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Research Article

Research of Control Strategy in the Large Electric Cylinder Position Servo System

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An ideal positioning response is very difficult to realize in the large electric cylinder system that is applied in missile launcher because of the presence of many nonlinear factors such as load disturbance, parameter variations, lost motion, and friction. This paper presents a piecewise control strategy based on the optimized positioning principle. The combined application of position interpolation method and modified incremental PID with dead band is proposed and applied into control system. The experimental result confirms that this combined control strategy is not only simple to be applied into high accuracy real-time control system but also significantly improves dynamic response, steady accuracy, and anti-interference performance, which has very important significance to improve the smooth control of the large electric cylinder.

1. Introduction

The electric cylinder is a kind of actuator which can convert the rotary motion of motor to linear motion by screw. In recent years, with the performance improvement of the servo motor and drive mechanism, the electric cylinder has made a significant breakthrough in the aspects of large stroke and heavy load, which will lead to a tendency of using it instead of hydraulic cylinder in some industrial applications in the future [1, 2]. The electric cylinder has been widely applied in military, medical, and industrial equipment because of high transmission efficiency, excellent dynamic characteristic, high reliability, good environmental adaptability, compact structure, and simple operation and maintenance [3–5]. Due to load disturbance, parameter variations, friction, and other nonlinear factors in the position servo system, robust control, fuzzy control, self-adaptive control, internal model control, and sliding mode control can greatly improve the stability and anti-interference ability [6–17]. But these nonlinear control algorithms are very difficult to be applied in the PLC controller or high accuracy real-time control system because of the complexity. Hence, this paper presents a simple piecewise control algorithm which respectively adopts position interpolation method and incremental PID with dead band in different control stages. The final experimental result indicates that the dynamic response process is fast and smooth and the positional accuracy is very high, which will promote the application of large electric cylinders.

2. System Introduction

The erecting mechanism in the missile launching vehicle can erect the missile launcher from horizontal to tilted or vertical position. The vehicle body, launcher, and driving mechanism compose erecting mechanism which has been applied in many kinds of missile launching vehicles (Figure 1). As the successful development of the large stroke and heavy load electric cylinder, it will replace the hydraulic cylinder and become the primary driving mechanism. This paper introduces a large electric cylinder whose stroke is 1.5 m and maximum output force is 30 t (ton), which can ensure the missile launcher rotation range of 0–90° and positional accuracy of 0.05°. The controller of the erecting mechanism is PLC and control cycle is 10 ms. When the position instruction is 30° and conventional PID is applied in the controller, the position response curve is shown in Figure 2. It indicates that the buffeting appears in the initial stage and system is unable

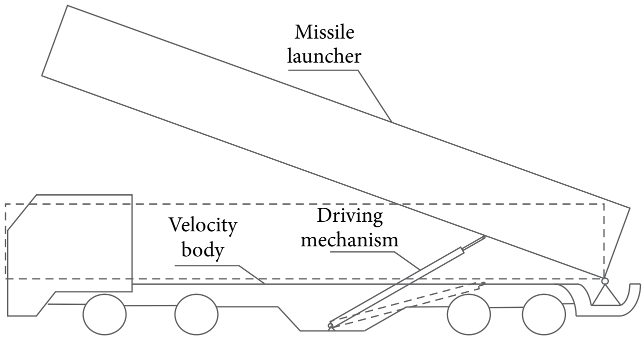

FIGURE 1: Erecting mechanism of the missile launcher.

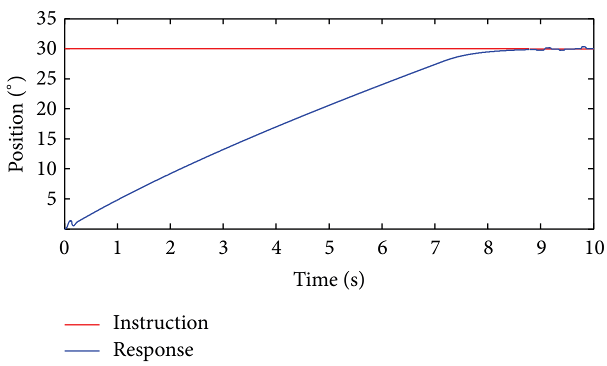

FIGURE 2: Position response curve.

to meet the stability precision because of oscillation in the close to desired position.

3. Modeling and Simulation Based on Simulink

In order to research the control strategy and apply it into control system, the model of the erecting mechanism is established and the simulation is applied to analyze the reason of the buffeting appearing in the initial stage based on Simulink.

3.1. Modeling of the Erecting Mechanism. This paper establishes the mathematical model of missile launcher that is driven by electric cylinder and simulates based on Simulink to analyze the reason of buffeting in the initial stage and design the controller.

Electric cylinder is mainly composed of servo motor, reducer, screw, and piston rod that can convert the rotary motion of the servo motor to linear motion (Figure 3). The transmission schematic diagram is shown in Figure 4 and the mathematic model is shown in

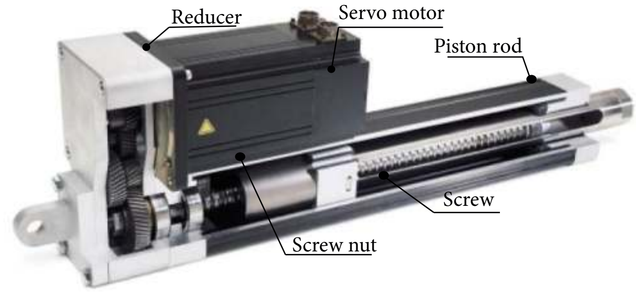

FIGURE 3: Electric cylinder.

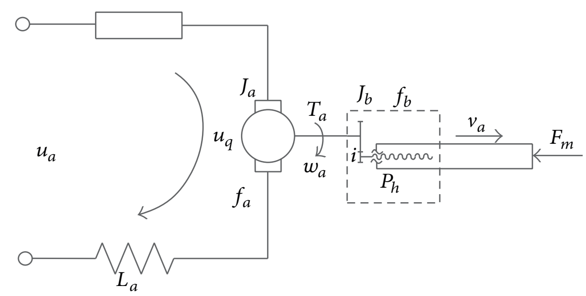

FIGURE 4: Transmission schematic diagram of the electric cylinder.

$$u_a - u_q = i_a R_a + L_a \frac{di_a}{dt},$$

$$T_a = K_m i_a,$$

$$T_a - T_b = J_a \frac{d^2\theta_a}{dt} + f_a \frac{d\theta_a}{dt},$$

$$u_q = K_e \frac{d\theta_a}{dt},$$

$$T_b - T_m = J_b \frac{d^2\theta_a}{dt} + f_b \frac{d\theta_a}{dt},$$

$$T_m = \frac{F_m P_h}{2\pi\eta i},$$

$$\Delta L = \frac{\theta_a P_h}{2\pi i}, \tag{1}$$

where u_a is the input voltage of the armature winding; i_a is the current of the armature winding; R_a is the resistance of the armature winding; L_a is the inductance of the armature winding; T_a is the electromagnetic torque of the motor shaft; K_m is the electromagnetic torque coefficient; T_b is the output moment of motor; J_a is the moment of inertia of the motor shaft; f_a is the viscous friction coefficient of the motor shaft; θ_a is the output rotation angle of motor; K_e is the voltage coefficient; T_m is the output moment of electric cylinder; F_m is the loading force; i is transmission ratio; P_h is screw lead; η is the mechanical transmission efficiency; J_b is the moment of inertia of the drive system; f_b is the viscous friction coefficient of the drive system; ΔL is the stretching-length of piston rod.

Structural schematic diagram of the erecting mechanism is shown in Figure 5 which describes the geometric relationship and force status among vehicle body, launcher, and electric cylinder.

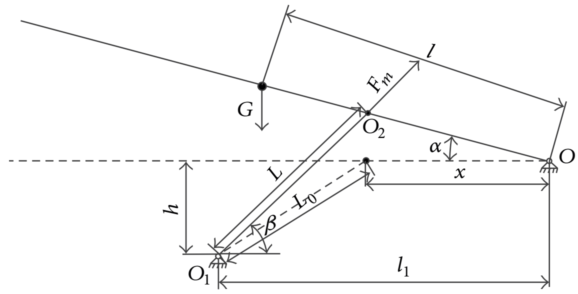

Figure 5: Structural schematic diagram of the erecting mechanism.

Table 1: Main parameters of the missile launcher.

$K_e/(\mathrm{V{\cdot}radps^{-1}})$	$K_m/(\mathrm{N{\cdot}m{\cdot}A^{-1}})$	L_a/H	R_a/Ω	η
1.691	2.7	0.0025	0.058	0.8
$J_b/(\mathrm{kg{\cdot}m^2})$	$f_b/(\mathrm{N{\cdot}m{\cdot}radps^{-1}})$	P_h/m	f_c	G/N
0.012	0.0063	0.02	0.3	68500
$f_a/(\mathrm{N{\cdot}m{\cdot}radps^{-1}})$	$J_a/\mathrm{kg{\cdot}m^2}$	i	M_c/kg	L_0/m
0.0153	0.0495	12	1200	2.56
x/m	h/m	l/m	l_1/m	$J/(\mathrm{kg{\cdot}m^2})$
1.0265	1.5	5	3.101	15000

O is the pivot point of the missile launcher; O_1 is the pivot point of the electric cylinder; O_2 is the joining point between missile launcher and electric cylinder; α is the rotation angle of the missile launcher; β is the horizontal angle of the electric cylinder; L_0 is the original length of the electric cylinder; L is the length of the working electric cylinder; G is the gravity of the missile launcher; F_m is the output force of the electric cylinder.

The following equation shows the mathematic model of the erecting mechanism:

$$\begin{gathered} F_m \cos\beta \times x \sin\alpha + F_m \sin\beta \times x \cos\alpha - Gl\cos\alpha = J\frac{d^2\alpha}{dt}, \\ \sin\beta = \frac{x\sin\alpha + h}{L}, \\ \sin\alpha = \frac{L^2 - l_1^2 - x^2 - h^2}{2x\sqrt{h^2 + l_1^2}} + \alpha_0, \\ \cos\alpha_0 = \frac{h}{\sqrt{h^2 + l_1^2}}, \\ \Delta L = L - L_0. \end{gathered} \tag{2}$$

Figure 6 shows the block diagram of the missile launcher through combining (1) with (2). The main parameters of the missile launcher are shown in Table 1. Figure 7 shows the position response in the simulation and experiment, which proves the correctness of the model.

3.2. Simulation of the Erecting Mechanism. In order to understand the reason of the buffeting that appears in the initial stage more intuitively, we analyze all the elements in the model applying the simulation environment. Figure 8 describes the load of the electric cylinder when the missile launcher erects from horizontal to vertical position, which indicates that the load gets smaller with the increase of the angle. Figure 9 shows that the impact current in the servo motor can reach up to 300 A which is far beyond the rated current 62 A and lasts about 1 s. The fluctuant current in the servo motor leads to the buffeting in the initial stage. The overload current will seriously reduce the service life and even damage the electric cylinder. Therefore, we must adopt control algorithm to suppress the impact current and improve the stability precision.

4. Design of the Controller

The ideal velocity curve should be trapezoid based on the optimized positioning principle. Hence, the position response process is divided into dynamic response and close to desired position periods (Figure 10). The dynamic response is composed of accelerative, constant velocity, and decelerating periods. The position interpolation method and incremental PID are applied to the dynamic response period to ensure the steady accuracy and rapidity and incremental PID with dead band is applied to close to desired position period to ensure the stability precision. Since the incremental PID cannot produce disturbance when switching control parameters, the different control parameters applied in the dynamic response and close to desired position periods can avoid buffeting and enhance adaptability.

4.1. Position Interpolation Method. Position interpolation method is to add some new position instructions between current and desired position according to acceleration, velocity, and control cycle of the system. It can make the dynamic response realize the ideal velocity curve through tracing the new position instructions. If the current position instruction is L_i, the next control cycle position instruction is $L_{i+1} = L_i + \Delta L$, where ΔL can be obtained by:

$$\Delta L = \begin{cases} at + \dfrac{1}{2}aT^2 & 0 \le L_i \le \dfrac{V_{\max}^2}{2a} \\ \dfrac{V_{\max}^2}{2a} & \dfrac{V_{\max}^2}{2a} < L_i \le L - \dfrac{V_{\max}^2}{2a} \\ V_{\max} - at_1 - \dfrac{1}{2}aT^2 & L_i > L - \dfrac{V_{\max}^2}{2a}. \end{cases} \tag{3}$$

a is the maximum acceleration of system requirement; t is the duration of the acceleration; T is control cycle; $V_{\max}$ is the maximum velocity of system requirement; t_1 is the duration of the deceleration; L is position instruction.

4.2. Incremental PID Control Algorithm. Incremental PID is to obtain control output by accumulating the increment $\Delta U(k)$. The sharp increase or decrease of the output can produce buffeting. The output $U(k)$ of incremental PID is

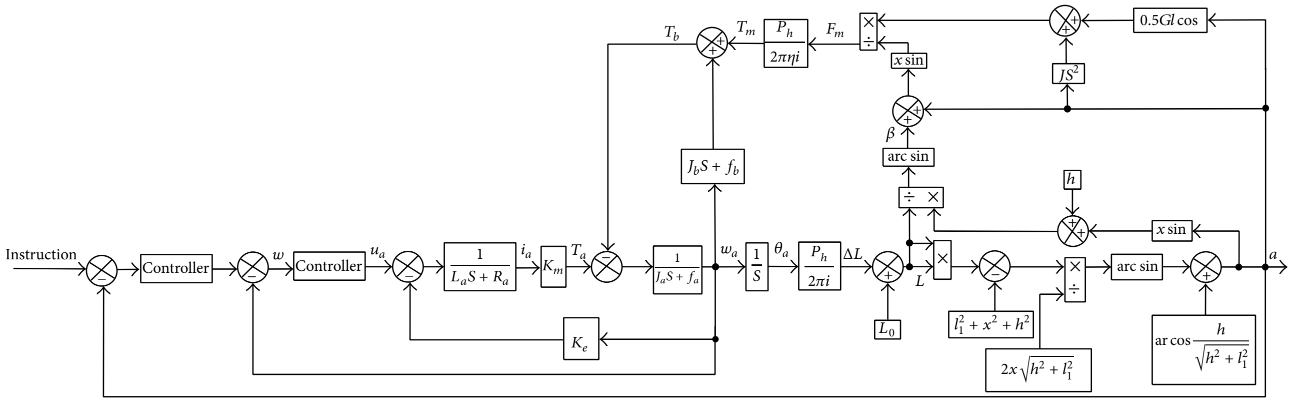

Figure 6: Block diagram of the missile launcher.

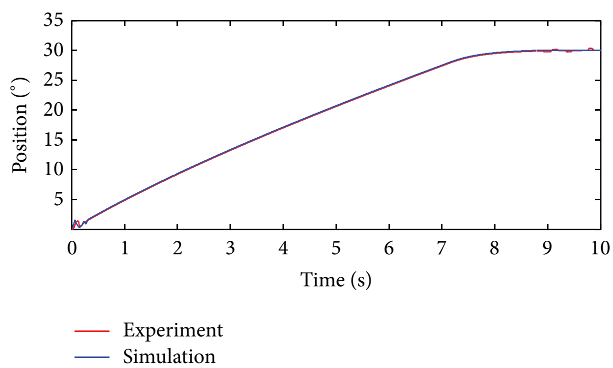

Figure 7: Position response.

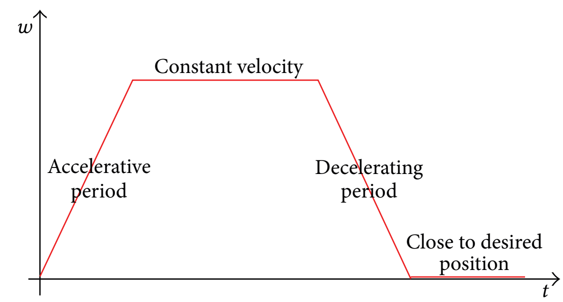

Figure 10: Ideal velocity curve.

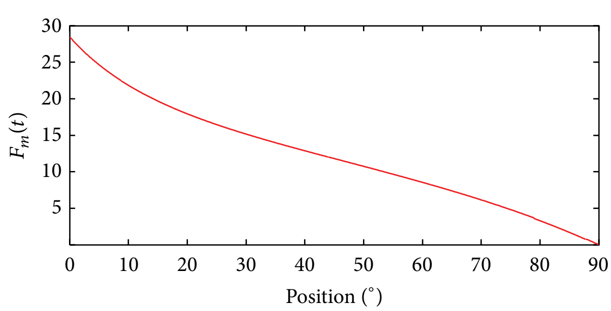

Figure 8: Load of the electric cylinder.

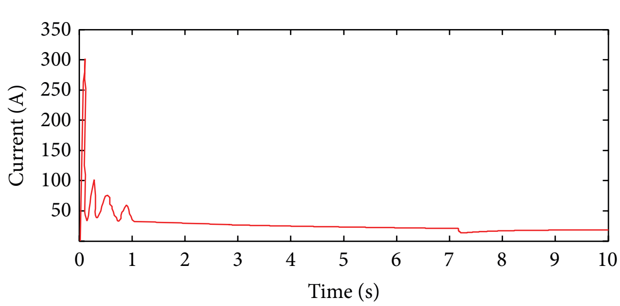

Figure 9: Current in the servo motor.

gradual change, which can avoid the chattering and integral saturation. $U(k)$ can be obtained by

$$\begin{aligned} U(k) &= U(k-1) + \Delta U, \\ \Delta U &= \Delta Up + \Delta Ui + \Delta Ud, \\ \Delta Up &= Kp\left(\Delta e(k) - \Delta e(k-1)\right), \\ \Delta Ui &= Ki\left(\Delta e(k) - \Delta e(k-1)\right) \times T, \\ \Delta Ud &= \frac{Kd\left(\Delta e(k) - 2\Delta e(k-1) + \Delta e(k-2)\right)}{T}, \end{aligned} \tag{4}$$

where $U(0) = 0$, $\Delta e(k) = L - L(k)$, L is desired position and $L(k)$ is current position sampling, and Kp, Ki, and Kd are the parameters of the incremental PID.

In the first control period, $\Delta e(k-1)$ and $\Delta e(k-2)$ are both 0, $e(1) = L$ is bigger, and $T = 0.01$ s is smaller. Then, $\Delta Up = Kp \times e(1)$ and $\Delta Ud = Kd \times e(1)/T$ are both bigger. Hence, Kp and Kd are both 0 in the first control period and adopt adaptable value in other control periods.

4.3. Incremental PID with Dead Band. When the missile launcher reaches the close to desired position, it will produce oscillation and cannot satisfy the stability precision due to the existence of nonlinear factors such as friction and lost motion. Therefore, we adopt incremental PID with dead band in the close to desired position.

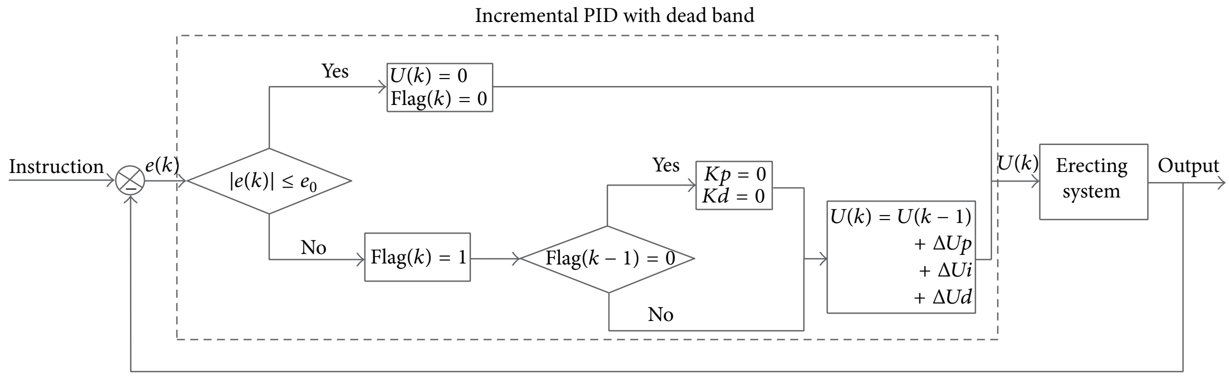

Figure 11: Flowchart of the incremental PID with dead band.

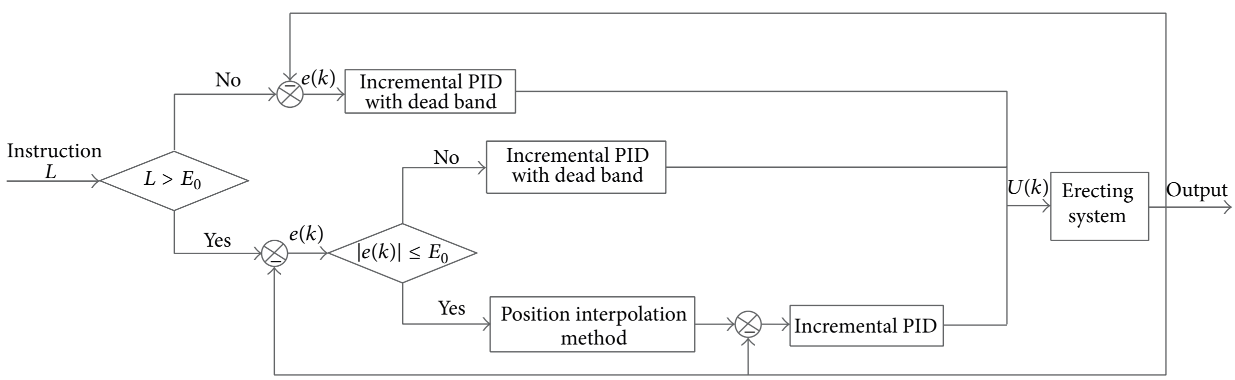

Figure 12: Flowchart of the control algorithm.

(1) Set the range of dead band e_0 that is little bigger than stability precision.

(2) As the displacement error $|e(k)| \leq e_0$, the control output is 0.

(3) As the displacement error $|e(k)| > e_0$, the control output is$U(k)$ of the incremental PID.

Figure 11 shows the flowchart of the incremental PID with dead band.

In the position servo control system of the missile launcher, the steps of the control algorithm are as follows.

(1) Set some parameters such as maximum acceleration a, maximum velocity $V_{\max}$, and range of close to desired position E_0.

(2) As the displacement error $|e(k)| \leq E_0$, the incremental PID with dead band is adopted.

(3) As the displacement error $|e(k)| > E_0$, position interpolation method and incremental PID are adopted.

Figure 12 shows the flowchart of the control algorithm.

After applying this combined control algorithm to the controller of position servo system in the missile launcher, Figures 13 and 14, respectively, show the position response and current of the servo motor when the desired position is 30°. Figure 13 indicates that the dynamic response process is fast and smooth and the buffeting disappears in the initial stage. When the missile launcher arrives at the desired position, the steady state error is 0.02° which is in the range of stability precision. Figure 14 indicates that the maximum current in the servo motor is 32 A and overload and impact current are both eliminated, which can prolong the service life of electric cylinder.

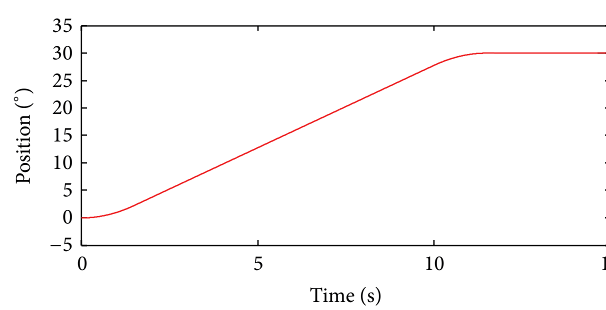

Figure 13: Position response.

5. Conclusion

The bigger load and acceleration in the initial stage cause the fluctuation and impact current in the servo motor, which can produce buffeting. The nonlinear friction and lost motion bring about the oscillation in the close to desired position. This paper proposes a piecewise control strategy based on

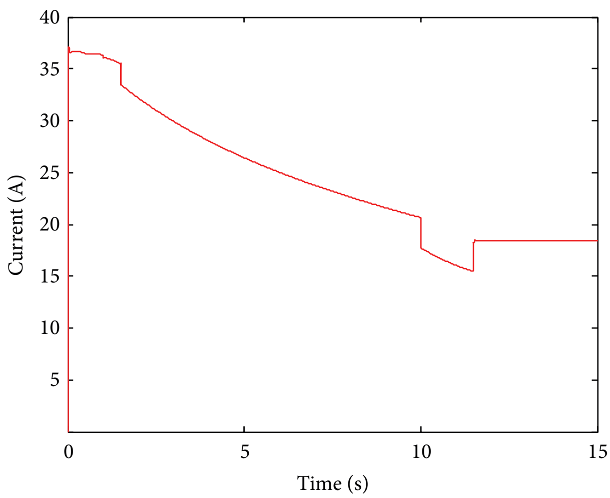

Figure 14: Current in the servo motor.

the optimized positioning principle. Position interpolation method and incremental PID with dead band are, respectively, applied into dynamic response and close to desired position periods. The position interpolation method significantly improves steady accuracy and rapidity performance, which can ensure the position response along the ideal curve. The incremental PID with dead band can largely enhance the stability precision. These control algorithms are easily applied to the high accuracy real-time control system and acquire excellent results, which will greatly promote the application of the large electric cylinder.

Conflict of Interests

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

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