Adaptive Backstepping Nonsingular Terminal Sliding Mode Control of Servo System Based on New Sliding Mode and Reaching Law

Qixin Zhu (bob21cn@163.com)
Suzhou University of Science and Technology

Jiaqi Wang
Suzhou University of Science and Technology - Shihu Campus: Suzhou University of Science and Technology

Yonghong Zhu
Jingdezhen Ceramic Institute

Original Article

Keywords: Servo system, sliding mode control, backstopping control, adaptive control, reaching law

Posted Date: September 20th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-898493/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License
Adaptive Backstepping Nonsingular Terminal Sliding Mode Control of Servo System Based on New Sliding Mode and Reaching Law

Qixin Zhu\textsuperscript{1,2*}, Jiaqi Wang\textsuperscript{1}, Yonghong Zhu\textsuperscript{3}

1. School of Mechanical Engineering, Suzhou University of Science and Technology, Suzhou, 215009, China, Email:bob21cn@163.com
2. Key Laboratory of Intelligent Building Energy Efficiency, Suzhou University of Science and Technology, Suzhou, 215009, China
3. School of Mechanical and Electronic Engineering, Jingdezhen Ceramic Institute, Jingdezhen 333001, China

Abstract: Aiming at the problem that the control accuracy of permanent magnet synchronous motor (PMSM) servo system is easily affected by parameter uncertainty, an adaptive backstepping nonlinear nonsingular terminal sliding mode control (ABNNTSMC) method is proposed in this paper. Based on the existing fast nonsingular terminal sliding mode, a new piecewise nonlinear nonsingular terminal sliding mode is proposed to improve the convergence speed and ensure the steady-state accuracy. At the same time, a new reaching law with attenuation term is proposed to reduce the vibration gradually. Finally, the adaptive law is used to estimate the moment of inertia and viscous friction coefficient of the system to improve the robustness of the system. Simulation results show that ABNNTSMC has higher steady-state accuracy and smaller vibration compared with several existing results.

Keywords: Servo system, sliding mode control, backstepping control, adaptive control, reaching law

1 Introduction

Permanent magnet synchronous motor has the advantages of high-power density, high efficiency, high positioning accuracy, fast response speed, strong anti-interference ability and so on. Therefore, PMSM is widely used in electro-hydraulic servo system [1-3], industrial robot [4], military equipment [5], aerospace [6], CNC machine tools, XY axis platform and other high-precision automation equipment. But at the same time, due to the influence of load disturbance, parameter changes, friction [7,8] and other uncertain factors, the control accuracy and tracking performance of PMSM will decline. Therefore, it is necessary to design a strong robust controller to effectively suppress the uncertainty, so as to improve the control performance of the servo system.

Sliding mode control has the advantages of good transient performance, insensitivity to parameter...
changes and strong robustness to disturbances. The common sliding surfaces are linear sliding surface [9], integral sliding surface [10], fractional sliding surface [11] and terminal sliding surface. Among them, the biggest advantage of the terminal sliding surface is that it can strictly prove the convergence time of the sliding surface, which provides a mathematical guarantee for the parameter tuning of the sliding surface. Then, with the continuous improvement of many scholars, the singular point problem of terminal sliding surface after derivation is solved, and further developed to fast nonsingular terminal sliding surface [12-14].

Besides the improvement of sliding mode surface, reaching law is also an important part of sliding mode control design. The design of reaching law not only determines the speed of the servo system converging to the sliding surface, but also affects the chattering. Reference [6] showed that a new reaching law combines exponential reaching law and power reaching law, which synthesizes the advantages of the two reaching laws. But these reaching laws all have a common problem, that is, the value is only related to s, so that the amplitude of buffeting does not decrease with the decrease of state error. Therefore, the reaching law with attenuation term has become an important research direction in recent years. Reference [15] showed that an improved adaptive variable rating exponential reaching law is proposed, which can shorten the time to reach the equilibrium point and reduce the chattering at the same time.

The advantage of backstepping control is that it can effectively deal with the nonlinear control problem of the system, adjust fewer parameters, and is easy to realize in engineering. Therefore, backstepping control has been widely valued by academia. Reference [16] showed that an adaptive backstepping control for nonlinear switched systems is proposed based on equivalent mapping. Reference [17] showed that the backstepping control is further combined with the recurrent Hermite polynomial neural network to provide adaptive error estimation for nonlinear backstepping control. Finally, sliding mode control is combined with backstepping control in many literatures. References [1,2] showed that adaptive sliding mode backstepping control is introduced to electro-hydraulic servo system, which overcomes the nonlinear problem in complex system. Reference [18] showed that adaptive radial basis function network based on sliding mode backstepping controller is introduced, which can overcome the uncertainty of the system.

Among the uncertainties of the system, the moment of inertia and viscous friction coefficient are
the key factors to determine the control performance of the system. Among the traditional parameter identification methods, the common ones are sine signal integration method [19,20], steady-state direct method [21,22], least square method with forgetting factor [23]. There is a significant problem in these methods, that is, they need to have specific conditions for speed and load torque. However, it is impossible for the system to keep in a specific motion condition all the time, so the adaptive identification algorithm will have more advantages. Reference [24] showed that genetic algorithm is used to optimize adaptive parameters to estimate unknown disturbances in perturbed systems. On the basis of backstepping control, Lyapunov function method is used to design adaptive estimation of load variables [25,26]. Therefore, the adaptive algorithm is introduced into the identification of moment of inertia and viscous friction coefficient to ensure that the estimated value can track the actual value in real time.

The contribution of this paper is that based on the traditional nonsingular terminal sliding surface, a nonsingular terminal sliding surface with nonlinear switching term is proposed. The sliding surface can ensure faster speed at start-up and higher steady-state accuracy when the response curve is close to the given signal. Then a reaching law with attenuation term is designed, which can further reduce the chattering as the error decreases. Finally, this paper combines sliding mode control with backstepping control, and introduces an adaptive identification algorithm for moment of inertia and viscous friction coefficient to enhance the robustness of the control system.

2 Design of sliding mode controller for PMSM

The derivation of sliding mode control algorithm is based on the mathematical model of permanent magnet synchronous motor [26]. The d-q models of motor in synchronous rotating coordinate system are expressed as follows:

\[
\begin{align*}
\dot{\theta} &= \omega \\
\dot{\theta} &= \frac{3P_n \Phi_f}{2J} i_q - \frac{B}{J} \omega \\
i_d &= -\frac{R}{L} i_d + P_n \omega i_q + \frac{1}{L} u_d \\
i_q &= -\frac{R}{L} i_q - P_n \omega i_d + \frac{1}{L} u_q - \frac{P_n \Phi_f}{L} \omega
\end{align*}
\]

(1)

where, \( \theta \) is the rotation angle, \( \omega \) is the rotation speed, \( P_n \) is the pole pair number, \( \Phi_f \) is
the permanent magnetic flux, \( J \) is the moment of inertia, \( B \) is the coefficient of viscosity, \( R \) is the stator resistance, \( L \) is the stator inductance, \( i_d, i_q \) is the d-q axis stator current, \( u_d, u_q \) is d-q axis stator voltage.

Based on the above mathematical model, the step input signal is defined as \( \theta_d \) firstly, then the tracking error \( e \) and the differential of tracking error \( \dot{e} \) are defined as follows:

\[
e = \theta_d - \theta
\]
\[
\dot{e} = \dot{\theta}_d - \dot{\theta} = -\omega
\]

Reference [14] defined a nonsingular terminal sliding mode as follow:

\[
s_1 = e + k_1 |e|^{\alpha} \text{sgn}(e) + k_2 |e|^{\beta} \text{sgn}(\dot{e})
\]

where, \( k_1, k_2 \) are positive constants, \( 1 < \beta < 2, \alpha > \beta \), \( \text{sgn}(\cdot) \) is the signum function.

This sliding mode has high convergence rate and can guarantee the convergence in finite time. However, when the system state is close to the equilibrium state, the convergence rate will decrease and the convergence accuracy is insufficient. In this paper, the sliding mode is improved as follow:

\[
s_2 = ce + \dot{e} + k_1 |e|^{\alpha} \text{sgn}(e) + k_2 |e|^{\beta} \text{sgn}(\dot{e})
\]

where, \( c \) is the coefficient of linear part of sliding mode, \( c > 0 \).

The comparison of the response curves of the two sliding modes is shown in Fig. 1:

![Comparison of two sliding modes](image)

**Fig. 1** Comparison of two sliding modes

It can be seen from Fig. 1 that the rising speed of \( s_1 \) is faster than that of \( s_2 \), but the convergence accuracy of \( s_2 \) is higher than that of \( s_1 \). Therefore, a new nonlinear switching sliding mode is proposed by combining the two sliding modes. When the error is large and the system state is
far away from the equilibrium state, the \( s_1 \) is adopted; when the error is small and the system state is close to the equilibrium state, \( s_2 \) is adopted.

\[
s = \begin{cases} 
  e + k_{11} |\dot{e}|^{\alpha} \text{sgn}(e) + k_{21} |\dot{\dot{e}}|^{\beta} \text{sgn}(\dot{e}), & |e| > \delta \\
  ce + \dot{e} + k_{12} |\dot{e}|^{\alpha} \text{sgn}(e) + k_{22} |\dot{\dot{e}}|^{\beta} \text{sgn}(\dot{e}), & |e| \leq \delta 
\end{cases}
\]  

(6)

where, \( \delta \) is the error threshold of sliding mode switching.

After the sliding mode is designed, a new reaching law is improved based on the reaching law in Ref. [14] as follows,

\[
\dot{s} = -ks - f(s)\left[ \xi |\dot{e}| s + \eta \text{sat}(s) \right] 
\]  

(7)

\[
f(s) = \left( \frac{2}{1 + \exp(-as)} - 1 \right)
\]  

(8)

where, \( k > 0 \), \( \xi > 0 \), \( \eta > 0 \), \( a > 0 \). In the reaching law, \( -ks \) can accelerate the reaching speed when the system state is far away from the sliding mode, and reduce the reaching speed when the system state is close to the sliding mode. When the system is in the start-up phase, \( |\dot{e}| \) is larger; When the system response is close to the given signal, the error \( e \) and \( |\dot{e}| \) are smaller. Therefore, the \( \xi |\dot{e}| s \) can ensure that the system has a larger reaching speed when it starts up. And when the system is close to the given signal, the \( \xi |\dot{e}| s \) can quickly reduce the reaching speed, so as to reduce the vibration. In order to further reduce the vibration caused by \( \xi |\dot{e}| s \) and \( \eta \text{sat}(s) \) after the system state reaches the sliding mode, a nonlinear function \( f(s) \) is multiplied before the two terms. When the system state is far away from the sliding mode, \( f(s) \) approaches to 1; when the system state reaches the sliding mode, \( f(s) \) approaches to 0, so vibration can be reduced.

After the reaching law is designed, the derivative of \( S \) is obtained and the saturation function \( \text{sat}(\cdot) \) is used to replace \( \text{sgn}(\cdot) \). According to Eq. (7), the first step of control laws is designed as follows,

\[
\dot{s} = \begin{cases} 
  \dot{e} + k_1 \dot{e} \alpha |\dot{e}|^{\alpha-1} + k_2 \dot{\dot{e}} \beta |\dot{\dot{e}}|^{\beta-1}, & |e| > \delta \\
  c\dot{e} + \dot{e} + k_1 \dot{\dot{e}} \alpha |\dot{e}|^{\alpha-1} + k_2 \dot{\dot{e}} \beta |\dot{\dot{e}}|^{\beta-1}, & |e| \leq \delta 
\end{cases}
\]  

(9)
\[
\begin{aligned}
\hat{e} &= \begin{cases} 
-k_s - f(s)[\xi |\epsilon| s + \eta \text{sat}(s)] - \dot{\epsilon} - k_{i_1} \dot{\epsilon} \alpha |\epsilon|^{\alpha-1}, & |\epsilon| > \delta \\
-k_s - f(s)[\xi |\epsilon| s + \eta \text{sat}(s)] - c \epsilon - k_{i_2} \epsilon \alpha |\epsilon|^{\alpha-1}, & |\epsilon| \leq \delta
\end{cases} 
\end{aligned}
\] (10)

According to Eq. (1) and Eq. (3), \( \dot{\omega} \) and \( i_q^* \) can be concluded as follows,

\[
\omega = \frac{3P_n \Phi_f}{2J} i_q - \frac{B}{J} \omega = -\dot{\epsilon}
\] (11)

\[
i_q^* = -\frac{2J}{3P_n \Phi_f} \dot{\epsilon} + \frac{2B}{3P_n \Phi_f} \omega
\] (12)

3 Design of adaptive backstepping controller

Backstepping controller is designed by introducing virtual state and virtual control function to ensure that the actual control quantity of each subsystem can approach the ideal control quantity, so as to achieve the purpose of system stability. According to Eq. (12), the current errors of d-q axis are defined as follows,

\[
e_q = i_q^* - i_q, e_d = i_d^* - i_d
\] (13)

The Lyapunov function \( V_1 \) and the derivative of \( V_1 \) are defined as follows,

\[
V_1 = \frac{1}{2} s^2 + \frac{1}{2} e_q^2 + \frac{1}{2} e_d^2
\] (14)

\[
\dot{V}_1 = s\dot{s} + \dot{e}_q e_q + \dot{e}_d e_d = s\dot{s} - k_1 e_q^2 - k_2 e_d^2 < 0
\] (15)

where, \( k_1 \), \( k_2 \) are positive constants.

According to Eq. (1) and Eq. (12), \( u_q \) and \( u_d \) can be concluded as follows,

\[
\begin{aligned}
u_q &= -\frac{2L}{3P_n \Phi_f} J \cdot \ddot{\epsilon} + \frac{2L}{3P_n \Phi_f} B \dot{\omega} + R_i q + P_n \omega L i_d + P_n \Phi_f \omega + k_q^2 \omega e_q \\
u_d &= R_i d - P_n \omega L i_q + k_d^2 \omega e_d
\end{aligned}
\] (16)

In practical application, the uncertainty of system parameters will have an important impact on the control effect. In particular, the moment of inertia and friction viscosity coefficient will inevitably change in the long-term work. Therefore, this paper uses the adaptive algorithm to estimate the moment
of inertia and viscous friction coefficient, and estimates $J$ and $B$ with $\hat{J}$ and $\hat{B}$, to provide accurate parameters for the control variables. At this time, the control quantity $u_q$ is as follows,

$$u_q = -\frac{2L}{3P_n\Phi_f} j \cdot \dot{e} + \frac{2L}{3P_n\Phi_f} \dot{\hat{B}} \omega + R_i + P_n \omega L_i + P_n \Phi_f \omega + k_f^2 L_e$$  \quad (17)$$

Errors of estimate $\hat{J}$ and $\hat{B}$ are defined as follows,

$$\hat{J} = J - \hat{J}, \hat{B} = B - \hat{B}$$  \quad (18)$$

Adaptive laws of $\hat{J}$ and $\hat{B}$ are defined as follows,

$$\begin{cases}
\dot{\hat{J}} = -\frac{2\mu_1}{3P_n\Phi_f} \ddot{e}_q \\
\dot{\hat{B}} = -\frac{2\mu_2}{3P_n\Phi_f} \omega \dot{e}_q
\end{cases}$$  \quad (19)$$

where, $\mu_1$, $\mu_2$ are positive constants.

The Lyapunov function $V_2$ is defined as follows,

$$V_2 = V_1 + \frac{1}{2\mu_1} \hat{J}^2 + \frac{1}{2\mu_2} \hat{B}^2$$  \quad (20)$$

Then, the result of the derivative of $V_2$ is as follows,

$$\begin{align*}
\dot{V}_2 &= ss - k_q^2 e_q^2 - k_e^2 e_d^2 - \frac{2}{3P_n\Phi_f} \ddot{e}_q (J - \hat{J}) + \frac{2}{3P_n\Phi_f} \omega \dot{e}_q (B - \hat{B}) - \frac{1}{\mu_1} \hat{J} + \frac{1}{\mu_2} \hat{B} \\
\dot{V}_2 &= ss - k_q^2 e_q^2 - k_e^2 e_d^2 - \left(\frac{2}{3P_n\Phi_f} \ddot{e}_q + \frac{1}{\mu_1} \hat{J}\right) \hat{J} + \left(\frac{2}{3P_n\Phi_f} \omega \dot{e}_q - \frac{1}{\mu_2} \hat{B}\right) \hat{B} \\
\dot{V}_2 &= ss - k_q^2 e_q^2 - k_e^2 e_d^2 < 0
\end{align*}$$  \quad (21)$$

According to Lyapunov stability theorem, the estimated value of system parameters will converge asymptotically, and the state of the system will converge to sliding mode surface. That is, even if the motor parameters are uncertain due to long-term operation, the state of the system can still ensure stable convergence and has strong robustness.

4 Simulations

The simulation model in this paper borrows the parameter data in Ref. [26], as shown in Table 1:
According to the parameters in Table 1, the simulation model is built, as shown in Fig. 2:

### Table 1 Model parameters and controller parameters

| Parameters                              | Value             |
|-----------------------------------------|-------------------|
| Inertia \( (kgm^2) \)                  | \( J = 0.001 \)   |
| Viscosity coefficient \( (Ns/m) \)     | \( B = 0.0001 \)  |
| Stator resistance \( (\Omega) \)       | \( R = 2 \)      |
| Stator inductance \( (mH) \)           | \( L = 6 \)      |
| Pole pair                               | \( p_s = 4 \)    |
| Permanent magnetic flux \( (Wb) \)     | \( \Phi_p = 0.8 \) |
| Parameter of sliding mode \( k_{11} \) | \( 600 \)   |
| Parameter of sliding mode \( k_{21} \) | \( 0.1 \)   |
| Parameter of sliding mode \( \alpha \) | \( 2 \)   |
| Parameter of sliding mode \( \beta \)  | \( 5/3 \)  |
| Parameter of sliding mode \( c \)      | \( 500 \)   |
| Parameter of sliding mode \( k_{12} \) | \( 10 \)   |
| Parameter of sliding mode \( k_{22} \) | \( 0.03 \) |
| Parameter of reaching law \( k \)      | \( 200 \) |
| Parameter of reaching law \( \xi \)    | \( 10 \) |
| Parameter of reaching law \( \eta \)   | \( 0.1 \) |
| Parameter of reaching law \( a \)      | \( 10 \) |
| Error threshold of sliding mode switching | \( \delta = 0.001 \) |
| Parameter of backstepping controller   | \( k_y = k_z = 100 \) |
| Parameter of adaptive controller       | \( \mu_1 = \mu_2 = 100 \) |

The simulation time is set as 0.3 s, and the input signal is step signal. The ABNNTSMC proposed in this paper is compared with the adaptive nonsingular fast terminal sliding mode control (ANFTSMC)
[14], adaptive linear sliding mode control (ALSMC) [5] and global sliding mode control (GSMC) [10].

The simulation results are shown in Fig. 3-Fig. 7.

Fig. 3  Comparison diagram of angle response tracking curve

(a)  Comparison of all position response tracking curves

(b)  Comparison of tracking curves of nonsingular terminal sliding mode angle response

Fig. 4  Comparison diagram of local amplification of angle response tracking curve
Fig. 5  Comparison diagram of angular velocity response curves

Fig. 6  Comparison diagram of approaching effect of sliding mode

(a)  Vibration diagram of ABNTTSMC
The comparison of simulation data of various sliding mode control is shown in Table 2:

|      | Tracking time | Maximum tracking speed | Arrival time of sliding surface | Vibration                                |
|------|---------------|------------------------|---------------------------------|------------------------------------------|
| ABNNTSMC | 0.008s       | 769.2rad/s             | 0.005s                          | The frequency is low and the amplitude decreases gradually |
| ANFTSMC  | 0.06s         | 66.9rad/s              | 0.06s                           | No improvement                           |
| ALSMC   | 0.08s         | 25.6rad/s              | 0.12s                           | The frequency is high                    |
| GSMC    | 0.1s          | 32.2rad/s              | 0.002s                          | The frequency is high and the amplitude decreases slightly |

It can be seen from Fig. 3 that ABNNTSMC has the strongest tracking performance, and it can track the input signal in 0.008s. And there is no overshoot at all because ABNNTSMC will switch to the sliding mode surface with smaller steady-state accuracy when it is close to the stable state. However,
the tracking performance of the other three methods is worse than ABNNTSMC, and GSMC has obvious overshoot. Therefore, ABNNTSMC is the best in tracking performance.

It can be seen from Fig. (a) of Fig. 4 that ABNNTSMC and ANFTSMC have the highest steady-state accuracy. Both ALSMC and GSMC have obvious vibration, which indicates that their steady-state accuracy is insufficient. It can be seen from Fig. (b) that ABNNTSMC and ANFTSMC can reach the steady-state accuracy of $10^{-4}$ within 0.1s, but the convergence accuracy of ABNNTSMC is higher than that of ANFTSMC. This shows that ABNNTSMC has the highest steady-state accuracy.

It can be seen from Fig. 5 that ABNNTSMC has the maximum rising speed, which can reach 769.2 rad/s. Moreover, when ABNNTSMC completes the tracking of the input signal, the speed can quickly drop to 0 rad/s, and the state is very stable. However, the rising speed of the other three methods is too slow, so it takes a longer time to complete the tracking of the input signal, resulting in response lag. This shows that ABNNTSMC can not only achieve high tracking speed, but also stabilize rapidly after tracking.

It can be seen from Fig. 6 that the GSMC belongs to the integral sliding surface, so the system state is on the sliding surface from the beginning. In addition to the other three kinds of sliding mode control, ABNNTSMC only needs 0.005s to reach the sliding mode surface without overshoot. ANFTSMC can also approach the sliding mode surface at 0.06s, but the later approaching speed is too slow. Although ALSMC has a fast approaching speed, it has serious overshoot and does not meet the requirements of high precision. This shows that ABNNTSMC has a fast approaching speed, and there is no overshoot. The reaching law proposed in this paper can meet the higher tracking requirements.

It can be seen from Fig. (a) of Fig. 7 that the vibration frequency of ABNNTSMC is very low, and the vibration amplitude is gradually decreasing, from $10^{-6}$ to $10^{-8}$, and then to lower. It can be seen from Fig. (b) and Fig. (c) that the vibration frequencies of ALSMC and GSMC are very large, and their amplitudes are not decreased. This shows that the reaching law proposed by ABNNTSMC has obvious effect in suppressing vibration.

5 Conclusion

For PMSM servo system, in order to improve the previous sliding mode control design, an adaptive backstepping nonlinear nonsingular terminal sliding mode control (ABNNTSMC) is proposed.
The sliding mode is designed by switching two sliding modes. When the error is large, the sliding mode with faster speed is used. When the system is close to the stable state, the sliding mode with higher steady-state accuracy is switched. This sliding mode can not only accelerate the convergence speed, but also ensure higher steady-state accuracy. Then a new reaching law is designed, which can reach the sliding mode faster and suppress vibration gradually. Finally, the adaptive backstepping control for moment of inertia and viscous friction coefficient is designed to further enhance the robustness in the case of parameter uncertainty. The simulation results show that the proposed method is feasible and practical.

Acknowledgement
Not applicable.

Availability of data and materials
Not applicable.

Competing interests
The authors declare no competing financial interests.

Funding
This work is partially supported by National Nature Science Foundation of China under Grant Nos.51875380 and 62063010.

Authors' contributions
QZ and JW were in charge of the controller design; QZ and JW wrote the manuscript. JW and YZ undertook simulation analysis and data processing. All authors read and approved the final manuscript.

References
[1] Tran, Duc Thien Ba, Dang Xuan Ahn, Kyoung Kwan, 2020, “Adaptive Backstepping Sliding Mode Control for Equilibrium Position Tracking of an Electrohydraulic Elastic Manipulator,” IEEE Transactions on Industrial Electronics, 67(5), pp. 3860-3869.
[2] Bui Lap Hien, Ha Thi Hoai Thu, Vo Quang Vinh, 2020, “Dynamic Surface Control Associates Adapting External Torque Algorithm for Electro-hydraulic Velocity Servo System,” International Organization of Scientific Research, 10(5), pp. 1-7.
[3] Xiangjian Chen, Di Li, Xibei Yang, Yuecheng Yu, 2018, “Identification Recurrent Type 2 Fuzzy
Wavelet Neural Network and L2-gain Adaptive Variable Sliding Mode Robust Control of Electro-hydraulic Servo System (EHSS),” Asian Journal of Control: Affiliated with ACPA, the Asian Control Professors’ Association, 20(4), pp. 1480-1490.

[4] Xin Huang, Yi Wan, Yao Sun, Jiarui Hou, 2020, “Indirect Adaptive Fuzzy Sliding-Mode Control for Hydraulic Manipulators,” Proceedings of International Conference on Mechanical Design, Oct. 01, pp. 229-242.

[5] Shoucheng Nie, Linfang Qian, Lingfei Tian, Quan Zou, 2018, “Adaptive Sliding Mode Control for Electro-hydraulic Position Servo System of the Elevation-balancing Machine of Artillery Platform,” Proceedings of IEEE Information Technology and Mechatronics Engineering Conference, Dec. 14, pp. 731-735.

[6] Xiaofei Zhang, Hongbin Ma, Zhuang Li, Wenchao Zhao, 2018, “An Adaptive Sliding Mode Controller with The Exponential and Power Reaching Law for Discrete Systems,” Proceedings of Chinese Control Conference, Jul. 25, pp. 2711-2716.

[7] Chengguang Wang, Haibo Zhao, 2017, “Backstepping Adaptive Fuzzy Control of Servo System with LuGre Friction,” MATEC Web of Conferences, 104, pp. 1-9.

[8] Fengfa Yue, Xingfei Li, 2018, “Robust Adaptive Integral Backstepping Control for Opto-electronic Tracking System Based on Modified LuGre Friction Model,” ISA Transactions, 80, pp. 312-321.

[9] Morawiec Marcin, Lewicki, Arkadiusz, Wilczynski, Filip, 2021, “Speed Observer of Induction Machine Based on Backstepping and Sliding Mode for Low-speed Operation,” Asian Journal of Control: Affiliated with ACPA, the Asian Control Professors Association, 23(2), pp. 636-647.

[10] Yao Xin, Xin Ping, 2018, “Global Robustness of Sliding Mode Control for Servo Systems,” Proceedings of Chinese Control and Decision Conference, Jun. 09, pp. 667-671.

[11] Yuanlong Xie, Xiaolong Zhang, Wei Meng, et al., 2021 “Coupled Fractional-order Sliding Mode Control and Obstacle Avoidance of A Four-wheeled Steerable Mobile Robot,” ISA Transactions, 108, pp. 282-294.

[12] Wule Zhu, Xu Yang, Fang Duan, Zhiwei Zhu, Bingfeng Ju, 2019, “Design and Adaptive Terminal Sliding Mode Control of a Fast Tool Servo System for Diamond Machining of Freeform Surfaces,” IEEE Transactions on Industrial Electronics, 66(6), pp. 4912-4922.
[13] Dongxue Fu, Ximei Zhao, 2020, “Adaptive Backstepping Global Fast Terminal Sliding Mode Control for Permanent Magnet Linear Synchronous Motor,” Transactions of China Electrotechnical Society, 35(8), pp. 1634-1641 (in Chinese).

[14] Dongxue Fu, Ximei Zhao, 2020, “Adaptive Nonsingular Fast Terminal Sliding Mode Control for Permanent Magnet Linear Synchronous Motor,” Transactions of China Electrotechnical Society, 35(4), pp. 717-723 (in Chinese).

[15] Yongdong Cheng, Jun Jiang, 2019, “Study on Control Strategies for an Antenna Servo System on a Carrier under Large Disturbance,” Transactions of the Institute of Measurement and Control, 41(9), pp. 2545-2554.

[16] Nguyen Truong Thanh, Pham Ngoc Sam, Dao Phuong Nam, 2019, “An Adaptive Backstepping Control for Switched Systems in Presence of Control Input Constraint,” Proceedings of International Conference on System Science and Engineering, pp. 196-200.

[17] Jungchu Ting, Derfa Chen, 2018, “Nonlinear Backstepping Control of SynRM Drive Systems Using Reformed Recurrent Hermite Polynomial Neural Networks with Adaptive Law and Error Estimated Law,” Journal of Power Electronics: A Publications of the Korean Institute of Power Electronics, 18(5), pp. 1380-1397.

[18] Zhixiang Chen, Qinhe Gao, Lilong Tan, 2018, “Adaptive Backstepping Sliding-mode Control for Permanent Magnet Linear Synchronous Motors,” Proceedings of Chinese Control Conference, Jul. 25, pp. 2690-2693.

[19] Yoo Min-Sik, Choi Seung-Cheol, Park Sang-Woo, Yoon Young-Doo, 2020, “Identification of Mechanical Parameters for Position-controlled Servo Systems Using Sinusoidal Commands,” Journal of Power Electronics: A Publications of the Korean Institute of Power Electronics, 20(6), pp. 1478-1487.

[20] Sungmin Kim, 2019, “Moment of Inertia and Friction Torque Coefficient Identification in a Servo Drive System,” IEEE Transactions on Industrial Electronics, 66(1), pp. 60-70.

[21] Chuanqiang Lian, Fei Xiao, Shan Gao, Jilong Liu, 2019, “Load Torque and Moment of Inertia Identification for Permanent Magnet Synchronous Motor Drives Based on Sliding Mode Observer,” IEEE Transactions on Power Electronics, 34(6), pp. 5675-5683.

[22] Lin Faa-Jeng, Chen Shih-Gang, Li Shuai, Chou Hsiao-Tse, Lin Jyun-Ru, 2020, “Online
Auto-Tuning Technique for IPMSM Servo Drive by Intelligent Identification of Moment of Inertia,” IEEE Transactions on Industrial Informatics, 16(12), pp. 7579-7590.

[23] F Liu, E Kang, N Cui, 2020, “Single-Loop Model Prediction Control of PMSM with Moment of Inertia Identification,” IEEJ Transactions on Electrical and Electronic Engineering, 15(4), pp. 577-583.

[24] Leiming Jiao, Yanhong Luo, Pengqiao Zhang, Linlin Li, Xiangtian Zheng, Ge Qi, Hong Jia, Hengyu Liu, 2017, “Design of the Self-Adaptive Sliding Mode Position Controller Based on Genetic Algorithm Optimization for the Servo Motor Drive System,” Proceedings of IEEE Information Technology and Mechatronics Engineering Conference, Oct. 03, pp. 812-825.

[25] Ximei Zhao, Tianhe Wang, Hongyan Jin, 2020, “Intelligent Second-order Sliding Mode Control for Permanent Magnet Linear Synchronous Motor Servo Systems with Robust Compensator,” IET Electric Power Applications, 14(9), pp. 1661-1671.

[26] Taihang Du, Chao Long, Chunhong Jiang, Jingyu Wang, 2018, “Adaptive Backstepping Control of Servo System Based on Load Estimation,” Electric Drive, 48(5), pp. 49-52(in Chinese).