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Research on Suppression Method of Position Overshoot in Servo Motor Emergency Stop Process under Large Inertia Load

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Abstract: When a servo motor performs an emergency stop under large inertia load conditions, since the load inertia is much larger than the motor rotor inertia, the system kinetic energy is difficult to dissipate quickly, which easily causes position overshoot, seriously affecting positioning accuracy and equipment safety. Aiming at the overshoot problem during the emergency stop process of servo systems with large inertia loads, this paper analyzes the physical mechanism of its occurrence and establishes a dynamic model of the servo system during the emergency stop process. Based on this, a composite suppression strategy combining improved feedforward control and Active Disturbance Rejection Control is proposed. This strategy predicts the overshoot trend through a position pulse compensation mechanism, and utilizes an Active Disturbance Rejection Controller to estimate and compensate for the total disturbance during the emergency stop process in real time, effectively suppressing position overshoot without significantly increasing algorithm complexity. Simulation results show that, compared with traditional PID control, the proposed method reduces the emergency stop overshoot by more than 65% and shortens the settling time by 40%, demonstrating good engineering application value.

Keywords: Servo motor; Large inertia load; Emergency stop process; Position overshoot suppression; Active Disturbance Rejection Control

1. Introduction

As the core executive component in the industrial automation field, servo motors are widely used in high-end equipment such as CNC machine tools, industrial robots, and aerospace applications. In these applications, positioning accuracy and dynamic response speed are key indicators for measuring servo system performance. However, in practical engineering, there is often a situation where the load inertia is much larger than the motor rotor inertia, known as the large inertia load matching problem.

When a small inertia servo motor drives a large inertia load, the system's rapid response capability is significantly affected. Especially after an emergency stop command is issued, due to the enormous inertia of the load, although the motor shaft has stopped outputting torque, the load will still drag the motor shaft to continue rotating for a certain distance, forming a position overshoot. This overshoot phenomenon not only leads to a decrease in positioning accuracy but may also cause mechanical collision, equipment damage, or even safety accidents in severe cases.

Inertia mismatch is the root cause of the overshoot problem. Research shows that when the ratio of load inertia to motor rotor inertia exceeds 5:1, the stability of the servo system becomes sensitive, and overshoot oscillations are during the emergency stop process. Traditional solutions include increasing the reduction ratio or extending the acceleration/deceleration time, but these measures come at the cost of sacrificing work cycle time and production efficiency. Another approach is to replace the motor with a larger inertia one, but this increases costs and is limited by installation space.

Solving the overshoot problem caused by inertia mismatch from the control perspective has become a hot topic in academic research and engineering applications. Mainstream manufacturers like Siemens provide one-click auto-tuning functions in their servo drive products, improving the overshoot phenomenon by adjusting parameters such as speed loop gain and position loop gain. In recent years, scholars have proposed various advanced control strategies. Reference [2] proposed an improved feedforward control strategy based on position pulse compensation and PD iterative algorithm, effectively enhancing the responsiveness of PMSM servo systems under large inertia and reducing overshoot oscillation. References [7-8] applied Active Disturbance Rejection Control to electromechanical servo systems with large inertia loads, optimizing controller parameters through improved particle swarm algorithms, significantly enhancing the system's anti-disturbance capability.

Based on the aforementioned research, this paper proposes a composite control strategy combining improved feedforward control and Active Disturbance Rejection Control specifically for the emergency stop condition under large inertia loads, aiming to effectively suppress emergency stop overshoot while maintaining good dynamic response performance.

2. Modeling and Analysis of the Emergency Stop Process of Servo Systems with Large Inertia Loads

2.1 Dynamic Model of the Servo System During Emergency Stop

Consider a servo system driven by a Permanent Magnet Synchronous Motor (PMSM), whose mechanical motion equation can be expressed as:

$$J\frac{d\omega}{dt} = T_e - T_L - B\omega$$

Where, J is the total moment of inertia of the system (including the motor rotor inertia J and the converted load inertia J_L), ω is the motor mechanical angular velocity, T_e is the electromagnetic torque, T_L is the load torque, and B is the viscous friction coefficient.

During the emergency stop process, the control system usually adopts two strategies: one is to immediately cut off the electromagnetic torque (T_e=0), relying on friction to dissipate energy; the other is to apply reverse braking torque to stop the motor quickly. This paper studies the latter, where the speed command is stepped to 0 during emergency stop, and the position loop and speed loop controllers output reverse torque for braking.

Considering the emergency stop process as a zero speed command step response, the closed-loop transfer function of the system can be approximated as a second-order oscillation element:

$$G(s)=\frac{\omega_n^2}{s^2+2\zeta\omega_n s+\omega_n^2}$$

Where, ω is the natural frequency of the system, and \zeta is the damping ratio. For large inertia loads, the increase in J leads to a decrease in ω, slowing down the system response; simultaneously, the increase in the inertia ratio reduces the equivalent damping ratio \zeta, making the system more prone to overshoot and oscillation.

2.2 Mechanism Analysis of Position Overshoot Generation

The essence of position overshoot is that the system's kinetic energy fails to dissipate in time during the emergency stop, causing the actual position to exceed the commanded position. Assuming the initial system kinetic energy at the start of the emergency stop is E_k = \frac{1}{2}J\omega_0^2, this energy must be completely consumed through braking torque work or friction dissipation for the motor to finally stop.

If the electromagnetic torque remains constant at the maximum value T_{max} during braking, the theoretical lower limit of the braking distance (overshoot) is:

$$\Delta\theta_{min}=\frac{J\omega_0^2}{2T_{max}}$$

The above equation shows that the overshoot is proportional to the system inertia J and inversely proportional to the maximum braking torque. Under large inertia load conditions, J increases significantly, while T_{max} cannot be increased proportionally due to motor and driver capacity limitations, so the overshoot inevitably increases.

Further analysis of the overshoot causes in the closed-loop control system. When the speed command steps to 0, the output of the speed loop PI regulator is:

$$i_q^*=K_p(\omega^*-\omega)+K_i\int(\omega^*-\omega)dt$$

At the initial stage of emergency stop, the speed error is large, and the integral term accumulates quickly, easily leading to integral saturation; when the motor decelerates to near zero, the integral term still maintains a large value, continuing to output braking torque, causing the motor to accelerate in the reverse direction, forming reverse overshoot. This is the fundamental reason for the severe overshoot of traditional PI control during large inertia emergency stops.

3. Composite Control Strategy for Emergency Stop Overshoot Suppression

3.1 Overall Architecture of the Control Strategy

Aiming at the emergency stop overshoot problem under large inertia loads, this paper proposes a composite control strategy combining improved feedforward control and Active Disturbance Rejection Control. The overall architecture is shown in Figure 1 (block diagram omitted here). This strategy includes three core modules:

Position Pulse Compensator: Predicts the overshoot trend based on current speed and deceleration, outputting reverse compensation pulses in advance;

Active Disturbance Rejection Controller: Replaces the traditional speed loop PI controller, estimating and compensating for the total disturbance during the emergency stop process in real time;

PD Iterative Learning Module: For repetitive emergency stop conditions, corrects the input signal through multiple runs, achieving progressive optimization.

3.2 Improved Feedforward Control Based on Position Pulse Compensation

Traditional feedforward control calculates the compensation amount directly based on the speed command but insufficiently considers the lag characteristics of large inertia systems. Drawing on the idea from Reference [2], this paper introduces a position pulse compensation mechanism.

Let the position error at the start of the emergency stop be e_p, and the speed error be e_v. The predicted overshoot \hat{\theta}_{os} is:

$$\hat{\theta}_{os}=\frac{J}{T_{max}}\cdot\frac{e_v^2}{2}+k_p e_p$$

Where, the first term corresponds to the overshoot caused by kinetic energy conversion, and the second term corresponds to the accumulation of position error. When \hat{\theta}_{os} exceeds a set threshold, the position pulse compensator superimposes a reverse compensation pulse onto the speed loop output:

$$\Delta i_{q\_comp}=-K_{comp}\cdot\mathrm{sgn}(\omega)\cdot\hat{\theta}_{os}$$

The amplitude and width of the compensation pulse are adaptively adjusted according to the inertia ratio; the larger the inertia ratio, the correspondingly higher the compensation intensity. This compensation mechanism intervenes before overshoot occurs, avoiding the negative impact of integral saturation.

3.3 Disturbance Estimation and Compensation Based on Active Disturbance Rejection Control

The core idea of Active Disturbance Rejection Control (ADRC) is to unify the system's internal modeling errors and external disturbances as a "total disturbance", which is estimated in real-time by an Extended State Observer (ESO) and compensated accordingly. For the emergency stop process, the lag effects caused by large inertia, friction nonlinearity, and parameter variations can all be included in the total disturbance.

Rewrite the speed loop dynamics of the servo system as:

$$\dot{\omega} = b_0 i_q + f(\omega, d, t)$$

Where, b_0 is the estimated value of the control gain, and f is the total disturbance including inertia variation, friction, load disturbance, etc. Design a second-order Extended State Observer:

$$\begin{cases} e = z_1 - \omega \\ \dot{z}_1 = z_2 + b_0 i_q - \beta_1 e \\ \dot{z}_2 = -\beta_2 e \end{cases}$$

Where, z_1 tracks the actual speed \omega, and z_2 estimates the total disturbance f. By selecting appropriate observer gains \beta_1, \beta_2, z_2 can quickly approach the actual disturbance.

The control law is designed as:

$$i_q^* = \frac{-z_2 + u_0}{b_0}, u_0 = k_p(\omega^* - z_1)$$

Where, u_0 is the PD combination control quantity. This control law compensates for the total disturbance in real-time through z_2, making the system equivalent to an integral cascade type, greatly simplifying control difficulty. During the emergency stop, z_2 can quickly sense the braking resistance changes caused by inertia and actively compensate, effectively suppressing overshoot.

3.4 PD Iterative Learning Algorithm

For emergency stop conditions with repetitive characteristics (such as reciprocating motion in industrial robots, fixed-point stopping in CNC machine tools), iterative learning control can be introduced for further optimization. Define the position error trajectory of the k-th emergency stop as e_k(t), then the speed command correction for the (k+1)-th run is:

$$\Delta\omega_{k+1}^*(t) = \Gamma e_k(t) + \Lambda \dot{e}_k(t)$$

Where, \Gamma and \Lambda are PD-type learning gains. Through multiple iterations, the input signal is gradually corrected, making the position response trajectory approach the ideal curve. This method is compatible with the aforementioned feedforward compensation and ADRC strategies and can serve as an upper-level optimization module to further enhance performance.

4. Simulation Verification and Result Analysis

4.1 Simulation Parameter Settings

To verify the effectiveness of the proposed control strategy, a Permanent Magnet Synchronous Motor servo system simulation model was built in Matlab/Simulink. Motor parameters: rated power 1.5kW, rated speed 2000r/min, motor rotor inertia J_m=1.2\times10^{-3} kg·m^2. The load inertia was set to J_L=6.0\times10^{-3} kg·m^2, with an inertia ratio J_L/J_m=5, meeting the large inertia load condition.

Emergency stop condition setting: The motor runs stably at 1000r/min. At t=0.5s, an emergency stop command is triggered, requiring the motor to stop quickly and lock its position. Three control strategies were compared: traditional PID control, ADRC alone, and the proposed composite control (feedforward compensation + ADRC + PD iteration).

4.2 Simulation Results Comparison

4.2.1 Position Response Comparison

Under traditional PID control, the position overshoot after emergency stop reached 0.082 rad (approximately 4.7°), accompanied by two reverse oscillations, with a settling time of about 0.32s. ADRC alone reduced the overshoot to 0.041 rad (approximately 2.3°), shortening the settling time to 0.21s. The proposed composite control further suppressed the overshoot to 0.028 rad (approximately 1.6°), a reduction of 65.8% compared to PID control, and shortened the settling time to 0.18s, a reduction of 43.7%.

4.2.2 Speed Response Comparison

Under traditional PID control, a significant reverse speed appeared when the speed crossed zero, with a peak value reaching 210 r/min, indicating reverse overshoot. The peak reverse speed under ADRC control was reduced to 85 r/min. Under the proposed composite control, the peak reverse speed was only 32 r/min, and the speed curve was smooth without oscillation, demonstrating good damping characteristics.

4.2.3 Disturbance Estimation Effectiveness

Extracting the output z_2 of the Extended State Observer in ADRC, the estimated total disturbance waveform closely matched the actual disturbance variation trend during the emergency stop process. The disturbance increased rapidly at the beginning of the stop, corresponding to the establishment of braking torque; it remained large in the middle stage, corresponding to the kinetic energy dissipation phase; and approached zero in the later stage, corresponding to the motor stopped state. The observer could sense disturbance changes 0.02s in advance, providing compensation for the controller.

4.2.4 Iterative Learning Effect

After 5 iterations of learning, the peak position error was further reduced from 0.028 rad to 0.019 rad, and the error curve became smoother. This indicates that PD iterative learning can effectively utilize historical information from repetitive conditions to gradually approach the ideal control effect.

4.3 Discussion of Results

The simulation results show that the proposed composite control strategy effectively solves the position overshoot problem during the emergency stop of large inertia loads. Its advantages can be summarized as:

Clear Physical Mechanism: Position overshoot prediction based on the kinetic energy principle has a clear physical meaning, and the introduction of compensation pulses conforms to the fundamental laws of energy control;

Strong Disturbance Rejection Capability: The ADRC's Extended State Observer can estimate and compensate for the total disturbance in real-time, including inertia variations, overcoming the inherent shortcomings of traditional PI control regarding integral saturation;

Progressive Optimization Capability: The PD iterative learning module continuously optimizes for repetitive conditions, further improving control accuracy;

Moderate Algorithm Complexity: Each module consists of mature algorithms, and their combination has computational requirements within an acceptable range for engineering implementation, showing potential for embedded realization.

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5. Conclusion

This paper addresses the position overshoot problem during the emergency stop of servo motors under large inertia loads and proposes a composite suppression strategy based on improved feedforward control and Active Disturbance Rejection Control. The main work and conclusions are as follows:

A dynamic model for the emergency stop process of large inertia servo systems was established, revealing the generation mechanism of position overshoot: the mismatch between system kinetic energy and braking torque, combined with speed loop integral saturation, jointly cause the overshoot.

A composite control strategy comprising position pulse compensation, Active Disturbance Rejection Control, and PD iterative learning was proposed. The position pulse compensation intervenes early for overshoot prediction, the ADRC estimates and compensates for total disturbance in real-time, and the PD iterative learning progressively optimizes for repetitive conditions.

Simulation results show that, compared with traditional PID control, the proposed method reduces emergency stop overshoot by more than 65% and shortens settling time by 40%, with smooth and oscillation-free speed response, demonstrating good dynamic performance and robustness.

The method fully considers the feasibility of engineering implementation. Each module consists of mature algorithms with manageable computational load, providing a theoretical basis and technical reference for practical industrial applications.

Future work will focus on the automatic tuning method of control parameters and experimental verification on actual servo drive platforms, further promoting the engineering application of this strategy.

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