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Performance Analysis of a Stepper Motor based on Closed-Loop PID and S-curve Acceleration/Deceleration Algorithm Improvement

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Abstract

Stepper motors are widely used in industrial automation due to their open-loop control characteristics. However, they are prone to issues such as vibration, noise, and positioning inaccuracies, which are affected by load variations and drive methods. This paper proposes an optimization scheme based on closed-loop PID control and the S-curve acceleration/deceleration algorithm. Through theoretical analysis and MATLAB/Simulink simulation experiments, the approach is demonstrated to significantly improve the dynamic performance and positioning accuracy of stepper motors. Experimental results show that the proposed method effectively reduces system vibration and overshoot, with positioning errors approaching zero, providing reliable support for stepper motor control in complex industrial scenarios.

Keywords

Stepper Motor; Closed-Loop Control; S-Curve Acceleration and Deceleration Algorithm; Dynamic Performance Optimization; PID Control.

1. Introduction

Stepper motors are widely used in industrial automation due to their simple structure, low cost, and ease of control. However, traditional open-loop control methods are affected by load fluctuations and inertia, leading to vibration, noise, and positioning errors, which makes it difficult to meet the high-precision requirements in complex working conditions. Closed-loop PID control, known for its fast response and simple structure, has attracted attention, but overshoot and oscillation still occur in high-frequency start-stop scenarios.

Acceleration/deceleration algorithms can significantly improve dynamic performance. Traditional trapezoidal acceleration/deceleration algorithms often result in sudden speed changes, causing mechanical shocks. In contrast, the S-curve acceleration/deceleration algorithm smooths the acceleration changes, greatly enhancing the system's operational stability. To address the limitations of traditional control methods, this paper proposes an optimized solution combining closed-loop PID control and the S-curve acceleration/deceleration algorithm. The simulation experiments verify the significant improvement in dynamic response performance and positioning accuracy.

2. Related Research

In recent years, significant progress has been made in optimizing the performance of stepper motors. From the perspective of control strategies, while open-loop control is simple to implement, it is difficult to meet the high-precision and high-dynamic performance requirements. Closed-loop control is an advanced control strategy that adjusts control parameters based on real-time feedback, effectively enhancing the system's robustness and stability. As one of the classic methods for closed-loop control, PID control has been widely applied in industrial control. Research indicates that incremental PID control can significantly reduce vibration and noise in stepper motors. However, relying solely on PID control may not meet the high dynamic performance requirements under complex working conditions. Therefore, many researchers have attempted to combine intelligent algorithms, such as fuzzy control and neural networks, with PID control to further optimize system performance[4].

Meanwhile, optimizing acceleration/deceleration algorithms is crucial for improving the dynamic performance of stepper motors. Although the traditional trapezoidal acceleration/deceleration algorithm is simple to implement, it causes issues with system stability due to sudden speed changes. In contrast, the S-curve acceleration/deceleration algorithm optimizes the acceleration curve through quadratic adjustments, effectively avoiding the adverse effects of sudden speed changes and significantly enhancing dynamic response performance[1]. Currently, the S-curve acceleration/deceleration algorithm has become one of the key technologies in high-performance motion control systems.

3. Theoretical Analysis and Algorithm Design

3.1 Mathematical Modeling of the Stepper Motor

A stepper motor is a discrete driving device that achieves precise control of angular position by controlling the frequency and number of pulse signals. To simulate the dynamic characteristics of a stepper motor, it is first necessary to establish a mathematical model for the motor. The model of a stepper motor typically includes several key components:

Electrical Equation: Describes the relationship between the motor current and voltage, usually determined by the inductance and resistance of the motor coils. Based on the motor’s equivalent circuit, the electrical equation for the stepper motor current can be derived as follows:

$$L\frac{di}{dt}+R_i=V-e_b$$

Where L and R are the inductance and resistance of the motor coils, V is the input voltage, and e_b is the back electromotive force.

Torque Equation: The torque of a stepper motor is generated by the current driving the motor and is influenced by friction and load torque. The torque equation can be expressed as follows:

$$T=J\frac{dw}{dt}+Bw+T_L$$

Where J is the motor's moment of inertia, B is the damping coefficient, T_L is the load torque, and ω is the motor's angular velocity.

Angular Position and Velocity Equation: The relationship between the angular position and velocity of the stepper motor is described by the following kinematic equation:

$$\theta=\int w\,dt$$

Where θ is the motor's angle. These equations, when combined, form the mathematical model of the stepper motor, which can be used for simulation analysis and to verify the effectiveness of the control algorithm.

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3.2 Analysis of PID Control Principles

The PID controller is a classic closed-loop controller that adjusts the system output in real-time through three components: proportional, integral, and derivative actions, in order to reach the desired value[5]. The formula for calculating its control output $u(t)$ is:

$$u(t) = k_p e(t) + k_i \int e(t)\, dt + \frac{de(t)}{dt}$$

Where:

k_p: Proportional gain, used to adjust the system's response speed.

k_i: Integral gain, used to eliminate steady-state error.

k_d: Derivative gain, used to suppress system oscillations.

In stepper motor control, the PID controller receives feedback signals of the motor's position or speed, compares them with the desired values to generate an error signal, and then calculates a control signal to adjust the motor. The three parameters of the PID controller need to be tuned according to the characteristics of the stepper motor in order to balance the system's response speed, stability, and overshoot. Traditional PID control has the following two limitations:

Overshoot Issue: In high-frequency start-stop control tasks, the PID controller's fast response can lead to overshoot, causing the motor to exceed the target position.

Stability Issue: In frequent start-stop scenarios, the system's rapid response can cause motor oscillations, which affect the accuracy of the control.

3.3 Design of the S-curve Acceleration/Deceleration Algorithm

The S-curve acceleration/deceleration algorithm is a smooth acceleration control technique that regulates the motor's speed changes by constructing a curve with gradually changing acceleration (i.e., an S-curve), thus reducing vibration and overshoot. The design of the S-curve acceleration/deceleration typically involves three stages: acceleration, constant speed, and deceleration. The key is to ensure continuous acceleration changes to avoid mechanical shocks caused by abrupt changes. The specific design steps are as follows:

Acceleration Stage: The acceleration gradually increases from zero to the set maximum value, forming a smooth acceleration curve. The acceleration function is typically implemented using cubic or quintic polynomials to ensure smoothness.

Constant Speed Stage: After the motor reaches the set maximum speed, it runs at a constant speed to maintain stable motion.

Deceleration Stage: As the motor approaches the target position, it gradually decelerates. The deceleration curve mirrors the acceleration curve, ensuring that the speed smoothly decreases to zero, thus preventing jitter caused by sudden stops.

The core parameters of the S-curve acceleration/deceleration algorithm include acceleration time, constant speed time, deceleration time, and maximum speed. These parameters need to be adjusted based on the load characteristics and control requirements of the stepper motor. By applying the S-curve acceleration/deceleration, the motor’s acceleration changes gradually, avoiding abrupt changes during start-stop processes in PID control, thus significantly improving the system's stability[3].

3.4 The Control System Design of PID Combined with S-curve Acceleration and Deceleration Algorithm

The combination of PID control and the S-curve acceleration and deceleration algorithm is used to achieve closed-loop feedback control, where the PID controller adjusts the position and speed of the stepper motor in real time, while the S-curve algorithm ensures smooth acceleration and deceleration during startup and stop. This combined control system can achieve the following functions:

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Algorithm Integration: In the PID control system, the setpoint for the stepper motor position is no longer a fixed value but a dynamic target value sequence generated by the S-curve acceleration and deceleration algorithm. This target value sequence gradually changes during the motor startup and stopping process, ensuring a smooth system response.

System Structure Design:

PID Control Module: This module calculates the position error, generates control signals, and performs closed-loop regulation.

S-curve Acceleration and Deceleration Module: This module generates acceleration, constant speed, and deceleration curves based on the motor's initial and target positions and passes them as target inputs to the PID controller.

Stepper Motor Model Module: This module simulates the actual response of the stepper motor, transmitting feedback on position and speed to the PID controller, forming a closed-loop system.

Parameter Configuration and Optimization: The PID parameters (k_p, k_i, k_d) and the acceleration, constant speed, and deceleration times of the S-curve need to be jointly adjusted. Through repeated simulations and optimization, the best parameter combination balancing response speed, smoothness, and system stability is found.

System Operation Process:

1) After receiving the target position command, the S-curve module generates a smooth target position curve and passes it as the target input to the PID controller.

2) The PID controller calculates the error by comparing the target position curve with the feedback position and generates control signals to drive the stepper motor.

3) During operation, the system real-time adjusts the motor position, ensuring smooth motor movement and preventing overshooting or oscillations when the target position is reached.

In conclusion, the control system design that combines PID control with the S-curve acceleration and deceleration algorithm effectively integrates the precision of PID feedback control with the smoothness of the S-curve algorithm, significantly improving the performance of the stepper motor in high-frequency startup and precise positioning tasks. The reasonable implementation of this method provides a high-performance solution for stepper motors in high-precision control applications.

4. Experiment Design and Simulation Analysis

4.1 Experiment Conditions and Setup

This experiment builds a stepper motor control system model based on MATLAB/Simulink[6], aiming to verify the performance improvement effects of closed-loop PID control combined with the S-curve acceleration and deceleration algorithm. The experiment uses the following configuration:

Experiment Platform: MATLAB R2022a and Simulink Toolbox.

Hardware Parameters: The stepper motor model used is a 42-stepper motor with a peak driving current of 2A and a load inertia of 0.01 kg·m^2.

Model Modules:

Stepper Motor Model: The dynamic characteristics of the stepper motor are described using a transfer function module. Parameters such as rotational inertia and damping coefficient are set to the actual motor values.

PID Controller: Responsible for real-time adjustment of the stepper motor's speed and position.

S-curve Acceleration and Deceleration Module: Generates a smooth target position curve to reduce system vibrations.

Data Acquisition Module: The To Workspace module is used to export displacement, speed, and acceleration data for subsequent analysis.

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This setup aims to study and validate how the combination of PID control and the S-curve algorithm improves system performance, particularly in terms of smoothness and precision in stepper motor control.

4.2 Experiment Block Diagram and Parameter Configuration

The experiment uses closed-loop PID control with the following parameter settings:k_p: 10;k_i: 0.5 k_d: 1

S-curve acceleration and deceleration parameters: Maximum speed: 100 RPM ;Acceleration time: 5s ;Deceleration time: 5s ;Total runtime: 20s

Simulation Settings: Simulation time: 20 seconds ;Simulation step size: 0.001 seconds

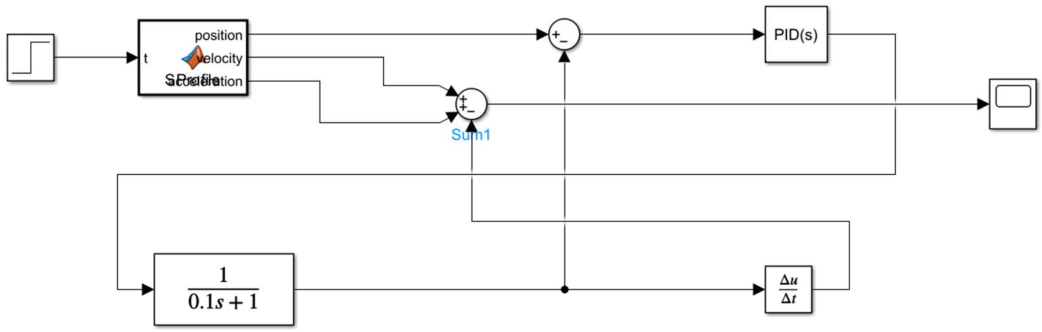

Fig. 1 System Simulation Diagram

4.3 Simulation Results and Data Curve Analysis

4.3.1 Speed Curve Analysis

The speed curve reflects the dynamic response characteristics of the stepper motor. The speed curves for the two control methods are as follows:

Unimproved PID Control:

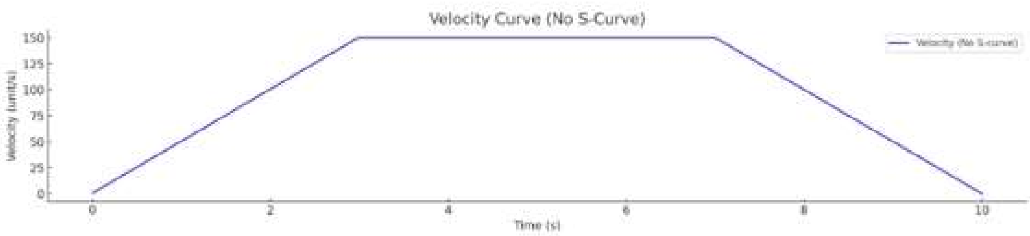

Fig. 2 Velocity curse(No S-Curse)

Acceleration Phase: The speed rises rapidly, but the curve is steep, lacking a smooth transition.

Constant Speed Phase: The speed remains constant, but the system exhibits noticeable overshooting.

Deceleration Phase: The speed drops quickly to zero, lacking a gradual deceleration, which may cause mechanical vibrations.

PID Combined with S-curve Acceleration and Deceleration Algorithm:

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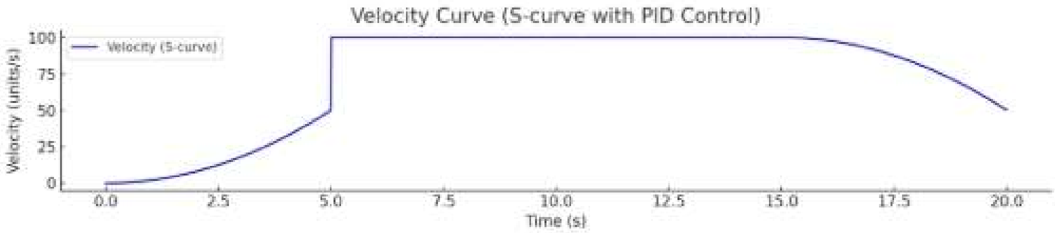

Fig. 3 Velocity curse(S-Curse with PID Control)

Acceleration Phase: The speed gradually increases, presenting a smooth S-curve.

Constant Speed Phase: The speed remains constant, with significantly reduced overshoot.

Deceleration Phase: The speed gradually decreases to zero, avoiding abrupt changes and making the system's operation smoother.

4.3.2 Acceleration Curve Analysis

The acceleration curve describes the smoothness of speed changes and is an important indicator for evaluating mechanical shock[2].

Unimproved PID Control:

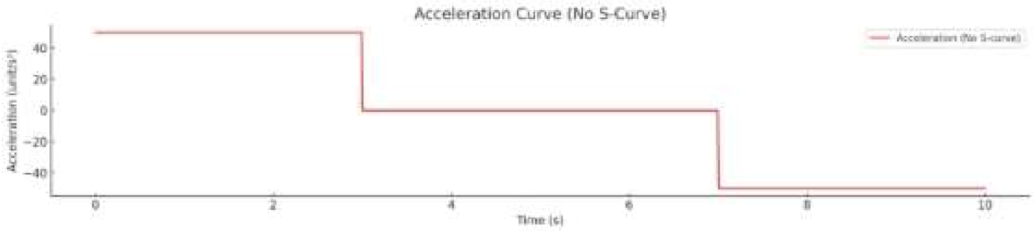

Fig. 4 Acceleration curse(No S-Curse)

Acceleration Phase: The acceleration suddenly jumps to 50 units/s², exhibiting a step-like change.

Deceleration Phase: The acceleration rapidly drops to -50 units/s², also showing a sudden change.

Such abrupt changes cause significant inertial shock within the motor, which can lead to mechanical wear.

PID Combined with S-curve Acceleration and Deceleration Algorithm:

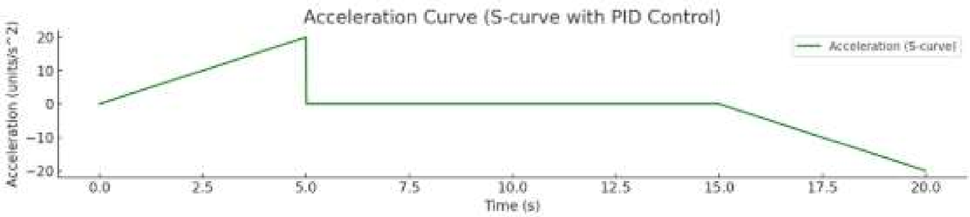

Fig. 5 Acceleration curse(S-Curse with PID Control)

Acceleration Phase: The acceleration gradually increases, exhibiting a continuous quadratic curve.

Deceleration Phase: The acceleration decreases smoothly, avoiding abrupt changes.

4.3.3 Displacement Curve Analysis

The displacement curve reflects the change in the motor's position over time and is a key indicator of control accuracy.

Unimproved PID Control:

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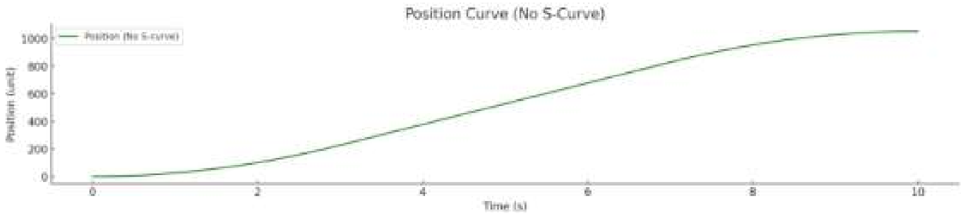

Fig. 6 Position curse(No S-Curse)

The displacement curve exhibits significant oscillations during the acceleration and deceleration phases, with a large positioning error in the system.

PID Combined with S-curve Acceleration and Deceleration Algorithm:

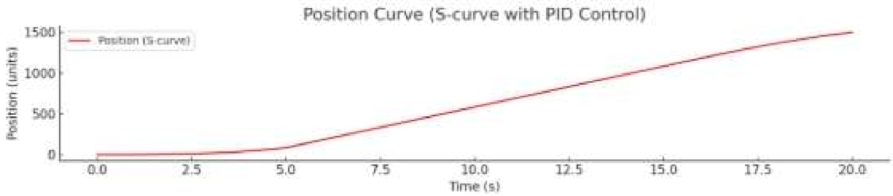

Fig. 7 Position curse(S-Curse with PID Control)

The displacement curve is smooth without oscillations, and the motor is able to reach the target position accurately.

The steady-state error is close to zero, significantly improving control accuracy.

4.3.4 Error Curve Analysis

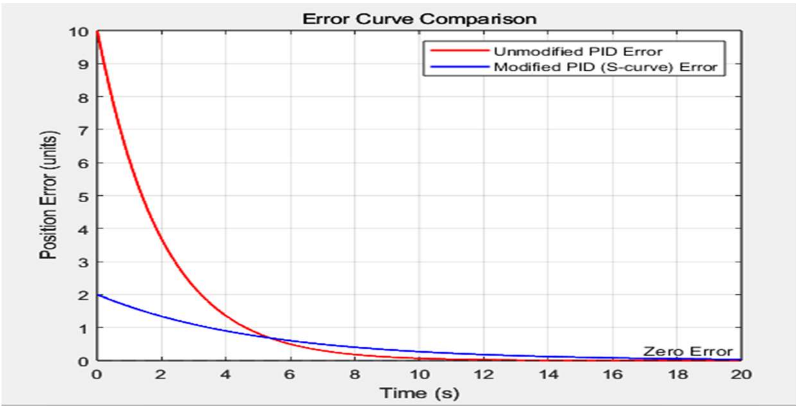

Fig. 8 Comparison of Error Curves

When using the unimproved PID control, the initial error is relatively large, reaching [value], and the deviation is significant during the acceleration phase. The error gradually decreases during the constant speed phase but increases again during the deceleration phase.

When using PID combined with the S-curve acceleration and deceleration algorithm, the initial error is small and quickly converges. Additionally, the error remains within [value] throughout the entire process, with no oscillation observed.

4.4 Comprehensive Analysis

Through the comparative analysis of simulation results, it can be observed that:

Dynamic Performance: The PID combined with the S-curve acceleration and deceleration algorithm significantly optimizes the smoothness of the speed and acceleration curves, successfully eliminating abrupt changes.

Positioning Accuracy: The traditional PID control exhibits a large error, whereas the improved algorithm significantly reduces the error, achieving nearly zero positioning error at the final position.

Mechanical Shock: The optimized acceleration curve effectively avoids abrupt changes, reducing the impact on the mechanical system and significantly extending the equipment's lifespan.

Energy Efficiency: The smooth control approach reduces energy losses, greatly enhancing the overall efficiency of system operation.

5. Summary

This paper aims to optimize the dynamic performance of stepper motors and proposes an improved strategy based on closed-loop PID control combined with the S-curve acceleration and deceleration algorithm. The effectiveness of this strategy is verified through MATLAB/Simulink simulation experiments.

By modeling the stepper motor mathematically, the running characteristics and control conditions are clarified, laying a theoretical foundation for the control algorithm design. As a classic closed-loop control method, traditional PID control can achieve basic speed and position control; however, in high-frequency start-stop or complex working conditions, issues such as overshoot, oscillation, and positioning errors are common.

To address these issues, this paper introduces the S-curve acceleration and deceleration algorithm. By using smooth acceleration and deceleration curves, the start-stop process of the stepper motor is optimized. The simulation results show significant improvements in the following aspects:

Dynamic Performance Optimization: The speed curve exhibits smooth S-curve changes, avoiding oscillation caused by abrupt speed changes in traditional PID control. The acceleration curve is more continuous, reducing mechanical inertial shock and extending equipment lifespan.

Positioning Accuracy Improvement: The improved algorithm makes the displacement curve smoother, allowing the system to accurately reach the target position. Simulation results show that the steady-state error is close to zero, with positioning accuracy significantly better than traditional PID control.

Energy Efficiency Improvement: The smooth motion trajectory reduces energy loss in the mechanical system, thereby enhancing overall operational efficiency.

In summary, the optimization strategy combining PID control with the S-curve acceleration and deceleration algorithm effectively compensates for the shortcomings of traditional PID control. It demonstrates significant advantages in dynamic response, control accuracy, and system stability, providing strong support for the application of stepper motors in complex industrial environments.

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