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Research Article

Position Tracking Control for Permanent Magnet Linear Motor via Continuous-Time Fast Terminal Sliding Mode Control

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For the position tracking control problem of permanent magnet linear motor, an improved fast continuous-time nonsingular terminal sliding mode control algorithm based on terminal sliding mode control method is proposed. Specifically, first, for the second-order model of position error dynamic system, a new continuous-time fast terminal sliding surface is introduced and an improved continuous-time fast terminal sliding mode control law is proposed. Then rigorous theoretical analysis is provided to demonstrate the finite-time stability of the closed-loop system by using the Lyapunov function. Finally, numerical simulations are given to verify the effectiveness and advantages of the proposed fast nonsingular terminal sliding mode control method.

1. Introduction

Permanent magnet linear motor (PMLM) is a conversion device that directly converts electrical energy into linear motion without any intermediate switching mechanism [1, 2]. The study of PMLM has attracted many researchers' interests from motor's design, material, and control due to its many advantages such as high speed, large pushing force, and high precision. And PMLM has been successfully applied in industry, military, and other kind of motion occasions which require high-speed, low thrust, small displacement, and high-precision positioning control [3, 4]. However, the model of PMLM is a typical nonlinear multivariable and coupled system and the PMLM control performance is easily affected by nonlinear factors particularly at unknown load and friction, which vary with different operating conditions. Thus the control problem of PMLM has been an important issue in the filed of PMLM and how to improve the control performance of PMLM system has obtained certain attentions in the literature [5–7].

With the emergence of demand based on PMLM equipment, a considerable amount of nonlinear control methods has been devoted to effectively control the PMLM. For example, the authors in [8] proposed a periodic adaptive compensation control method. And for the modelling and considering both ripples and friction compensations, the improved control scheme was given in [9]. Considering the applications in real industry, the sliding mode control algorithms have been designed to solve the motor control problem due to its significant advantages. The sliding mode control algorithm is easy to use and makes the system state have a good robustness. In particular, even if the controlled systems are suffering from the uncertainty of parameters and external disturbances, SMC can theoretically determine the final tracking accuracy by constructing the reaching law and designing the sliding surface [10–12]. For example, in [13], an equivalent disturbance observer based on sliding mode control method and proportional-integral (PI) was proposed. In order to overcome the uncertainty and interference, based on radial-basis function-network (RBFN), a smart complementary sliding mode control (ICSMC) method was proposed in [14].

However, most of the designed sliding surfaces only guarantee that the system state asymptotically converges to the equilibrium with infinite convergence time. To improve the closed-loop system's dynamic performance and guarantee that the state of the system can converge to the equilibrium within a finite-time, the terminal sliding mode control (TSMC) method is introduced in [15–18]. Due to the superiority of the terminal sliding mode control method, this method was designed as a controller in [19] for PMLM. In addition, when the state of the system is far from the equilibrium, a fast terminal sliding mode control (FTSMC) method was proposed in [20, 21] to improve the convergence rate of the system state. The (finite-time) transient convergence both at a distance from and at a close range of the equilibrium can be obtained since the merits of the TSMC control.

For the PMLM position tracking control problem and the advantages of TSMC, in this paper, a fast nonsingular TSMC law for PMLM will be designed. The contribution/novelty of this paper is that a new nonlinear control algorithm is designed, i.e., the fast terminal sliding mode control (FTSMC) algorithm. The main advantage of this algorithms is that the fast convergent rate of the closed-loop system can be guaranteed no matter the state is near or far from the equilibrium. To improve the tracking accuracy of the system state, the fast terminal sliding mode surface is obtained and the improved continuous-time nonsingular fast terminal sliding mode control law based on TSMC method is designed. Meanwhile, the rigorous stability analysis for the closed-loop system is presented. The validity and stability of the scheme are verified by employing the Lyapunov function analysis method. Simulation results are provided to show that the continuous-time fast nonsingular TSMC can improve the closed-loop system dynamic performance and robustness against uncertainties and disturbances by comparing with the traditional PID control method.

Note that the work [22] also considered the position tracking control for permanent magnet linear motor. However, the main differences of this manuscript are listed as follows. (i) The model is different: the model considered in this paper is the continuous-time model of permanent magnet linear motor while the work [22] considered the discrete-time model of permanent magnet linear motor based on Euler's discretization. (ii) The method is different: the design method of this paper is based on the continuous-time fast nonsingular terminal sliding mode control method while the work [22] employed discrete-time fast terminal sliding mode control method plus time-delayed disturbance compensation technique. (iii) The stability analysis is different: the Lyapunov function used in this paper is based on a continuous-time Lyapunov function which shows that the finite-time convergence of the closed-loop system can be guaranteed. Note that the work [22] employed a discrete-time Lyapunov function and analyzed the ultimate bound for the steady state.

The rest of the paper is organized as follows. Section 2 provides the description of system model and control objective. Section 3 presents the proposed SMC laws for PMLM. Section 4 discusses the simulation results, and Section 5 concludes this paper.

2. Description of System Model and Control Objective

2.1. Continuous-Time Model of PMLM. For a permanent magnet linear motor, the mathematical model can be described as [3]

$$\begin{aligned} \dot{x}_1(t) &= x_2(t), \\ \dot{x}_2(t) &= -\frac{k_f k_e}{Rm} x_2(t) + \frac{k_f}{Rm} u(t) - \frac{d(t)}{m}, \\ y(t) &= x_1(t), \end{aligned} \tag{1}$$

where x_1 is the linear displacement, x_2 is the linear velocity, $u(t)$ is the input voltage, R is the resistance, m is the motor mass, k_f is the force constant, k_e is the back electromotive force, and $d(t)$ can be counted as the lumped disturbances including the friction and ripple force.

2.2. Control Objective. The control objective of PMLM is to design a controller such that the reference trajectory can be tracked by the linear displacement. Generally, assume that the reference signal is $x_r(t)$, whose first-order and second-order derivatives are bounded.

For the brevity, denote

$$\begin{aligned} a &= \frac{k_f k_e}{Rm}, \\ b &= \frac{k_f}{Rm}, \\ F &= \frac{d(t)}{m}, \end{aligned} \tag{2}$$

under which (1) is rewritten as

$$\begin{aligned} \dot{x}_1(t) &= x_2(t), \\ \dot{x}_2(t) &= -a x_2(t) + b u(t) - F, \\ y(t) &= x_1(t). \end{aligned} \tag{3}$$

Define

$$\begin{aligned} e_1(t) &= x_r(t) - x_1(t), \\ e_2(t) &= \dot{x}_r(t) - x_2(t), \end{aligned} \tag{4}$$

as the tracking errors for linear displacement and speed signal. Then it can be obtained from (3) that the error dynamic equation is

$$\begin{aligned} \dot{e}_1(t) &= e_2(t), \\ \dot{e}_2(t) &= -a e_2(t) - bu + F + a\dot{x}_r + \ddot{x}_r, \\ y &= x_1. \end{aligned} \tag{5}$$

The main objective of this paper is to employ the method of sliding mode control to achieve this control objective due to its many advantages, such as simple design idea and good robustness [10, 12]. There have been many results about the sliding control algorithms for PMLM in the literature, such as [13, 19], and the most of control laws are based on the design of continuous-time SMC laws with asymptotical convergence. The main objective of this paper is to design a continuous-time fast TSMC law for PMLM.

About the disturbance, the following case will be considered in this paper.

Assumption 1. The disturbance F is assumed to be bounded, i.e., $|F| \leq d^*$ with a constant d^*.

2.3. Some Definitions and Lemmas

Definition 2 (finite-time stability [23]). Consider the system

$$\begin{aligned} \dot{x} &= f(x), \\ f(0) &= 0, \\ x(0) &= x_0, \\ x &\in R^n, \end{aligned} \tag{6}$$

where $f(\cdot) : R^n \longrightarrow R^n$ is continuous. The equilibrium $x = 0$ of system (6) is finite-time stable if it is Lyapunov stable and finite-time convergent; i.e., there exists a finite time $T(x_0)$ which is dependent on the initial condition x_0 such that $\lim_{t \longrightarrow T(x_0)} x(t) = 0$ and $x(t) = 0$ for all $t \geq T(x_0)$.

Lemma 3 (see [23]). *For system (6), suppose that there exists a positive definite and proper function $V(x) : R^n \longrightarrow R$ such that $(\partial V(x)/\partial x) f(x) + c(V(x))^{\alpha} \leq 0$ for all $x \in R^n$, where $c > 0$, $\alpha \in (0,1)$. Then, this system is globally finite-time stable.*

3. Design of Nonsingular Fast Terminal Sliding Mode Controller

Theorem 4. *For the error dynamic system (5), if the nonsingular terminal sliding mode controller is designed as*

$$\begin{aligned} u &= u_a + u_b, \\ u_a &= \frac{1}{b}\left[-ae_2 + a\dot{x}_r + \ddot{x}_r + F + \frac{1}{\beta_1\gamma_1}\left|e_2\right|^{2-\gamma_1}\operatorname{sign}(e_2) \right. \\ &\quad \left. + \frac{\beta_2}{\beta_1}\left|e_2\right|^{2-\gamma_1}\left|e_1\right|^{\gamma_1-1}\right], \\ u_b &= \frac{1}{b}\left[k_1 s + k_2\operatorname{sign}(s)\right], \\ s &= e_1 + \beta_1\left|e_2\right|^{\gamma_1}\operatorname{sign}(e_2) + \beta_2\left|e_1\right|^{\gamma_1}\operatorname{sign}(e_1), \end{aligned} \tag{7}$$

where $k_1 > 0, k_2 > d^*$, $\beta_1 > 0, \beta_2 > 0$, $1 < \gamma_1 < 2$, then the error system state (e_1, e_2) will converge to zero in a finite time.

Proof.

Step 1. Choose the fast nonsingular terminal sliding mode surface.

For the error dynamic system (5), the nonsingular fast terminal sliding mode surface is chosen as

$$s = e_1 + \beta_1\left|e_2\right|^{\gamma_1}\operatorname{sign}(e_2) + \beta_2\left|e_1\right|^{\gamma_1}\operatorname{sign}(e_1) \tag{8}$$

with $\beta_1 > 0, \beta_2 > 0$, $1 < \gamma_1 < 2$.

If the sliding mode surface $s = 0$ can be reached in a finite time, then one obtains that

$$e_1 + \beta_1\left|e_2\right|^{\gamma_1}\operatorname{sign}(e_2) + \beta_2\left|e_1\right|^{\gamma_1}\operatorname{sign}(e_1) = 0, \tag{9}$$

which results into

$$\begin{aligned} e_2 = &-\frac{1}{\beta_1}\left|e_1 + \beta_2\left|e_1\right|^{\gamma_1}\operatorname{sign}(e_1)\right|^{1/\gamma_1} \\ &\times \operatorname{sign}\left(e_1 + \beta_2\left|e_1\right|^{\gamma_1}\operatorname{sign}(e_1)\right). \end{aligned} \tag{10}$$

Since $\dot{e}_1 = e_2$, then

$$\begin{aligned} \dot{e}_1 = &-\frac{1}{\beta_1}\left|e_1 + \beta_2\left|e_1\right|^{\gamma_1}\operatorname{sign}(e_1)\right|^{1/\gamma_1} \\ &\times \operatorname{sign}\left(e_1 + \beta_2\left|e_1\right|^{\gamma_1}\operatorname{sign}(e_1)\right). \end{aligned} \tag{11}$$

Construct the following Lyapunov function $V_1 = (1/2)e_1^2$, which leads to

$$\dot{V}_1 \leq -\frac{1}{\beta_1}\left|e_1\right|^{1+1/\gamma_1} = -\frac{1}{\beta_1}2^{(1+1/\gamma_1)/2}V_1^{(1+1/\gamma_1)/2}. \tag{12}$$

It follows from Lemma 3 that the system state e_1 will converge to zero in a finite time.

Step 2. Design the nonsingular fast terminal sliding mode controller.

Choose a Lyapunov function as $V_2 = (1/2)s^2$, whose derivative along the error system (5) is

$$\begin{aligned} \dot{V}_2 &= s\dot{s} = s\left(e_2 + \beta_1\gamma_1\left|e_2\right|^{\gamma_1-1}\dot{e}_2 + \beta_2\gamma_1\left|e_1\right|^{\gamma_1-1}e_2\right) \\ &= s\left(e_2 + \beta_2\gamma_1\left|e_1\right|^{\gamma_1-1}e_2 \right. \\ &\quad \left. + \beta_1\gamma_1\left|e_2\right|^{\gamma_1-1}\left[-ae_2(t) - bu + F + a\dot{x}_r + \ddot{x}_r\right]\right) \end{aligned} \tag{13}$$

□

Substituting the terminal sliding mode control law (7) into (13) leads to

$$\begin{aligned} \dot{V}_2 &= s\left[e_2 + \beta_1\gamma_1\left|e_2\right|^{\gamma_1-1}\left(-\frac{1}{\beta_1\gamma_1}\left|e_2\right|^{2-\gamma_1}\operatorname{sign}(e_2) \right.\right. \\ &\quad \left.\left. - \frac{\beta_2}{\beta_1}\left|e_2\right|^{2-\gamma_1}\left|e_1\right|^{\gamma_1-1} + F - k_1 s - k_2\operatorname{sign}(s)\right)\right] \\ &= s\left[e_2 - \left|e_2\right|\operatorname{sign}(e_2) - \beta_1\gamma_1\left|e_2\right|^{\gamma_1-1}(F + k_1 s \right. \\ &\quad \left. + k_2\operatorname{sign}(s))\right] \leq -\beta_1\gamma_1 k_1\left|e_2\right|^{\gamma_1-1}s^2 - \beta_1\gamma_1(k_2 \\ &\quad - d^*)\left|e_2\right|^{\gamma_1-1}|s|. \end{aligned} \tag{14}$$

There are two possibilities for the state e_2. For the first case $e_2 \neq 0$, there is a constant $\rho > 0$ such that

$$\dot{V}_2 \leq -\rho s^2 - \rho |s| \leq -2\rho V_2 - \rho\sqrt{2V_2}. \tag{15}$$

It follows from Lemma 3 that the sliding mode state s will converge to zero in a finite time. Next, we show that $e_2 = 0$ is not an attractor in the reaching phase. Note that

$$\begin{aligned}\dot{e}_2 = &-\frac{1}{\beta_1\gamma_1}|e_2|^{2-\gamma_1}\operatorname{sign}(e_2) - \frac{\beta_2}{\beta_1}|e_2|^{2-\gamma_1}|e_1|^{\gamma_1-1} + F \\ &- k_1 s - k_2 \operatorname{sign}(s).\end{aligned} \tag{16}$$

Under the condition $e_2 = 0$ and $s \neq 0$, then it follows from (17) that

$$\dot{e}_2 = F - k_1 s - k_2 \operatorname{sign}(s) \neq 0, \tag{17}$$

which means that $e_2 = 0$ is not an attractor in the reaching phase. Thus, the finite-time stability of the error system (5) can be achieved.

Remark 5. From the work [15], we know that the traditional terminal sliding mode surface is usually chosen as

$$s = e_1 + \beta_1 |e_2|^{\gamma_1}\operatorname{sign}(e_2), \tag{18}$$

with $0 < \gamma_1 < 1$. Once the sliding mode face is reached and kept, i.e., $s = 0$, then

$$e_2 = -\frac{1}{\beta_1}|e_1|^{1/\gamma_1}\operatorname{sign}(e_1) = \dot{e}_1. \tag{19}$$

It implies that the state e_1 will converge to zero in a finite time. However, if the sliding mode surface is chosen as in this paper, i.e.,

$$s = e_1 + \beta_1 |e_2|^{\gamma_1}\operatorname{sign}(e_2) + \beta_2 |e_1|^{\gamma_1}\operatorname{sign}(e_1), \tag{20}$$

then on the sliding mode face $s = 0$, it follows from (11) that

$$\begin{aligned}\dot{e}_1 = &-\frac{1}{\beta_1}\left|e_1 + \beta_2 |e_1|^{\gamma_1}\operatorname{sign}(e_1)\right|^{1/\gamma_1} \\ &\times \operatorname{sign}\left(e_1 + \beta_2 |e_1|^{\gamma_1}\operatorname{sign}(e_1)\right).\end{aligned} \tag{21}$$

The term $\beta_2|e_1|^{\gamma_1}\operatorname{sign}(e_1)$ will guarantee that there is a faster convergent rate for the state e_1 compared with the traditional terminal sliding mode control (19). Therefore, it is called the fast terminal sliding mode control. In addition, it should be pointed out that there is no singularity problem in the proposed controller (7) since $1 < \gamma_1 < 2$.

4. Simulation Results

In this section, numerical simulations results are supported to illustrate the efficiencies of the designed fast nonsingular terminal sliding mode controller (FTSMC). All the simulation data is based on the Matlab/Simulink model. The system's parameter values of PMLM are given as that in [22], i.e., the mass $m = 5.4$ kg, the resistance $R = 16.8$ ohms, the force constant $k_f = 130$ N/A, and the back electromotive force $k_e = 123$ V/m/s.

Table 1: Controllers' gains.

Control schemes	Values
PID	$k_p = 300,\ k_i = 5,\ k_d = 2$
FTSMC	$k_1 = 100,\ k_2 = 500,\ \beta_1 = \beta_2 = 0.1,\ \gamma_1 = 1.1$

The disturbance is composed of two parts, i.e., friction force and ripple force. Definitely, let

$$d = F_{fric} + F_{ripple}, \tag{22}$$

where F_{fric} is the friction force and F_{ripple} is ripple force. The friction force is defined as

$$F_{fric} = \left[f_c + (f_s - f_c)\, e^{-(\dot{x}/\dot{x}_s)^2} + f_v\dot{x}\right]\operatorname{sign}(\dot{x}), \tag{23}$$

where $f_c = 10$N is the Coulomb friction coefficient, $f_v = 10$N is the static friction coefficient, $f_s = 20$N is the static friction coefficient, and $\dot{x}_s = 0.1$ is the lubricant parameter. The ripple force is given as

$$F_{fipple} = A_1 \sin(\omega x) + A_2 \sin(3\omega x) + A_3 \sin(5\omega x), \tag{24}$$

with $A_1 = 8.5$, $A_2 = 4.25$, $A_3 = 2.0$, and $\omega = 314$ rad/s.

In this section, a step signal with amplitude of 200mm and a sinusoidal signal with amplitude of 5mm and the frequency of 1 rad/s, i.e., $x_r = 5\sin(t)$, are, respectively, considered as the desired displacement.

To achieve the position tracking control, the PID control algorithm and the proposed nonsingular fast terminal sliding mode controller (FTSMC) are employed. The controllers' parameters are summarized in Table 1.

(1) Step response: the step signal with amplitude of 200mm is chosen as the desired displacement. Under the PID controller and proposed continuous-time nonsingular FTSMC, the response curves for the displacement of PMLM are shown in Figure 1. It can be found that the proposed fast TSMC can offer a faster convergent rate and a smaller steady-state error.

(2) Tracking a sinusoid signal: a sinusoidal signal for displacement with amplitude of 5mm and the frequency of 1rad/s is investigated. Similarly, the response curves are given in Figure 2. The tracking error is given in Figure 3. It is shown that the proposed continuous-time nonsingular FTSMC can profoundly reduce the steady-state error.

In summary, according to simulation results, it can be concluded that the closed-loop system's performance can be improved under the proposed continuous-time fast nonsingular terminal sliding mode control method.

5. Conclusions

This paper has investigated the position control problem for permanent magnet linear motors. Based on the terminal sliding mode control theory, an improved continuous-time fast nonsingular terminal sliding mode control method has

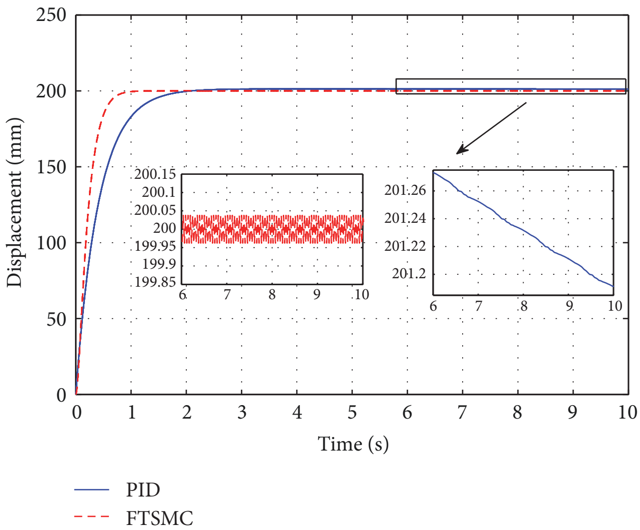

FIGURE 1: The response curves for displacement under step response.

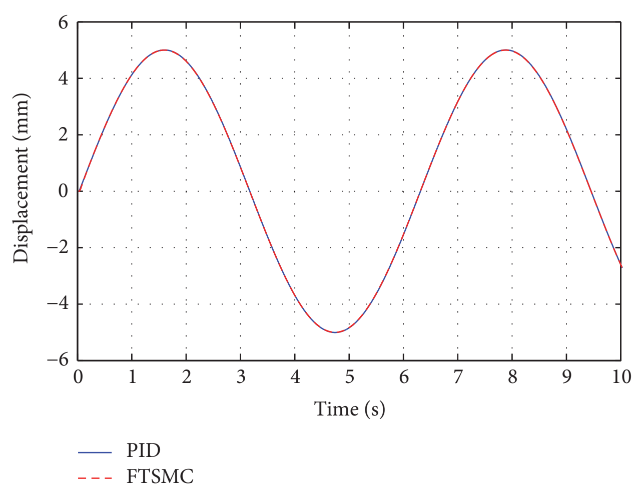

FIGURE 2: The response curves for displacement under step response.

been proposed. In addition, it also has been theoretically proved that the closed-loop system is finite-time stable by the Lyapunov function analysis method. Simulation results have been verified by the results of theoretical analysis and the effectiveness of the proposed control algorithm by comparing with traditional PID controller.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

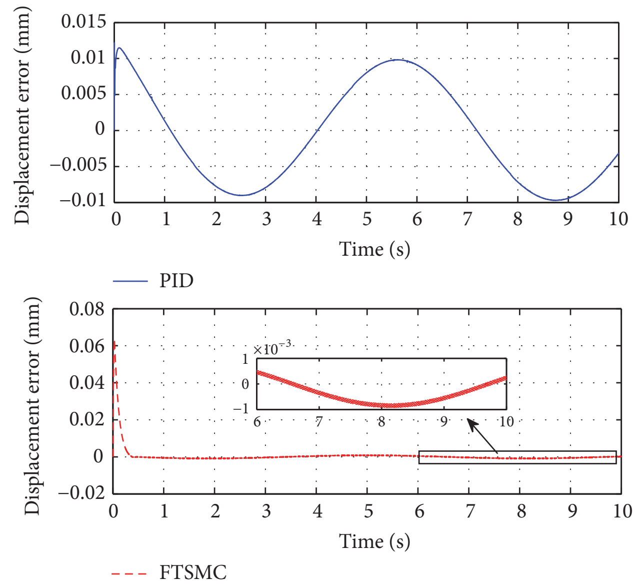

FIGURE 3: The response curves for displacement error for tracking a sinusoid signal.

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