tracking precision of piezoceramic actuators with hysteresis and creep nonlinearities. Rather than the commonly used approach to construct an inverse of the hysteresis model in the feedforward path, a direct inverse hysteresis compensation method is used to linearize the asymmetric hysteresis nonlinearity with a modified Prandtl-Ishlinskii model. Considering the limitation of the robustness of the feedforward controller, a proportional integral derivative controller is integrated in the feedback loop to mitigate the modeling uncertainty and creep nonlinearity. To demonstrate the performance improvement of the feedforward-feedback control strategy, a piezoceramic actuated platform is built, and comparative tests are conducted on the experimental platform. In comparison with the open-loop operation, the maximum tracking error of the feedforward-feedback controller is reduced from 6.47 μm to 30 nm, and the maximum hysteresis caused error is reduced from 13.19% to less than 0.1% with respect to the desired displacement range. The experimental results clearly demonstrate the feasibility and effectiveness of the developed feedforward-feedback controller using the modified Prandtl-Ishlinskii model.

Keywords: Hysteresis, piezoceramic actuator, modified Prandtl-Ishlinskii model, feedforward control, feedback control.

1 Introduction

Piezoceramic actuators (PCAs) have been recognized as the most popular actuation devices for micro/nano manipulations to achieve high-precision motion control tasks [2,9]. However, due to the presence of hysteresis and creep nonlinearity in the piezoceramic material, it is quite challenging to design a high-precision motion controller for PCAs.

Hysteresis is a multi-valued nonlinear phenomenon between the applied voltage and the output displacement, which is a consequence of the effects of domain switching in the piezoceramic materials due to the action of the applied electric

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field. Creep is the drift of the output displacement for a constant applied voltage under low-speed operations, which is caused by the follow-up polarization of the piezoceramic materials.

In order to remedy the nonlinearities in PCAs, various control techniques have been developed in the literature, which can be roughly classified into three categories: i) charge control, ii) feedforward control, and iii) feedback control. In comparison with voltage control, charge control [3] is an effective method to mitigate the hysteresis based on the fact that there is a less hysteresis between the displacement of a PCA and the applied charge than that between displacement and applied voltage. However, charge control has not been widely applied due to the implementation complexity and cost. Feedforward control is a common control technique to mitigate the nonlinear effects of PCAs in the voltage control case. The key of the feedforward control technique is to construct an inverse hysteresis model, cascaded with the PCA to linearize the actuator response. Various models have been developed for this purpose, for example, the Jiles-Atherton model [16], the Preisach model [18,10], the Prandtl-Ishlinskii (P-I) model [12,1], and the ellipse-based model [7], and so on. With the hysteresis model based compensators, the inverse creep models [11,14] have been designed to compensate for the creep nonlinearity. Rather than using the inverse creep compensation, feedback control is an alternative effective choice. To further improve the tracking precision, feedback controllers are generally integrated with the feedforward controller to eliminate the positioning error caused by the modeling uncertainties of the developed models, which was pioneered by Ge and Jouaneh [4]. The reader may refer to [17,13,6,15] for a recent review on feedforward-feedback control progresses of PCAs.

Following this line, the feedforward-feedback control strategy is implemented in this work to improve the tracking performance of the PCA. Different from the commonly used approach on feedforward control of hysteresis that constructs an inverse of the hysteresis model as the compensator, a direct inverse hysteresis compensation method with the modified Prandtl-Ishlinskii (MPI) model [5] is utilized to mitigate the asymmetric hysteresis nonlinearity of the PCA. Considering the limitation of the robustness of the feedforward controller, a feedback controller is integrated to handle the modeling uncertainty and creep nonlinearity. The main contribution of this paper is to design a novel real-time feedforward-feedback controller with a direct inverse hysteresis compensator, that utilizes the asymmetric MPI model in the feedforward path, to improve the tracking precision of the PCA. To demonstrate the precision enhancement of the developed feedforward-feedback control strategy, we establish a PCA actuated platform and comparative tests are conducted for verification.

The remainder of this paper is organized as follows. In the next section, the MPI model is introduced. In Section 3, several tracking control schemes are presented. The experimental platform and comparative experiments to verify the different control schemes are presented in Section 4, followed by the conclusion in Section 5.

2 MPI Model

The MPI model [8] is defined in terms of weighted play operators and a polynomial input function to describe the asymmetric hysteresis effect of the PCA. In this section, a brief introduction of the MPI model is given.

The play operator is the basic hysteresis operator with symmetric and rate-independent properties. Generally, the one-dimensional play operator can be recognized as a piston with plunger of length $2r$. The output $F_r[x](t)$ is the position of the center of the piston, and the input x is the plunger position. Considering the positive excitation nature of the used PCA, an one-side play (OSP) operator with $r \geq 0$ is adopted as follows [8]

$$\begin{aligned} F_r[x](0) &= f_r(x(0), 0) \\ F_r[x](t) &= f_r(x(t), F_r[x](t_i)) \end{aligned} \tag{1}$$

for $t_i < t \leq t_{i+1}, 0 \leq i \leq N-1$ with

$$f_r(v, w) = \max(v - r, \min(v, w)) \tag{2}$$

where $0 = t_0 < t_1 < \ldots < t_N = t_E$ is a partition of $[0, t_E]$, such that the function $x(t)$ is monotone on each of the subintervals $[t_i, t_{i+1}]$. The argument of the operator $F_r[x]$ is written in square brackets to indicate the functional dependence, since it maps a function to another function.

On the basis of the OSP operator (1), the MPI model is, for asymmetric hysteresis description, expressed as [8]

$$y(t) = g(x(t)) + \int_0^R p(r) F_r[x](t) dr \tag{3}$$

where $g(x(t)) = a_1 x^3(t) + a_2 x(t)$ is a polynomial input function with constant a_1 and a_2, and $p(r)$ is a density function that is generally calculated from the experimental data. The density function $p(r)$ usually vanishes for large values of r , while the choice of $R = \infty$ as the upper limit of integration is widely used in the literature for the sake of convenience [12]. It should be noted that the difference between the MPI model (3) and the classical P-I model is the selection of the input function $g(x(t))$. If $g(x(t))$ is selected as $g(x(t)) = p_0 x(t)$, the MPI model can be reduced to a classical case. The advantage for choosing such an nonlinear input function $g(x(t))$ is that the MPI model can describe a more general class of hysteresis shapes in the piezoelectric actuator with the asymmetric behavior. The reader may refer to [8] for a detailed discussion. In the following development, a real-time direct hysteresis compensation method with the MPI model (3) will be used for asymmetric hysteresis reduction.

3 Feedforward-Feedback Controller Design

In this section, a feedforward-feedback controller is designed to improve trajectory-tracking precision of PCAs. Firstly, the MPI model with the identified parameters is directly adopted to develop the feedforward controller for hysteresis cancelation. Then, a proportional-integral-derivative (PID) feedback controller is developed to compensate for the modeling uncertainty and creep nonlinearity. Finally, we integrate the feedforward controller in conjunction with the PID feedback loop for tracking control of the PCA. It is worthy of mentioning that such feedforward-feedback integration does not limit the choice of the feedback controller, that is, the model-based feedforward technique can be utilized with other feedback approaches, for instance, sliding model control, disturbance-observer control, and robust adaptive control. Without losing generality, the PID feedback control is selected in this work due to its simple implementation and structure. Moreover, the integrated approach provides robustness to parameter variation and simplifies the computation of the feedforward input because modeling of the creep behavior is not required in the combined feedforward-feedback controller.

3.1 Feedforward Controller

The feedforward controller is used to predict and linearize the hysteresis nonlinearity using the MPI hysteresis model. As addressed in our early research without constructing an inverse of the hysteresis model [5], the feedforward controller is based on the direct hysteresis compensation method, which directly applies the MPI model to characterize the inverse hysteresis loops. According to the experimental data, an identification algorithm is adopted to identify the parameters of the MPI model for feedforward controller design.

In order to implement the feedforward controller in a digital signal processor, the compensation signal $v_{ff}(t)$ is obtained by a discrete form of the MPI model (3)

$$v_{ff}(t) = g(y_d(t)) + \sum_{i=1}^{n} b(r_i) F_{r_i}[y_d](t) \tag{4}$$

where $y_d(t)$ is the desired trajectory, $g(y_d(t)) = p_1 y_d^3(t) + p_2 y_d(t)$, n is the number of the adopted play operators for modeling, and $b(r_i)$ is the weighted constant for the threshold r_i.

3.2 Feedback Controller

In the absence of the analytical dynamic model on the plant, the PID algorithm is a good choice for controller design [4,13,6]. The PID controller in the continuous time domain can be described by the following

$$v_{fb}(t) = k_p(e(t) + k_i \int_0^t e(\tau)d\tau + k_d \dot{e}(t) \tag{5}$$

where k_p, k_i and k_d are the proportional gain, integral gain and derivative gain respectively, $e(t)$ is the tracking error between the actual position and desired position. Genarally, the trail and error method can be adopted to tune PID parameters [4].

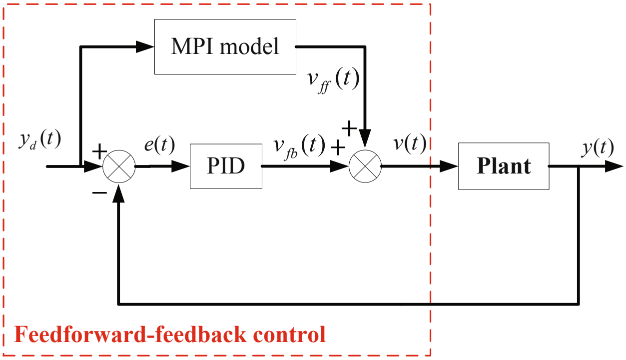


Fig. 1. Block diagram of feedforward-feedback control for the PCA

3.3 Feedforward-Feedback Controller

Fig. 1 shows the block diagram of the feedforward-feedback tracking control system that is composed of a feedforward control loop and a PID feedback loop. In the feedforward loop, the control voltage $v_{ff}(t)$ corresponding to the desired displacement $y_d(t)$ is real-time obtained through (4), whose parameters are identified based on the prior experimental data. In the feedback loop, the desired displacement $y_d(t)$ is compared with the real-time displacement $y(t)$ of the PCA, and the error signal $e(t)$ is transferred to the PID controller (5) to calculate the feedback control voltage v_{fb}. Therefore, the control voltage $v(t)$ of this feedforward-feedback controller for the plant is expressed as

$$v(t) = p_1 y_d^3(t) + p_2 y_d(t) + \sum_{i=1}^{n} b(r_i) F_{r_i}[y_d](t) + k_p(e(t) + k_i \int e(\tau)d\tau + k_d \dot{e}(t). \quad (6)$$

4 Experiments

In this section, an experimental platform with a PCA shall be established and experimental tests are conducted to verify the effectiveness of the developed feedforward-feedback controller for high-precision tracking control of the PCA.

4.1 Experimental Setup

For tracking control of a PCA, the experimental setup is shown in Fig. 2, which consists of a dSPACE DS1103 controller board, a PCA, a piezo amplifier, a strain gauge sensor (SGS) and a signal conditioner. The dSPACE DS1103 (from dSPACE in Germany) rapid prototyping system equipped with 16-bit DAC and 16-bit ADC modular boards are employed to implement the developed controller with the help of the Matlab/Simulink environment. The DAC board produces an analog voltage output for the piezo amplifier, which is then amplified by

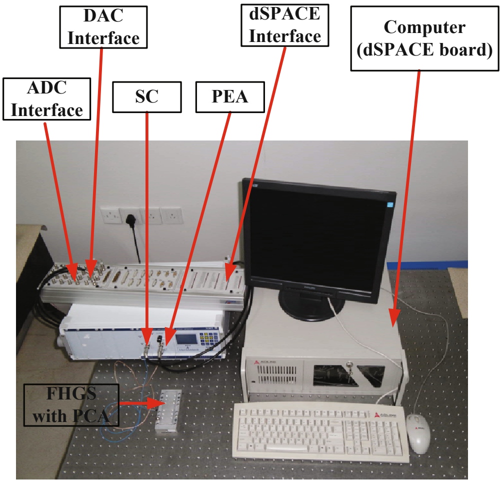


Fig. 2. Experimental setup

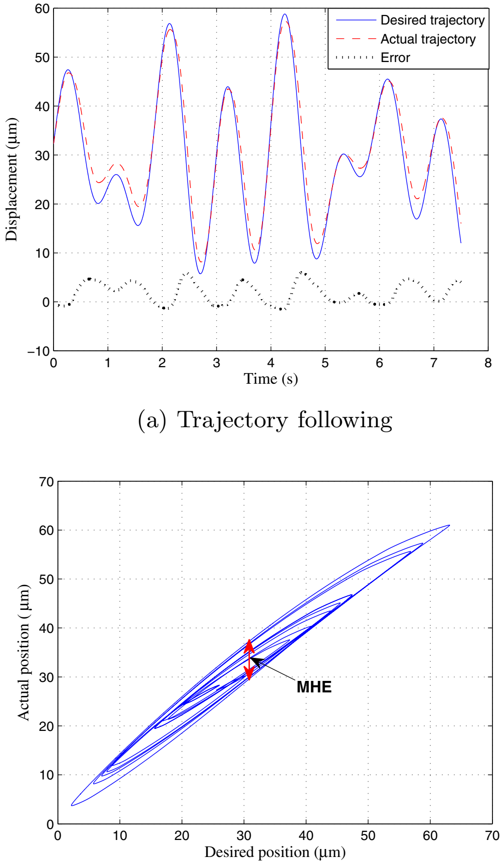
15 times to drive the PCA with excitation voltage ranging from 0 to 150 V. The PCA is a preloaded piezoelectric stack actuator (PSt 150/7/100 VS12 from Piezomechanik in Germany), which is used to drive the one-dimensional flexure hinge guiding stage (FHGS) with the nominal 75 μm displacement. The high-resolution SGS integrated with the PCA is adopted to measure the real-time position. The output signals of the SGS pass through the signal conditioner, which are simultaneously sampled by the 16-bit ADC for the feedback controller.

4.2 Open-Loop Control without Compensation

In order to compare the tracking performance of each control scheme, an open-loop test without compensation was firstly conducted on the piezoceramic actuated platform. It is necessary to serve as a reference for the following comparative tests. In this test, the desired trajectory is shown in Fig. 3(a), which is indicated by the solid blue line. In this figure, it can also be seen that the actual trajectory deviates from the desired trajectory, exhibiting considerable errors. The maximum error of the open-loop system is about 6.47 μm. Fig. 3(b) shows the experimental output-input relationship, which is asymmetric hysteresis loops. From Fig. 3(b), we obtain that the maximum hysteresis caused error is about $e_{mhe} = 13.19\%$, defined as

$$e_{mhe} = \max|\frac{MHE}{\max(y_d) - \min(y_d)}| \times 100\%. \tag{7}$$

Therefore, we can see that the tracking precision of the PCA is unacceptable in open-loop operation. It is why the following feedforward-feedback controller is presented in this paper to improve the tracking precision.



(a) Trajectory following

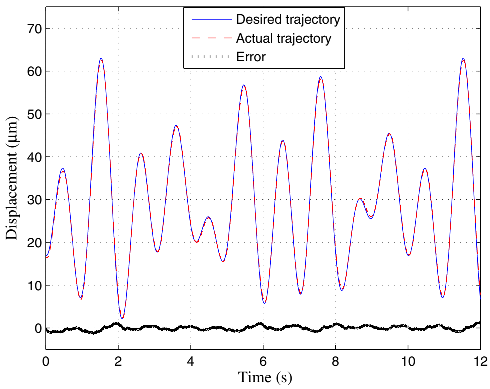
(b) Output-input relationship

Fig. 3. Open-loop tracking control response without compensation

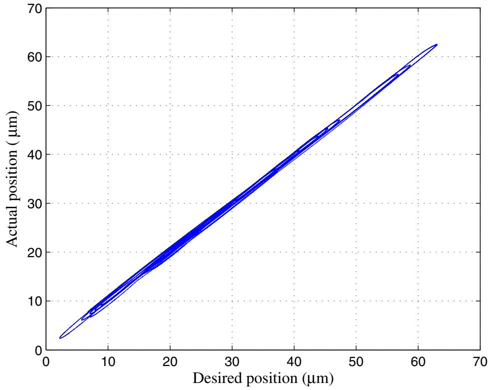
4.3 Feedforward Control with the MPI Model

This set of experiments was conducted by only using the feedforward control when $v_{fb}(t) = 0$ as shown in Fig. 1. The feedforward controller (4) was designed based on the MPI model to cancel the hysteresis nonlinearity. Before implementing the controller, the parameters n, r_i, p_1, p_2 and $b(r_i)$ should be identified firstly. In general, it may be more accurate to describe the inverse hysteresis loops if a larger n is selected. However, more efforts should be made in the real-time calculation of compensation signals. In this work, ten play operators (i.e. $n = 10$) were chosen for identification and compensation with fixed threshold values r_i defined as

$$r_i = \frac{i}{n}||y_d(t)||_\infty, \ i = 0, 1, 2, ..., n-1 \tag{8}$$



(a) Trajectory following

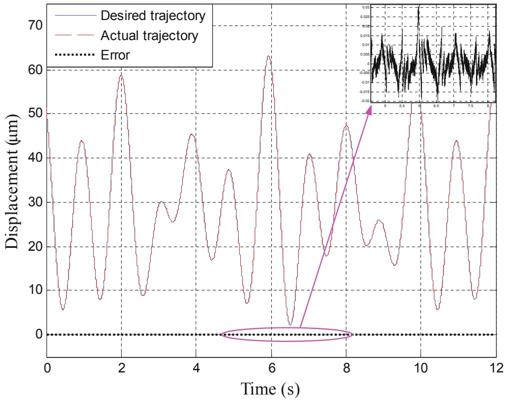


(b) Output-input relationship

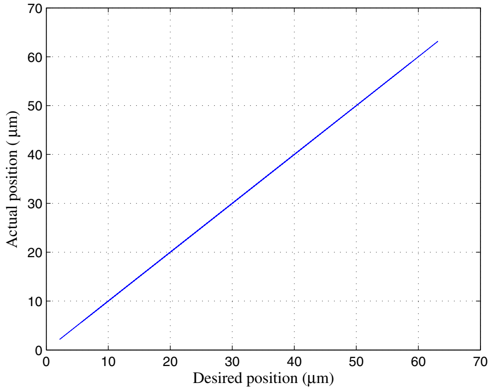
Fig. 4. Feedforward tracking control response

with $||y_d(t)||_\infty = 1$ in the normalized case. Then, the other parameters p_1, p_2 and $b(r_i)$ were identified by a particle swarm optimization algorithm [5].

The multi-amplitude sine signal was also used to evaluate the performance of the feedforward controller that utilized the direct hysteresis compensation method. Fig. 4 shows the feedforward tracking control results with the multi-amplitude sine signal. The maximum error of the feedforward system is about 1.24 μm. As described in Fig. 4(b), the maximum hysteresis caused error is about $e_{mhe} = 2.46\%$, which is reduced by up to 81.35% comparing with the open-loop response as illustrated in Fig. 3(b). From Fig. 4(b), it can also be observed that the hysteresis nonlinearity is greatly mitigated and the resulted relationship between the desired position and the actual position is almost symmetric. Therefore, the results of feedforward control demonstrate the effectiveness of the MPI model for asymmetric hysteresis compensation. However, due to the existence of modeling uncertainty and creep nonlinearity, the tracking errors



(a) Trajectory following



(b) Output-input relationship

Fig. 5. Feedforward-feedback tracking control response

cannot converge to zero. In the following development, the feedback control will be combined to eliminate these errors by using the actual position deviations from the desired position.

4.4 Feedforward-Feedback Control

Finally, the combined feedforward-feedback control strategy (6) was tested. Before implementing the PID controller, the control parameters k_p, k_i and k_d were tuned as $k_p = 0.8$, $k_i = 1000$ and $k_d = 0.00001$ by the trail and error method [4]. With these tuned parameters of the PID control law and the feedforward compensator, Fig. 5 shows the feedforward-feedback tracking control response of the PCA. It can be observed, from Fig. 5(a), that the actual trajectory well follows the desired trajectory. The maximum error of the feedforward-feedback

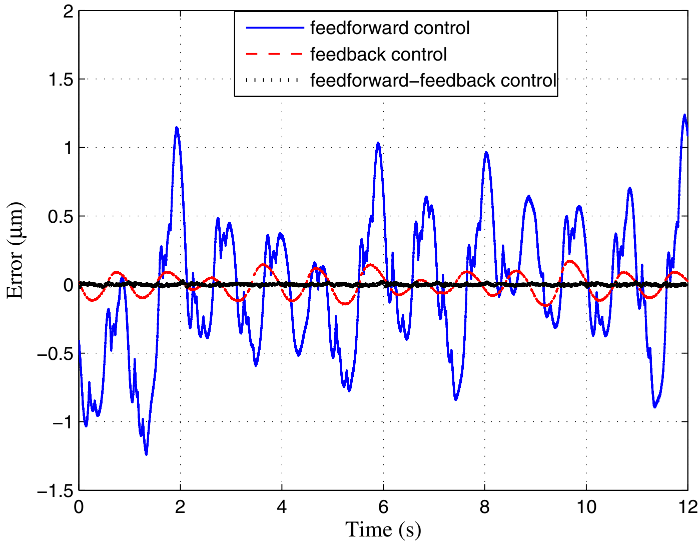


Fig. 6. Comparisons of tracking errors with different control strategies

control system is about 30 nm. Fig. 5(b) shows the resulted output-input relationship between the desired position and actual position, where the hysteresis nonlinearity is exactly mitigated. From Fig. 5, we can see that the maximum hysteresis caused error e_{mhe} is less than 0.1%. To further elucidate the advantage of feedforward-feedback control, Fig. 6 gives the comparisons of tracking errors with three kinds of control strategies. It can be concluded that by compensating for hysteresis, the performance of the feedback system designed is enhanced. In summary, the comparative experimental results demonstrate that the developed feedforward-feedback controller with the MPI model is quite feasible and effective to improve the tracking performance of the PCA with asymmetric hysteresis and creep nonlinearities.

5 Conclusion

In this paper, a MPI model is adopted to characterize the asymmetric hysteresis of the PCA. Based on the model, a direct inverse hysteresis controller is utilized in the feedforward path to cancel the asymmetric hysteresis nonlinearity. In order to further improve the tracking precision, a PID controller is combined to mitigate the modeling uncertainty and creep nonlinearity. In comparison with the open-loop operation, the maximum tracking error is reduced from 6.47 μm to 30 nm, and the maximum hysteresis caused error is reduced from 13.19% to less than 0.1% with respect to the desired displacement range. In the future, advanced model-based feedback control approaches will be used to replace the PID control law for further enhancement of the tracking performance.

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