Hindawi
Journal of Applied Mathematics
Volume 2022, Article ID 3340331, 12 pages
https://doi.org/10.1155/2022/3340331

Research Article

Research on a New Control System Based on L1 Adaptive Control Scheme for the Voice Coil Motor

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Received 23 August 2022; Revised 13 November 2022; Accepted 17 November 2022; Published 22 December 2022

Academic Editor: Tudor Barbu

With the continuous development of voice coil motors, it has also been widely used in today's sports competitions. For example, the Hawk-Eye system in tennis matches uses voice coil motors to focus on the camera to capture the trajectory of the tennis ball. Therefore, in order to better solve the problem of dynamic parameter uncertainty, external load disturbance, and tracking control of the voice coil motor servo system in motion, this paper proposes for the first time the strategy of using L1 adaptive control algorithm to control the voice coil motor servo system. First, it briefly analyzes the working principle and control method of the voice coil motor, and then constructs the uncertain parameter model according to the mathematical model of the voice coil motor. The closed-loop system of voice coil motor is simulated and analyzed by L1 adaptive controller. The results show that the L1 adaptive control method effectively suppresses the high-frequency interference caused by the voice coil motor in operation, can control the tracking error to gradually converge and so the tracking effect is better, and has strong robustness to the perturbation of system parameters. It can be applied to voice coil motor servo control.

1. Introduction

This year, with the continuous development of science and technology, the voice coil motor (VCM) has become more compact and more sophisticated, and the voice coil motor control algorithm has become more and more mature [1, 2]. The voice coil motor is a directly driven nonhysteresis device. Its principle is similar to that of a loudspeaker. Its working principle is based on the principle of ampere force. It uses the interaction between the magnetic field generated by the permanent magnet and the energized coil to generate the driving force, the size, and application of the force. The current on the coil is proportional. The voice coil motor is a special linear motor with simple structure, small size, low noise, compact size, high accuracy, high acceleration, fast response, and no hysteresis [3], so it has been widely used in the field of optical systems. For example, the Eagle Eye system in a tennis match places a high-resolution camera around the tennis court, captures the running trajectory of the tennis ball through the camera's autofocus function, and then simulates the calculation to present the complete trajectory on a large screen. The autofocus function of the camera is realized by locking the camera into the voice coil motor, and when the coil is energized, a magnetic field is generated, and the coil magnetic field interacts with the permanent magnet, thereby prompting the camera in the coil to move; when the coil is deenergized, the elastic force of the shrapnel drives the camera back to the initial position [4]. VCM has the advantages of simple structure, good rigidity, fast response speed, and no cogging effect, and it has been widely used in precision motion control. However, VCM are difficult to control, so they are still the destination and difficulty of application research. Therefore, the control of the voice coil motor is not easy to implement. At present, the conventional PID controller and adaptive fuzzy PID controller are still the first choice of control engineers due to their easy implementation, low cost, and simple structure. But in the case of that under high nonlinearity and interference, it cannot obtain a high-precision control level [5, 6]. The poor robustness of these control algorithms is reflected in the time-varying characteristics of parameters and external interference. Therefore, the trajectory tracking control of the voice coil motor servo system is affected by the uncertainty of mechanical parameters, external disturbances, and load disturbances, so its control effect is nonideal, and the positioning accuracy has a large transient error, which cannot meet the ideal control requirements [7]. At the same time, the existing voice coil motor-sliding mode control can solve the problem that uncertain parameters of the voice coil motor and has high robustness to the control system, but it cannot solve the influence of external load disturbance [8].

In response to the above-mentioned problems in the control strategy, this paper proposes a new type of control algorithm (L1 adaptive control) to systematically control the voice coil motor for the first time, and this algorithm was jointly proposed by Chang et al. and Cao and Hovakimyan of the United States in 2006 [9, 10]. Its characteristic is to improve and evolve on the basis of the traditional adaptive control mechanism and ensure the gradual stability of the system by introducing a low-pass filter and increasing the adaptive gain; at the same time, it also has good robustness and the ability of the system to adapt quickly. The L1 adaptive control algorithm has been successfully applied to NASA'SGTM and X-488 aircraft, as well as in the field of UAV control [10–12]. This paper uses the strong robustness of the L1 adaptive controller to perform servo control on the closed-loop system of the voice coil motor, which is affected by external load disturbances and the uncertainty of dynamic parameters due to inaccurate modeling, so that the trajectory tracking control system is adaptive, and tracking error index quickly converges, improves the transient and steady-state performance of the system, and ensures the high-precision control strategy of the voice coil motor.

2. Establishment of Mathematical Model of Voice Coil Motor Control System

The voice coil motor is designed based on the Lorentz magnetic force. Aiming at the uncertainty of the voice coil motor servo system model and tracking control problems, the research based on the Lorentz magnetic principle, dynamic description, and working status is performed; then the mathematical model of the voice coil motor is established and the state space equation of the voice coil motor is constructed.

2.1. Principles of Magnetism. The basic working principle of the voice coil motor is based on the principle of ampere force. When an energized conductor is placed in a magnetic field, an electromagnetic force F_e will be generated. The magnitude of the electromagnetic force depends on the strength of magnetic field B_σ, current ⊠, and the direction of the magnetic field and current [13], as shown in Figure 1:

If the voice coil motor has W turns and N wires, the average effective length of each turn of the coil conductor in the magnetic field is l; when placed in the magnetic field, the electromagnetic force experienced by the voice coil motor can be expressed as:

$$F_e = B_\sigma L i_a = B_\sigma l W N i_a. \tag{1}$$

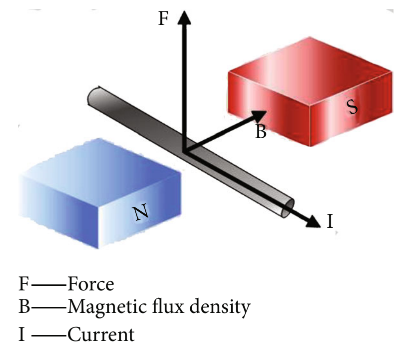

Figure 1: Schematic diagram of ampere force.

In the formula, W means the number of coil turns; N means the number of parallel windings; l means the average effective length of each turn of the coil conductor in the magnetic field, the unit is m;B_σ means the magnetic induction intensity of the space where the coil is located, the unit is T; and I means the current in the coil conductor, the unit is A.

It can be seen from Figure 1 that the direction of the force is a function of the current direction and the magnetic field vector, which is the interaction of the both. In the structure of the voice coil motor, the DC voice coil motor is a tubular coil winding located in the radial electromagnetic field, as shown in Figure 2. The magnetic field inside the ferromagnetic cylinder is generated by a permanent magnet, so that the magnet attached to the coil has the same polarity. The inner core of ferromagnetic material is arranged on the center line of the circular axis and connected with one endpoint of the permanent magnet to form a magnetic circuit. When the coil is energized, it is subjected to the action of the magnetic field according to the principle of ampere force to generate a force along the axis between the coil and the magnet, the polarity of the voltage on the both endpoints of the energized coil determines the direction of the force. As long as the electromagnetic force received by the coil is greater than the static friction force F_σ existing in the coil support, the coil can be moved linearly.

2.2. Mathematical Model of Voice Coil Motor. In a voice coil motor, when the coil is energized with direct current, the current i_a in the coil will generate a magnetic field force, thus the motor movement, and at the same time, a back electromotive force e_a is also generated. The magnitude of it can be expressed as

$$e_a = B_\sigma L v = B_\sigma L \dot{x}. \tag{2}$$

In the formula, v means the speed at which the armature cuts the magnetic line of force (m/s); $B_\sigma L$ means constant of force. Defining $k_s = B_\sigma L$, B_σ and L are two characterization of the motor that only depends on the size and material of the motor [14].

Analyzing the coil circuit of the voice coil motor combined with the working principle of the voice coil motor, the voltage at the armature endpoint of the voice coil motor is u_a (generally the signal voltage), and the resistance of the

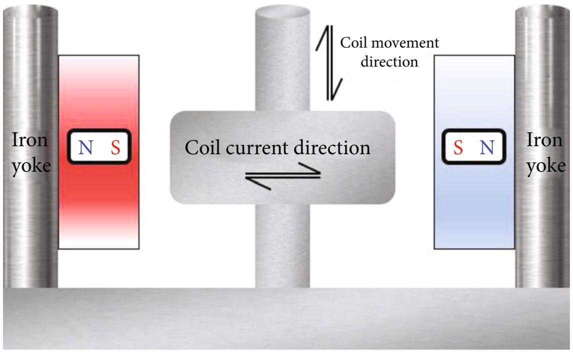

Figure 2: Voice coil motor structure diagram.

armature circuit is R_a (the resistance of the coil itself and the resistance in the drive circuit connected in series).

According to Kirchhoff's voltage law, the voltage balance equation of the armature circuit at steady state is

$$u_a = e_a + i_a R_a = K_s \dot{x} + i_a R_a. \tag{3}$$

In reality, the voice coil motor is usually under a dynamic circumstances in the control system, so the inductance of the armature winding also needs to be considered; as a result, the dynamic voltage balance equation is

$$u_a = e_a + i_a R + L_a \frac{d_{i_a}}{dt}. \tag{4}$$

The electromagnetic force of the voice coil motor in motion overcomes the inertial force experienced by the mover motion, Fm, according to Newton's second law.

$$F_m = ma = m\frac{dv}{dt} = m\ddot{X}. \tag{5}$$

In the formula, m is the total mass of the mover part; a is the acceleration of mover motion; v is the linear velocity of the mover's motion; and x is the displacement of the mover in a certain period of time.

The mover of the voice coil motor is driven by the ampere force F_e, and there is a dynamic friction force F_c while it moves; it is opposite to the direction of the mover's movement. Suppose the coefficient of dynamic friction is kc, according to Formulas (1)–(5), the dynamic balance equation of motor force can be expressed as

$$F_m = F_e - F_c = B_\sigma L i_a - k_c v = m\ddot{X}. \tag{6}$$

According to the voltage dynamic equation and the force dynamic balance equation of the voice coil motor, it can be obtained that

$$\begin{aligned} u_a &= e_a + i_a R_a + L_a \frac{di_a}{dt}, \\ F_m &= m\ddot{x}, \\ F_m &= F_e - F_c, \\ F_e &= B_\sigma L i_a, \\ F_c &= k_c v, \\ e_a &= K_s \dot{x}. \end{aligned} \tag{7}$$

According to Formula (7), the relationship between the control voltage u_a of the voice coil motor and the displacement x of the mover movement can be expressed as

$$u_a = K_s + \frac{R_a}{K_s}(m\ddot{x} + k_c\dot{x}) + \frac{L_a}{K_s}(m\ddot{x} + k_c\dot{x}). \tag{8}$$

According to the dynamic description and the study of the working status of the voice coil motor, it is found that there are some problems in the uncertainty of the dynamic parameters and the influence of the external load disturbance of the voice coil motor in the servo control system. Based on the above problems, the dynamic description of the servo system whose control object is voice coil motor can be described as

$$m\ddot{x} + k_c\dot{x} + kx = F_e + d. \tag{9}$$

In the formula, x is the displacement of the voice coil motor mover relative to the balance point; m is the total mass of the mover part; k_c is the coefficient of dynamic friction generated by the mover of the motor driven by electromagnetic force; k is the equivalent stiffness; F_e is the electromagnetic force generated by the moving of voice coil motor that under the influence of magnetic field and current; $d$is the Coulomb friction and eddy current loss produce unknown disturbances, which are unknown parameters and disturbances.

Denote the speed, acceleration, and jerk as v, a, and j; then, the dynamic equation can be obtained according to Formula (9), which is expressed as

$$\begin{aligned} \dot{x} &= v, \\ \dot{v} &= \frac{F_e + d - kx - k_C v}{m}, \\ \dot{v} &= v, \\ \dot{x} &= \dot{j}. \end{aligned} \tag{10}$$

In addition, it can be obtained from Equation (8)

$$u_a = \frac{kR_a}{K_s}x + \left(K_s + \frac{kR_a + kL_a}{K_s}\right)v + \frac{mR_a + L_a K_c}{K_s}a + \frac{mL_a}{K_s}j - \frac{d}{K_s}. \tag{11}$$

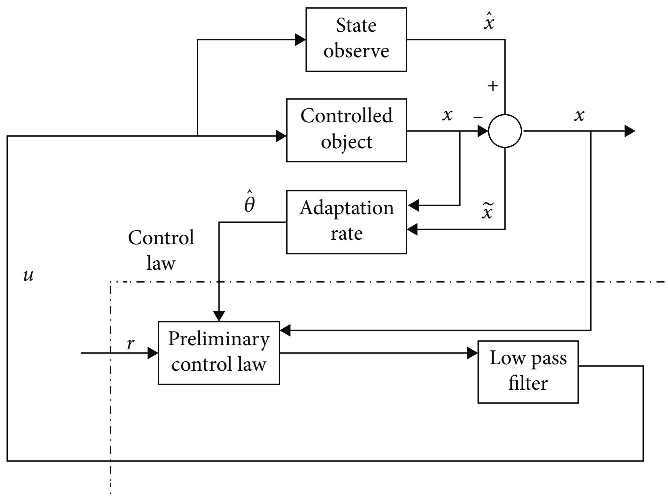

Figure 3: L1 adaptive control system structure.

And there is $u_a = K'x + C'v + M'a + L'j - D'$, which is

$$U_a(t) = L'x(t)''' + M'x(t)'' + C'x(t)' + K'x(t) - D', \quad (12)$$

where $L' = mL_a/K_s$, $M' = mR_a + L_aK_c/K_s$, $C' = K_s + kR_a/K_s + kL_a/K_s$, and $D' = d/K_s$.

3. L1 Adaptive Control Design

The L1 adaptive control algorithm has strong robust adaptive characteristics; it aims to solve the problems of high-frequency oscillation and model parameter uncertainty in adaptive control. This algorithm uses a low-pass filter to eliminate unnecessary high-frequency signal, effectively suppresses high-frequency oscillations caused by adaptive control, and ensures that the tracking error is close to zero. Based on the above advantages, according to the problems of the voice coil motor affected by kinematics, the L1 adaptive control algorithm can better solve these problems in the dynamic operation of the voice coil motor. Therefore, this paper uses the L1 adaptive control algorithm to design the linear motion control law of the voice coil motor for the first time, and then converts the nonlinear part of the voice coil motor dynamic model and the parameter uncertainty affected by dynamics into the state observer in the L1 adaptive control structure. Finally, it estimates the uncertain parameters and solves the controller through the adaptive law designed by the projection operator. L1 adaptive control through estimating the uncertainty of the model quickly ensures the performance of the system, while ensuring the robustness of the system [15].

3.1. The Composition of L1 Adaptive Control System. The L1 adaptive control system consists of four parts: the controlled object, the state observer, the adaptive rate, and the control rate; the control law includes a low-pass filter and a controller that match the state observer's initial control object parameter input; the state observer is used to estimate and monitor the state of the dynamic model and its changes; the adaptive law takes the error between the state observer and the controlled object as the main input to ensure stability in the sense of Lyapunov and obtain the estimation of the uncertainty parameter; and the low-pass filter link in the control law is to filter out the high-frequency components in the controlled object, reduce its interference to the control, and achieve the stability of the control. The structure of L1 adaptive control system is shown in Figure 3.

3.2. State Feedback Configuration. For the dynamic model of the voice coil motor and some of the external disturbances it suffers, the uncertain model of the system is constructed as $\dot{x} = Ax(t) + bu(t) + \delta$. The measurable and uncertain parameters of the system are decomposed into A, b, and δ. The parameters caused by the structure of the voice coil motor are decomposed into A, the input parameters are decomposed into b, the unknown parameters in the control system are decomposed into θ, and the interference parameter suffered by the system is δ. Then, the controlled object model can be expressed as

$$\begin{aligned} \dot{x} &= Ax(t) + b\left(u(t) + \theta^T x(t) + \delta(t)\right), \\ y(t) &= c^T x(t), x(0) = x_0. \end{aligned} \quad (13)$$

Among them, $x(t) \in Rn$ is the system state vector (measurable), $u(t) \in R$ is the control signal, b and $c \in Rn$ are the known constant vectors, and A is the known nn matrix; it is required that (A, b) be controllable, the unknown parameter $\theta \in Rn$ belongs to a given compact convex set $\theta \in \Omega$, $\delta(t)$ is a time-varying disturbance, and $y(t) \in R$ is the output of the system. The above parameters must be required

$$\theta(t) \in \Theta, \delta(t) \le \Delta, t \ge 0. \quad (14)$$

Then the control structure is as follows:

$$u(t) = u_1(t) + u_2(t), u_1(t) = -K^T x(t). \quad (15)$$

K is the design gain, which can be taken as zero, and the choice of K is required to satisfy the Hurwitz condition: $A_m = A - bK^T$. Combining Formula (15) with Formula (13) to obtain the controlled object

$$\begin{aligned} \dot{x} &= A_m x(t) + b\theta^T x(t) + bu_2(t) + b\delta(t), \\ y(t) &= c^T x(t), x(0) = x_0. \end{aligned} \tag{16}$$

According to the voice coil motor control system model, $u_a(t) = L' x(t)''' + M' x(t)'' + C' x(t)' + K' x(t) - D'$, establish the state space equation of the voice coil motor. Set the interference value and the uncertain parameter $D' = 0$ of the voice coil motor control model and select the state variable to eliminate the higher-order terms. Set

$$\begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} = \begin{bmatrix} \dot{x} \\ \ddot{x} \\ \dddot{x} \end{bmatrix}. \tag{17}$$

Then there is

$$\begin{bmatrix} z_1 \\ \dot{z}_1 \\ \dot{z}_2 \\ \dot{z}_3 \end{bmatrix} = \begin{bmatrix} x \\ z_2 \\ z_3 \\ \dddot{x} \end{bmatrix}. \tag{18}$$

The changes of system variables over time can be expressed as

$$\begin{aligned} \begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \\ \dot{z}_3 \end{bmatrix} &= \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -\dfrac{K'}{L'} & -\dfrac{C'}{L'} & -\dfrac{M'}{L'} \end{bmatrix} = \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \dfrac{1}{L'} \end{bmatrix}, \\ x &= \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} + [0] u_a(t), \end{aligned} \tag{19}$$

Simplify Formula (13) according to Formula (19); the following formula can be obtained:

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -\dfrac{K'}{L'} & -\dfrac{C'}{L'} & -\dfrac{M'}{L'} \end{bmatrix}, \tag{20}$$

$$b = \begin{bmatrix} 0 \\ 0 \\ \dfrac{1}{L'} \end{bmatrix}, \tag{21}$$

$$c = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}. \tag{22}$$

3.3. State Predictor Design. On the basis of introducing uncertain parameters and the mathematical model of the controlled object obtained by solving the state feedback configuration matrix, replace the

evaluation parameters to obtain the mathematical model of the state predictor, which is consistent with the mathematical model of the controlled object; the two mathematical models have different emphasis on parameter variables; the mathematical model of the controlled object focuses on the response of the system to the time domain, while the state predictor focuses on evaluating the impact of parameter changes on the controlled object.

$$\begin{aligned} \dot{\hat{x}}(t) &= A_m \hat{x}(t) + b\hat{\theta}^T x(t) + bu_1(t) + b\hat{\delta}(t), \\ \hat{y}(t) &= c^T \hat{x}(t), \hat{x}(0) = x_0. \end{aligned} \tag{23}$$

Among them, $\hat{x}$, $\hat{\theta}$, $\hat{\delta}$ are estimated values of x, θ, and δ, respectively.

3.4. Adaptive Law Design. The adaptive control law takes the error between the state predictor and the controlled object as input and outputs the relevant estimated parameters to the state predictor through the projection algorithm, so that the error becomes small and close to zero and ensures that the response characteristics of the state predictor and the controlled object are consistent. The adaptive law of system position parameters is as follows:

$$\begin{aligned} \dot{\hat{\theta}}(t) &= \Gamma_\theta \mathrm{Proj}\left(\hat{\theta}(t), -x(t)\tilde{x}^T(t)Pb\right), \\ \hat{\theta}(0) &= \hat{\theta}_0, \tilde{x}(t) = \hat{x}(t) - x(t), \\ \dot{\hat{\delta}}(t) &= \Gamma_\delta \mathrm{Proj}\left(\hat{\delta}(t), -\tilde{x}^T(t)Pb\right), \\ \hat{\delta}(0) &= \hat{\delta}_0. \end{aligned} \tag{24}$$

In the formula, Γ is the adaptive gain, $p = P^T > 0$; $A^T P + PA = -Q$ is the Lyapunov equation; for any $Q = Q^T$, there is a unique symmetric positive definite solution; $\mathrm{Proj}(.)$ is a projection operator to ensure that the estimated parameters are bounded and convergent [16].

3.5. Control Law Design. Since the controlled object is introduced into the state predictor, the L1 adaptive control law needs to solve the inconsistency in response characteristics caused by it; then

introduce uncertain parameters to eliminate its influence, but it will also cause high-frequency oscillations in the output of the controlled object. In order to solve for the above problems, it is necessary to add a low-pass-filtering link to the design of the control law to ensure that there is no steady-state error from the input parameter r to the output of the state predictor.

After performing Laplace transform on the output equation $\hat{y}(t) = c^T \hat{x}(t)$, Formula (25) can be obtained

$$\hat{y}(s) = c^T (sI - A_m)^{-1} b \left(u_2(s) + \hat{\theta}^T(s) x(s) + \hat{\delta} \right). \quad (25)$$

When time tends to infinity, it can be obtained that

$$\hat{y}(s) = c^T (sI - A_m)^{-1} b \left(u_2(s) + \hat{\theta}^T(s) x(s) + \hat{\delta} \right), \text{to ensure}\, \hat{y}(s). \quad (26)$$

t ⟶ ∞ = r(s), and it can be obtained that

$$u_2(s) = -\frac{1}{c^T A_m^{-1} b} r(s) - \theta^T(s) x(s) - \delta. \quad (27)$$

Design a low-pass filter

$$C(s) = \frac{kD(s)}{1 + kD(s)}. \quad (28)$$

It can eliminate the high-frequency vibration caused by the fast adaptive control, if $D(s) = 1/s$, the input after adding the filter is

$$u_2(s) = \frac{k}{s+k} \left(-\frac{1}{c^T A_m^{-1} b} r(s) - \theta^T(s) x(s) - \delta \right). \quad (29)$$

Deforming the above formula, it can be obtained that $u_2(s) = -kD(s)(-k_g r(s) + \hat{\eta}(s))$, which is the standard input form of L1 adaptive control. Among them, $k_g = -1/c^T A_m^{-1} b$ and $\hat{\eta}(s) = u_2(s) + \hat{\theta}^T(s) x(s) + \hat{\delta}$.

In summary, the L1 control law is as follows:

$$\begin{aligned} u(s) &= u_1(s) + u_2(s), \\ u_1(s) &= -K^T x(s), \\ u_2(s) &= -kD(s)\left(-k_g r(S) + \hat{\eta}(s)\right). \end{aligned} \quad (30)$$

4. Experimental Result and Analysis

From Formula (21) and (22), rank $(b, Ab) = 2$ can be obtained, so it can be known that the system is controllable; since A does not satisfy the Hurwitz condition, take the damping ration $\delta = 0.05$, and $K = [2.0863, 5.0552, 4.4525]$ can be obtained, as a result

$$A_m = A - bK^T = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -5.8 & -10.3 & -5.6 \end{bmatrix}. \quad (31)$$

Design the state estimator and parameter adaptation law of the closed-loop system of the voice coil motor, take $\Gamma = 10000$, as a result

$$P = \begin{bmatrix} 74.52 & 91.10 & -0.0003 \\ 91.10 & 112.37 & 0.06 \\ -0.0003 & 0.06 & 0.07 \end{bmatrix}. \quad (32)$$

The input form of the adaptive control law is as follows:

$$u_a(s) = -kD(s)\left(-k_g r(s) + \hat{\eta}(s)\right). \quad (33)$$

Set $K = 10$, according to $k_g = -(1/c^T A_m^{-1}) b$ after calculation, it can be obtained that $k_g = -5.84$.

In response to the establishment of the mathematical model of the voice coil motor in this paper, taking the PID controller that is most commonly used in the current closed-loop control method of the voice coil motor as a reference, its parameter can be design as $K_p = 9.5, K_i = 13.5$, $K_i = 13.5, K_d = 0.15$.

In response to the two cases that no disturbance and enhanced disturbance, the designed L1 adaptive control and PID control methods are comparatively simulated; then the optimal control method of the closed-loop control of the voice coil motor is obtained.

4.1. No Disturbance. When there is no disturbance, according to the closed-loop control system of the voice coil motor, the same input parameter is set to 2 mm, and the output response comparison curves of the L1 adaptive control method and the PID control method are shown in Figure 4. At the same time, the L1 adaptive control method and PID controller both have good command tracking ability, smooth response, achieve stable control, and with good convergence effect. The PID control effect of the closed-loop control of the voice coil motor is shown in Figure 5 and the application of L1 adaptive control effect is shown in Figure 6. It can be seen from the figure that although the rise time of PID control is shorter than the running time of L1 adaptive control method, there is a certain overshoot and system oscillates is more severely. When control system of the voice coil motor tends to be stable, the adjustment time of PID control is slightly slower than that of L1 adaptive control.

4.2. Enhance High-Frequency Disturbance. Adding certain external disturbance $\delta_1 = 2.5 \sin(0.3t)$, take $r = \begin{cases} 0 & t \le 5 \\ 2 & t > 5 \end{cases}$ as the reference input; then according to references, take the adaptive gain $\Gamma_c = 1000$, $Q = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$.

When the disturbance signal δ_1 is added as shown in Figure 7, the low-pass filter is added to the L1 adaptive control method, and its steady-state error is shown in Figure 8;

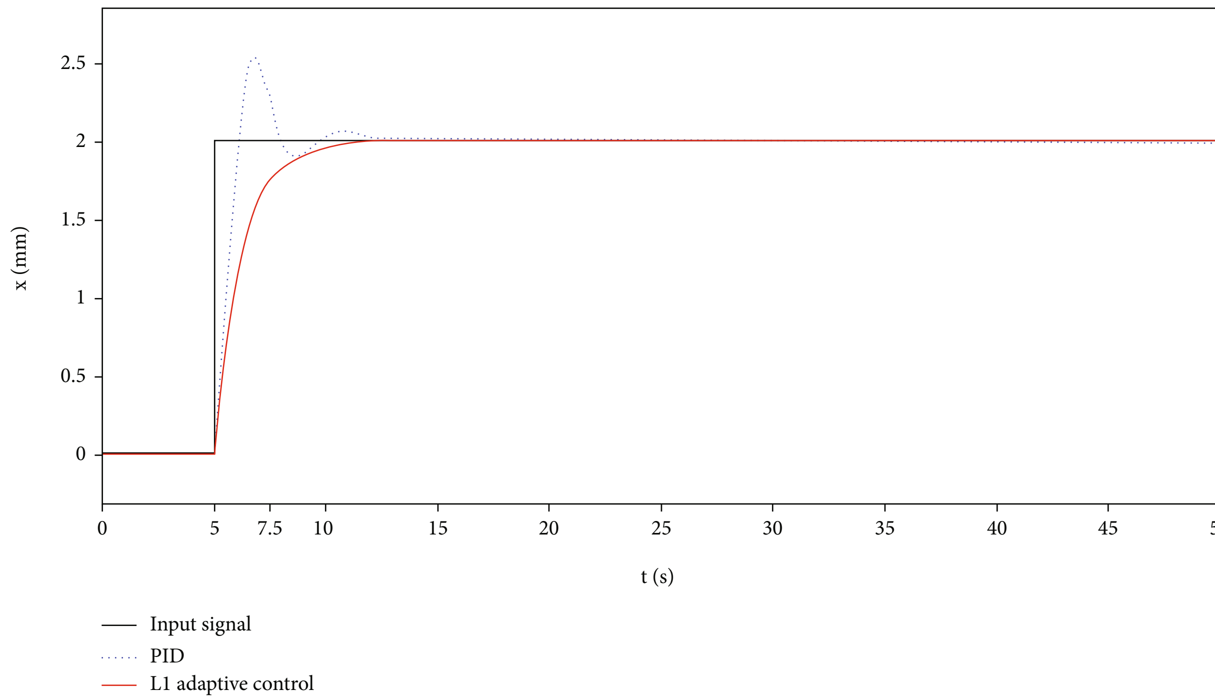

FIGURE 4: Track signal response when L1 has no interference.

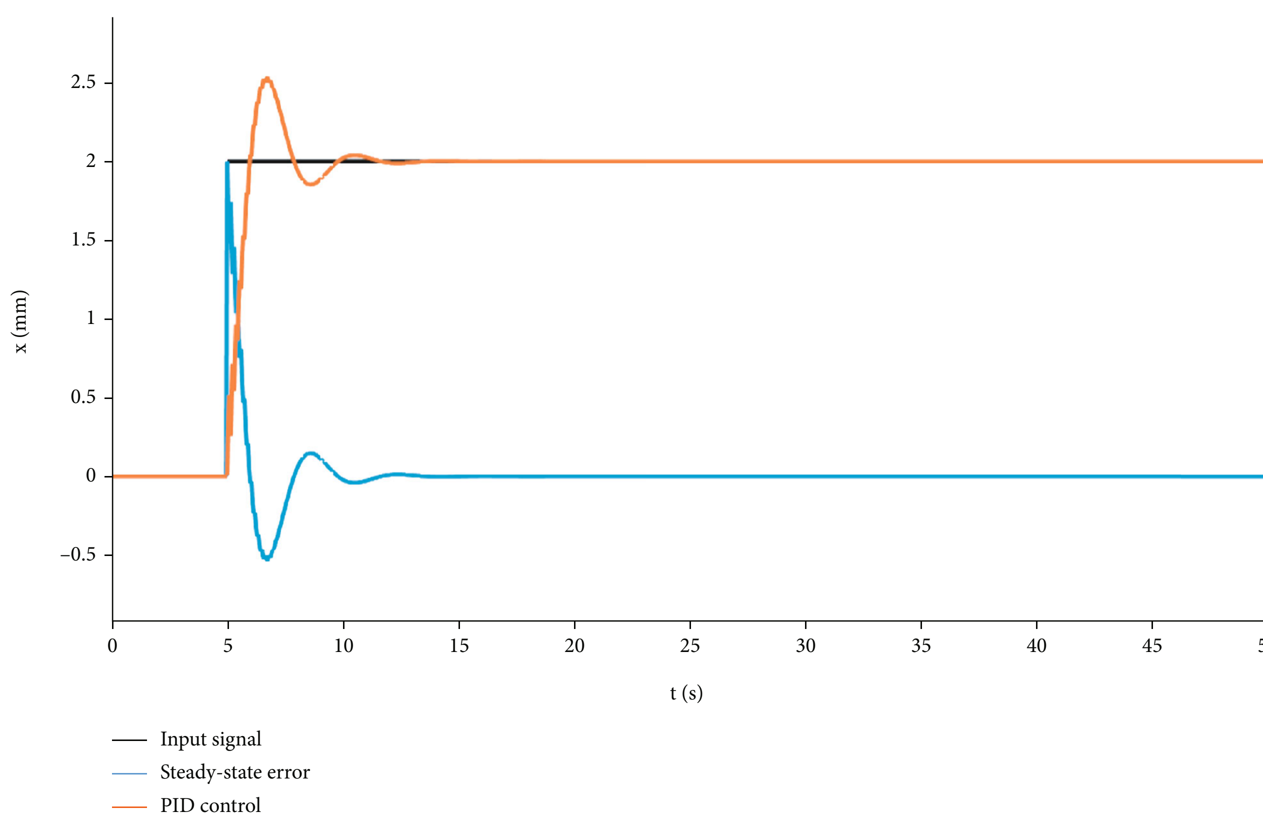

FIGURE 5: PID control tracking signal response.

at this time, the PID control effect is shown in Figure 9; it can be seen from the steady-state error and the final stability that the L1 adaptive control is obviously better than the PID control; the simulation results are shown in Figure 10. It can be seen from Figure 10 that when a certain disturbance is added to the voice coil motor closed-loop system, compared

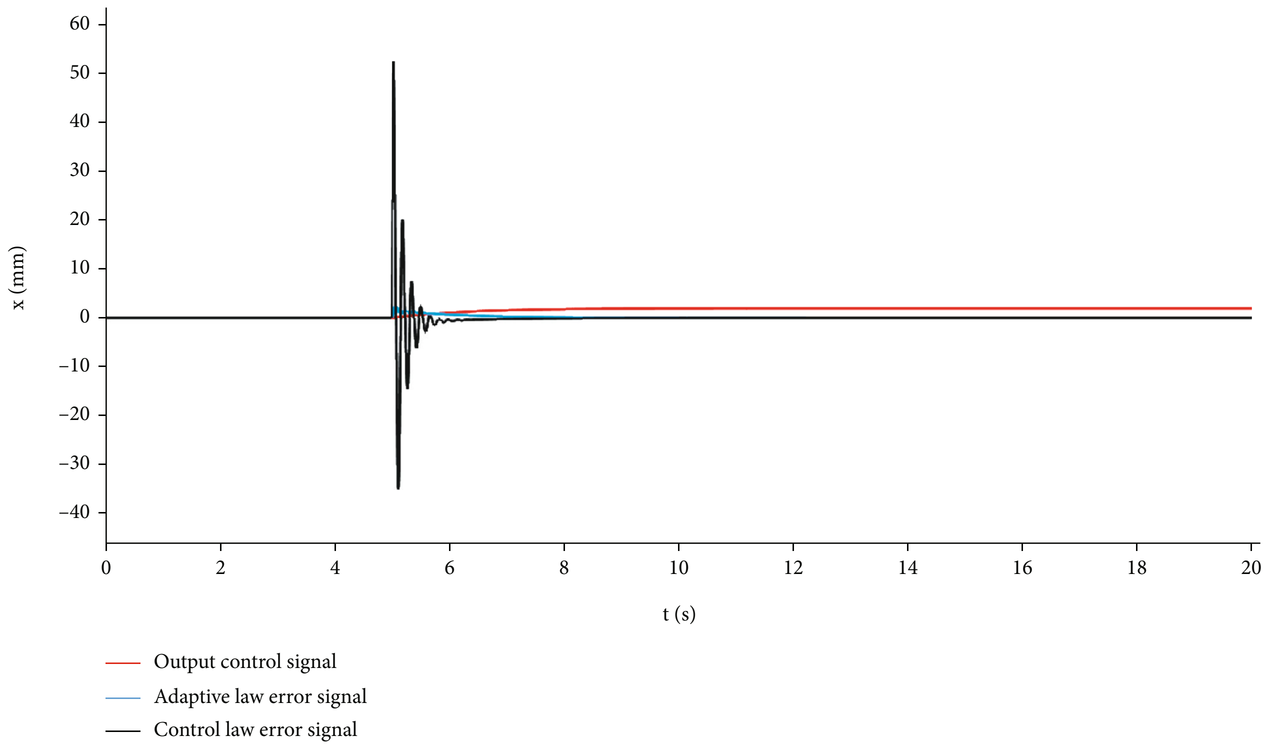

Figure 6: L1 adaptive control tracking signal response.

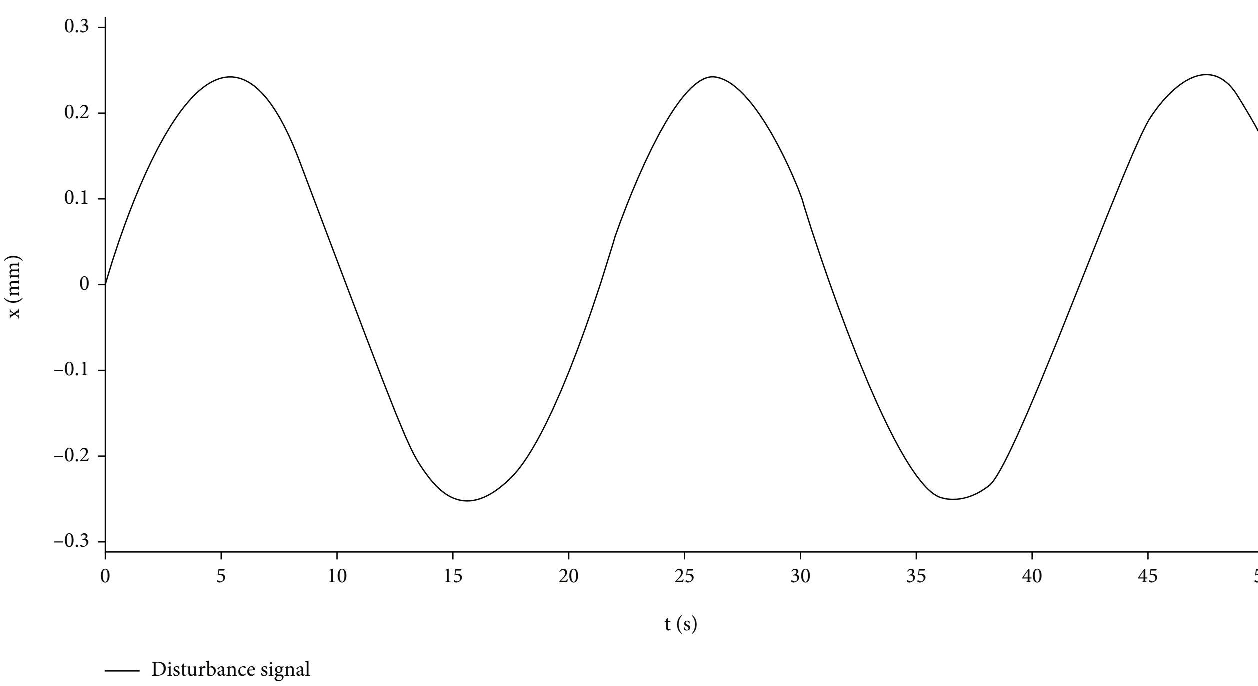

Figure 7: Disturbance signal.

with PID control, L1 adaptive control has a good response speed and can resist high-frequency interference, so it ensures the consistent and smooth transient performance of the system under uncertain high-frequency external disturbances, which has good robustness and steady-state performance; however, the obvious fluctuation of PID control is large, the steady-state performance is relatively poor, and it cannot realize the stability control of the precise positioning of the voice coil motor very well.

4.3. Experimental Effect and Analysis of Input Sine Signal in Different States. In order to further understand the dynamic

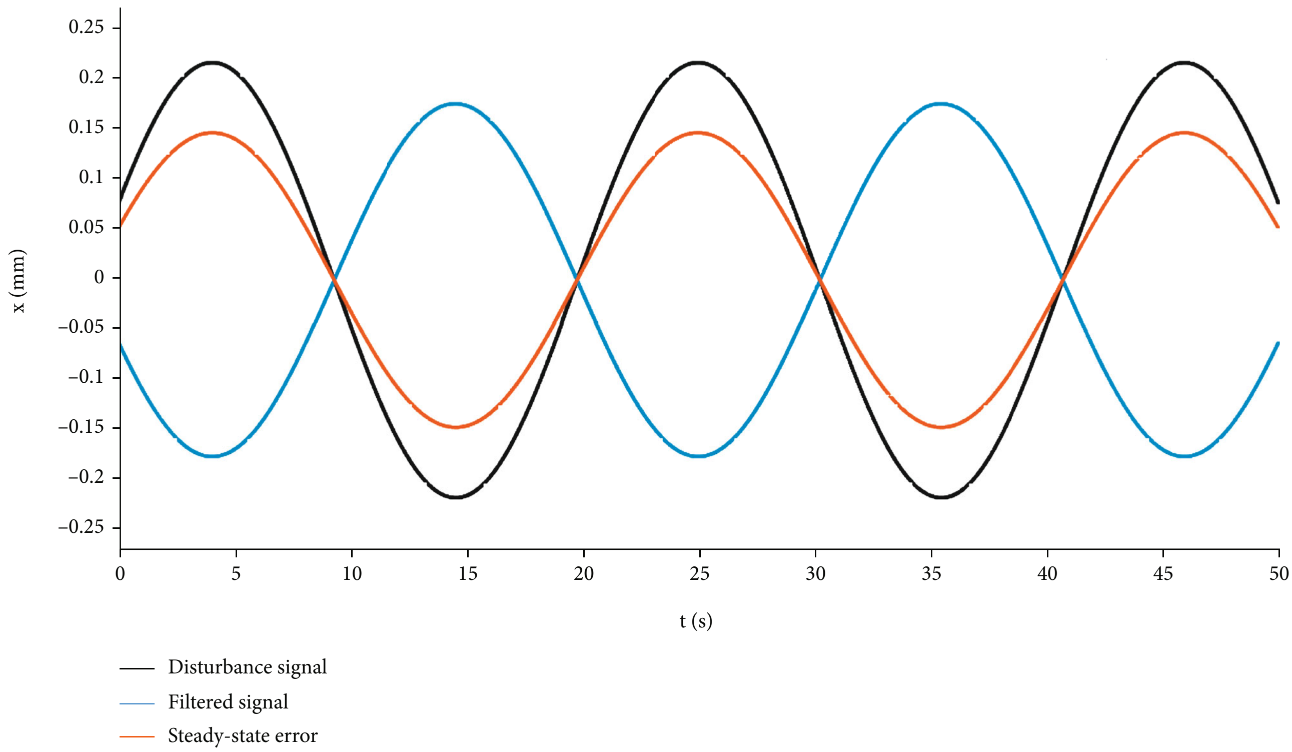

Figure 8: L1 adaptive control tracking error signal.

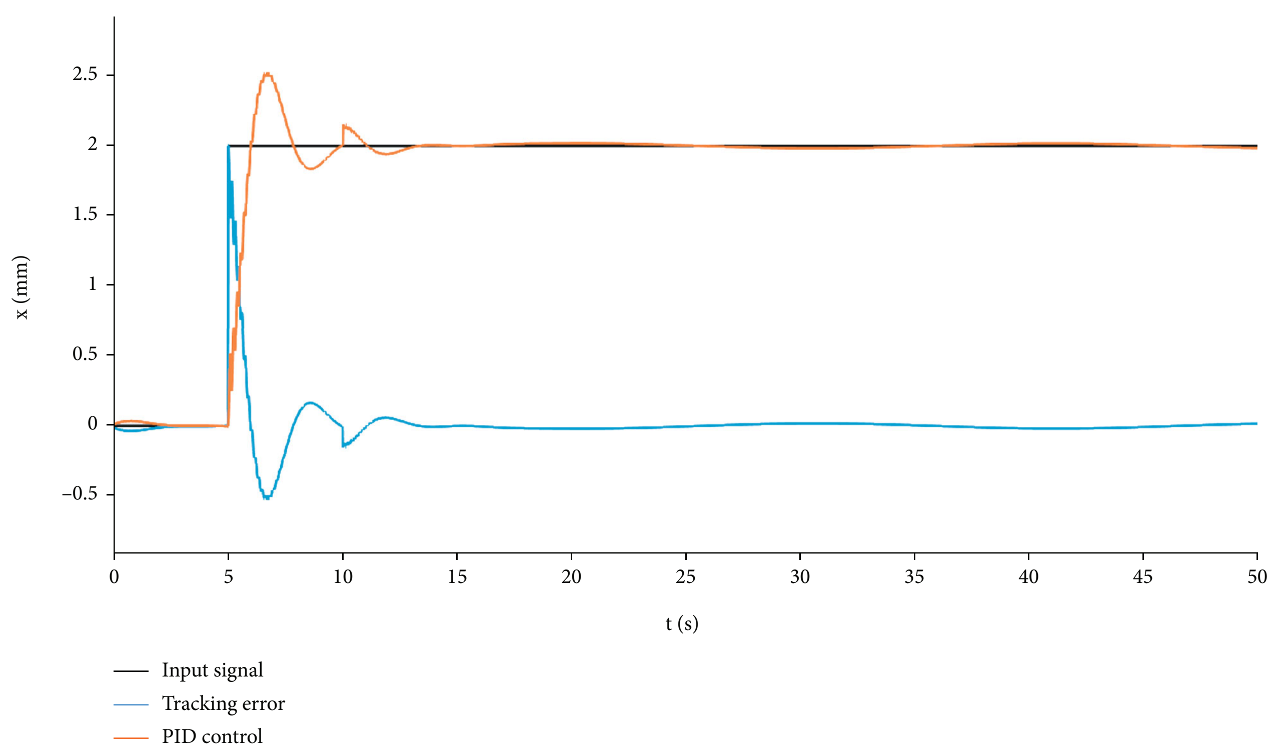

Figure 9: PID control.

characteristics and steady-state performance of L1 adaptive control, a tracking simulation is performed on a given sinusoidal signal $r = 2\sin(0.15t)$, and the simulation result is shown in Figure 11 without adding a certain interference signal. It can be seen from the experimental results that under the condition of no disturbance and changing the model parameters within a certain range at will, then the L1 adaptive controller can make the system signal response

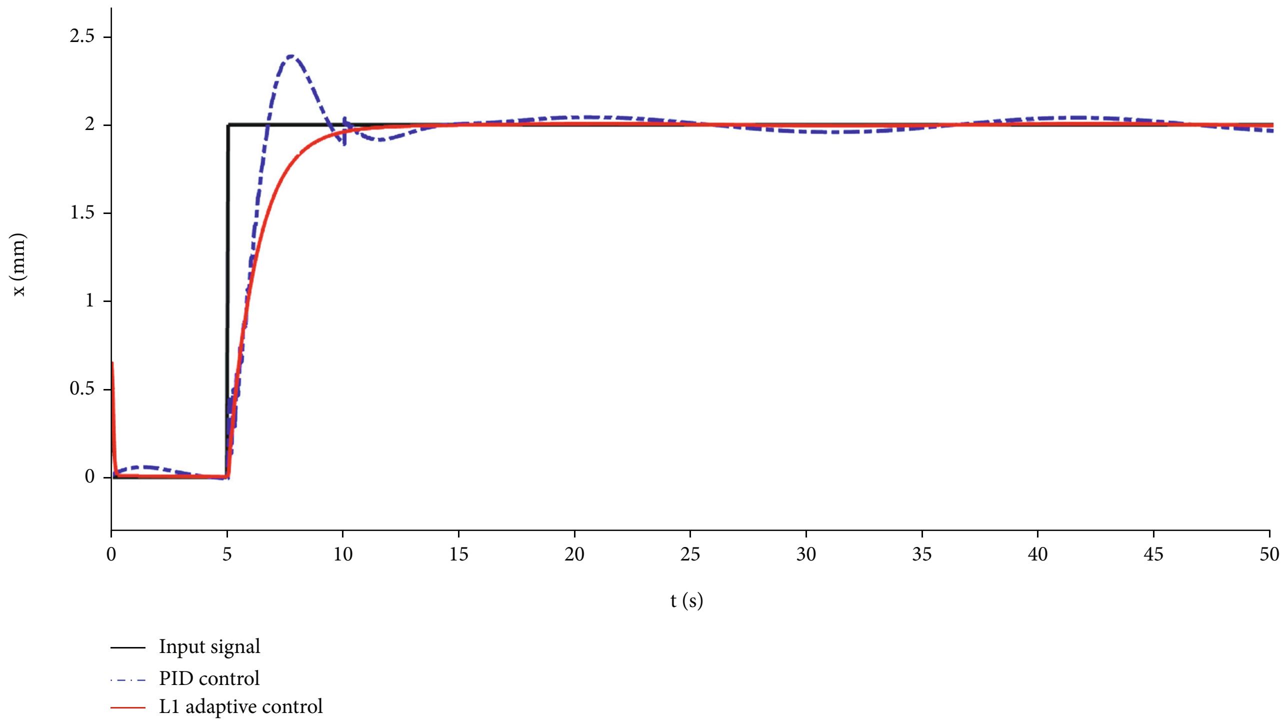

Figure 10: Track signal response during high-frequency disturbances.

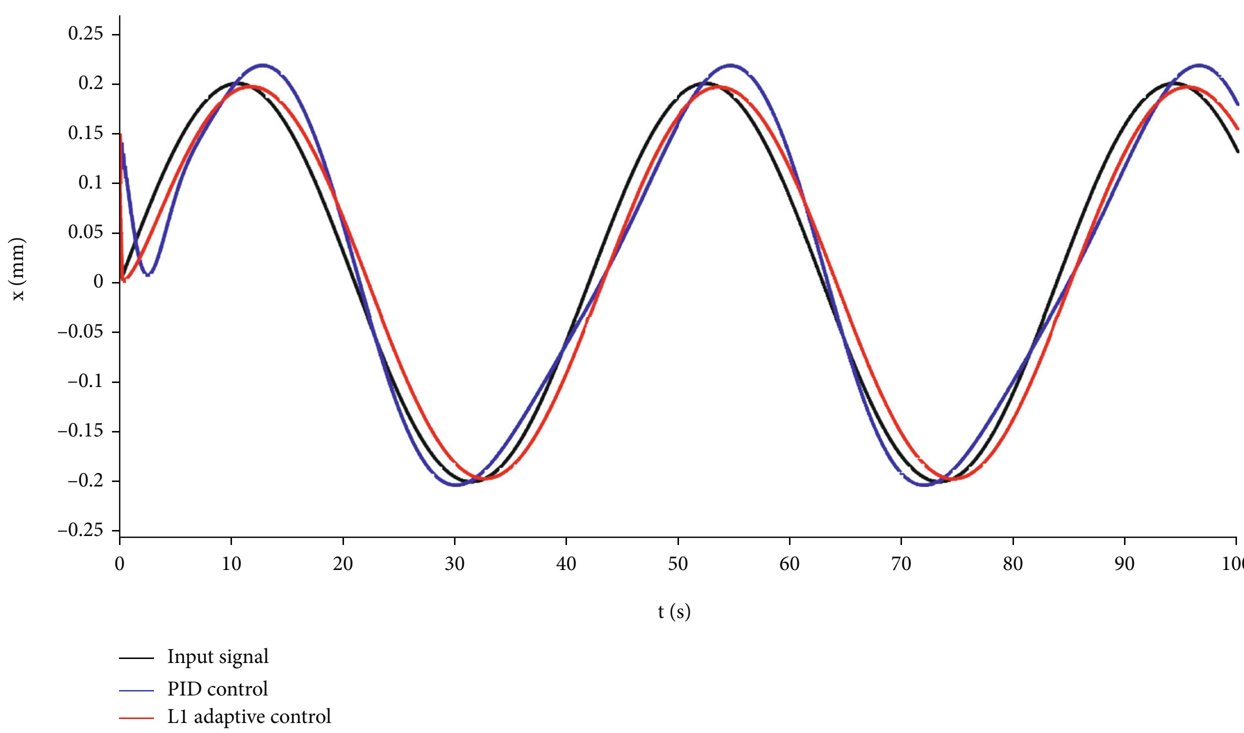

Figure 11: Input sinusoidal signal without interference in tracking signal response.

always track the reference signal better, so it has strong robustness to system parameter perturbation, and the control effect is obviously better than PID control.

Regarding the uncertainties of dynamic parameters of the voice coil motor as time-varying parameters, the load disturbance it receives as interference, after adding interference $\delta 2 = 2.5 \sin(0.3t) + 1.5 \cos(0.2t) + 1.2$ and changing a certain range of model parameters, the experimental results are shown in Figure 12. It can be seen from Figure 12 that the L1 adaptive control has strong robustness,

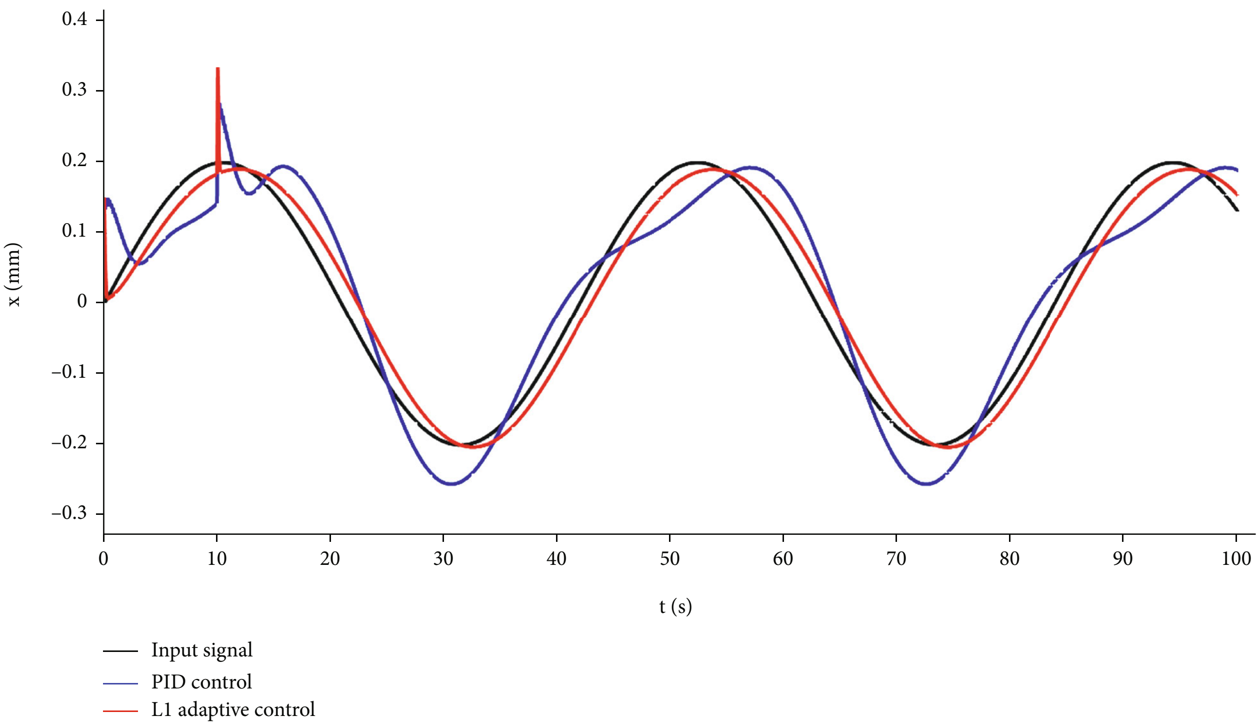

Figure 12: Input sine signal to track signal response in high-frequency interference.

it breaks through the traditional control's limit of the frequency of time-varying parameters, effectively suppressing the high-frequency oscillation caused by the adaptive control, and ensuring tracking error close to zero.

5. Conclusion

In this paper, by analyzing the voice coil motor servo system model, in response to the problems that the uncertainty of voice coil motor servo system model (including dynamic parameters and external load disturbance) and the tracking control, this paper proposes a new voice coil motor control algorithm-L1 adaptive control algorithm, established a mathematical model for it, construct L1 adaptive controller, solve model parameters, conduct simulation, and analyzes the experiments. The result of the experiments shows that the system response can always track the reference signal well; it also can effectively suppress the influence of external interference and uncertain factors and ensure the transient performance and robustness of the voice coil motor in the working state very well. At the same time, it also shows that the L1 adaptive control algorithm has stronger anti-interference ability than the conventional PID control algorithm, especially for high-frequency interference. This paper also verified the correctness of the application of the algorithm.

Data Availability

The data used to support the results of this study have been deposited at https://gitee.com/li-ying_a/research-on-voice-coil-motor.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work is supported by the Guangdong University of Technology Higher Education Research Fund GXLX20210213, the Guangzhou Philosophy and Social Sciences Co-Construction Project (No. 2020GZGJ115), and the Guangdong Social Science Co-Construction Project (No. GD20XTY16).

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