Continuous Fast Terminal Sliding Mode Control of Permanent Magnet Linear Synchronous Motor

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Abstract. The permanent magnet linear synchronous motor (PMLSM) with direct driving method, which can obtain faster speed and acceleration, has been widely used in the industrial field in recent years. However, due to the lack of transmission links and the influence of nonlinear factors, the control of PMLSM is more difficult. In order to solve the problem that the control system is easy to be affected by nonlinear friction, external disturbance and other uncertain factors, the mathematical model of PMLSM with uncertain factors is established, and a continuous fast terminal sliding mode control (TSMC) method is proposed in this paper. The exponential reaching law (ERL) is used in this method to make the motion track reach the sliding surface quickly and effectively weaken the chattering of the system. The singular problem in the fast TSMC is solved by selecting the parameters to ensure the robustness of the system and improve the response speed of the system. The simulation results show that the continuous fast TSMC method has the ability of accurate position tracking and fast response of the system, so it has great practical value.

Keywords: Permanent Magnet Linear Synchronous Motor, Fast Terminal Sliding Mode Control, Responding Speed, Tracking Accuracy

1. Introduction

PMLSM is widely used in high-precision engineering projects, such as numerical control machine, medical equipment, national defence and military industry, because of its high reliability, high precision, high efficiency and high thrust⁴⁻². With the emergence of rare earth permanent magnet materials and the reduction of the processing cost of PMLSM, the traditional rotary motor used in linear motion requirements is gradually replaced³. PMLSM is a multivariable, strong coupling and nonlinear controlled object. It is difficult to obtain the accurate mathematical model of the system. However, in practical engineering, the mathematical model can be approximately equivalent to the real dynamic system. There are many uncertain factors and external disturbances in PMLSM, such as the external interference of load change, friction, end effect and so on, which are difficult to measure, but will have a great impact on the system⁴. In order to suppress the disturbance in the system, the relatively mature sliding mode control (SMC) can be used to improve the tracking accuracy and
dynamic performance of the PMLSM control system, but the chattering phenomenon in SMC will affect the system performance [5]. In order to eliminate the chattering phenomenon, the method of improving the ERL is adopted in reference [6], but the fast response performance of the system is not improved. A nonlinear SMC is proposed to improve the convergence rate of state trajectories, and the approach law and saturation function are used to weaken chattering [7]. However, it is difficult to select the gain of reaching law. The boundary layer method is used to reduce chattering effectively by using continuous control instead of discontinuous control, but the performance of the controller is affected by the disturbance. TSMC (TSMC) is a control method in nonlinear SMC [8]. TSMC is used to improve the performance of PMLSM, but the chattering phenomenon in the system has not been effectively solved [9]. In this paper, TSMC is improved by introducing equivalent reaching term and exponential reaching term, and a control scheme of continuous fast TSMC (CFTSMC) scheme is proposed. Firstly, TSMC is used to suppress the unknown nonlinear term to improve the tracking accuracy and response speed of the system. In order to further improve the tracking performance of the system, the equivalent control law is used to improve the robustness of the system. Secondly, the ERL is used to make the system reach the desired trajectory quickly, which further reduces the chattering phenomenon in the system. Finally, through the analysis of experimental results, the proposed CFTSMC control scheme can better meet the requirements of high-precision control.

2. System mathematical model

In order to obtain good control performance, the PMLSM servo control system is designed by using field oriented control. The vector control block diagram of PMLSM is shown in Figure 1.

The electromagnetic thrust equation is

\[ F_e = \frac{3n_p \psi_f \tau}{2\pi} i_q = K_f i_q \]  

(1)

where \( F_e \) is electromagnetic thrust, \( \psi_f \) is fundamental magnetic linkage, \( n_p \) is polar logarithm, \( \tau \) is polar distance, \( i_q \) is \( q \) shaft current, and \( K_f \) is electromagnetic thrust constant. The mechanical motion equation of PMLSM is

\[ F_e = M\ddot{x} + B\dot{x} + F \]  

(2)

Where \( M \) is the mass of the mover, \( B \) is viscous friction coefficient, \( \dot{x} \) is the acceleration of the mover, and \( F \) is the total uncertainty factors include parameter variation, nonlinear friction and external disturbance.

Based on the equation (1) and equation (2), PMLSM actual output speed is \( \dot{x}(t) \), ignoring the influence of \( F \), the dynamic equation of the motor in ideal state is

\[ \ddot{x}(t) = -\frac{B}{M} \dot{x}(t) + \frac{K_f}{M} i_q \]  

(3)
where $\ddot{x}(t)$ is the acceleration of the mover. In the presence of disturbance, the equation of motion is

$$\ddot{x}(t) = -\frac{B}{M} \dot{x}(t) + \frac{K_i}{M} i_q + H$$  \hspace{1cm} (4)

where $H$ is system uncertainties. Suppose $H$ is bounded, the equation of motion is

$$H = \Delta A \ddot{x}(t) + \Delta B u + (C_n + \Delta C) F$$  \hspace{1cm} (5)

where $\Delta A$, $\Delta B$ and $\Delta C$ are system parameters; $M$ and $B$ are the uncertainty.

3. Continuous fast TSMC system

3.1 Controller design

Firstly, the tracking error is defined as

$$e = x_t - x$$  \hspace{1cm} (6)

where $x$ is the actual position of the mover, and $x_t$ is given position of mover. According to equation (4)

$$\ddot{x} = m \ddot{i}_q + d$$  \hspace{1cm} (7)

where $m = \frac{K_i}{M} i_q$, $d = -\frac{B}{M} \dot{x} + H - \frac{K_i}{M} (\ddot{i}_q - \dot{i}_q)$. According to equation (7),

$$\ddot{e} = \ddot{x} - \ddot{x} = \ddot{x}_e - \ddot{x}_u - m \ddot{i}_q - d$$  \hspace{1cm} (8)

The sliding surface of the continuous fast terminal is designed as

$$s = \dot{e} + \hat{\lambda}_1 |\dot{e}|^{\alpha_1} \text{sign} (\dot{e}) + \hat{\lambda}_2 |\dot{e}|^{\alpha_2} \text{sign} (e)$$  \hspace{1cm} (9)

where $\hat{\lambda}_1$ and $\hat{\lambda}_2$ are normal number, and $\text{sign}$ is symbolic function. When TSMC system is in a certain subspace of the state space, the output signal of TSMC may be infinite, which is called singular problem. Although the nonsingular problem can be solved by switching between TSMC and linear SMC, this method does not solve the nonsingular problem fundamentally. In order to solve the singular problem in TSMC directly, the setting parameters are $0 < \alpha_1 < 2$, $\alpha_2 > \alpha_1$, $\alpha_1 = \frac{p}{q}$, where $p$, $q$ are positive odd number, This design can solve the above problems directly from the sliding mode design.

In order to ensure the fast convergence of the control system and weaken the chattering in the system, the control law is designed as

$$\ddot{i}_q = m^{-1} (u_{eq} + u_b)$$  \hspace{1cm} (10)

Where $u_{eq}$ is equivalent control, $u_b$ is the exponential approach term. The equivalent control law is designed as

$$u_{eq} = \ddot{x}_e + \hat{\lambda}_1 |\ddot{e}|^{\alpha_1} \text{sign} (\ddot{e}) + \hat{\lambda}_2 |\ddot{e}|^{\alpha_2} \text{sign} (e)$$  \hspace{1cm} (11)

The equivalent control term is introduced into the control system to improve the robust performance and fast response performance of TSMC, but the chattering problem in the control system has not been well solved. Therefore, the ERL is introduced into the control system to improve the control system effectively. The ERL is designed as

$$u_b = k_s s + k_2 |s|^{\alpha_1} \text{sign} (s)$$  \hspace{1cm} (12)

Where $k_s$ and $k_2$ are normal number, and $0 < \alpha_1 < 1$. By introducing the exponential approach term, the chattering phenomenon caused by high frequency switching in sliding mode control is weakened. In order to satisfy the reaching condition of SMC, the stability of the designed controller is analyzed by Lyapunov function.
\[ V = \frac{1}{2} s^2 \]  

According to equation (10),
\[ s = \ddot{x}_r - m \ddot{q} - d + \lambda_1 |e|^\alpha \text{sign}(\dot{e}) + \lambda_2 |e|^\beta \text{sign}(e) \]  

By introducing equation (9) and equation (10) into equation (11) to equation (13),
\[ s = \ddot{x}_i - m \left( \frac{1}{m} (u_{aq} + u_{ib}) \right) - d + \lambda_1 |e|^\alpha \text{sign}(\dot{e}) + \lambda_2 |e|^\beta \text{sign}(e) , \]  

which can be simplified as
\[ s = -u_b - d . \]  

By deriving equation (16),
\[ \dot{s} = -u_b - d = -\left( k_1 \dot{s} + \alpha k_2 |s|^{q_3-1} \dot{s} \right) - d , \]  

and by deriving equation (14),
\[ \dot{V} = s \dot{s} = s \left[ -\left( k_1 \dot{s} + \alpha k_2 |s|^{q_3-1} \dot{s} \right) - d \right] . \]  

From equation (18), the stability of the controller is proved.

PMLSM control is a kind of nonlinear control system, which is easy to be disturbed by many external disturbances, such as parameter variation, nonlinear friction, etc. The traditional PI control can not meet the tracking requirements of high-precision control system, so the CFTSMC scheme can be used to achieve high-precision control. CFTSMC system is shown in Figure 2.

![Figure 2. Block diagram of PMLSM control system based on CFTSMC](image)

4. System experiment analysis

In order to verify the effectiveness of the proposed control strategy, the system adopts TSMC and CFTSMC respectively. The parameters of PMLSM are \( K_t = 57.0 \text{N/A} \), \( R = 17.2 \Omega \), \( M = 12.2 \text{kg} \), \( \tau = 32 \text{mm} \), \( L_q = L_i = 46.5 \text{mH} \), \( B = 9.0 \text{N} \cdot \text{s} / \text{m} \), and \( \psi_f = 0.06 \text{wb} \). The controller parameters are \( \lambda_1 = 28 \), \( \lambda_2 = 3.5 \), \( k_1 = 10 \), \( k_2 = 10 \).

In order to verify the response speed of CFTSMC system, TSMC and CFTSMC are respectively used to control the system through the given step position signal with the amplitude of 1mm. The position tracking curve of the mover is shown in Figure 3. After the system inputs the given position signal, CFTSMC first achieves steady state. According to the experimental results, CFTSMC has faster response speed. The system position error diagram is shown in Figure 4. According to experimental Figure 4 (a), the steady-state tracking error range of TSMC system is -15 \( \mu \text{m} \) to 10 \( \mu \text{m} \), while according to experimental Figure 4 (b), the steady-state tracking error range of CFTSMC system is -5 \( \mu \text{m} \) to 6 \( \mu \text{m} \). Obviously CFTSMC system has better tracking effect.
In order to verify the tracking performance of CFTSMC system, a sine wave position signal with a given period of 10s and amplitude of 1mm is shown in Figure 5. The tracking error curve of TSMC and CFTSMC is shown in Figure 6. It can be seen from Figure 6(a) that the system tracking error of TSMC is between -8 μm and 8 μm. Figure 6(b) shows that the tracking position error of CFTSMC is between ±5 μm. Thus, the performance of CFTSMC can be better tracked.

5. Conclusion

By analyzing the problem that the performance of PMLSM nonlinear servo system is easy to be affected by system parameter changes, friction, end effect and other uncertain factors, a continuous fast TSMC scheme is designed. Due to the use of fast TSMC, the mathematical model of the controlled object is not required, and the response speed of the system can be effectively improved by
using TSMC. At the same time, the equivalent control law and the ERL are applied to improve the speed of the system approaching motion, and then weaken the system chattering. The experimental results show that the proposed control method has better speed response performance and effectively improves the tracking accuracy of the system.

![Position tracking error curve based on TSMC](image1)

![Position tracking error curve based on CFTSMC](image2)

**Figure 6.** The system position tracking error curve when the input is a sine wave signal

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