Hysteresis compensation of piezoelectric actuator for open-loop control

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The hysteresis nonlinearity of piezoelectric actuator is one of the main defects in the control of deformable mirror which is widely used as a key component in adaptive optics system. This letter put forward a modified Prandtl-Ishlinskii (PI) model in order to precisely describe the hysteresis nonlinearity of piezoelectric actuator. With this proposed model, an inverse-model based controller used for trajectory tracking in open-loop operation is designed to compensate the hysteresis nonlinearity effect. Then, some tracking control experiments for the desired triangle trajectory are performed. From the experimental results, we can see that the positioning precision in open loop operation is significantly improved with this inverse-model based controller.

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In adaptive optical systems, piezoelectric actuators are widely used in order to well control mirror surface to get better optical resolution and sensitivity. However, the hysteresis[1,2] nonlinearity existing in piezoelectric ceramic can reduce the performance of an adaptive optics system, in both bandwidth and residual wave-front. Therefore, it is worthwhile to give some analysis on how to reduce the positioning error of piezoelectric actuator in open-loop operation.

Piezoelectric actuator is extremely popular due to its ultra-fine resolution, high output force, fast response time, compactness, and electro-magnetic compatibility. However, the hysteresis nonlinearity existing in piezoelectric actuators can severely degrade the performance of the actuator by giving rise to undesirable inaccuracy in the open loop system. If the hysteresis is not modeled and incorporated in the controller design, it is impossible to reach a high positioning accuracy.

In order to compensate for the hysteresis effect, tremendous amount of research methods have been documented in the past. Many models are proposed to compensate for hysteresis, and the most popular feed-forward models include: the Maxwell's slip model[3], Duhem model[4], Krasnosel'skii-Pokrovskii model[5], Preisach model[6], Prandtl-Ishlinskii (PI) model[7], Bouc-Wen model[8], and second or higher order polynomial model[9].

The Maxwell model has explicit physical meanings and simple mathematical description, but the description for hysteresis characteristic is not integral. Duhem model has clear mathematical expressions, but the static model error cannot be neglected. Preisach model can well describe hysteresis loop with multi-extremum, but this model is not suitable for real-time applications, moreover, it is difficult to get its inverse model. Krasnosel'skii-Pokrovskii model is a variation of Preisach model. PI model has simple analytical mathematical expressions which is easy to get its inverse. The major advantage of Bouc-Wen model is that the parameters which need to be identified are very few, however this model cannot depict the asymmetrical hystersis curves. It is also difficult to get the inverse of polynomial model due to the computation complexity. Which situation a model can be used in is often decided by its characteristics.

In order to get a better tracking accuracy in the open-loop real-time application, this letter propose a modified PI model which can precisely describe the hysteresis curve to correct the hysteresis nonlinearity of piezoelectric actuators. With this model, an inverse-model based controller is designed to track periodic reference inputs in open loop operation. From the experimental results, we can see that the positioning precision in open loop operation is significantly improved with this inverse-model based controller.

PI hysteresis model is purely phenomenological, and the hysteresis is modeled only based on the experimental observations. The PI hysteresis model proposed by Ikuta[10] made use of the play operator to characterize the input-output relationship. With a positive threshold value r, the play operator's behavior between input and output is depicted by Fig. 1.

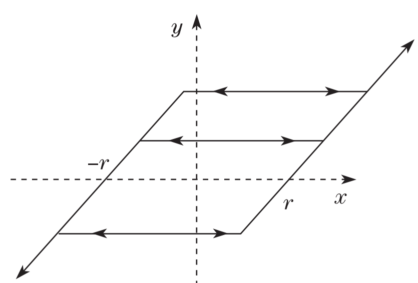

Fig. 1. The input-output relationship of play operator.

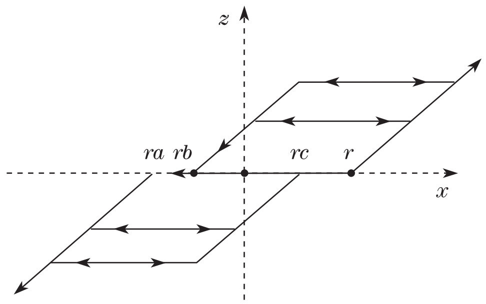

Fig. 2. Input-output relationship of CP operator.

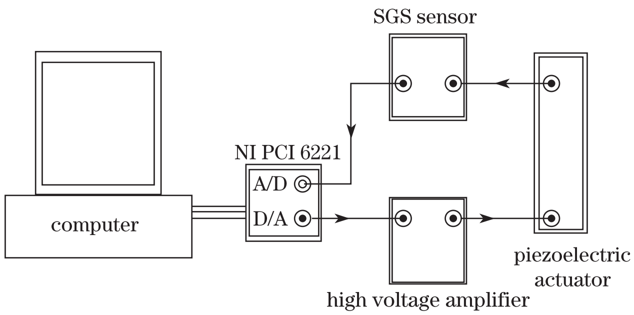

Fig. 3. Test system.

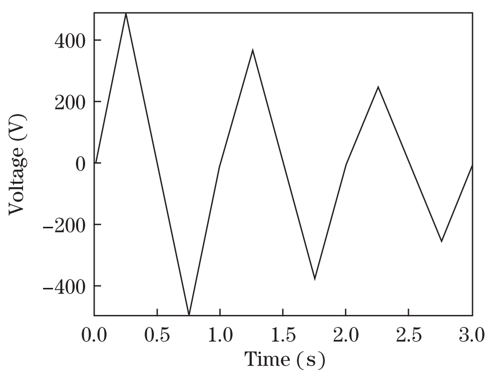

Fig. 4. Input voltage signal.

In the discrete-time domain, a play operator is defined by

$$\begin{aligned} y(t) &= H_r[x, y_0](t) \\ &= \max\{x(t) - r, \min(x(t) + r), y(t - T)\}, \end{aligned} \qquad (1)$$

where x is the input, y is the output response, r is the threshold value of the control input, and T represents the sampling period. The initial consistency condition of Eq. (1) is given by

$$y(0) = \max\{x(0) - r, \min(x(0) + r), y_0\}, \qquad (2)$$

with $y_0 \in R$, and is usually initialized to zero.

PI model has simple analytical expressions and do not need much computation, so it is very suitable for real-time application. Its inverse is easy to solve and also of a PI type. PI model and its inverse are symmetry and convex. However, most hysteresis loops are asymmetric and concave around the origin in experiments. The PI hysteresis model lacks accuracy in regulating the residual displacement near the origin due to play operator's symmetry properties about a center point. In this letter, a novel modified PI modeling method which can describe the asymmetric and concave properties is proposed to solve the problem. In the method, a coupled-play (CP) operator shown in Fig. 2 is used as the elementary operator. The CP operator can be formulated as

$$z(k) = H[x(k), x_0(k-1), z_0(k-1), r, ra, rb, rc](k)$$

$$= \begin{cases} x(k) - r, & x(k) \geqslant x(k-1); x(k) \geqslant rc; x(k) - r \geqslant z(k-1) \\ x(k) - rc, & x(k) \geqslant x(k-1); x(k) < rc; x(k) - rc \geqslant z(k-1) \\ x(k) - ra, & x(k) < x(k-1); x(k) \leqslant -rb; x(k) + ra, \leqslant z(k-1) \\ x(k) - rb, & x(k) < x(k-1); x(k) > -rb; x(k) + rb \leqslant z(k-1) \\ x(k-1), & \text{others} \end{cases} \qquad (3)$$

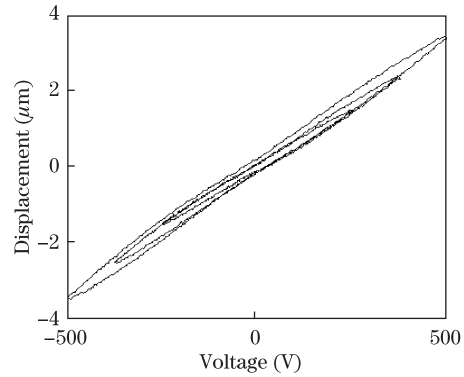

Fig. 5. Response of the piezoelectric actuator.

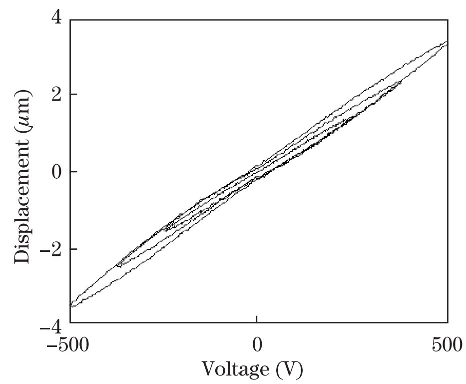

Fig. 6. Response of the modified PI model.

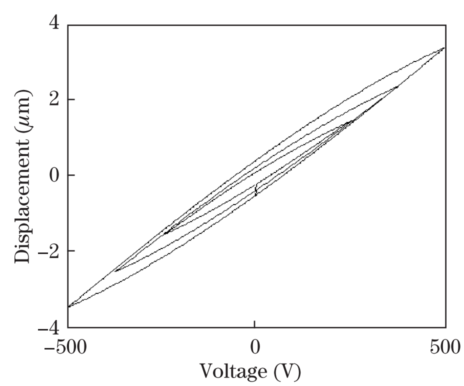

Fig. 7. Response of conventional PI model.

where ra, rb, rc and r are the thresholds of the CP operator; $x(k)$ represents the current input; x_0 $(k{-}1)$ and z_0 $(k{-}1)$ represent previous input and output, respectively. Generally, the initial consistency condition of Eq.(3) is: x_0 $(k{-}1){=}0$, z_0 $(k{-}1) = 0$. Then, the complex modified PI model can be got by a linearly weighted superposition of many CP operators with different weight and threshold values. That is, the modified PI model can be formulated by

$$y(k) = \mathbf{w}^T\mathbf{H}[x(k), \mathbf{x_0(k-1)}, \mathbf{z_0(k-1)}, \mathbf{r}, \mathbf{ra}, \mathbf{rb}, \mathbf{rc}](k)$$
$$= \sum_{i=1}^{n} w_i H_i[x(k), x_0(k-1), z_0(k-1), r_i, ra_i, rb_i, rc_i](k), \tag{4}$$

where $i = 1, \cdots, n$; $\mathbf{w}{=}[w_1, \cdots, w_n]^{\mathrm{T}}$ is the weight vector; $\mathbf{H}[x(k), \mathbf{x_0(k-1)}, \mathbf{z_0(k-1)}, \mathbf{r}, \mathbf{ra}, \mathbf{rb}, \mathbf{rc}](k) = [H_1[x(k), x_01(k-1), z_01(k-1), r_1, ra_1, rb_1, rc_1](k), \cdots, H_n[x(k), x_0n(k-1), z_0n(k-1), r_n, ra_n, rb_n, rc_n](k)]^{\mathrm{T}}$ is the vector of the CP operators; $\mathbf{x_0} = [x_0, \cdots, x_0n]^{\mathrm{T}}$ and $\mathbf{z_0} = [z_01, \cdots, z_0n]^{\mathrm{T}}$ are the initial state vectors; $\mathbf{r} = [r_1, \cdots, r_n]^{\mathrm{T}}$, $\mathbf{ra} = [ra_1, \cdots, ra_n]^{\mathrm{T}}$, $\mathbf{rb} = [rb_1, \cdots, rb_n]^{\mathrm{T}}$ and $\mathbf{rc} = [rc_1, \cdots, rc_n]^{\mathrm{T}}$ are the threshold vectors.

In order to validate the effectiveness of the proposed modified PI modeling method, an experimental platform is established as shown in Fig. 3. A computer generates the desired reference input position signals and implements the control procedure for the piezoelectric actuator. This signal is converted by a 16-bit D/A converter (built in NI PCI 6221) and amplified by a high voltage amplifier (from Institute of Optics and Electronics (IOE), Chinese Academy of Sciences (CAS)). The actual output displacement of the piezoelectric actuator is measured by a strain gauge sensor (from IOE, CAS) and converted to a digital signal by a 16-bit A/D converter.

Next, the proposed novel modified hysteresis model is investigated by a set of experimental tests. For a set of CP operators with predefined thresholds r_i, we need to identify the weighted parameters and suitable values of ra, rb, and rc, in order to obtain a minimal error between the experimental output results and model output response. For this purpose, 20 CP operators are used here to cover the input signal range of −500 to 500 V. Threshold values r_i are chosen in an orderly ascending sequence with equally spaced intervals.

Here, a least-square optimization algorithm is employed for error minimization. The identification input shown in Fig. 4 is designed so that it can cover the entire input range. Figure 5 demonstrates the real output response of the piezoelectric actuator. And, Figs. 6 and 7 illustrate the simulated output responses of the modified and conventional PI models, respectively. Figure 8 compares the modeling errors between the conventional PI model and modified one. The maximum errors for the conventional and modified model are got as 5.31% and 1.02%, respectively. From Fig. 8, we can observed that the modified PI model can reach a better response over the conventional one.

Inverse model based hysteresis compensation was effective. The foremost idea of an inverse-model feed-forward controller is to cascade the inverse model with the actual actuator to get an identity mapping between desired output and real response for the actuator. The inverse of PI type hysteresis model is also of PI type with different thresholds and weight values. Analogously, the inverse of the modified PI hysteresis model can be obtained as

$$y'(k) = \mathbf{w}'^T\mathbf{H}^{-1'}[x(k), \mathbf{x_0(k-1)}, \mathbf{z_0(k-1)}, \mathbf{r}', \mathbf{ra}', \mathbf{rb}', \mathbf{rc}'](k)$$
$$= \sum_{i=1}^{n} w_i' H_i^{-1}[x(k), x_0(k-1), z_0(k-1), r_i', ra_i', rb_i', rc_i'](k). \tag{5}$$

The hysteresis nonlinearity of piezoelectric actuator can be regarded as a kind of system disturbance, so feed-forward compensation method which is based on inverse model can be employed. The control scheme is shown as Fig. 9.

The experiment setup used for tracking control is identical to that in the parameter identification experiments. The control algorithm was implemented with a 1-kHz sampling rate. Hysteresis nonlinearity exists in piezoelectric actuator, so the input fails to precisely control the output under open-loop operation. As shown in Fig. 10, when the tracking control experiment makes use of a 1-Hz triangular wave with a 3.0-μm amplitude, the tracking error is between –0.33 and 0.33 μm, around 11.0% full

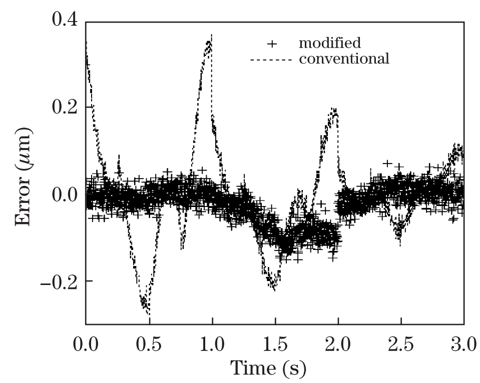

Fig. 8. Modeling errors of the conventional and modified PI models.

Fig. 9. The block diagram of the feed-forward compensation method.

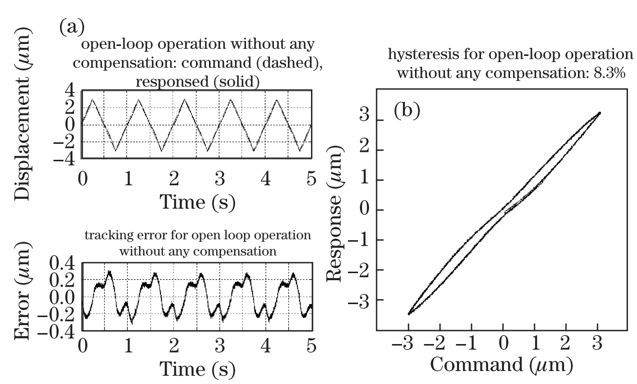

Fig. 10. Actuator response in open-loop operation without correction. (a) Desired and real outputs, and the error; (b) hysteresis curve.

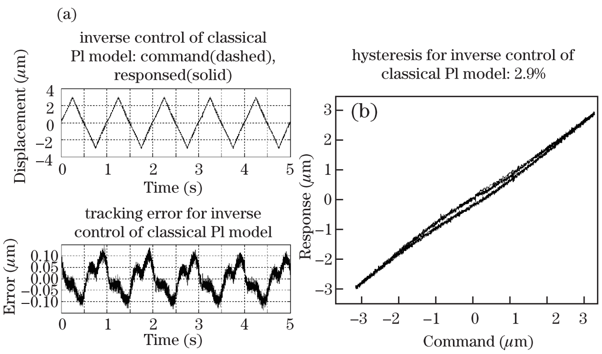

Fig. 11. Actuator response in open-loop operation with inverse controller of classical PI model. (a) Desired and real outputs, and the error; (b) hysteresis curve.

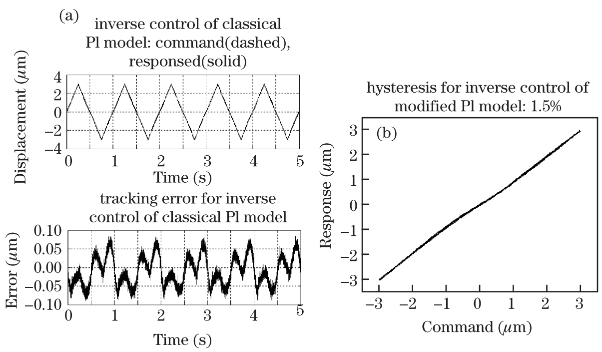

Fig. 12. Actuator response in open-loop operation with inverse controller of modified PI model. (a) Desired and real outputs, and the error; (b) hysteresis curve.

scale range (FSR). And the hysteresis can reach to 8.3% without any compensation.

Compensation for hysteresis nonlinearity using cascaded connections of an inverse model was confirmed to be effective. In order to compare tracking performances, two kinds of inverse-model feed-forward controllers were used to reduce the tracking error between the real actuator output and the desired actuator output. The trajectory command input signal is same to the one which is used in the open loop operation without any compensation. The tracking performances of the two controllers are shown in Figs. 11 and 12. From Fig. 11, we can see that the tracking error is bound within –0.140 to +0.150 μm and reduced to less than 4.8% FSR. The value of hysteresis has been reduced into 2.9%. From Fig. 12, we can see that the tracking error is bound within –0.08 to +0.08 μm and greatly reduced to less than 2.6% FSR. The value of hysteresis has been reduced into 1.5%.

The two inverse-model-based controllers have derived a better tracking performance compared to the operation without correction. And the modified PI model based inverse controller has a better tracking performance compared to the classical PI model.

The main contribution of this letter is to use an asymmetric PI model to describe the hysteresis of the actuator for low-frequency real-time trajectory tracking application. Combining this modified PI model, an inverse-model feed-forward controller is designed to reduce the tracking error in open-loop operation and experimental results show that the tracking precision is significantly improved. In this work, the creep phenomenon is not considered because its effect is not significant due to the symmetry of the input excitation. Future research will account for the creep effect.

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