Adaptive backstepping complementary sliding mode control with parameter estimation and dead-zone modification for PMLSM servo system

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Abstract
An adaptive backstepping complementary sliding mode control (ABCSMC) with dead-zone parameter modification applicable to the permanent magnet linear synchronous motor is proposed in order to achieve high-performance servo control fields. On the theoretical foundation of backstepping control and sliding mode control, a strong robust controller, ABCSMC is designed to compensate the uncertainties such as parameter variations and external disturbances occurring in the system. Additionally, an adaptive saturation function is utilized in ABCSMC to avoid the difficulty of parameter selections, so that the optimal parameters can be tuned by the adaptive laws in real time. Moreover, in order to avoid the parameter-drift phenomenon of the adaptive laws, dead-zone parameter modification is hereby proposed by setting a performance threshold to solve the overtraining problem. Finally, the stability of the system is proved through Lyapunov theorem and Barbalat’s lemma. To investigate the capabilities of the proposed scheme, an experimental platform based on digital signal processor is implemented. The comparison results demonstrate that the proposed controller is capable of achieving higher tracking performance and stronger robustness to uncertainties with respect to parameter variations and external disturbances.

1 | INTRODUCTION

As demands increase for the servo control fields, the permanent magnet linear synchronous motors (PMLSMs), which have many advantageous characteristics such as high reliability, low costs and simpler structure, have been increasingly applied to precision applications [1, 2]. However, owing to the elimination of mechanical transmission components, the performance of the PMLSM is more vulnerable to the influences of parameter variations, external disturbances and various uncertain electromechanical phenomena compared to rotary motors [3, 4]. Therefore, it is imperative to design controllers which are robust to the uncertainties for improving the performance of the PMLSM servo system.

Considering the adverse effects caused by the inaccurate modelling of PMLSM servo system including uncertainties, various non-linear control strategies have received increasing attention in recent years, such as neural network control [5, 6], fuzzy logic control [7] and fuzzy neural network control schemes [8, 9]. The common feature of these methods is to estimate the uncertainty of the system, thereby eliminating restrictions on the uncertain non-linear functions. Although the system achieves better control performance by adopting the above control methods, the design of these intelligent controllers and the selections of parameters increase the complexity of the operability [10].

During the past decades, sliding mode control (SMC) has been developed, which has led to significant performance improvement in the control of PMLSM due to its strong robustness [11]. However, it should be noted that SMC can be applied to the system when all uncertainties are bounded, and the most notable disadvantage of SMC lies in the chattering phenomenon [12]. Therefore, in practical applications, the most critical handicaps of applying SMC must be overcome [13]. In [14, 15], SMC...
with the adaptive switching gain and the fuzzy switching gain applied to the designed system, though the dynamic response performance is improved, the robustness becomes worse. In
### TABLE 1  Main parameters of the PMLSM

| Parameters and units                  | Value  |
|--------------------------------------|--------|
| Resistance $R_s$ (Ω)                 | 2.1    |
| Magnet flux $\Psi_f$ (Wb)            | 0.09   |
| Inductance $L_d/L_q$ (mH)            | 41.4   |
| Pole pitch $\tau$ (mm)               | 32     |
| Number of pole pairs $p_v$           | 3      |
| Thrust coefficient $K_f$ (N/A)       | 50.7   |
| Mover mass $M$ (kg)                  | 16.4   |
| Viscous friction coefficient $B$ (N·s/m) | 8.0    |

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In addition, owing to the robust control performance and easy-to-be implemented nature, backstepping control (BC) has achieved closed attention [21]. However, the exact system dynamics must be known in advance in BC methods. Therefore, adaptive, intelligent and hybrid BC schemes are proposed during the past decades. In [22], an adaptive backstepping control (ABC) method is proposed to obtain the adaptiveness and robustness of the system. Moreover, the adaptive backstepping sliding mode control (ABSMC) methods combining the merits of SMC and ABC are reported in [23, 24]. By utilizing these composite approaches, the better performance of the system is achieved with respect to the parameter perturbations and external disturbances.

In view of the analysis above, an adaptive backstepping complementary sliding mode control (ABCSMC) with parameter estimation and dead-zone modification is proposed to confront the uncertainties for a surface-mounted PMLSM. First, the electrical and the mechanical dynamics of PMLSM including uncertainties are established. Then, ABCSMC with an adaptive saturation function is developed to suppress the uncertainties of the system so as to achieve high tracking accuracy and strong robustness. The on-line parameter adapting laws, which are derived using the Lyapunov stability theorem and Barbalat's lemma, are used to adjust the parameters in real time. Next, in order to overcome the overtraining problem of the adaptive
laws, a dead-zone parameter modification (DPM) method with a performance threshold is proposed for the parameter tuning processes. Finally, the effectiveness of the proposed method is verified by implementing on DSP. Experimental results demonstrate that the superior performance of the proposed control scheme compared to ABC [16], CSMC [22] and ABSMC [23] is achieved.

2 DESCRIPTION AND MODELLING OF PMLSM

In order to establish a more accurate modelling, the electrical and the mechanical dynamics are considered respectively. In the synchronous reference frame, the voltage equation and the flux equation are described as

\[
\begin{align*}
\psi_d &= L_{d1}i_d + \psi_d - \pi \nu \psi_q / \tau, \\
\psi_q &= L_{q1}i_q + \psi_q - \pi \nu \psi_d / \tau, \\
\psi_f &= L_{f1}i_f, \\
\psi &= L_{q1}i_q, \\
\end{align*}
\]

where \(u_d\), \(u_q\), \(i_d\), \(i_q\), \(\psi_d\), \(\psi_q\), \(L_{d1}\), \(L_{q1}\) represent the voltage, current, inductance and flux of \(d\)-axis and \(q\)-axis, \(R\) is the resistance, \(v\) is the linear velocity of the mover, \(\tau\) is the pole pitch. In the surface-mounted PMLSM, \(L_{d1}=L_{q1}\), \(i_f=I_f\) are defined as constants.

The developed electromagnetic thrust is expressed as

\[
Fe = \frac{3\pi}{2\tau} p_n \left[ \psi_f i_q + (L_{d1} - L_{q1}) i_d i_q \right],
\]

where \(F_e\) is the electromagnetic thrust, \(p_n\) is the number of pole pairs. Because \(L_{d1}=L_{q1}\) in the surface-mounted PMLSM, \(F_e\) can be simplified as

\[
F_e = K_f i_q,
\]

where \(K_f\) is the thrust coefficient.

The mover dynamic equation of the PMLSM using the electromagnetic thrust shown in (6) can be denoted as

\[
M \ddot{v} = F_e - Bv - F_S,
\]
Experimental results of PMLSM servo systems using ABC-SMC with DPM when $S_{th} = 0.5$ in case 1: (a) Position response, (b) tracking error, and (c) control signal

\[ i = -Bv/M + K_r/q_v M - F_{Σ}/M, \]  

where $M$ is the nominal mass of the mover, $B$ is the viscous friction coefficient, $F_{Σ}$ is the lumped uncertainty including parameter variation (mass variation) and external disturbance and is defined as $F_{Σ} = (M_a - M)v + F_L$, where $M_a$ is the actual mass of the mover. Besides, it is assumed that $F_{Σ}$ is constant (but unknown) within a sampling interval.

### 3 PROPOSED CONTROL SYSTEM

Since the PMLSM servo system is usually vulnerable to the time-varying uncertainties, the designed controllers must be robust enough. Therefore, a strong robust controller combining both the merits of ABC and CSMC is employed. First, ABC-SMC with parameter estimation is designed to reduce chattering and improve the robustness. Subsequently, DPM is applied to avoid the parameters-drift phenomenon for the parameter tuning process. Finally, the stability of the system is proved through Lyapunov theorem and Barbalat’s lemma. The overall configuration of the proposed control scheme for the PMLSM servo system is depicted in Figure 1.

#### 3.1 ABC-SMC design

The dynamics of the PMLSM servo system are highly time-varying and non-linear, it is better to suppress the lumped of uncertainty to achieve the superior control performance. Consequently, the control object is to design a control law so that the mover of PMLSM can track different reference trajectories closely. To simplify the controller design, the position tracking error of the mover is defined as

\[ \epsilon_1 = d^* - d, \]
where $d^*$ is the reference position trajectory, $d$ is the position of the mover, and $d = \dot{r}$, $e_1$ is the position tracking error.

Backstepping control is an effective systematic and recursive design tool for the nonlinear system. The most appealing point of BC is to use the virtual control variable to make the system simple; thus, the final control outputs can be derived step by step. Consequently, a virtual variable $\bar{r}$ is chosen to stabilize the position tracking error, which can be chosen as

$$\dot{r} = \dot{d}^* + k_1 e_1 = \dot{d}^* + k_1 e_1,$$

where $\bar{r}$ is the virtual velocity, $k_1$ is a positive constant. According to the virtual velocity, the virtual velocity tracking error is defined as

$$e_2 = \bar{r} - r.$$  \hspace{1cm} (13)

where $e_2$ is the virtual velocity tracking error. By using (12) and (13), and differentiating $e_1$ with respect to time, the following equation is obtained:

$$\dot{e}_1 = \dot{d}^* - \dot{r} = \dot{d}^* - v
= \dot{r} - k_1 e_1 - v = e_2 - k_1 e_1.$$  \hspace{1cm} (14)

The following equation can be obtained by using (10) and (12)–(14):

$$\dot{e}_2 = \frac{1}{M} \left[ -F_i + (\bar{r} - e_2) B + F_\Sigma + M \dot{r} \right]
= -B e_2 + \frac{1}{M} \left[ -F_i + M \dot{r} + \bar{r} (B - \bar{B}) + (\bar{F}_\Sigma - F_\Sigma) \right].$$  \hspace{1cm} (15)

In PMLSM servo system, the time-varying parameters have a certain impact on the control performance of the system. Therefore, in the design of the controller, the real-time parameter variations are estimated by the adaptive law instead of the nominal parameters, which can further improve the system performance. Define $\bar{B} = \bar{B} - \bar{B}$ and $\bar{F}_\Sigma = \bar{F}_\Sigma - \bar{F}_\Sigma$, (15) can be rewritten as

$$\dot{e}_2 = \frac{1}{M} \left[ -F_i + (\bar{r} - e_2) B + F_\Sigma + M \dot{r} \right]
= -B e_2 + \frac{1}{M} \left[ -F_i + M \dot{r} + \bar{r} (B - \bar{B}) + (\bar{F}_\Sigma - F_\Sigma) \right].$$  \hspace{1cm} (16)

where $\bar{B}$ and $\bar{F}_\Sigma$ are the estimated values of $B$ and $F_\Sigma$, which are estimated by the adaptive laws. $\bar{B}$ and $\bar{F}_\Sigma$, which are obtained by the difference between the actual value and the estimated value of the system.
Due to the proposed ABCSMC method combines the merits of ABC and CSMC, virtual velocity error \( e_2 \) is used as the variable instead of position tracking error in the design of sliding surfaces. The sliding surfaces are defined as

\[
\begin{align*}
    s_1 &= e_2 + k_2 \int_0^t e_2(\tau) d\tau, \\
    s_2 &= e_2 - k_2 \int_0^t e_2(\tau) d\tau,
\end{align*}
\]

where \( s_1 \) is the generalized sliding surface, \( s_2 \) is the complementary sliding surface, which is used to combine with \( s_1 \) to improve the dynamic behaviour of the system. \( k_2 \) is a positive constant, which is designed based on the desired drive system dynamics such as rise time, overshoot and settling time.

It can be seen from (17) and (18) that the relationships between two sliding surfaces are as follows:

\[
\begin{align*}
    s_3 &= s_1 + s_2 = 2e_2, \\
    i_2 + k_2 (s_1 + s_2) &= i_1,
\end{align*}
\]

where \( s_3 = s_1 + s_2 \), which is the summation of the sliding surfaces.

(20) can be rearranged by using (15)–(19) as

\[
\begin{align*}
    i_1 - k_2 e_2 &= i_2 + k_2 e_2 - k_2 e_2 \\
    &= \frac{B}{M} e_2 + \frac{1}{M} \left[ -F_i + M \dot{v} + \ddot{v} \left( \dot{B} - B \right) + \left( F_s - F_s \right) \right]. \\
    + k_2 e_2 - k_2 e_2
\end{align*}
\]

By using (6) and (21), the control law is designed as

\[
\begin{align*}
    i_{q_1} &= \frac{F_i}{K_f} / K_f \\
    &= \left( M \ddot{v} + \eta_1 \text{sat} (s_3) + \eta_2 |v| \text{sat} (s_3) + \frac{1}{M} \right) / K_f, \\
    + (-Mk_2 e_2 + Mk_2 s_1 + k_3 s_3 + \ddot{v} B) / K_f
\end{align*}
\]

where \( i_{q_1} \) is the control input, \( \eta_1 \) is the upper bound of \( F_s \), \( |F_s| < \eta_1 \), \( \eta_2 \) is the upper bound of \( B \), \( |B| < \eta_2 \), \( k_3 \) is a positive constant, \( \text{sat}(\bullet) \) is the saturation function, which is designed as

\[
\text{sat} \left( \frac{s_3}{\phi} \right) = \begin{cases} 
    \text{sgn} (s_3) & |s_3| \geq \phi \\
    \frac{1}{\phi} & |s_3| < \phi,
\end{cases}
\]

where \( \phi \) is the boundary layer thickness, \( \text{sgn}(\bullet) \) is the sign function.
FIGURE 16 Experimental results of PMLSM servo systems using ABC-SMC with DPM when \( \theta_s = 20 \) in case 2: (a) Tracking error, (b) control signal, and (c) estimated value of \( F_\Sigma \)

FIGURE 17 Line chart of the performance indexes in case 2

In the conventional SMC, the existence of discontinuous sign function makes the system easy to produce chattering with high frequency and small amplitude. The use of saturation function shown in (23) increases the boundary layer control and effectively weakens chattering phenomenon. However, it will reduce the robustness of the system caused by the boundary layer, so the steady-state error cannot be completely weakened [25]. In order to further improve the chattering suppression and reduce the steady-error within the boundary layer, an adaptive saturation function is designed as follows:

\[
\hat{\rho} s_3 = \begin{cases} 
\text{sgn} (s_3) & |s_3| \geq \phi \\
\hat{\alpha}^T \hat{\psi} (s_3) & |s_3| < \phi
\end{cases},
\]

where \( \hat{\psi} (s_3) = [s_3, \int_0^t s_3 d\tau]^T \), and \( \hat{\alpha} = [k_p, k_f]^T \) is adjusted by an adaptive law to approximate the optimal value \( \alpha^* = [k_p, k_f]^T \), where \( k_p > 0, k_f > 0 \). Therefore, \( \alpha^* \) can be obtained as

\[
\alpha^* = \arg \min_{\hat{\alpha} \in \mathbb{R}^2} \left[ \sup_{s \in \mathbb{R}} |\hat{\alpha}^T \hat{\psi} (s_3) - \text{sgn} (s_3)| \right],
\]

\[
\rho^* s_3 = \begin{cases} 
\text{sgn} (s_3) & |s_3| \geq \phi \\
\alpha^*^T \hat{\psi} (s_3) & |s_3| < \phi
\end{cases}.
\]

By incorporating the adaptive saturation function into the ABC-SMC method, the control law and the parameter adaptive laws can be obtained by using (24) to replace the saturation function in (23)

\[
i_q = \left( M\hat{\tau} + \eta_1 \hat{\rho} s_3 + \eta_2 \hat{B} \right) + \frac{\hat{\rho}_2 - M k_2 s_2}{K_f} \hat{\alpha}^T \hat{\psi} (s_3) + \frac{\hat{F}_\Sigma}{K_f} + \hat{\alpha}^T \hat{\psi} (s_3),
\]

\[
\dot{\hat{\alpha}} = \eta_1 \hat{\alpha} + \eta_2 \hat{\alpha} \hat{\alpha} \hat{\psi} (s_3),
\]

where \( \gamma_1, \gamma_2, \gamma_3, \gamma_4 \) are positive constant gains, \( \Gamma = \text{diag}(\gamma_3, \gamma_4) \), and \( \gamma_3, \gamma_4 \) are positive constant gains. It can be seen that (29)–(31) are the adaptive laws of \( \hat{B}, \hat{F}_\Sigma \) and \( \hat{\alpha} \), which are used to estimate the parameters and the adaptive gain, thereby further improving the adaptiveness and the robustness of the system.

3.2 Proof of stability

For demonstrating the stability of the control scheme, Lyapunov stability theorem and the Barbalat’s lemma are employed in this part. The Lyapunov function candidate is adopted as

\[
V = \frac{1}{2} \dot{\hat{\alpha}}^2 + \frac{1}{2} M\dot{\hat{\tau}}^2 + \frac{1}{2} M_{11}\dot{s_1}^2 + \frac{1}{2} M_{12}\dot{s_2}^2 + \frac{1}{2} M_{21}\dot{s_2}^2 + \frac{1}{2} \hat{B}^2 + \frac{1}{2} \hat{F}_\Sigma^2 + \frac{1}{2} \hat{\alpha}^T \Gamma^{-1} \hat{\alpha},
\]
EXPERIMENTAL RESULTS

3.3 Dead-zone parameter modification design

In the PMLSM servo system based on ABCSMC, the parameters of the system can be estimated effectively by using the adaptive laws, thus the influence of uncertainties on the system can be restrained, and the adaptiveness and robustness can be improved. Though the asymptotic stability of the ABCSMC system is proved in (38), the convergence of tracking error does not mean that the estimated value $\hat{B}$ and $\hat{F}_2$ will converge to the real value $B$ and $F_2$. This means that the estimation error will exist, even if the adaptive laws in (29)–(31) constantly adjust the parameters to reduce the estimation error. Although the training times of parameters affect the convergence accuracy, the overtraining problem will affect the response speed, even the stability of the system. Therefore, a DPM method is proposed to cope with the parameters-drift problem.

The purpose of DPM is to set an index to control the parameter tuning process. Assume that the trajectory is periodic and $\gamma_{\Delta}$ is selected as the cycle time, thus the tracking performance index $S_{\text{index}}$ is given as [27]

$$S_{\text{index}} = \int_{\gamma_{\Delta}}^{\gamma_{\Delta}+\gamma_{\Delta}} |\hat{a}|^2 dt.$$  \hspace{1cm} (39)

The adaptive laws in (29)–(31) are corrected as

$$\hat{B}_{e} = \begin{cases} Y_{1} \hat{\tau}(s_{3}), & \text{if } S_{\text{index}} \geq S_{th} \\ 0, & \text{if } S_{\text{index}} < S_{th} \end{cases} \hspace{1cm} (40)$$

$$\hat{F}_{\Sigma} = \begin{cases} Y_{2} (s_{3}), & \text{if } S_{\text{index}} \geq S_{th} \\ 0, & \text{if } S_{\text{index}} < S_{th} \end{cases} \hspace{1cm} (41)$$

$$\hat{\alpha} = \begin{cases} (\eta_{1} + \eta_{2} |\hat{\tau}|) s_{3} \Gamma \psi_{3}, & \text{if } S_{\text{index}} \geq S_{th} \\ 0, & \text{if } S_{\text{index}} < S_{th} \end{cases} \hspace{1cm} (42)$$

where $\hat{B}_{e}$, $\hat{F}_{\Sigma}$, and $\hat{\alpha}$ are the corrected adaptive laws, respectively, which is modified by DPM. $S_{th}$ is a performance threshold. It can be seen from (40)–(42) that when the tracking performance index $S_{\text{index}}$ is smaller than performance threshold $S_{th}$, the updating will stop. That is,

$$\text{Learning} = \begin{cases} \text{Enabled}, & \text{if } S_{\text{index}} \geq S_{th} \\ \text{Disabled}, & \text{if } S_{\text{index}} < S_{th} \end{cases}.$$ \hspace{1cm} (43)

Therefore, the DPM behaves in the same way as the conventional adaptive laws in (29)–(31) outside the dead-zone, the system is still stable in that region. On the contrast, the parameter tuning process will stop to avoid the parameters – drift problem when $S_{\text{index}} < S_{th}$. In addition, the selection of the performance threshold $S_{th}$ is of great significance in the design of DPM. Smaller performance threshold $S_{th}$ achieves better accuracy, but unfavourable dynamic response, even parameter-drift eventually. Larger performance threshold achieves a faster tuning process, but the accuracy is not as good as small $S_{th}$. As a result, there must be a trade-off between the dynamic response and the tracking accuracy of the system.

4 EXPERIMENTAL RESULTS

4.1 Experiment setup

In order to investigate the feasibility of the proposed control scheme, the experiments of the proposed ABCSMC with DPM
are carried out. Figure 2 is the PMLSM control system based on DSP TMS320F28335. The test bench utilizes a PMLSM produced by Kollmorgen, America, the specifications of which are listed in Table 1.

For the proposed ABCSMC method, the parameters, especially the ones in adaptive laws, are very important. Therefore, the following analysis is carried out. Selection of the upper bounds \( \eta_1 \) and \( \eta_2 \) for \( \tilde{F}_2 \) and \( B \) has significant effect on the control performance of the system. A larger value will aggravate the chattering phenomenon, while a smaller value will affect the convergence speed. Regarding the proposed ABCSMC system, the parameters \( \phi_1, \phi_2, \phi_3 \) and \( \gamma_4 \) are the coefficients of the adaptive laws. If the parameters are chosen as large values, high adaptive speed will be achieved, but the accuracy in the control effort will be affected; instead, the convergence of the system maybe degraded due to small values. Besides, the parameters \( k_1, k_2, \) and \( k_3 \) are usually selected based on the significance of tuning objects. Regarding the boundary layer thickness \( \phi \), if \( \phi \) is chosen as a large value, the chattering becomes severe, which affects the tracking accuracy; whereas, when the smaller value \( \phi \) is selected, the tracking accuracy of the system is improved, but the robustness becomes worse. Therefore, considering the requirements of stability and possible operating conditions, the trial-and-error method is mainly used for the selection of parameters in ABCSMC, which is to adjust the parameters continuously to achieve the best dynamic and steady-state performance in experimentation. Based on the above arguments, the parameters in ABCSMC are as follows: \( k_1 = 12, k_2 = 25, k_3 = 2, \eta_1 = 0.4, \eta_2 = 0.2, \phi = 0.15, \gamma_1 = 0.04, \gamma_2 = 0.05, \gamma_3 = 0.06, \gamma_4 = 0.03 \).

To make the structure of this method clearer and easier to understand, the flowcharts of the proposed ABCSMC with DPM is shown in Figure 3. It can be seen that the real-time control process includes main program and interrupt programs. The initializations of parameters and I/O are set in the main program. Then, the two interrupt programs (IR1 and IR2) are set.

### 4.2 Experimental results and analysis

In order to highlight the superior characteristics of our proposed ABCSMC with parameter estimation and dead-zone modification, three controllers including (i) ABC [16], (ii) CSMC [22], (iii) ABSMC [23] are applied to the PMLSM servo system for comparison. In addition, two test conditions including the external disturbance case (case 1) and the parameter variation case (case 2) are tested of the reference trajectory. Moreover, three performance indexes – the average value of the tracking error \( (E_{\mu}) \), the standard deviation of the tracking error \( (E_{\mu d}) \), and the steady-state tracking error \( (E_{\mu s}) \) – are used to measure the performance of the controllers. \( E_{\mu} \) and \( E_{\mu s} \) can be used to demonstrate the tracking accuracy of the controllers, and that \( E_{\mu d} \) can represent the oscillation of the tracking error.

Firstly, in order to test the effectiveness of the proposed ABCSMC, the disturbance rejection experiments are investigated by adding a subsequent external disturbance of 50 N at 15 s in case 1. The experimental results of the PMLSM servo system using ABC [16], CSMC [22], ABSMC [23] and the proposed ABCSMC are shown in Figures 4 to 7, respectively. It can be seen that under the four control methods, the system position response curves in Figures 4(a), 5(a), 6(a) and 7(a) can track the sinusoidal and trapezoidal hybrid reference trajectories with time varying amplitude and frequency accurately, but the tracking accuracies are different a lot. Comparing Figure 4(b) with Figure 5(b), it is obvious that the position tracking error of the two controllers is basically the same, the steady-state error is about \(-20\) to \(-20\, \mu m\). Additionally, it can be found from Figure 6(b) and Figure 7(b) that both ABSMC and ABCSMC achieve better tracking accuracy owing to the combination of ABC and CSMC, but ABCSMC has the smaller chattering than ABSMC. Moreover, the tracking error of the PMLSM servo system using ABSMC and ABCSMC is about \(20\, \mu m\) under the condition of subsequent external disturbance, which is \(35\%\) and \(28\%\) of the error values for the ABC and CSMC methods, respectively. Consequently, the proposed ABCSMC achieves favourable performance when the external disturbance occurs in the PMLSM servo system.

Next, in order to verify the DPM proposed in this paper, experiments of ABCSMC with DPM for different performance thresholds are carried out. The corresponding experimental results are demonstrated in Figure 8 and Figure 9. In addition, the parameters of DPM are selected as \( \delta_0 = 0.5, \tau = 1 \) for Figure 8 and \( \delta_0 = 20, \tau = 1 \) for Figure 9. Comparing Figures 8(b) and 9(b) with Figure 7(b), we can see that by combining ABCSMC with DPM, the smaller tracking errors and the smoother tracking curves are achieved. However, the tracking error curve of ABCSMC with DPM for small performance threshold in Figure 8(b) achieves better tracking accuracy, but slower response speed than that in Figure 9(b). The reason is that smaller performance threshold may cause overtraining problem, thereby affecting the dynamic response and the settling time of the system. On the contrary, the response curve in Figure 9(b) controlled by ABCSMC with DPM for large performance threshold achieves faster response speed, but larger tracking error. For better performance comparison of the controllers, the line chart of the performance indexes in case 1 is shown in Figure 10. It is obvious that the proposed ABCSMC with DPM has achieved the best control performance, no matter whether the performance threshold is large or small. Therefore, the tracking accuracy and the disturbance rejection ability of the PMLSM servo system can be significantly improved by using the proposed method.

Finally, the parameter variation condition is given by adjusting the actual mass \( M_a = 2 \, M = 32.8 \, kg \) to further verify the control performance for suppressing the uncertainties. The reference trajectory is the same as that in case 1. The experimental results including tracking error curves and control signal curves of the PMLSM servo system when using ABC, CSMC, ABSMC, ABCSMC and ABCSMC with DPM are shown in Figures 11 to 16, respectively. Besides, in order to testify the accurate approximation capability of ABCSMC, the estimated curves of \( \tilde{F}_2 \) are shown in Figures 14(c), 15(c) and 16(c). For performance
comparison, the line chart of the performance indexes is depicted in Figure 17. It can be seen from Figures 11(a) to 14(a) that when the parameter variations occur in the system, the tracking errors of ABC and CSMC will still be unfavourable compared with the ABSMC and ABCSMC. This proves that the combination of BC and SMC can effectively improve the control performance of the system. Comparing Figures 15 and 16 to Figure 14, it can be seen that the tracking error curves are greatly smoothed and the error fluctuations are clearly reduced by using the ABCSMC with DPM. This proves that the proposed DPM algorithm is feasible and effective in improving the servo performance. Additionally, by observing the line chart in Figure 17, we can see that the proposed ABCSMC with DPM has the most favourable performance among these controllers owing to its capabilities of parameter estimation and dead-zone modification.

From the above two groups of experimental results, it can be concluded that, the proposed ABCSMC with DPM in this paper has achieved superior control performance, whether in the presence of external disturbances or parameter variations. Compared to ABC [16], CSMC [22] and ABSMC [23], the PMLSM servo system in our proposed method is exhibited by improved accuracy and strong robustness in servo performance.

5 | CONCLUSION

This study involved demonstrating the effectiveness of the proposed ABCSMC with DPM method for a PMLSM servo system by considering uncertainties such as parameter variations and external disturbances. The ABCSMC method combines the merits of the backstepping controller and the sliding mode controller, which is capable of estimating parameter variations and compensating uncertainties. In order to further reduce the steady-state error, an adaptive saturation function is incorporated into the ABCSMC. The parameters can be adjusted on-line by the adaptive laws, so that the control law can be implemented easily. Additionally, a DPM algorithm is designed for solving the overtraining problem of the adaptive laws to further improve the adaptiveness and robustness. The stability of the system is proven by the Barbalat’s lemma and the Lyapunov theorem. Finally, the more accurate tracking performance and stronger robustness of the proposed control scheme compared to conventional approaches have been confirmed through comparative experimental studies implemented on a DSP. For future works, some optimization methods, such as finite time and the fastest speed control, can be used to improve the convergence performance of the system in practice.

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REFERENCES

1. Park, E., et al.: A design of optimal interval between armatures in long distance transportation PMLSM for end cogging force reduction. J. Electr. Eng Technol. 11(2), 361–366 (2016)
2. Chen, M., Liu, J.: High-precision motion control for a linear permanent magnet iron core synchronous motor drive in position platform. IEEE Trans. Ind. Inf. 10(1), 99–108 (2014)
3. Song, B., et al.: Fractional order modeling and nonlinear fractional order pi-type control for PMLSM system. Asian J. Control 1(2), 99–108 (2017)
4. Zhi, F., et al.: Analysis and elimination of harmonics in force of ironless permanent magnet linear synchronous motor. Proc. CSEE 37(7), 2101–2109 (2017)
5. Ding, X., Liu, T.: Intelligent adaptive neural network control for permanent magnet linear synchronous motor using self-evolving probabilistic fuzzy neural network. IET Electr. Power Appl. 11(6), 1043–1054 (2017)
6. Wang, Y., et al.: A robust adaptive neural network control method based on permanent magnetic linear synchronous motor for the reticle stage of lithography. Trans. China Electrotech. Soc. 36(16), 38–46 (2016)
7. Chen, S.Y., Liu, T.S.: Intelligent adaptive fuzzy logic controller for DC motor speed control. Ain Shams Eng. J. 5(3), 803–816 (2014)
8. Ting, C.S., et al.: An adaptive FNN control design of PMLSM in stationary reference frame. J. Control, Autom. Electr. Syst. 27(4), 391–405 (2016)
9. Yu, J., et al.: Adaptive fuzzy dynamic surface control for induction motors with iron losses in electric vehicle drive systems via backstepping. Inf. Sci. 376(10), 172–189 (2017)
10. El-Sousy, F., Abubakel, K.A.: Intelligent adaptive dynamic surface control system with recurrent wavelet Elman neural networks for DSP-based induction motor servo drives. IEEE Trans. Ind. Appl. 55(2), 1998–2020 (2019)
11. Guo, Y., Long, H.: Self-organizing fuzzy sliding mode controller for the position control of a permanent magnet synchronous motor drive. Ain Shams Eng. J. 2(2), 109–118 (2011)
12. Lee, H., et al.: Global robust terminal sliding mode control for PMLSM servo system. Appl. Mech. Mater. 273, 280–285 (2013)
13. Hsu, C.: Adaptive neural complementary sliding-mode control for induction motors. Int. J. Autom. Comput. 10(4), 303–311 (2013)
14. Jamoussi, K., et al.: Robust sliding mode control using adaptive switching gain for induction motors. Int. J. Autom. Comput. 10(4), 303–311 (2013)
15. Lu, L., et al.: Design sliding mode control of fuzzy switching gain for lift-feedback fin stabilizers. Int. J. Naval Archit Ocean Eng. 11(1), 584–596 (2019)
16. Zhao, X., Zhao, J.: Complementary sliding mode variable structure control for permanent magnet linear synchronous motor. Proc. CSEE 35(10), 2552–2557 (2015)
17. Liu, S., et al.: Modified complementary sliding mode control for the longitudinal motion stabilization of the fully-submerged hydrofoil craft. Int. J. Naval Archit Ocean Eng. 11(1), 584–596 (2019)
18. Lin, FJ, et al.: FPGA-based intelligent complementary sliding mode control for PMLSM servo drive system. IEEE Trans. Power Electron. 25(10), 2573–2587 (2010)
19. Hsu, C.: Adaptive neural complementary sliding-mode control via functional-linked wavelet neural network. Eng. Appl. Artif. Intell. 26(4), 1221–1229 (2013)
20. Hsu, C., Kuo, T.: Intelligent complementary sliding-mode control with dead-zone parameter modification. Appl. Soft Comput. 23, 355–365 (2014)
21. Trabelsi, R., et al.: Backstepping control for an induction motor using an adaptive sliding rotor-flux observer. Electr. Power Syst. Res. 93, 1–15 (2012)
22. Ting, C.S., et al.: Adaptive backstepping control for permanent magnet linear synchronous motor servo drive. IET Electr. Power Appl. 9(3), 265–279 (2015)
23. Li, J., et al.: Adaptive backstepping sliding mode control for the oscillation displacement system of continuous casting mold with mismatched disturbances. IEEE Access. 7, 148731–148740 (2019)
24. Jiang, X., et al.: An adaptive backstepping sliding mode method for flight attitude of quadrotor UAVs. J. Central South Univ. 25(3), 616–631 (2018)

25. Huang, Y., et al.: DC-Link voltage regulation for wind power system by complementary sliding mode control. IEEE Access 7, 22773–22780 (2019)

26. Aounallah, T., et al.: A novel algorithm on fuzzy adaptive backstepping control of fractional order for doubly-fed induction generators. IET Renew. Power Gener. 12(8), 962–967 (2018)

27. Hsu, C.F.: Intelligent total sliding-mode control with dead-zone parameter modification for a DC motor driver. IET Control Theory Appl. 8(11), 916–926 (2013)

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