High-precision motion control method for permanent magnet linear synchronous motor

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Abstract In this paper, aiming at the known or unknown uncertainties in permanent magnet linear synchronous motor (PMLSM) servo system, an intelligent backstepping terminal sliding mode control (IBTSMC) method is proposed for accurate position tracking of the servo system. The designed controller makes use of the advantage of backstepping terminal sliding mode control theory to ensure fast convergence and robustness. Finally, the stability analysis is carried out by using Lyapunov stability theory, and the effectiveness of the designed control scheme is proved by experiments.

Keywords: permanent magnet linear synchronous motor (PMLSM), backstepping terminal sliding mode control, Lyapunov, robustness

Classification: Power devices and circuits

1. Introduction

With the continuous upgrading and optimization of intelligent manufacturing industry, the improvement of product performance is particularly important. This indirectness puts forward high-precision production requirements for the servo system [1, 2, 3]. At present, the high-performance servo system mainly uses permanent magnet linear synchronous motor (PMLSM) to convey power to complete the conversion from electric energy to mechanical energy [4, 5, 6]. PMLSM has the advantages of simple structure, high efficiency and high precision, so it is the first choice for high-speed and high-precision equipment. While the traditional rotating motor needs the complex transmission mechanisms, which virtually results in many shortcomings such as complex structure and low efficiency [7, 8, 9, 10]. However, the simplification of the transmission link will lead to a series of uncertain factors acting on the actuator, thus increasing the difficulty of control [11, 12, 13].

The sliding mode control (SMC) can only make the tracking error asymptotically converge [14, 15, 16, 17]. In order to solve the problem that the SMC cannot converge in finite time. In [18], a terminal sliding mode control (TSMC) strategy is proposed. But the disadvantage is that there is a singularity problem in the system. In [19], a nonsingular fast terminal sliding mode control (NTSMC) method for time-delay estimation is proposed, which not only solves the singularity problem, but also makes the system state in finite

time converges to zero and the tracking performance is improved. However, the control methods proposed above are all based on parameter models.

Neural network control has nonlinear approximation characteristics and self-learning and self-organization capabilities. Most importantly, it does not require an accurate model of the controlled plant to realize adaptive control of the servo control system [20, 21, 22, 23]. At present, the control methods combining intelligent control and sliding mode control have made many research results [24, 25, 26, 27]. In [28], an adaptive decentralized tracking controller is constructed through the combination of backstepping method and neural network technology, and the neural network is used to estimate the uncertainty in the system. In [29], an adaptive fuzzy wavelet neural network backstepping sliding mode control method is proposed. However, the algorithm implementation and calculation degree of adaptive fuzzy wavelet neural network are complex.

Hence, this paper designs an intelligent backstepping terminal sliding mode control (IBTSMC) method to eliminate the influence of external disturbance and uncertainties. RBF neural network is used to estimate the external disturbance and uncertainties in the system, and does not require precise mathematical model to ensure the tracking accuracy of the system. The saturation function with boundary layer is used instead of discontinuous sign function to improve the chattering phenomenon.

2. Problem description

The mechanical motion equation of PMLSM is

$$M\dot{v} + Bv + F = F_e \quad (1)$$

where M is the total mass of the mover of PMLSM, B is the coefficient of viscous friction; v is the velocity of the mover, and F is the nonlinear disturbance, including the external disturbance of the system, nonlinear friction force and motor parameter changes, etc.

The electromagnetic thrust F_e is expressed as

$$F_e = \frac{3\pi n_p}{2\tau} [\psi_{PM} - (L_q - L_d) i_d] i_q \quad (2)$$

where i_d , i_q , L_d , L_q are d, q axis current and inductance respectively; n_p is the number of polar pairs; τ is the polar moment; ψ_{PM} is the fundamental magnetic linkage.

According to the principle of magnetic field orientation, take $i_d^* = 0$. For design convenience, $L_d = L_q = L$, electromagnetic thrust can be simplified as

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$$F_e = \frac{3\pi n_p}{2\tau} \psi_{PM} i_q = K_f i_q \quad (3)$$

$$K_f = \frac{3\pi n_p}{2\tau} \psi_{PM} \quad (4)$$

where K_f is the electromagnetic thrust constant.

When there is no nonlinear disturbance F , the dynamic equation of PMLSM is

$$\ddot{d}(t) = -\frac{B}{M} \dot{d}(t) + \frac{K_f}{M} i_q = A_n \dot{d}(t) + B_n u \quad (5)$$

where $d(t)$ is the mover position; $A_n = -B/M$; $B_n = K_f/M$; u is the controller output, $u = i_q$, which is the thrust current.

When there is a nonlinear disturbance F , the dynamic equation of PMLSM is

$$\ddot{d}(t) = (A_n + \Delta A) \dot{d}(t) + (B_n + \Delta B) u + (C_n + \Delta C) F \\ = A_n \dot{d}(t) + B_n u + D \quad (6)$$

$$D = \Delta A \dot{d}(t) + \Delta B u + (C_n + \Delta C) F \quad (7)$$

where $C_n = -1/M$; ΔA , ΔB , and ΔC are the uncertainties caused by the system parameters M and B . Here, suppose D is bounded, that is, $|D| \leq \delta$, δ is the upper bound of the sum of uncertainties D , which is a constant.

3. Design of PMLSM control system

3.1 Backstepping terminal sliding mode controller design

Define the position tracking error as:

$$e_1 = d_m - d \quad (8)$$

where d_m and d are reference position input and actual position output, respectively.

Define the stable function α_1 as:

$$\alpha_1 = \lambda_1 e_1 + \lambda_2^{-1} e_1^{q/p} \quad (9)$$

where λ_1 , λ_2 are random constants, q , p are positive odd numbers and $1 < q/p < 2$.

Define the speed error as:

$$e_2 = \dot{e}_1 + \alpha_1 \quad (10)$$

where the tracking error of speed increases with the increase of the stability function.

The first Lyapunov function is:

$$V_1 = \frac{1}{2} e_1^2 \quad (11)$$

$$\dot{V}_1 = e_1 e_2 - \lambda_1 e_1^2 - \lambda_2^{-1} e_1^{1+q/p} \quad (12)$$

Derived from Eq. (6) and Eq. (10),

$$\dot{e}_2 = \ddot{d}_m - B_n \left[u - B_n^{-1} (-A_n \dot{d} - D) \right] + \lambda_1 \dot{e}_1 + \frac{q}{\lambda_2 p} e_1^{q/p-1} \dot{e}_1 \quad (13)$$

The second Lyapunov function is:

$$V = V_1 + \frac{1}{2} s^2 \quad (14)$$

The following provides the requirements for the tracking error from the arrival phase to the sliding phase, that is, the

condition can be reached.

$$\dot{V} < 0, s \neq 0 \quad (15)$$

The sliding surface is:

$$s = e_1 + e_2 \\ = e_1 + \dot{e}_1 + \lambda_1 e_1 + \lambda_2^{-1} e_1^{q/p} \\ = (1 + \lambda_1) e_1 + \lambda_2^{-1} e_1^{q/p} + \dot{e}_1 \quad (16)$$

Differentiating V with respect to time

$$\dot{V} = e_1 e_2 - \lambda_1 e_1^2 - \lambda_2^{-1} e_1^{1+q/p} \\ + s \left[\dot{e}_1 (1 + \lambda_1) + \frac{q}{\lambda_2 p} e_1^{q/p-1} \dot{e}_1 + \ddot{d}_m - \ddot{d} \right] \quad (17)$$

The total control law is:

$$u = u_0 + u_s \quad (18)$$

Substituting Eq. (18) into Eq. (17) gives

$$\dot{V} = e_1 e_2 - \lambda_1 e_1^2 - \lambda_2^{-1} e_1^{1+q/p} \\ + s \left[\dot{e}_1 (1 + \lambda_1) + \frac{q}{\lambda_2 p} e_1^{q/p-1} \dot{e}_1 \right. \\ \left. + \ddot{d}_m - B_n (u_0 + u_s) - A_n \dot{d} - D \right] \quad (19)$$

Without considering disturbances and uncertain factors, combining Eq. (5) to derive s and let $\dot{s} = 0$, the equivalent control law u_0 is obtained as:

$$u_0 = B_n^{-1} \left[\dot{e}_1 (1 + \lambda_1) + \frac{q}{\lambda_2 p} e_1^{q/p-1} \dot{e}_1 + \ddot{d}_m - A_n \dot{d} \right] \quad (20)$$

When the equivalent control law cannot provide ideal tracking performance, an additional control is needed to eliminate unpredictable disturbances and uncertainties until the tracking error gradually disappears, which means that the sliding mode surface becomes stable.

From Eq. (19) and Eq. (20), we get

$$\dot{V} = e_1 e_2 - \lambda_1 e_1^2 - \lambda_2^{-1} e_1^{1+q/p} + s(-B_n u_s) \quad (21)$$

To satisfy the Lyapunov stability condition, the switching control law u_s is:

$$u_s = B_n^{-1} \left[s^{-1} \left(e_1 e_2 - \lambda_2^{-1} e_1^{1+q/p} \right) + k_w \text{sign}(s) \right] \quad (22)$$

Substituting Eq. (22) into Eq. (21) yields

$$\dot{V} = -\lambda_1 e_1^2 - s k_w \text{sign}(s) \quad (23)$$

where k_w is the switching gain.

$$\dot{V} \leq -\lambda_1 |e_1|^2 - k_w |s| \quad (24)$$

where $|s| = s \text{sign}(s)$. Since the discontinuity of the sign function $\text{sign}(\cdot)$ will have a chattering effect on the control input signal, the hyperbolic tangent function $\tanh(\cdot)$ is selected.

$$\dot{V} \leq -\lambda_1 e_1^2 - k_w s \tanh(s) \quad (25)$$

The improved switching control law u_s is as follows:

$$u_s = B_n^{-1} \left[s^{-1} \left(e_1 e_2 - \lambda_2^{-1} e_1^{1+q/p} + k_w \tanh(s) \right) \right] \quad (26)$$

To eliminate discontinuity in u_s , the saturation function with boundary layer is designed as follows:

$$\text{sat}\left(\frac{s}{\phi}\right) = \begin{cases} \tanh\left(\frac{s}{\phi}\right), & \left|\frac{s}{\phi}\right| \geq 1 \\ \frac{s}{\phi}, & \left|\frac{s}{\phi}\right| < 1 \end{cases} \quad (27)$$

where ϕ is the thickness of the boundary layer.

Therefore, the switching control law u_s is:

$$u_s = B_n^{-1} \left[s^{-1} \left(e_1 e_2 - \lambda_2^{-1} e_1^{1+q/p} \right) \right] + k \tanh\left(\frac{s}{\phi}\right) \quad (28)$$

where $k = B_n^{-1} k_w$.

3.2 Intelligent backstepping terminal sliding mode controller design

The block diagram of the PMLSM servo system based on IBTSMC is shown in Fig. 1. Due to the modeling uncertainty, a large switching gain is needed, which results in chattering. For this reason, RBF neural network is used to estimate the uncertainty in the system, and then eliminate the impact of uncertainty on the system.

Define the approximation function $f(x)$ as:

$$f(x) = W^T h(x) + \varepsilon \quad (29)$$

where $h(x) = [h_1(x), h_2(x), h_3(x), \dots, h_m(x)]^T$ is the Gaussian radial basis function output of the network, x is the input of the network, m is the node of the hidden layer of the network, W is the ideal weight, and ε is the approximation error.

The RBF is defined as:

$$h_i(x) = \exp\left(-\frac{\|x - c_i\|^2}{2b_i^2}\right), i = 1, 2, \dots, m \quad (30)$$

where c_i is the center, b_i is the width of the i neuron.

Rewrite Eq. (16) as:

$$s = (1 + \lambda_1)e_1 + \lambda_2^{-1}e_1^{q/p} + \dot{e}_1 = \dot{d}_r - \dot{d} \quad (31)$$

$$\dot{d}_r = \dot{d}_m + (1 + \lambda_1)e_1 + \lambda_2^{-1}e_1^{q/p} \quad (32)$$

Derived from Eq. (6) and Eq. (31)

$$B_n^{-1}\dot{s} = \frac{A_n}{B_n}s + f(x) - u \quad (33)$$

$$f(x) = B_n^{-1}\ddot{d}_r - B_n^{-1}A_n\dot{d}_r - B_n^{-1}D \quad (34)$$

Fig. 1 Block diagram of PMLSM servo system based on IBTSMC

If the network input is $x = [d_m^T, d^T]^T$, then the network output is

$$\hat{f}(x) = \hat{W}^T h(x) \quad (35)$$

where $h(x)$ is the basis function, $\hat{W}$ is the neural network adjustment law.

Transform Eq. (33) into

$$B_n^{-1}\dot{s} = A_n B_n^{-1}s + \tilde{W}^T h(x) + \hat{W}^T h(x) + \varepsilon^* - u \quad (36)$$

where $\tilde{W} = W^* - \hat{W}$, W^* is ideal weights and ε^* is approximation error.

The total control law is designed as follows:

$$u = u_0 + u_s + u_{NN} \quad (37)$$

$$u_s = k_1 s + k \tanh\left(\frac{s}{\phi}\right) \quad (38)$$

$$u_{NN} = \hat{W}^T h(x) \quad (39)$$

The adaptive law of neural network parameter $\hat{W}^T$ is as follows:

$$\dot{\hat{W}}^T = -\dot{\tilde{W}}^T = B_1 h(x)s \quad (40)$$

where B_1 is a positive definite matrix.

Construct the Lyapunov function as follows

$$V = \frac{1}{2}s^2 E + \frac{1}{2}\text{tr}(\tilde{W}^T B_1^{-1} \tilde{W}) \quad (41)$$

$$\dot{V} = \frac{1}{2}s^2 \dot{E} + sE\dot{s} + \text{tr}(\tilde{W}^T B_1^{-1} \dot{\tilde{W}}) \quad (42)$$

where $E = B_n^{-1}$.

Substituting Eq. (36) into Eq. (42) yields

$$\begin{aligned} \dot{V} &= \frac{1}{2}s^2(\dot{E} + 2A_n E) \\ &\quad + s \left[\tilde{W}^T h(x) + \varepsilon^* - k_1 s - k \tanh\left(\frac{s}{\phi}\right) \right] + \text{tr}(\tilde{W}^T B_1^{-1} \dot{\tilde{W}}) \end{aligned} \quad (43)$$

Since $\dot{E} + 2A_n E$ is a skew symmetric matrix, the first term in Eq. (43) becomes zero. By Eq. (25) and Eq. (40) to get $\dot{V}$:

$$\begin{aligned} \dot{V} &= s \left[\tilde{W}^T h(x) + \varepsilon^* - k_1 s - k \tanh\left(\frac{s}{\phi}\right) \right] + \text{tr}(\tilde{W}^T B_1^{-1} \dot{\tilde{W}}) \\ &= -k_1 s^2 + s\varepsilon^* + s\tilde{W}^T h(x) - sk \tanh\left(\frac{s}{\phi}\right) + \text{tr}(\tilde{W}^T B_1^{-1} \dot{\tilde{W}}) \\ &= -k_1 s^2 + s\varepsilon^* - \tilde{W}^T B_1^{-1} \dot{\tilde{W}} - sk \tanh\left(\frac{s}{\phi}\right) + \text{tr}(\tilde{W}^T B_1^{-1} \dot{\tilde{W}}) \\ &\leq -k_1 s^2 + \|s\|\delta_0 \end{aligned} \quad (44)$$

where $\|s\|\delta_0 \leq \frac{1}{2}(\|s\|^2 + \rho\delta_0^2)$, δ_0 is the upper bound of $\|\varepsilon^*\|$, here $\rho > 0$, so $\int_0^\infty \rho dt < \infty$.

Thus get

$$\dot{V} \leq -k_1 \|s\|^2 + \frac{1}{2}(\|s\|^2 + \rho\delta_0^2) \quad (45)$$

From $t = 0$ to $t = T$, integrate both sides of Eq. (45) at the same time.

$$V(T) - V(0) \leq -\left(k_1 - \frac{1}{2}\right) \int_0^T \|s\|^2 dt + \frac{1}{2}\delta_0^2 \int_0^T \rho dt \quad (46)$$

Since $V(T) \geq 0$ and $\int_0^\infty \rho dt < \infty$ are established, then

$$\begin{aligned} \lim_{T \rightarrow \infty} \sup \frac{1}{T} \int_0^T \|s\|^2 dt \\ \leq \left(k_1 - \frac{1}{2}\right)^{-1} \left[V(0) + \frac{1}{2}\delta_0^2 \int_0^\infty \rho dt \right] \lim_{T \rightarrow \infty} \sup \frac{1}{T} = 0 \end{aligned} \quad (47)$$

From Eq. (46) and Eq. (47), we can see that when $t \rightarrow \infty$, $s \rightarrow 0$ is obtained, indicating that the system state has moved to the sliding mode surface. It follows from Eq. (31) that when $t \rightarrow \infty$, the tracking error of position and velocity converges to zero asymptotically. Therefore, the IBTSMC method satisfies the stability criterion.

4. System experiment analysis

The model of the DSP microprocessor used in this experiment is TMS320F28335, and the experimental device diagram of PMLSM control system is shown in Fig. 2. The specific parameters of the PMLSM for the experiment are shown in Table I.

Fig. 2 Experimental device diagram of PMLSM control system

Table I Specific parameter values of the PMLSM.

Symbol	PMLSM
M	16.4 kg
B	8 N*s/m
K_f	50.7 N/A
R	2.1 Ω
τ	32 mm
L_d	41.4 mH
L_q	41.4 mH
Ψ_f	0.09 Wb

To verify the effectiveness of the proposed control scheme, three schemes of SMC, BTSMC and IBTSMC were used for experimental analysis. The sliding mode surface of the SMC is $s = \dot{e} + \lambda e = 0$ and the control law u_{SMC} is Eq. (48) [30]. The parameters are shown in Table II. The number of three-layer neurons is 2, 5, and 1, respectively.

$$u_{SMC} = B_n^{-1} \left[\ddot{d}_m - A_n \dot{d} + \lambda \dot{e} + \rho \text{sat} \left(\frac{s}{\phi} \right) \right] \quad (48)$$

During the experiments, the step signal and sinusoidal signal are input to the system for comparative analysis. The experimental conditions are as follows: ① Step signal with amplitude of 1mm, sudden non-periodic disturbance at 0.5s. ② Variable frequency sinusoidal signal with amplitude of 1mm.

Under condition ①, a non-periodic change disturbance close to the actual condition of the project is suddenly added. The maximum disturbance value is 50N, and its variable load disturbance curve is shown in Fig. 3. The system position tracking curves of the three control schemes are shown in Fig. 4. At the moment of motor start-up, a certain amount of overshoot appears in IBTSMC, indicating that its rapid

Table II Control parameters of three methods

Symbol	Parameters	Values
SMC	$\lambda, A_n, B_n, \phi, \rho$	55, -0.49, 3.09, 0.001, 5
BTSMC	$\lambda_1, \lambda_2, q, p, k_w, A_n, B_n, \phi$	98, 100, 5, 3, 300, -0.49, 3.09, 0.1
IBTSMC	$\lambda_1, \lambda_2, q, p, k_w, A_n, B_n, \phi, k_1, b_i, c_i$	98, 100, 5, 3, 300, -0.49, 3.09, 0.1, 60, 0.5, [-1, -0.5, 0, 0.5, 1]

Fig. 3 Variable disturbance curve for PMLSM

Fig. 4 Variable disturbance position tracking curves of SMC, BTSMC and IBTSMC

Fig. 5 Variable disturbance position error curves of SMC, BTSMC and IBTSMC

response performance is good. And quickly make the system state reach the equilibrium point, its convergence speed is faster than SMC and BTSMC. Then, in order to prove the robust performance of the system, three groups of experiments are suddenly disturbed by variable load at 0.5s. In 0.5s~1s period, as the load disturbance gradually increases, the SMC, BTSMC and IBTSMC position tracking curves begin to gradually deviate from the given position curve, but the degree of deviation of the IBTSMC position tracking curve is small; In 1s~1.5s period, the load increases to 50N and remains unchanged. During this period, the deviation of the position tracking curves under the three control schemes also reach their respective maximum extent. After that, as the load decreases, the position tracking curves under the three control schemes start to approach the given position curve, and maintain good tracking performance.

The variable disturbance position error curves of SMC, BTSMC and IBTSMC are shown in Fig. 5. Under the maximum disturbance, the maximum position error of SMC is about 13 μ m, the maximum position error of BTSMC is

Table III Error normalization

	SMC	BTSMC	IBTSMC
0-5s (Max error)	0.2	0.17	0.1
5-10s (Max error)	0.6	0.4	0.25
Range	0.4	0.23	0.15
Normalization	51.28%	29.49%	19.23%

about $11\mu\text{m}$, and the maximum position error of IBTSMC is about $6\mu\text{m}$.

Fig. 6 Tracking total errors using BTSMC and IBTSMC

It can be seen from the above analysis that the control performance of SMC is poor. In order to better illustrate the problem, we will only compare BTSMC and IBTSMC. The total tracking errors under the two control methods are shown in Fig. 6. In 0s-0.5s, the PMLSM starts operation without external disturbance, in which the total tracking error of the BTSMC is greater than that of the IBTSMC; In 0.5s-1.5s, although there are external disturbances, the total tracking errors of BTSMC and IBTSMC are far less than the total tracking errors of 0s-0.5s, and the total error of IBTSMC is about half of that of BTSMC, indicating that IBTSMC method has stronger robust performance; In 1.5s-2s, the system has stabilized and there is no external disturbance. At this time, the total error of IBTSMC is about 1/13 of the total error of BTSMC, indicating that the use of IBTSMC can further improve the tracking accuracy of the system.

Under condition ②, the system position tracking curves are shown in Fig. 7. From the figure, the SMC, BTSMC and IBTSMC can track the given position curve very well. In order to further compare the advantages and disadvantages of the three control schemes, the system position error curves are shown in Fig. 8. From the macro perspective, the position error of SMC is the largest, followed by the position error of BTSMC, and the position error of IBTSMC is the smallest. After 5s, increase the frequency of the signal, and through normalization processing, the variation range of the error before and after the SMC is obviously up to 51.28%, and the control performance is the worst. At the same time, the position error of IBTSMC has a small change of 19.23%, which shows that IBTSMC has the best control performance. Table III is error normalization.

5. Conclusion

In this paper, intelligent backstepping terminal sliding mode control (IBTSMC) has been proposed for PMLSM servo system with unknown factors. The introduction of the satu-

Fig. 7 Position tracking curves of SMC, BTSMC and IBTSMC **Fig. 8** Position error curves of SMC, BTSMC and IBTSMC

ration function with the boundary layer avoids the discontinuity of the switching control, weakens the chattering, and ensures the smoothness of the control input. To improve the robustness and tracking accuracy, the RBF neural network estimation algorithm is adopted to ensure the closed-loop stability when the uncertainties is unknown. Moreover, the stability and effectiveness of the controller have also been proved by the system experiments.

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